CHARLES PANKOW
FOUNDATION
Building Innovation through Research

Assessing the Impact of "Green" Concrete Mixtures on Building Construction

Submitted By

ASCC Education, Research & Development Foundation

December 2013

EDUCATION, RESEARCH & DEVELOPMENT
ASCC
FOUNDATION
AMERICAN SOCIETY OF CONCRETE CONTRACTORS

PROVIDING THE MEANS TO ADVANCE CONCRETE CONSTRUCTION

Project Participants

Principal Investigator

- Ward R. Malisch, PhD, PE, FACI – Concrete Construction Specialist ASCC

Industry Champion

- Bruce A. Suprenant, PhD, PE, FACI – Technical Director ASCC

Authorized Organizational Representative

- Bev Garnant – Executive Director ASCC

Industry Collaborators

- Mike Donovan, Central Concrete Supply - A U.S. Concrete Company
- David Mar, Tipping Mar
- Phil Williams, Webcor Builders
- Tarek Khan, BASF

Funding
Charles Pankow Foundation
ASCC Education, Research & Foundation
ACI Concrete Research Council

PROVIDING THE MEANS TO ADVANCE CONCRETE CONSTRUCTION

Preface

The American Society of Concrete Contractors submitted a proposal to the Charles Pankow Foundation for preparation of a *Users' Guide to "Green" Concrete in Building Construction.* In this context, "green" refers to concretes made with supplementary cementitious materials (SCMs) replacing varying amounts of portland cements to reduce the carbon footprint. As part of the preparation, several green concrete mixtures were tested and the data presented to provide information about mixture composition that is usually proprietary and not available to the industry or public. The relationship between cylinder strength and strength of cores from the same batch of concrete was of particular interest. The data was intended to supplement the limited amount of published data related to field experience with green concrete.

Bruce Suprenant and Ward Malisch, the authors of this report, became interested in this topic as a result of Suprenant's troubleshooting work on projects that utilized green concrete with acceptance testing done at 56 or 90 days rather than the standard 28 days. This later testing compensates for slower rates of strength gain when large amounts of portland cement are replaced by SCMs, but with a downside: more concrete has been placed when the test results become available at test ages greater than 28 days. If a strength test result is lower than allowed, and subsequent core testing indicates that the in-place strength is also lower than allowed, repair or removal and replacement generally costs more because of the larger volume of concrete in place. Schedule delays resulting from needed decisions on acceptance may also be more critical at this point.

As our test results became available, we realized that the relationships between strengths of field-cast, wet-cured cylinders and cores from large blocks cast in the field were particularly puzzling. At ages of 28 to 180 days, the core/cylinder ratios ranged from about 0.40 to 0.90, with an overall average of about 0.65 for all but one of the 11 mixtures studied. Core/cylinder relationships for a control mixture containing no SCMs followed the same trend as those for fly ash, slag, ternary, and quaternary mixtures. This led to a literature search related specifically to the core/cylinder strength ratios for normal or high-strength concretes made with straight cements and varying SCM contents. That search resulted in questions concerning the ACI 318 code requirement that the average core strength of three cores must equal 0.85 times the design strength of the concrete, with no core in the set of three lower than 0.75 times the design strength.

As a result, we changed the title of our report to "Assessing the Impact of "Green" Concrete Mixtures on Building Construction." The report still covers construction rather than performance. But we acknowledge that our test results are for a combination of one cement, SCM, and admixture source and that, in field tests, the control mixture containing no SCMs performed similarly to mixtures made with varying percentages of SCMs. The scope for our field experiments did not include a factorial approach to evaluating the interactions between the cement and admixtures, nor do we suggest that the results of the field experiments can be generalized to include all green concretes. We do believe that, for confirmation, the results require further research of green concretes using differing cements and admixtures and in differing geographic regions. We also agree with the following recommendation in ACI 363.2R-11,"Guide to Quality Control and Assurance of High-Strength Concrete:"

"… a correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 4 in. [102 mm]) in diameter) to the strength of specimens used for acceptance testing, that is, 6 x 12 in. (152 x 305 mm) or 4 x 8 in. (102 x203 mm) cylinders. Then, if coring becomes necessary, the relationship has been established, agreed upon, and is ready for conclusive interpretation."

The correlation between core strength and the strength of specimens used for acceptance testing should be discussed at a preconstruction conference so the engineer of record, concrete producer, and concrete contractor are in agreement on steps to be taken when core tests are needed.

As the title of our original proposal implied, we were primarily interested in topics related to construction as opposed to performance of the green concrete after construction. Thus our testing program did not directly address durability because assessment of durability requires long-term testing or development of models for predicting durability, neither of which was within the scope of our proposal.

Bruce A. Suprenant
Ward R. Malisch

Assessing the Impact of “Green” Concrete Mixtures on Building Construction

Table of Contents

1. Introduction
    - 1.1 Materials for “Green” Concrete
        - 1.1.1 SCM Sources, Usage, and Effects on Concrete Properties
            - Fly ash
            - Slag cement
            - Silica fume
    - 1.2 Significance of High-volume SCM Effects on Concrete Properties
    - 1.3 References

2. Compressive Strength
    - 2.1 Laboratory Trial Mixtures
        - 2.1.1 Early-Age Strength Data
        - 2.1.2 Core-to-Cylinder Relationships
    - 2.2 Later-age Strength Verification
    - 2.3 Seal- versus Water-cure Compressive Strengths
        - 2.3.1 Sanjayan and Sioulas Tests on Slag-cement Concrete
        - 2.3.2 Wu et al. Tests on Fly Ash Concrete
        - 2.3.3 Aitcin et al. Tests on Concrete Containing no SCM’s
        - 2.3.4 Pankow Tests on Fly Ash, Slag-cement and Ternary Concrete
    - 2.4 Compressive Strength of Concretes Cured by Air-drying
    - 2.5 Comparison of Researcher’s Data
    - 2.6 References

3. Low-strength Investigation: Core-to-Cylinder Relationship
    - 3.1 ACI Core acceptance Criteria: A History
        - 3.1.1 How Core Conditioning Affects Core Strength-Test Results
    - 3.2 Project Experience with Green Concrete Core-Strength Test Results
        - 3.2.1 Mat Foundation in California
        - 3.2.2 Columns in Ohio
        - 3.2.3 Personal Communication at an NRMCA Conference
        - 3.2.4 Industry Literature Confirmation
        - 3.2.5 Is 85 Percent of f’c an Appropriate Acceptance Value for Green Concrete Cores?
    - 3.3 The Bloem 1965 and 1968 Data
        - 3.3.1 Basic Test Data

3.3.2 Limitations of Bloem's Research
Strength levels
Supplementary cementitious materials
Water-cement ratio and curing method
Heat generation
3.3.3 Bloem's Core-to-Cylinder Relationships
3.4 Pankow Core-to-Cylinder Data
3.4.1 Raw Core-to-Cylinder Data
3.4.2 Retest Cores at 282 Days
3.4.3 Curing Adjustment
3.4.4 Internal Temperature Adjustment
3.4.5 Comparison to Bloem's Data
3.4.6 Comparison with ACI 363.2R-11 and ACI 214.4R-10
References
Cook 1989
Burg and Ost 1992
Bickley et al. 1991, 1994
Aiticn and Riad 1988
3.5 References

4. Early-age Compressive Strength and Construction Operations
4.1 Early-age Construction Operations
Vertical Form Removal
Early-age Freezing
Saw-cutting Joints
Post-tensioning
Elevated Form Removal
Miscellaneous Construction Operations
4.2 Pankow Early-age Compressive Strength Data
4.3 Project Experiences
4.4 The Need for Early-age Compressive Strength Data Prior to Bidding
4.5 Flexible Engineering is Needed
4.6 References

5. Fresh Concrete Properties and Construction Operations
5.1 Fresh Concrete Construction Operations
Placing Concrete in Vertical Forms
Consolidating Concrete
Finishing Concrete
Curing during Finishing
Final Curing

5.2 Understanding Time of Setting Measurements
5.3 Evaluating Time of Setting at Different Temperatures
5.4 How Setting Time Influences Plastic Shrinkage Cracking
5.5 Setting Time and Form Pressures
5.6 Evaluation of Pankow Setting Time Data
5.7 References

6. Recommendations for Using “Green” Concrete Mixtures
6.1 Background
6.2 Recommendations

List of Tables

Table 2.1 Sanjayan and Sioulas compressive strength of slag-cement concrete
Table 2.2 Pankow data: Average ratio of sealed to standard-cure cylinder strengths for all mixes
Table 2.3 Lab study: Ratio of sealed- and air-dry cure 4x8-in. cylinders to standard cure 4x8-in. cylinders at 28, 56, 90, and 120 days
Table 2.4 Field study: Ratio of sealed and air-dried cure 4x8 field-cast cylinders to 4x8 field-cast standard-cure cylinders at 7, 28, 56, 90, 120 and 180 days
Table 2.5 Pankow data: Average ratio of air- to standard-cure cylinder strengths for all mixes
Table 3.1 Retest strength and variability of cores from field constructed blocks
Table 3.2 Core-to-cylinder ratio statistics
Table 5.1 Lab study: Summary of ASTM C 403 set times at 60F, 72F and 90F

List of Figures

Figure 2.1 Compressive strength of concrete with 25% fly ash replacement tested at ages from 7 to 358 days.
Figure 2.2 Pankow Data: Sealed-cure to water-cure strength ratios for cylinders at ages up to 180 days.
Figure 2.3 Average sealed-cure to water-cure and air-cure to water-cure strength ratios for cylinders at ages up to 180 days.
Figure 3.1 From Bloem’s 1965 work.
Figure 3.2 From Bloem’s 1868 work.
Figure 3.3 Average core-to-cylinder ratios at same age for Bloem’s 1965 well-cured slabs and one column.
Figure 3.4 Average same-age core-to-cylinder ratios for Bloem’s 1968 well-cured slabs.
Figure 3.5 Raw (uncorrected) core/standard-cure cylinder ratio vs. coefficient of variation for all tests at Ages 28 to 280 Days

Figure 3.6 Core/sealed-cure cylinder ratio vs. coefficient of variation for all tests at Ages 28 to 180 Days
Figure 3.7 Core/sealed-cure cylinder ratio with temperature correction vs. coefficient of variation for all tests at Ages 28 to 180 Days
Figure 4.1 Early-age compressive strength of standard–cure, field cast cylinders from 11 Pankow research mixtures.
Figure 5.1 Penetration resistance versus time showing initial and final set (from ASTM C 403).
Figure 5.2 Delaying the set time, moving from green to red line, can cause the concrete to reach a critical point where the cumulative evaporation exceeds the cumulative bleeding and plastic shrinkage cracks occur.
Figure 5.3 Initial setting times for concrete mixtures as measured by ASTM C 403. Initial setting times vary from a low of 190 minutes for the 100% cement mixture to greater than 780 minutes for the 70% ternary mixture with a carbohydrate-based admixture. Note that the carbohydrate-based admixture did not substantially increase initial setting time when used with the 100% cement mixture. All other concrete mixtures contained a polycarboxylate water-reducing admixture.
Figure 5.4 Penetration resistance versus time for three different mixtures at 60^{o}F: 100% portland cement, 50% fly ash and 70% ternary with low water-cementitious ratio. Note that the use of SCM's significantly delayed setting.

Assessing the Impact of “Green” Concrete on Building Construction

Chapter 1 Introduction

Concrete is an inherently “green” material as is indicated by many measures of construction-material sustainability. Well-proportioned, properly placed concrete reduces the life-cycle costs of buildings because it is a durable material. The effects of transportation on the environment are reduced because concrete is produced locally, as are the largest proportions of its ingredients, and its producers often use recycled materials that would otherwise be a part of the waste stream destined for landfills. Concrete’s thermal mass can reduce the energy required for heating and cooling buildings and its light color can reduce interior lighting demands in buildings. The demonstrated safety and security of fire- and storm-resistant concrete buildings is enhanced even further by structural design that emphasizes resilience—the ability to maintain building functionality after an earthquake or other natural disaster. But because carbon dioxide is emitted during manufacture of portland cement, green concrete building construction often involves reducing the carbon footprint by replacing some or all of the portland cement.

One approach is completely replacing portland cement with carbon-neutral cements that can be produced by using a magnesium oxide feedstock instead of calcium carbonate, adding a liquid activator to coal ash, or other such methods for reducing carbon dioxide emissions. But the most widely practiced approach is to simply replace increasingly larger percentages of the portland cement with supplementary cementitious materials (SCMs) that have been used in concrete for many years. The most common SCMs used green concrete include fly ash, slag cement, and silica fume.

1.1 Materials for “Green” Concrete

Ready-mixed concrete is used in nearly all concrete for building construction. A survey by the National Ready Mixed Concrete Association indicates that SCMs were used in about two-thirds of all ready-mixed concrete produced in the U.S. (Obla et. al. 2012). Most of the SCMs are byproducts of energy production or manufacturing processes that, if not used in concrete, would be destined for landfills or other storage facilities for industrial wastes. This enhances their value as sustainable alternatives to portland cement consumption.

<u>1.1.1 SCM Sources, Usage, and Effects on Concrete Properties</u>

Fly ash —This most widely used SCM is a byproduct of coal combustion in electric power plants and has been used to replace cement and to improve many desirable properties of concrete for more than 75 years. ASTM C618, “Standard Specification for Coal Fly Ash and Raw of Calcined Natural Pozzolan for Use in Concrete,” describes two classes. Class F fly ash is produced by burning anthracite or bituminous coal and is a pozzolan that reacts with byproducts of portland cement hydration to form additional calcium silicate hydrates—the basic cementing compound in concrete. Class C fly ash is produced by burning lignite or subbituminous coal and reacts with byproducts of portland cement hydration to form additional calcium silicate hydrates. It also has some cementitious properties when it reacts with water. Class F fly ash normally replaces 15% to 25% by mass of cementitious material and Class C fly ash is normally used at dosages of 15% to 40% (ACI 232.2R-03).

Table 4.4.2 in ACI 318-11, "Building Code Requirements for Reinforced Concrete," includes the following limits on fly ash in concrete subject to Exposure Class F3—exposed to freezing and thawing, in continuous contact with moisture, and exposed to deicing chemicals:

Cementitious material	**Max. % of total cementitious material by mass**
Fly ash conforming to ASTM C618	25%
Total of fly ash, slag, and silica fume	50%
Total of fly ash and silica fume	25%*

* Fly ash and silica fume shall constitute no more than 25% and 10% respectively.

Most concrete used in building construction is not in Exposure Class F3. In these cases, ACI 318-11 does not prohibit the use of percentages of fly ash exceeding 50% in green concrete, nor does it limit slag and silica fume.

The reduced volume of pores resulting from formation of calcium silicate hydrates improves concrete resistance to chemical attack by decreasing the rate at which water and aggressive chemicals such as sulfates can enter the concrete. Some Class F fly ash replacement percentages also reduce the harmful effects of alkali silica reactions in concrete. Improved durability has a positive effect on sustainability by extending concrete's service life in addition to reducing its initial carbon footprint.

Slow setting and slow early strength gain are the major disadvantages when replacing large amounts of portland cement with fly ash to reduce the carbon footprint. Steps that can be taken to offset this effect are discussed later in this report.

There is some anecdotal evidence that concrete containing fly ash may reject coatings such as paint and flooring adhesives, thus resulting in loss of adhesion between the coating or adhesive and the concrete substrate (Lick, 2013). No studies have identified the mechanism by which this happens, however, or a critical percentage replacement at which the adhesion loss occurs. This Pankow study did not include adhesion of coatings or adhesives within the project scope.

As of the date of this report, the future use of fly ash in concrete may be impacted by pending regulatory action by the U.S. Environmental Protection Agency, which is considering regulating fly ash as a hazardous waste rather than an exempt waste.

Slag cement — Previously called ground granulated blast furnace slag (GGBFS), slag cement is a byproduct of iron production for use in steel making. ASTM C989, "Standard Specification for Slag Cement for Use in Concrete and Mortars," provides for three strength classifications based on a slag activity index: Grades 120, 100, and 80 are ranked in order of decreasing slag activity, which is related to 7- and 28-day strength results. When used in building construction, slag cement may comprise 30% to 70% of the cementitious material with the larger percentage replacements used in mass concrete, especially in foundations. Delays in setting time can be expected when more than 25% slag cement replaces portland cement in concrete mixtures. When compared with portland cement concrete mixtures, concrete containing Grade 120 slag cements typically results in reduced strength within one to three days of placement and increased strength at seven days and beyond (ACI 233R-03). Slag cement reacts with sodium and calcium hydroxides present in fresh concrete, with that reaction producing calcium silicate hydrates that reduce porosity and pore size. This reduces the ability of aggressive chemicals to penetrate concrete and thus improves durability in a way similar to that of fly ash. Again, improved durability enhances sustainability by extending concrete's service life. Light color is a further sustainability advantage of slag cement concretes because the lighter color reduces lighting requirements.

Because sodium and calcium hydroxides released during portland cement hydration serve as activators for slag cement hydration, replacing all of the portland cement with slag cement would result in very slow setting and strength gain. As with fly ash, slow setting and slow early strength gains resulting from large portland cement replacements with slag cements can be offset by methods discussed later in this report.

Silica fume **—** Also known as condensed silica fume or microsilica, this SCM is an extremely fine, highly reactive pozzolan that is an industrial byproduct of the silicon metal and ferrosilicon industry. ASTM C1240, "Standard Specification for Silica Fume Used in Cementitious Mixtures," describes three forms in which silica fume can be added to concrete: as-produced, as a slurry mixed with water, or as a densified product. The densified product is most commonly used in the U.S.

Whereas fly ash and slag cement can replace large quantities of portland cement, silica fume is not used primarily as a cement replacement. Dosage rarely exceeds 10% by weight of cementitious material. It is commonly used in concretes that incorporate portland cement and either fly ash or slag cement because its small particle size and chemical reactivity improve the rate of early strength gain and durability of these concretes (ACI 234R-06). Because of its small particle size and resultant large surface area, the water demand of concrete containing silica fume increases with increasing amounts of silica fume. Addition of a water-reducing or high-range water-reducing admixture is mandatory to retain the strength and durability improvements.

To achieve desired performance objectives while reducing the carbon footprint, some green concretes are ternary mixtures containing portland cement, fly ash, and slag cement, while other quaternary mixtures contain three SCMs—fly ash, slag cement, and silica fume—plus portland cement. Results from testing ternary and quaternary mixtures, a binary mixture containing only fly ash and portland cement, and a straight portland cement mixture are discussed in this assessment.

1.2 Significance of High-volume SCM Effects on Concrete Properties

Replacing large amounts of portland cement with fly ash or slag cement can result in slower concrete setting and slower strength gain at both early and later ages. Unless the potential early-age effects are offset by using admixtures or altering the proportions of cementitious materials, the following effects are likely:

- Finishing delays that increase the contractor’s labor costs
- Plastic shrinkage cracking or settlement cracking as a result of slower setting.
- Damage to formed surfaces or delayed form removal, creating repair costs, reducing the economies from form reuse, or both
- Delays in stressing post-tensioning tendons that also delay forming and shoring removal

All of these possible effects can slow progress on project completion, which also increases costs.

Slower than normal strength gain at ages later than 7 days is sometimes accommodated by specifying design strengths based on cylinders tested at 56 or 90 days. This has drawbacks because on some green concrete projects, low 56- or 90-day cylinder breaks for field-cast laboratory-cured cylinders have led to core testing that resulted in low core strengths. Some sets of three cores on these projects did not reach 85% of the specified 56-day design strength as required by ACI 318-11, even at ages of 90 days or more. Strength retrogression in shear wall and column cylinder strengths was also noted (See Section 3.2.1).

In ACI 318-11, strength test results for field-cast, laboratory-cured cylinders are used for *acceptance* of the concrete. For concrete design strengths of 5000 psi or more, strength level is considered satisfactory if:

(a) Every arithmetic average of any three consecutive strength tests equals or exceeds the design strength.
(b) No strength test falls below the design strength by more than 10% of the design strength.

If either requirement is not met, steps must be taken to increase the average of subsequent strength test results. If the (b) requirement is not met, further analysis or testing is indicated, as discussed in Section 3.1 of this report.

Also ACI 318-11 indicates that strength test results for field-cast cylinders field-cured in accordance ASTM C31 may be required to check the adequacy of curing and protection of concrete in the structure. If strength of field-cured cylinders at the test age designated for determination of the design strength is less than 85% of that of companion laboratory cylinders, procedures for protecting and curing concrete must be improved. See Section 2.6 of this report for a discussion of this requirement as applied to the Pankow research laboratory data.

1.3 Selected References and Association Websites

- ACI 232.2R-03 “Use of Fly Ash in Concrete”
- ACI 233R-03 “Slag Cement in Concrete and Mortar”
- ACI 234R-06 “Guide for the Use of Silica Fume in Concrete”
- ASTM C 311 “Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete”
- ASTM C 595-13 “Standard Specification for Blended Hydraulic Cements”
- ASTM C 618-12a “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete”
- ASTM C 989-12a “Standard Specification for Slag Cement for Use in Concrete and Mortar”
- ASTM C 1697-10 “Standard Specification for Blended Supplementary Cementitious Materials”
- ASTM C 1240-12 “Standard Specification for Silica Fume used in Cementitious Mixtures”
- ASTM C 1709-11 “Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) in Concrete”
- Lick, David, “Best Practices: When the Substrate Rejects the Coating,” *MPI Newsletter,* Oct.2 , 2013, http://www.durabilityanddesign.com/news/?fuseaction=view&id=10308&nl_versionid=3543
- Obla, K., Lobo, C., and Kim, H., “The 2012 NRMCA Supplementary Cementitious Materials Use Survey,” *Concrete InFocus Magazine*, Fall 2012

Associations

- American Concrete Institute www.concrete.org
- American Coal Ash Association www.acaa-usa.org
- American Society of Concrete Contractors www.ascconline.org
- American Society of Testing and Materials www.astm.org
- National Ready-Mixed Concrete Association www.nrmca.org
- Silica Fume Association www.silicafume.org
- Slag Cement Association www.slagcement.org

Chapter 2 Compressive Strength

The procedures for selecting and verifying compressive strength when proportioning green concrete for buildings are similar to those followed for traditional concrete used in buildings. There are, however, a few notable exceptions for green concrete mixtures because using them may result in:

- The need for laboratory trial mixtures containing SCM materials and proportions for which no historical field strength data are available.
- Specified strengths being measured with field-cast cylinders tested at 56 days, 90 days, or later because of slow strength gain.
- Concrete mixtures with lower water-cementitious ratios to compensate for lower strength-gain rates of SCMs. Cylinder strengths for these mixtures are more sensitive to the differing effects of curing with external water or sealing the cylinders so internal water is the only source for curing.
- Core strengths not meeting the common acceptance requirement that the average of three cores must equal 85% of the specified strength.

2.1 Laboratory Trial Mixtures

Specifying strength levels at 56 or 90 days allows either the use of lower cementitious contents to achieve a desired strength or allows a higher strength to be achieved for a given cementitious content. Green concrete often requires laboratory trial mixture proportioning based on strength data obtained at 56 or 90 days, which can increase the lead time for starting concrete construction. Pre-planning is essential for setting construction schedules when no off-the-shelf green concrete mixtures are available.

The later age strength verification requires the design and construction team to be prepared for trial mixtures that might take 3 to 4 months to produce strength results. This time frame is based on having to do only one trial mixture; multiple trial mixtures performed consecutively would add to the required lead time. One ready-mixed concrete producer in California starts developing green concrete mixtures about a year before construction is scheduled to begin. Also in California, owners and the design team anticipate required lead times for multiple laboratory trial mixtures by an early addition of the ready-mixed concrete producer to the construction team.

In other cases, ready-mixed concrete producers develop green concrete mixtures in advance of getting a contract for a project. They understand that having both laboratory and field strength data available for their green concrete mixtures prior to initiation of a project gives them a distinct competitive advantage. Consider the advantage to concrete contactors if they can avoid starting a 3 to 4 month laboratory trial mixture process by:

- Selecting a green concrete mixture with laboratory and field strength data already available
- Initiating a concrete mixture design submittal and, when the submittal is approved,
- Starting concrete placement.

2.1.1 Early Age Strength Data**:** Cylinder strengths are obviously needed at the specified age, whether 28, 56 or 90 days. Knowing early-age strengths, however, is important for planning construction operations such as formwork removal, post-tensioning, and continuing construction. Laboratory cylinder strengths at 1, 3, 7, 14 and 28 days should be determined. Contractors can use these strengths to assist in planning and scheduling construction operations. Also these earlier strength values can be used as check points when cylinders are to be tested at ages greater than 28 days.

Even if the acceptance is at 90 days, it is wise to have field-made cylinders cast and tested at earlier ages to judge the potential of the concrete to reach the specified strength at 90 days. These "early-warning" cylinders can be used to gauge the amount of construction that can continue based on the current strength of the concrete.

While early-age laboratory cylinder strengths are useful for pre-planning and scheduling, the contractor must utilize field-made and field-cured cylinders to determine how to sequence and continue construction operations. For green concrete buildings, it is best to set a minimum strength level as a criterion for continuing construction rather than using a concrete age criterion.

2.1.2 Core-to-Cylinder Relationships**:** Core-to-cylinder relationships are discussed in Chapter 3. This Chapter recommends making field specimens with minimum dimensions that match those of the structural members, then taking cores at the test age for cylinder strength acceptance to establish the core-to-cylinder strength relationship for that mixture. It's preferable to do this during the laboratory trial mixture phase so these results can be discussed prior to starting construction.

2.2 Consequences of Later-Age Strength Verification

Later age strength verification affects the cost of remedial action when acceptance testing indicates that the concrete strength does not meet specification requirements. Section R5.6.5 of ACI 318-11 includes procedures to be followed if strength test results don't meet the requirements of Section 5.6.3.3(b). Section R5.6.5 suggests that the building official should apply judgment as to the significance of low test results and whether they indicate need for concern. Nondestructive tests of the in-place concrete may be may be used to confirm the strength tests results from field-cast cylinders. Per

Section 5.6.5.2 states that if the likelihood of low-strength concrete is confirmed, and calculations indicate that load-carrying capacity is significantly reduced, tests of cores drilled from the area in question shall be permitted. Section R.5.6.5 indicates that cores are to be taken in extreme cases, but doesn't define extreme cases. It is our experience that core tests are common if strength tests are low. If the average core strength doesn't meet the requirements of Section 5.6.5.4 of ACI 318-11, and the structural adequacy remains in doubt, Section 5.6.5.4 states that strength evaluation in accordance with Chapter 20 is permitted or other appropriate action may be taken. Following these requirements and suggestions is complicated when later age strength verification is required.

At 56 or 90 days, as opposed to 28 days for acceptance testing, more concrete has been placed when the test results become available. If a strength test result is lower than allowed, and subsequent core testing indicates that the in-place strength is also lower than allowed, repair or removal and replacement will cost more because of the larger volume of concrete in place. Schedule delays resulting from needed decisions on acceptance may also be more critical at this point. Thus, later age strength verification increases risk for both the owner and contractor. This increased risk should be discussed prior to construction. Possible considerations for reducing this risk would be:

- Having check cylinders tested at earlier ages.
- Having plans for core testing to be implemented when a low strength test triggers an investigation and other options have been investigated.
- Having a plan to alter the sequence or staging of construction when time is needed to address a low-strength investigation.
- Having in place a preliminary strengthening plan that could be implemented effectively and efficiently to minimize any work delay.

Specifications for a few green building projects have incorporated multiple strength requirements at different ages. For instance, one project in California had both 28- and 365-day strength requirements. The concrete met the strength requirement at 28 days. It is unclear whether cylinder strength tests were conducted at 365 days. But if they had been, and the results failed to meet specification requirements, the remedial measures available would have been severely limited because the concrete work was completed and other trades were almost finished with their work.

For traditional projects, contractors are accustomed to multiple field strength requirements needed to continue construction, such as minimum strengths for post-tensioning, form stripping, or shoring removal. But it's best to avoid multiple acceptance strength requirements for concrete based on laboratory cylinders. Otherwise, the concrete could be accepted at 56 days but rejected at 90 days. This creates problems for the owner and contractor with respect to determining how to proceed.

Engineers need to consider alternate methods of describing when formwork stripping, removal of shores, and post-tensioning can proceed. It may not be appropriate to specify a requirement for strengths of 75% or 85% of f_c' when f_c' is designated to be 8000 psi at 90 days. This would mean that a strength of 6000 or 6800 psi is required for starting construction operations needed much earlier than 90 days after concrete is placed.

2.3 Sealed- versus Water-Cured Compressive Strengths

Test cylinders molded in the laboratory are cured in accordance with ASTM C 31 “Standard Practice for Making and Curing Concrete Test Specimens in the Field,” which requires final cylinder curing in water storage tanks or moist rooms. These curing options provide external moisture that is not available when curing concrete by sealing the cylinders in the laboratory or using water-retention field curing methods for structural members. Sealed curing of test cylinders represents the best possible field curing. But for low water-cement ratio concretes, the cylinders cured by sealing or field concrete cured using water retention can undergo self-desiccation as described by Meeks and Carino (1999):

> **Self-Desiccation of Low Water-Cementitious Concrete**
>
> "One of the potentially detrimental side effects from the use of the low water-cement ratio concretes is self-desiccation, Self-desiccation refers to the process by which concrete dries itself from the inside. Internal moisture is consumed from within the paste by the hydration reactions, and the internal relative humidity continues to decrease to the point at which there is not enough water to sustain the hydration process. The result is that the hydration and maturity of the concrete will terminate at an early age if additional moisture is not provided. Therefore, self-desiccation effects are important considerations in the performance of high-performance concrete, particularly in the curing practices that involve “sealing” the concrete."

Several investigators have studied the effect of a water-cure versus a sealed-cure on compressive strength of concretes containing only portland cement and concretes in which some of the portland cement was replaced with SCMs.

2.3.1 Sanjayan and Sioulas Tests on Slag-cement Concrete: This paper reports the strength development of 16 full-scale columns made with 100% general purpose (GP) portland cement and GP portland cement-slag cement blends containing up to 70% slag cement. One slag cement blend also contained silica fume.

The study included mixtures with strength grades of 100, 80, 60, and 40 MPa (14,500, 11,600, 8700, and 5600 psi, respectively). Of the 1250 specimens tested, 800 were cores. The influence of moisture availability was systematically studied by subjecting standard cylinder specimens to water-bath and sealed curing conditions. Table 2.1 shows strength ratios of sealed-cure (SC) to water-bath cured (BC) cylinders at ages 7, 28, 56 and 91 days.

The average ratios of sealed-cure cylinder strengths to water-bath cured cylinder strengths for the 100% GP cement mixtures were 0.90, 0.90 and 0.96 at 28, 56 and 91 days, respectively. The average ratios of sealed-cure cylinder strengths to water-bath cured cylinder strengths for the GP cement-slag cement blends were 0.87, 0.84 and 0.82 at 28, 56 and 91 days, respectively.

Table 2.1 Sanjayan and Sioulas Compressive Strength of Slag-cement Concrete

Ratio of Sealed-cure Cylinder Strength to Water-bath-cure Cylinder Strength				
Mixture	7 days	28 days	56 days	91 days
100GP	1.04	0.96	0.97	1.01
100GB70/30	0.91	0.87	0.88	0.86
100GB50/50	0.95	0.93	0.88	0.89
100GB30/70	0.96	0.90	0.74	0.75
100GB45/45SF10	0.99	0.88	0.85	0.84
80GP	0.99	0.91	0.89	0.98
80GB50/50	0.84	0.82	0.83	0.77
60GP	0.79	0.85	0.86	0.91
60GB50/50	0.93	0.79	0.83	0.77
40GP	0.89	0.87	0.87	0.93
40GB50/50	1.00	0.89	0.86	0.83
Average without 100% GP mixes	0.93	0.87	0.84	0.82

Table 2.1 Note: Description of the labeling system adopted are as follows: xGP; where GP indicates general purpose portland cement and x indicates the strength grade in MPa. xGBy/z; where GB indicates General Blended cement, x indicates the strength grade, y and z indicate the percentage of portland cement and slag in the binder, respectively. 100GB45/45SF10 is a 100 MPa-grade mixture containing 45% portland cement, 45% slag, and 10% condensed silica fume.

Based on their data, Sanjayan and Sioulas concluded:

> "An inspection of the results showed that a lack of moist curing adversely affected compressive strength development of the slag-blended cements irrespective of slag content. The SC cylinders attained medium- and long-term compressive strengths lower than their respective BC cylinders. Although the early-age (7 days) strengths did not significantly differ between the SC and BC specimens, the detrimental effects of isolating specimens from a continuous supply of moisture were realized in the long term. Depriving the GP specimens of moisture did not adversely affect their long-term strength development."

2.3.2 Wu et al. Tests on Fly Ash Concrete: This study used fly ash concrete specimens at 25% replacement with a w/cm of 0.40 and three curing conditions; water-, sealed- and air-dried curing. Reference concretes without fly ash were also tested. Compressive strength was measured at 7, 28, 91, 182, 273 and 358 days. Figure 2.1 shows the compressive strength for the three curing conditions. Note that the compressive strengths of the sealed-cure specimens were lower than those of the water-cured specimens by approximately 10 to 15% at ages from 91 through 358 days. The researcher's data for reference concrete mixtures showed only a slight difference in strength between water- and sealed-cure compressive strength at all ages.

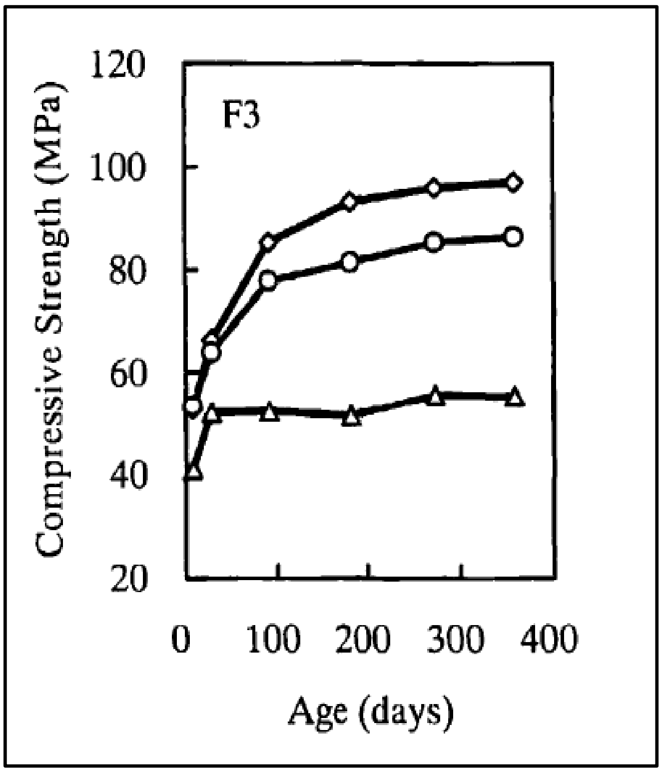


Figure 2.1 Compressive strength of concrete with 25% fly ash replacement tested at ages from 7 to 358 days (Wu et al, 2004). Symbols: diamonds, circles and triangles represent water-, sealed- and air-curing, respectively. Note that, as expected, the compressive strengths of the sealed-cure specimens are lower than those of the water-cured specimens by approximately 10 to 15% at the test ages greater than 28 days.

2.3.3 Aitcin et al. Tests on Concrete Containing no SCM's: This study used ready-mixed concrete made with only portland cement and with target compressive strengths of 5000, 13,000 and 17,500 psi for 4-, 6- and 8-in. diameter cylinders under different curing conditions: water-, sealed- and air-cured. The w/c ratios were 0.45, 0.31 and 0.25. Cylinder compressive strengths were measured at 7, 28, 91 and 365 days. The ratio of sealed- to water-cure compressive strength for the concrete mixtures with the three differing w/c ratios was 0.96.

2.3.4 Pankow Tests on Fly Ash, Slag-cement and Ternary Concrete: This work consisted of two phases: a laboratory and field study for concretes containing varying proportions, types, and amounts of SCMs; types of aggregate; and differing curing conditions. The compressive strength data is summarized in Table L3 and Table F3 in the Phase I report. Table 2.2 summarizes the sealed-cure to water-cure compressive strength ratio for all mixtures used in the study and tested at ages from 7 to 180 days. Tables 2.3 and 2.4 summarize sealed-cure to water-cure compressive strength ratios for individual mixtures in the laboratory and field study.

At 7 days the strengths of water-cure and seal-cure cylinders were about equal. Table 2.2 shows that at 7 days the sealed- to water-cure compressive strength ratios ranged from 0.90 to 1.10, with an average of 0.99 for the field-cast, laboratory-cured cylinders. After 7 days, however, the sealed- to water-cure compressive strength ratios for all mixtures ranged from 0.72 to 0.97 in the laboratory study with the average for 28 through 120 days being 0.86. In the field study ratios for all mixtures ranged from 0.73 to 1.03 with the average for all 28 through 180 days being 0.83. Tables 2.3 and 2.4 show that the ratios for mixtures containing no SCMs followed the same trend as those for fly ash, slag and ternary mixtures. The only difference was for the ternary concrete containing lightweight fines for which the sealed- to water-cure compressive strength ratio remained close to 100% through 90 days.

Figure 2.2 shows a graph of the Pankow field data for sealed- to water-cure strength ratios at varying ages. At 7 days, the ratios for all mixtures fell into a pattern ranging from 0.90 to 1.10. At ages later than 7 days, the range in ratios for any age was greater than that at 7 days, and the average ratios at any age were less than those at 7 days. The decrease in ratios, however, was not proportional to age; ratios were about the same at ages of 28, 58, 90, 120, and 180 days as indicated by a nearly horizontal trend line through the averages. This confirms Meeks and Carino's findings that self-desiccation reduces the internal relative humidity to a point that no further hydration occurs.

2.4 Compressive Strength of Concretes Cured by Air-drying

The compressive strength data for concrete specimens that were cured by air-drying are provided in Table L3 and Table F3 in the Phase I report. Table 2.5 summarizes the air-cure to water-cure compressive strength ratios for all mixtures at ages from 7 to 180 days in the laboratory and field studies. Tables 2.3 and 2.4 summarize air-cure to water-cure compressive strength ratios for individual mixtures in the laboratory and field studies.

As expected, the compressive strengths of air-dried cylinders were much lower than those of seal- or water-cured cylinders. The concrete mixtures containing lightweight fines generally performed better, with higher air- to-water-cure strength ratios than the other mixtures. Concrete containing SCM's followed about the same general trend as the concrete without SCM's. The data suggests that air-curing concrete containing SCM's is as detrimental to strength as air-curing concrete without SCM's.

2.5 Comparison of Researcher's Data

Figure 2.3 compares the average sealed to water-cure and the average air to water-cure strength ratios for Pankow, Sanjayan, Aitcin and Wu. For the sealed to water-cure strength ratios, Aitcin's and Wu's data are about 0.90 or higher. Recall that Aitcin used concrete containing no SCMs and Wu used a single binary concrete mixture containing 25% fly ash replacement. The Sanjayan and Pankow sealed to water-cure strength ratio data are similar for the range of fly ash, slag and ternary mixes. Aitcin's data represents the average of three mixtures, Wu used one binary mixture, Sanjayan used 11 mixtures and the Pankow research included results for 11 mixtures.

For the seal- to water-cure data for concrete mixtures containing no SCM's, Aitcin, Sanjayan and Wu all found strength ratios to be near 1.0. In other words, sealed curing was as good as water curing when portland cement was the only cementitious material used. The Pankow data did not follow this trend. The sealed curing produced significantly lower strength for both the mixtures containing SCMs and those for which portland cement was the only cementitious material. Only one cement source was used in the Pankow research, so this finding may simply be due to behavior specific to that cement source.

For the air- to water-cure strength ratio data, Aitcin again had the highest values while the ratios from the Wu and Pankow studies were similar, with Wu having slightly higher values. Sanjayan had no air- to water-cure data.

2.6 Implications of the Effect of Curing on Compressive Strength

The lack of water curing had a greatest effect on concrete mixtures containing SCM's. For the Sanjayan and Pankow research, the difference between the sealed-cure and water-cure compressive strength ratios was about 0.15, with the water cure resulting in the higher ratio. This is a dramatic reduction for high-strength concretes. Sealed curing represents the best possible field curing. Thus, designers will need to determine whether the water-cured strength or the seal-cured strength should be used for design. This has a significant implication with respect to the economy of using green concrete mixtures.

The sealed-cure data can also be analyzed by comparing the sealed-cured to water-cured strength ratios with ACI 318-11 criteria for comparing strengths of field-cured cylinders to the specified strength, f_c'. As described in Section 1.2 of this report, strength tests of field cured cylinders are sometimes used to check the adequacy of curing and protection of concrete in the structure. ACI 318-11 requires such cylinders to be molded in accordance with ASTM C31 and at the same time and from the same samples as laboratory-cured test cylinders. ASTM C31 requires storing the cylinders in or on the structure as near to the point of deposit of the concrete represented as possible. The cylinders must be provided with the same temperature and moisture environment as the structural work.

Based on the results of tests on field-cured cylinders, Section 5.6.4.4 of ACI 318-11 states the following:

> "Procedures for protecting and curing concrete shall be improved when strength of field-cured cylinders at test age designated for determination of f_c' is less than 85 percent of that of companion laboratory-cured cylinders."

In the Pankow research, with sealed cylinders testing at an average strength about 85 percent of that for the laboratory-cured cylinders, and assuming a normal distribution, one-half of the concrete mixtures tested would be expected to fall below the acceptance level set by ACI 318-11 for field curing. For these mixtures, ACI 318 would require improved procedures for protecting and curing concrete. It is unclear how better curing and protection in the field could duplicate the results from a complete seal provided by a plastic cylinder mold with a lid.

If cores had been removed from the sealed-cure cylinders, the core strength is anticipated to be lower as a result of damage due to drilling. Thus, concrete represented by at least one-half of the cylinders would also not meet the core acceptance criteria in ACI 318-11. This problem is discussed in much more detail in the following chapter.

2.7 References

Aitcin, Pierre-Claude, Miao, Buquan, Cook, William D and Mitchell, Dennis, "Effects of Size and Curing on Cylinder Compressive Strength of Normal and High-Strength Concretes," ACI Materials Journal, July-August 1994, pp. 349-354.

Meeks, Kenneth W. and Carino, Nicholas J. "Curing of High-Performance Concrete: Report of the State-of-the-Art," National Institute of Standards and Technology, NISTIR 6295, March 1999, 191 pages.

Sanjayan, J.G. and Sioulas, Bill, "Strength of Slag-Cement Concrete Cured in Place and in Other Conditions," *ACI Materials Journal*, September-October 2000, pp. 603-611.

Wu, F.-R., Masuda, Y. and Nakamura, S., "Influence of Different Curing Conditions on Strength Development of High-Strength Concrete using Fly Ash", , *SP-221: Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, American Concrete Institute, 2004, pp. 181-194.

Table 2.2 Pankow Data: Average Ratio of Sealed to Standard-cure Cylinder Strengths for All Mixes

Age	Lab Study			Field Study		
	Minimum	Maximum	Average	Minimum	Maximum	Average
7 days	-----	-----	-----	0.90	1.10	0.99
28 days	0.80	1.01	0.88	0.77	0.94	0.84
56 days	0.74	0.91	0.86	0.77	1.03	0.84
90 days	0.77	0.98	0.86	0.73	0.89	0.82
120 days	0.72	0.93	0.83	0.76	0.91	0.83
180 days	-----	-----	-----	0.74	0.99	0.84

Table 2.3 Lab Study: Ratio of Sealed- and Air-dry Cure 4x8-in. Cylinders to Standard Cure 4x8-in. Cylinders at 28, 56, 90, and 120 days

	100% PC	**20% FA**	**30% FA**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Silica Fume**	**Tern+ 3/8-in. Ltwt**	**Tern+ Ltwt Fines**	**Tern+ Low w/cm**	**15% FA 4000 psi**			
28 Days	A	B	C	D	E	F	G	H	I	J	k	l			
													Min	Max	Average
Sealed/Standard	0.82	0.89	0.80	0.91	0.86	0.85	0.85	0.89	0.87	1.01	0.87	0.94	0.80	1.01	0.88
Air/Standard	0.79	0.70	0.68	0.69	0.71	0.66	0.68	0.75	0.74	0.84	0.70	0.76	0.66	0.79	0.77
56 Days															
													Min	Max	Average
Sealed/Standard	0.83	0.74	0.79	0.82	0.85	0.90	0.84	0.88	0.91	0.98	0.90	0.94	0.74	0.91	0.86
Air/Standard	0.69	0.60	0.62	0.54	0.73	0.71	0.71	0.59	0.92	0.80	0.79	0.69	0.54	0.92	0.70
90 Days															
													Min	Max	Average
Sealed/Standard	0.77	0.80	0.80	0.79	0.89	0.82	0.80	0.97	0.84	0.98	0.88	0.92	0.77	0.98	0.86
Air/Standard	0.50	0.51	0.55	0.44	0.75	0.62	0.56	0.60	0.70	0.70	0.75	0.65	0.44	0.75	0.61
120 Days															
													Min	Max	Average
Sealed/Standard	0.72	0.76	0.84	0.86	0.86	0.82	0.83	0.90	0.72	0.93	0.88	0.89	0.72	0.93	0.83
Air/Standard	0.47	0.41	0.43	0.64	0.53	0.53	0.66	0.57	0.47	0.67	0.74	0.64	0.41	0.66	0.56

Table 2.4 Field Study: Ratio of Sealed and Air-Dried Cure 4x8 Field-cast Cylinders to 4x8 Field-cast Standard-Cure Cylinders at 7, 28, 56, 90, 120 and 180 Days

	100% PC	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern.**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**			
7 Days	1	2	3	4	5	6	7	8	9	10	11			
												Min	Max	Average
Sealed/Standard	0.96	0.95	0.93	0.99	0.90	1.00	1.10	0.92	0.97	1.07	1.09	0.90	1.10	0.99
Air/Standard	0.89	0.92	0.84	0.98	0.84	0.98	0.94	0.92	0.84	0.92	1.05	0.84	1.05	0.92
28 Days														
												Min	Max	Average
Sealed/Standard	0.77	0.84	0.77	0.94	0.82	0.84	0.84	0.87	0.82	0.90	0.85	0.77	0.94	0.84
Air/Standard	0.64	0.62	0.63	0.67	0.66	0.71	0.62	0.67	0.60	0.65	0.56	0.56	0.71	0.64
56 Days														
												Min	Max	Average
Sealed/Standard	0.77	0.78	0.82	1.03	0.79	0.84	0.83	0.81	0.84	0.88	0.85	0.77	1.03	0.84
Air/Standard	0.60	0.46	0.61	0.52	0.65	0.60	0.52	0.58	0.52	0.61	0.45	0.45	0.65	0.56
90 Days														
												Min	Max	Average
Sealed/Standard	0.81	0.73	0.81	0.89	0.81	0.84	0.81	0.78	0.81	0.88	0.88	0.73	0.89	0.82
Air/Standard	0.58	0.45	0.58	0.51	0.56	0.46	0.52	0.53	0.45	0.59	0.41	0.41	0.59	0.51
120 Days														
												Min	Max	Average
Sealed/Standard	0.80	0.76	0.79	0.83	0.85	0.84	0.85	0.82	0.80	0.91	0.87	0.76	0.91	0.83
Air/Standard	0.54	0.41	0.53	-----	-----	-----	0.45	0.53	0.41	0.55	0.37	0.37	0.55	0.47
180 Days														
												Min	Max	Average
Sealed/Standard	0.84	0.80	0.76	-----	-----	-----	0.90	0.74	0.79	0.99	0.88	0.74	0.99	0.84
Air/Standard	0.51	0.41	0.57	-----	-----	-----	0.47	0.46	0.40	0.56	0.32	0.32	0.57	0.46

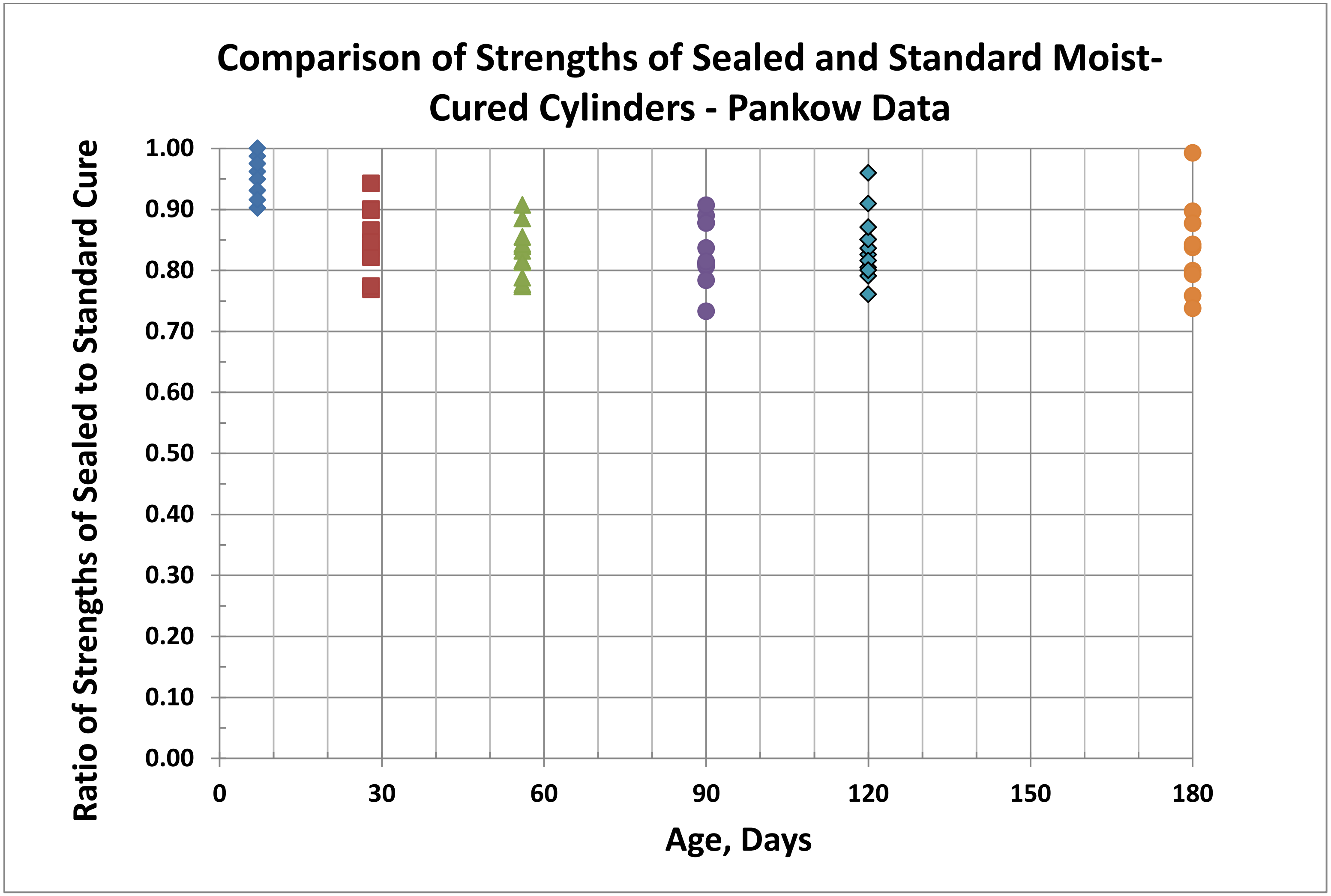


Figure 2.2 Pankow Data: Sealed-cure to water-cure strength ratios for cylinders at ages up to 180 days

Table 2.5 Pankow Data: Average Ratio of Air- to Standard-cure Cylinder Strengths for All Mixes

Age	Lab Study			Field Study		
	Minimum	Maximum	Average	Minimum	Maximum	Average
7 days	-----	-----	-----	0.84	1.05	0.92
28 days	0.66	0.79	0.77	0.56	0.71	0.64
56 days	0.54	0.92	0.70	0.45	0.65	0.56
90 days	0.44	0.75	0.61	0.41	0.59	0.51
120 days	0.41	0.66	0.56	0.37	0.55	0.47
180 days	-----	-----	-----	0.32	0.57	0.46

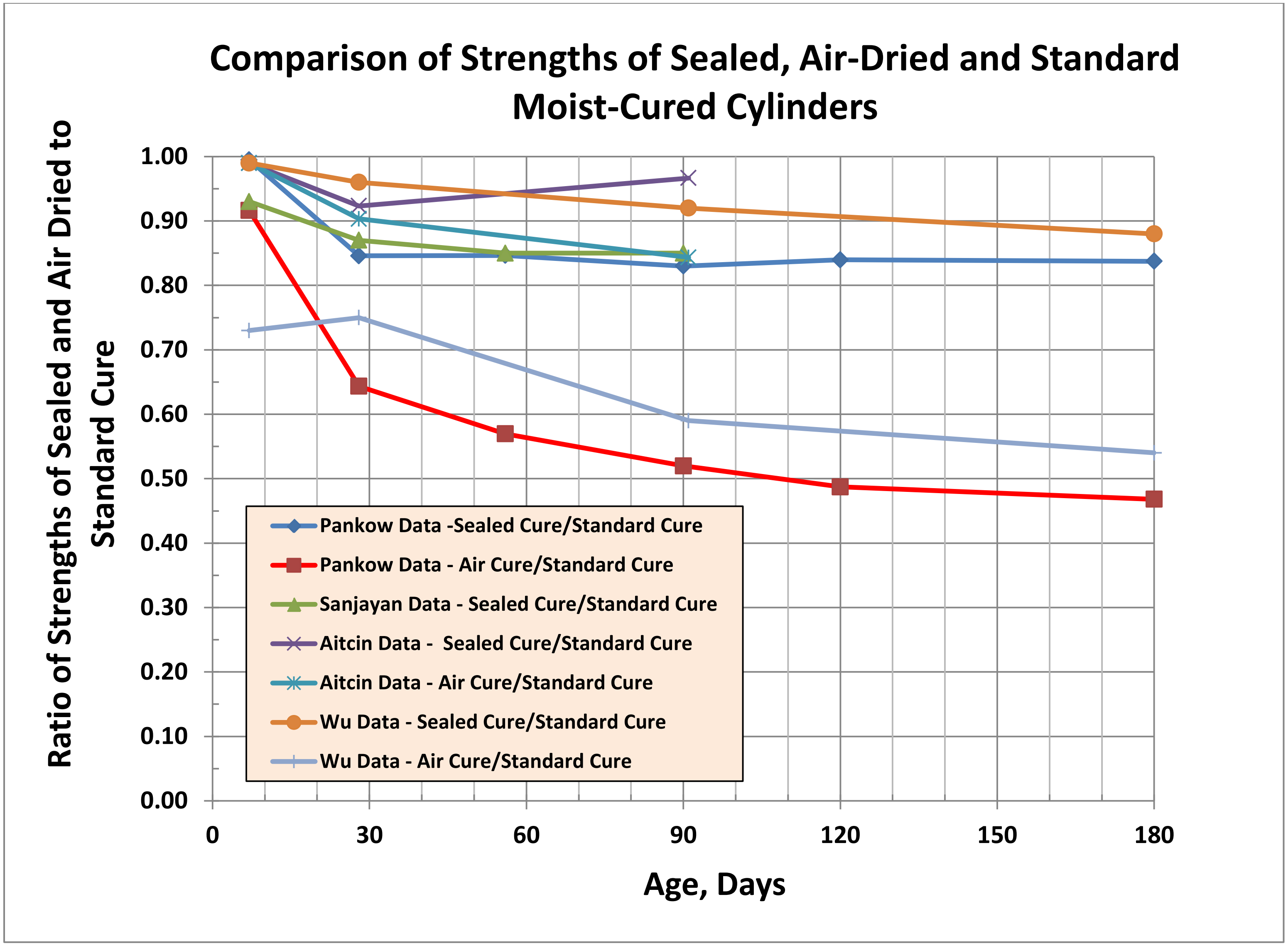


Figure 2.3 Average sealed-cure to water-cure and air-cure to water-cure strength ratios for cylinders at ages up to 180 days.

Chapter 3 Low-strength Investigation: Core-to-Cylinder Relationship

Section 5.6.2.4 of ACI 318-11, "Building Code Requirements for Structural Concrete," defines a strength test as the average of the strengths of at least two 6 by 12 in. cylinders or at least three 4 by 8 in. cylinders made from the same sample of concrete and tested at the age designated for determination of the specified strength, ***f_c'***.. Section 5.6.5 provides the procedure to be followed if a strength test result fails to meet specified acceptance criteria. A low-strength investigation isn't required unless a strength test result falls below the specified compressive strength, f_c', by more than 500 psi when f_c' is 5000 psi or less, or by more than 0.10 f_c' when f_c' is more than 5000 psi. In these cases, as stated in Section 5.6.5.1 of ACI 318-11, steps must be taken to ensure that the load-carrying capacity of the structure is not jeopardized. Chapter 2 of this report describes procedures used to confirm the likelihood of low-strength concrete that significantly reduce load carrying capacity, based on calculations. Section 5.6.5.2 states the following:

> "If the likelihood of low-strength concrete is confirmed and calculations indicate that load-carrying capacity is significantly reduced, tests of cores drilled from the area in question in accordance with ASTM C42 shall be permitted."

Note that drilling and testing cores is not required by the Code section quoted. The Commentary states further that, *in extreme cases*, core tests may be conducted:

> "The building official should apply judgment as to the significance of low test results and whether they indicate need for concern. If further investigation is deemed necessary, such investigation may include nondestructive tests or, in extreme cases, strength tests of cores taken from the structure."

Even with these requirements and guidance, however, low strength tests usually result in cores tests, the results of which must meet the following requirements from Code Section 5.6.5.4:

> "Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 percent of f_c' and if no single core is less than 75 percent of f_c'. Additional testing of cores extracted from locations represented by erratic core strength results shall be permitted."

In buildings using green concrete mixtures, the strength level that initiates a low-strength investigation, the procedures for such investigations, and requirements for structural adequacy are the same as those just described. But with concrete containing large amounts of SCMs—and often with the low w/cm ratios needed to offset slow strength gain—should the core acceptance criteria be the same as for all other concretes? Answering that question requires tracing the background of the ACI 318 core-test acceptance criteria.

3.1 ACI Core Acceptance Criteria: A History

The core-strength acceptance criteria were first published in the 1971 revision of ACI 318. They have remained essentially the same for 40 years, through the 2011 revision.

The ACI 318-71 Commentary provided background details (cited references) and intent (conservatively safe acceptance criteria) as shown below.

> "For cores, if required, conservatively safe acceptance criteria have been provided which, if met, should assure structural adequacy for virtually any type of construction. [4.2, 4.3]"
>
> 4.2. Bloem, Delmar L., "Concrete Strength Measurement- Cores Vs. Cylinders,'' *ASTM Proceedings*, 1965, pp. 668-696.
>
> 4.3. Bloem, Delmar L., "Concrete Strength in Structures," *ACI Journal*, *Proceedings* V. 65, No. 3, Mar. 1968, pp. 176-187.

It's important to note that the core strength acceptance criteria were considered "conservatively safe" for "virtually any type of construction" and were based on work by Bloem in 1965 and 1968. Bloem's work is evaluated in a later section of this document, as an aid in understanding why the core acceptance criteria are conservatively safe. In addition, Bloem's work will be reviewed to compare his concrete materials and properties with those of green concrete and if his test specimens and procedures approximate those currently used.

The ACI 318-83 Commentary added two new references (Malhotra 1976; Malhotra 1977) on cores but did not change the low-strength investigation procedure or core strength acceptance criteria. Unlike Bloem's work, which was still referenced in 1983 with the same sentence shown in the 1971 edition, the two papers by Malhotra were included in the references.

A final reference to the Commentary regarding investigation of low-strength test results (Bartlett and MacGregor, 1994) was added to ACI 318-02. This reference presented data on the effect of moisture condition on core strengths, which did result in Code changes concerning core conditioning. The low-strength investigation procedure and core strength acceptance criteria remained the same.

<u>3.1.1 How Core Conditioning Affects Core Strength-Test Results:</u> It is important to note the effect of core conditioning methods on core strength-test results. Cores are conditioned in accordance with ASTM C 42. ASTM C 42 is explicit with respect to most issues involved in the testing process, but allows the specifying authority to direct a method for conditioning the cores prior to test.

ACI 318-1999 and earlier revisions directed that cores be:

- soaked for at least 40 hr. prior to test and tested wet if the cores represent concrete that will be more than superficially wet under service conditions, or
- tested dry after 7 days of air drying at 60°F to 80°F and less than 60% relative humidity if the cores represent concrete that will be dry under service conditions

Based on the Bartlett and MacGregor research, ACI 318-02 and later editions directed that cores be obtained, moisture conditioned by storage in watertight bags or containers, transported to the laboratory, and tested in accordance with ASTM C42. Testing was required no earlier than 48 hours and not later than 7 days after coring unless approved by the registered design professional. ASTM C42 requires wiping drilling water from core surfaces and allowing surface moisture to evaporate for up to 1 hour after drilling before placing the cores in plastic bags. These revisions were based on Bartlett and MacGregor's research, which indicated that different core conditioning methods resulted in different measured core strengths. The strength of air-dried cores was on average 14 percent higher than the strength of soaked cores. The strength of cores with a negligible moisture gradient, conditioned in accordance with the current ACI 318 requirements, was on average 9 percent larger than that of soaked cores.

Thus, the strengths of cores conditioning by bagging were about 5% lower than the strengths of cores conditioned by air drying. Because ACI 318 still requires the average of three cores to equal or exceed 85 percent of the specified concrete strength, meeting that requirement is now less likely for cores taken from structures that would be dry under service conditions.

The strength differences for cores conditioned by differing methods should be considered when evaluating core-strength test results reported in the literature.

3.2 Project Experience with Green Concrete Core-Strength Test Results

As background information for an in-depth analysis of Bloem's work, experience on construction projects utilizing high-strength green concrete is summarized as follows.

<u>3.2.1 Mat foundation in California:</u> In 2010, the concrete for a mat foundation contained 200 lb of portland cement, 267 lb of slag cement, and 200 lb of Class F fly ash totaling 667 lb of total cementitious materials. The w/cm was 0.36 and the specified concrete compressive strength was 8000 psi at age 90 days. At 90 days, the 32 compressive strength test results for <u>field-cast</u> and lab-cured concrete cylinders averaged 8540 psi with a minimum of 8120 psi and a maximum of 9190 psi. Thus the cylinder strength test results for all 32 cylinder sets met the specified strength of 8000 psi.

Because a question arose about core-to-cylinder strength relationships in another part of the structure, six 6-in. and seven 3-in. nominal diameter cores were removed from the top of the mat foundation 160 days after concrete placement. The core strength test results for the 6-in.-diameter cores averaged 5820 psi with a minimum of 5270 psi and a maximum of 6200 psi. The core strength test results for the 3-inch diameter core averaged 5820 psi with a minimum of 5270 psi and a maximum of 6200 psi. The combined average core strength was 5940 psi.

No cylinders had been tested after 90 days and no hold cylinders were available for testing at 160 days. Thus, in calculating the core-to-cylinder strength ratio, the average 90-day cylinder strength test result of 8540 psi was used. The ratio of the average 160-day core strength to 90-day cylinder strength ratio was 0.70. This was considered to be an overestimate because the green concrete cylinder strength would be expected increase with time. Thus, the estimated core-to-cylinder ratio for equal age cores and cylinders was even lower than 0.70—far below the ACI 318 core strength acceptance ratio of 0.85. For the 13 cores tested, only two of the 3-inch nominal diameter cores had a core-to-cylinder ratio of 0.85 or above. Strength retrogression with age was also noted.

Fortunately, the mat foundation concrete had been previously accepted based on the 32 cylinder strength test results, and the engineer's calculations demonstrated structural adequacy even with the lower than expected core strength results. The broader question remain unaddressed: How do we explain that the 90-day cylinder-test results showed the mat foundation concrete to be acceptable when the core-test results indicated a strength less than 0.85 f_c', for in-place concrete cored 70 days later? Which measure gives the better indication of a structural member's load-carrying capacity?

3.2.2 Columns in Ohio: In 2011, high strength 4 x 4-ft square green concrete columns, were specified for a 15-story building in Ohio. The concrete contained 873 lbs. of portland cement, 218 lbs. of fly ash and 109 lbs. of silica fume totaling 1200 lbs. of total cementitious materials. The water-to-cementitious materials ratio was 0.20. The specified compressive was 10,000 psi at 28 days. Because the contractor and ready-mixed concrete producer were concerned about the strength development in such a high cementitious content mix, a full-size mock-up was constructed and tested prior to construction.

The 28-day standard-cured cylinder compressive strength was 10,925 psi. Six 4-in. nominal diameter cores were removed at 28 days and tested. The average core strength test result was 6435 psi with a minimum of 5700 psi and with a maximum of

7630 psi. The average 28-day core-to-cylinder ratio was 0.59. Again, for this project, the cylinder strengths from concrete placed in the mock-up column met ACI 318 cylinder strength criteria whereas the tested cores from the column did not meet the ACI core-strength criteria.

3.2.3 Personal communication at the NRMCA International Concrete Sustainability Conference: The authors presented a paper, "Comparison of Cylinder and Core Strengths for Low-Carbon-Footprint Concretes" at the NRMCA International Concrete Sustainability Conference held May 6-8, 2013, in San Francisco. After the presentation, one attendee briefly described his company's experience on a construction project for which core-to-cylinder ratios were less than the ACI directed 0.85 even though all of the tests on laboratory-cured cylinders molded at the jobsite yielded compressive strengths in excess of the specified strength. He noted that his project was in litigation over this issue with several million dollars at stake, so he could not discuss further details.

Section 3.2.3 describes anecdotal evidence, whereas the information described in Sections 3.2.1 and 3.2.2 resulted from two field investigations for which specific data were available but with limited sample sizes. In the concrete literature dealing with core strength to cylinder strength ratios, however, conclusions from one study were based on large samples sizes and many different concrete mixtures.

3.2.4 Industry literature confirmation: Strength data from 771 cores taken from large elements cast using 22 concrete mixtures reported in five investigations were analyzed (Bartlett and MacGregor 1997). The researchers concluded that the ratio of in-place strength to standard cylinder strength decreases as the maximum temperature sustained during hydration increases. If the concrete mixture contained silica fume, Class C fly ash, or slag cement, the ratio of the in-place strength at 28 days to the standard 28-day cylinder strength of the same concrete was markedly less than that observed for concretes not containing supplementary cementitious materials. The ratio of the average 28-day core strength to the average 28-day cylinder strength was 0.15 smaller than that for concretes not containing these supplementary cementitious materials.

Note that the cores from the mat foundation in California and the column in Ohio were all conditioned by bagging. The core-test results used by Bartlett and MacGregor were all corrected to equivalent bagged core strengths using correction factors to account for conditioning effects on cores either soaked or dried as recommended in ASTM C42 core testing standards used before 2003.

3.2.5 Is 85 percent of f_c' an appropriate acceptance value for green concrete cores? Why have core-strength test results for the projects cited not reached a core-to-cylinder strength ratio of 0.85, even at core ages greater than 120 days? Several factors, alone or in combination, may be a part of the cause.

- Concrete studied in Bloem's 1965 and 1968 research is not representative of today's high-strength concretes.
- Concrete studied in Bloem's 1965 and 1968 research is not representative of concretes with large percentages of cement replaced by SCMs.
- Concrete in Bloem's 1965 and 1968 research is not representative of concretes with much lower w/cms than the w/cs he used.
- Cores taken from Bloem's 1965 and 1968 test slabs and column are not representative for cores taken from much larger structural elements where temperature increases reduce in-place strength.

In this Chapter, the influence of these factors is explored in more detail.

3.3 The Bloem 1965 and 1968 Data

The first step in exploring the factors mentioned is reviewing Bloem's concrete composition, fresh and hardened concrete properties, size of the specimens from which cores were removed, and core conditioning methods. The cylinder and core-test results and the core-to-cylinder relationships are also reviewed.

<u>3.3.1 Basic Test Data: </u>The information for Bloem's 1965 and 1968 research is shown below.

<u>1965 Mix Information (Ingredients, Quantities, Properties) and Size of Test Specimens</u>

- Three mixes: gravel, expanded shale, crushed limestone aggregates
- Cement content: 525, 578, 527 pcy (no SCM)
- No specified water content, all batched to slump: 4.8, 1.3, 3.5 inch
- No admixtures except for air-entraining agent
- Strength Levels, estimated f'c: 4500, 3500, 3500 psi
- Test Specimens: 4- and 8-in thick slabs; 8 x 26-in columns
- Cores tested wet and dry.

<u>1968 Mix Information (Ingredients, Quantities, Properties) and Size of Test Specimens</u>

- Strength Levels, estimated f'c: 4750, 3000, 3500 psi
- Water/Cement Ratios: 0.68, 0.69, 0.77
- Test Specimens: 6-inch thick slabs
- Cores tested wet and dry.

TABLE 1—CHARACTERISTICS OF FRESH CONCRETE (SERIES 189)*

Date mixed	Description of cement	Cement content	Water content	Slump	Unit weight	Air content	Temperature
U. S. customary units							
		lb per cu yd	lb per cu yd	in.	lb per cu ft	percent	F
2-21-66	Type III, Sample 1	427	292	1.8	148.5	2.4	71
3-15-66	Type I	478	333	6.8	140.8	7.2	63
4-18-66	Type III, Sample 2	413	317	4.8	142.8	5.3	70

It is obvious that Bloem's materials and methods, while appropriate in the 1960's don't represent many current concrete compositions, in-place concrete masses, and core testing procedures with respect to the following:

- The total cementitious contents were between 413 and 578 lb/yd^3
- No supplementary cementitious materials (SCMs) were used.
- The water-to-cement ratios were high (0.68 to 0.77).
- No water-reducing admixtures were used.
- The minimum specimen dimensions were small for the 4-, 6-, and 8-in.-thick slabs and one vertical specimen; an 8x26-in. cross-section column.
- Cores were tested after conditioning by air drying or soaking in water instead of bagging them to reduce any moisture gradients.

3.3.2 Limitations of Bloem's Research: Although Bloem's research used concrete ingredients and quantities producing properties typical of the mid-1960, they do not represent the concrete mixtures used for green concrete today. For instance, California is a leader in using green concrete for buildings; however, the state is in a very active seismic region with designers using specified strengths, f_c', that range from 6000 psi to 12,000 psi. These strengths are much higher than those for the concrete in Bloem's research, which had *estimated* f_c', values that range from 3000 psi to 4750 psi. The strength levels reported for many current of the green concrete projects fall outside the range of Bloem's test values. In agreement with the lower strength levels are the lower amounts of total cementitious materials used—all less than 600 lb/yd^3. The limitations are further discussed as follows.

Strength Levels—The difference in strength levels may be important. ACI 363.2R-11 "Guide to Quality Control and Testing of High-Strength Concrete" recommends that the current ACI 318 core-strength acceptance criteria be used only if a separate core-to-cylinder relationship for the mixture has not been established. As the following excerpt from ACI 363.2R-11 states, a correlation curve for each high-strength mix should be established. Note that ACI 363 defines high-strength concrete as that which exceeds a specified strength level, f_c', of 6000 psi.

> "A correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 4 in. in diameter) to the strength of specimens used for acceptance testing, that is, 6 by 12 in. or 4 by 8 in. cylinders. Then, if coring becomes necessary, the relationship has been established, agreed upon, and is ready for conclusive interpretation. In the absence of correlation data, the provision 5.6.5.4 of ACI 318-08 should be used."

Supplementary Cementitious Materials—No SCMs were used in any of Bloem's work. Based on the analysis of core data (Bartlett and MacGregor 1997), concretes containing

SCMs show a lower core-to-cylinder ratio (by 0.15) than concrete with no SCMs. This is a significant difference.

Water-Cement Ratio and Curing Method—Bloem reported water-cement ratios (w/c) in his 1968 paper as 0.68, 0.69 and 0.77. Almost all of the current green concrete mixtures have water-to-cementitious-materials ratios (w/cm) less than 0.50. Many have a w/cm ratio less than 0.40 and some approach 0.30. Bloem used what he called good curing and poor curing. Good curing consisted of the concrete being sprayed with a curing compound and later covered with wet burlap and sheet plastic for 14 days. Poor curing consisted of leaving the slab uncovered after placement. Water curing can have a beneficial effect on increasing the strength of small-sized specimens with w/cm ratios less than 0.40. Bloem's work doesn't approximate the w/cms and curing methods used today.

Heat Generation—Bloem's specimens were, for the most part, slabs that were 4-, 6-, and 8-in. thick. One 8x26-in. cross-section vertical column was tested. None of his specimens were massive enough or contained enough cement to generate a high internal temperature gain. Section 3.3 of ACI 214.4R-10, "Guide for Obtaining Cores and Interpreting Compressive Strength Results," describes strength loss with increased internal temperatures as follows:

> "Similarly, data analysis from large specimens reported by Yuan et al. (1991), Mak et al. (1990, 1993), Burg and Ost (1992), and Miao et al. (1993) indicate a strength loss of approximately 3% of the average strength in the specimen for every 10°F increase of average maximum temperature sustained during early hydration (Bartlett and MacGregor 1996a). Maximum temperatures recorded in these specimens varied between 110 and 200°F."

Although Bloem's 1965 paper acknowledges that the maximum internal temperature affects early and later age strengths, the internal temperature was not measured in either of his studies. Based on the analysis by Bartlett and MacGregor (1997) this is a serious limitation. Mat foundations are often designed to be 5 to 10 ft. thick and columns can approach 4 to 6 ft. thick. While SCM's are used to lower the internal temperature, it may still reach the commonly specified maximum temperature of 160ºF.

For instance, assume that current green concrete mixes are used in 4-ft square column. Also assume that the temperature rise the column is 40F higher than that in any of Bloem's specimens. Based on Bartlett and MacGregor's work cited in ACI 214.4R-10, the strength for a core from near the center of the 4-ft. square column would be 12% lower (3% for every 10F or 12% for a 40F difference) than the strength of a core from a smaller size column. Because of the lower core strength, if the original core-to-cylinder ratio was 0.85, it would reduce to 0.73 due to the sustained internal temperature. This is a significant effect that is unaccounted for in Bloem's work and thus unaccounted for in the ACI 318 target core-acceptance value of 0.85.

3.3.3 Bloem's Core-to-Cylinder Relationships

Bloem presented the core and cylinder strength data in both tables and graphical formats. Test results for the 8x26-in. cross-section column (Bloem 1965) are shown in Figure 3.1 and the test results for a 6-in.-thick slab (Bloem 1968) in Figure 3.2. Red lines are shown in each figure to denote the ACI 318 target value for acceptable core strength— 85% of f_c'.

Note the following regarding column data:

- Core strength at 91 days is compared to cylinder strength at 28 days
- Core strength is for water-soaked cores
- Good and poor curing methods were used

It is current practice to take cores almost immediately after receiving the test report stating that cylinder strength is low. In this case, the core strength and cylinder strength are measured at about the same age. The core strength at 91 days represents an expected strength increase due to 63 extra days of curing that is not measured with the 28-day cylinders. The water-soaking results in a decrease in strength when compared with bagged cores (current core conditioning requirement of ACI 318). If these opposite effects are assumed to offset each other, the core strengths could be reasonably close to strengths of same-age and bagged cores. With that as a preamble, it is interesting to note that for the well-cured columns, 4 of the 8 core strengths (85% to 90%) would meet the ACI 318 required 85% value and the other 4 (83% to 60%) would not meet the requirement.

The core-to-cylinder ratio of 0.60 for the core drilled near the top of the column is probably due to water-gain at the top of the 8-ft-tall column. This was noted by Bloem but readers were cautioned not to take cores from the top of a column. Cores are not usually removed from the top of a wall or column, however, because it is difficult to set the core drilling machine that high on a scaffold or anchor it to the wall or column. In practice, cores *are* removed from the top of mat foundations, which could result in a strength decrease caused by water-gain due to the mat depth. This possibility needs to be addressed. Otherwise, it is likely that most cores removed from the top of mat foundations will not meet the 85% ACI 318 acceptance value.

Figure 3.2 shows the core-to-cylinder relationship for a 6-inch thick slab. For the curve labeled 2, at 28 days, air-dried cores from a well-cured slab had a core-to-cylinder ratio of about 0.85 but that ratio dropped to 0.83 at 90 days and 0.74 at 364 days. Curiously, for this slab, core acceptance might have depended on the age at which the core was taken. Also note that curve 2 represents air-dried core strengths that, on average, would be 5% higher than bagged-core strengths.

Bloem's data presents the possibility of two undesirable outcomes:

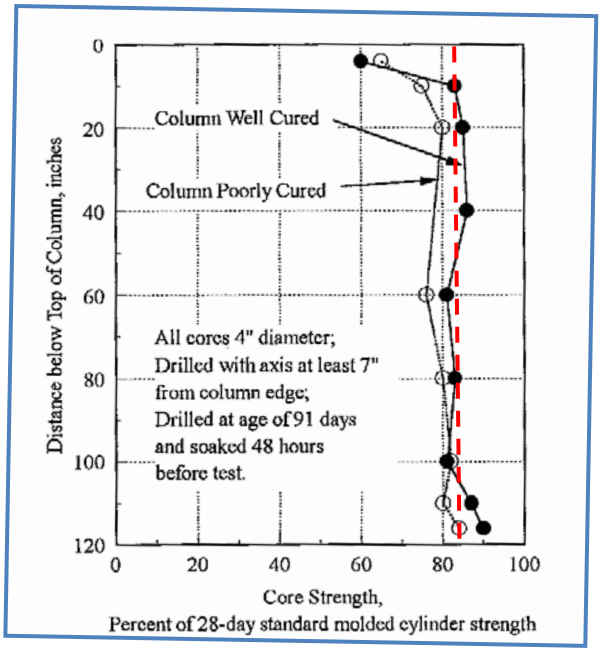
- Core taken from different locations along the same column will sometimes pass and sometimes fail to achieve the strength required by ACI 318 for acceptance
- Cores taken from a slab may sometimes pass and sometimes fail to achieve the strength required by ACI 318 for acceptance, depending only on the age of the cores when core strengths are measured.

These possible outcomes represent an unreasonable construction problem: The concrete is acceptable on the basis of standard-cured cylinder strengths, but the same concrete may not be acceptable based on strengths of cores taken at different locations or tested at different ages.

Figures 3.3 and 3.4 graphically summarize Bloem's core-to-cylinder relationships. These show the core-to-cylinder strength ratios for well-cured slabs and for a column, but with core and cylinder strengths measured at the same age. Note in Figure 3.4 that very few core-to-cylinder ratios exceed 0.85; only 4 out of 48 exceed 0.85 for Bloem's 1968 work. Including all of Bloem's core-to-cylinder ratios for well-cured concrete and air-dried cores puts the average about 0.80. The 0.85 core-to-cylinder ratio chosen by ACI 318 in 1971 represents about the 85^{th} percentile. This summary emphasizes the statement in the ACI 318-71 Commentary that the core strength acceptance criteria is considered to be "conservatively safe" for "virtually any type of construction."

However appropriate this conservatism may have been for Bloem's test results in 1965 and 1968, it might not be suitable for the current green concrete construction in buildings. That was one of the reasons for planning and implementing the extensive laboratory and field research funded by the Charles Pankow Foundation, details of which and described in our companion Pankow Foundation Phase I report entitled "Lab and Field Data for Guide to the Use of "Green Concrete" in Building Construction." In Section 3.4, data from the companion report is used to further explore core-to-cylinder test results for green concrete.

See NEXT PAGE for Figs. 3.1 and 3.2



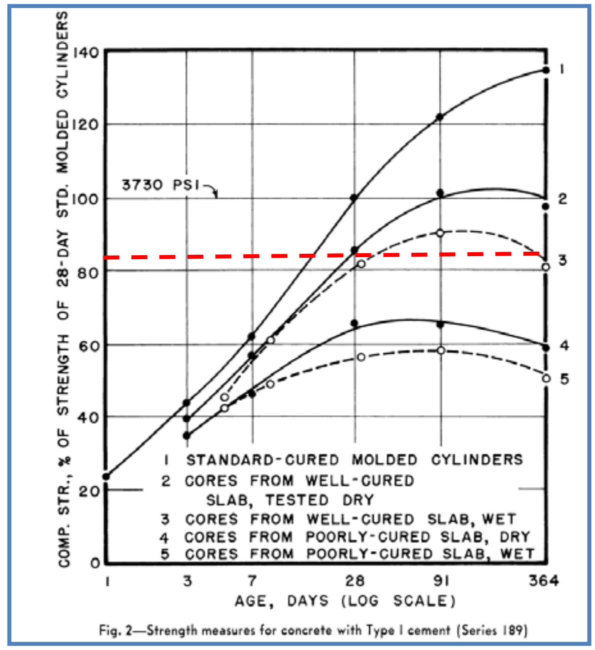


Figure 3.1. From Bloem's 1965 work. Red line shows the 0.85 ACI limit.

Figure 3.2. From Bloem's 1968 work. Red line shows the 0.85 ACI limit.

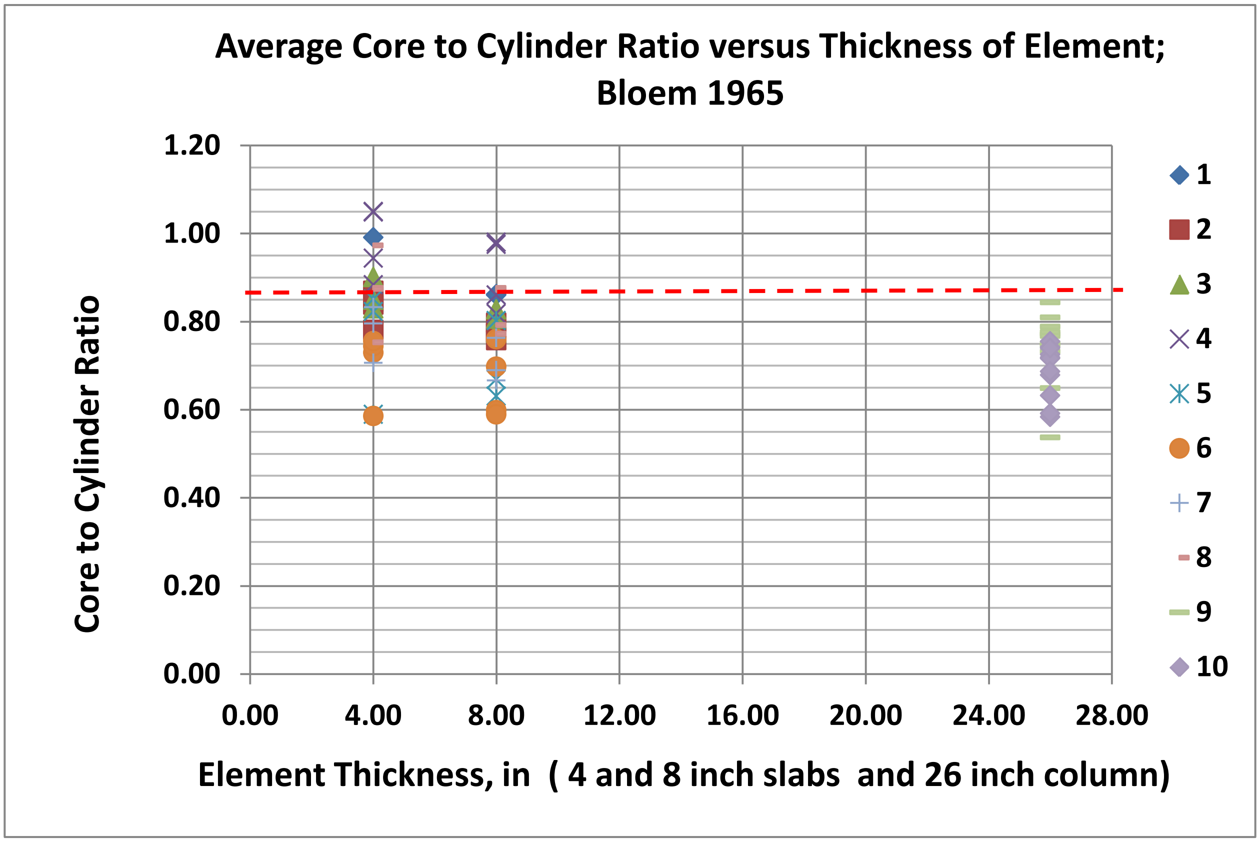


Figure 3.3. Average core-to-cylinder ratios at same age for Bloem's 1965 well-cured slabs and one column. Note column data differs from that presented in Figure 3.2 since that data was for a ratio of 91-day core strength to 28-day cylinder strength.

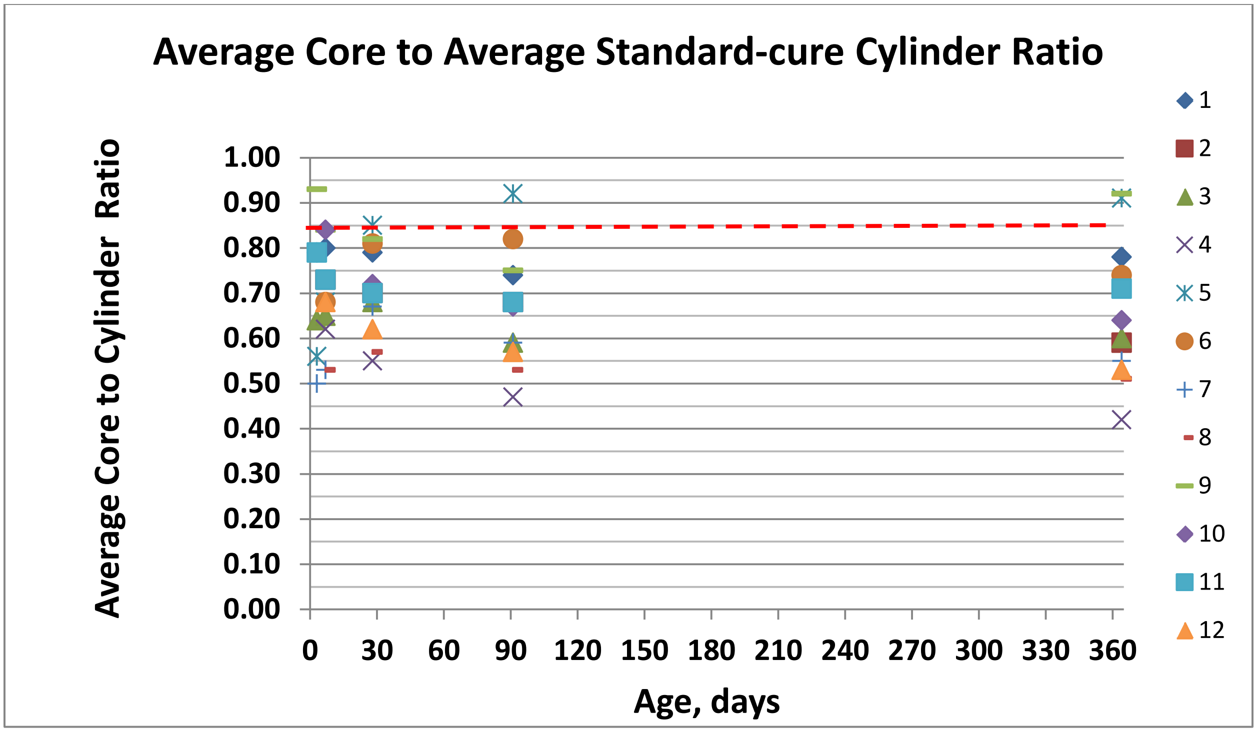


Figure 3.4 Average same-age core-to-cylinder ratios for Bloem's 1968 well-cured slabs. Note that very few results show a core-to-cylinder ratio above 0.85.

3.4 Pankow Core-to-Cylinder Data

The originally planned test data included results of 122 tests on cores and field-cast cylinders to establish the core-to-cylinder ratio for concrete at ages from 28 to 180 days. The mix ingredients, proportions, and properties of fresh and hardened concrete are reported in Phase I of this study. The raw data comparing core-to-standard-cure cylinder strength are shown in Figure 3.5. Figure 3.6 shows the data with sealed- instead of standard-cure (water) cylinder strengths used. Sealed cylinders more closely simulate the curing conditions for structural members. Figure 3.7 shows the core-to-sealed-cure cylinder strengths with an adjustment for internal temperature as recommended by ACI 214.4R-10. Adjusting for the lower strength due to the lack of moisture to cure the concrete (sealed curing) and the lower strength due to internal temperature increases the core-to-cylinder ratio.

<u>3.4.1 Raw Core-to-Cylinder Data:</u> The average core strength (based on three 4-in. nominal diameter cores) versus the average cylinder strength (based on three 4x8-in. cylinders) is plotted in Figure 3.5 versus the coefficient of variation of the three core strengths. Using the coefficient of variation of the core set as the x-axis was intended to determine whether the core-to-cylinder strength ratio was consistent at all levels of core variability. A visual inspection of the data points shows that the core-to-cylinder ratio appears to be unaffected by core-test variability levels. In addition, the regression line

plotted in Figure 3.5 shows that the core-to-cylinder ratio is approximately constant for all x-axis values. The y-axis values include standard-cured core and cylinder strengths. The cores were bag-cured in accordance with ASTM C 42 and the cylinders were water-cured in accordance with ASTM C 31. Refer to Phase I of this study for the details.

Of the 122 core-to-standard-cure cylinder strength ratios, only 4 would pass the ACI 318 required value of 0.85. This pass rate represents about 3% of the tests. The average core-to-cylinder ratio for the 122 test data was 0.65. This is considerably lower than the ACI limit of 0.85. As shown previously, however, this result somewhat mirrored Bloem's results in that the majority of core-to-cylinder ratios in his research did not meet the 85 percent acceptance criteria in ACI 318.

3.4.2 Retest Cores at 282 Days: Using the coefficient of variation of the core set as the x-axis for Figure 3.5 was prompted by the within-test coefficient of variation for the cores ranging from less than 2% to more than 35%. This was a possible indication of poor quality core sampling, moisture conditioning, capping, and testing. The intent of was to determine whether the core-to-cylinder strength ratio was consistent at all levels of core variability. The ratio was consistent, as indicated by the data in Figure 3.5. But there was still some concern about core testing quality.

To investigate the accuracy of the core testing, three 30-in.-long cores were drilled from field cure blocks containing five different concrete mixtures at an age of 282 days. Each 30-in. core was to be treated as follows:

- Concrete Central Supply cored, sawed, conditioned, capped, and tested specimens (15-4x8-in. cores)
- Concrete Central Supply cored, sawed, conditioned, and capped specimens, which Inspection Services Inc. (a privately owned laboratory) tested (15-4x8-in. cores)
- Inspection Services Inc. cored, sawed, conditioned, capped, and tested specimens (15-4x8-in. cores)

The results are given in Table 3.1. One of the cores was defective and yielded only one specimen for testing. Note that the coefficient of variation ranged from 3.0% to 22.7%, with the lowest values for four of the five blocks corresponding to the specimens cored, sawed, conditioned, capped, and tested by Inspection Services. In two cases, however, the average strengths for the Central Concrete Cores were more than 1000 psi higher than those from Inspection Services and in two other cases the average strengths were within about 300 to 400 psi of each other. This confirms the absence of a systematic error in Central Concrete's procedures that resulted in lower core strengths. In addition, it confirms the range of coefficient of variation found in the original data.

In further support of the wide range for within-test coefficient in cores tests, review of another research project currently in progress (Darwin 2013) showed that for 30 different concretes, the coefficient of variation of three-core strength tests ranged from about 1% to 20%. For the 122 tests conducted in this study, only 15 percent of the core strength tests had a coefficient of variation more than 20 percent.

3.4.3 Curing Adjustment

Based on the data presented in Chapter 2, sealed-cured cylinders did not reach as high a strength as water-cured cylinders at equal ages. That chapter presents Pankow test data and data from other researchers that show a strength difference of more than 1000 psi between cylinders. Optimum field curing of structural concrete members would usually consist of sealing the concrete, i.e., using a curing compound to minimize moisture loss. The core strength would then represent concrete that has been sealed while the standard-cure cylinder strength would represent concrete with water available for continued hydration of test specimens with a much higher area-to-volume ratio. This difference is especially important for w/cm ratios below 0.42, the approximate ratio at which there is just enough mixing water in the concrete for complete hydration of the cement (Mindess et. al. 2003).

Comparing a core strength from field concrete that is sealed to a water-cured cylinder strength will inevitably lead to a lower core-to-cylinder strength ratio. The lower core-to-cylinder strength ratio is not due to a difference in the concrete but to a difference in the curing. And even if water curing is used for the field concrete, the effect on cover concrete strength is greater than the effect on the interior concrete strength. Thus, to adjust the core and cylinder to the same level of curing, the core strength was compared to the sealed cylinder strength as shown in Figure 3.6

The core-to-cylinder strength ratio with sealed curing for cylinders was 0.75. This is a significant increase over the core to water-cured cylinder strength ratio of 0.65. This increase implies that the core strength represented by the 0.65 ratio simply indicates that the cores did not benefit from the water curing advantage given to the cylinders. It does not seem appropriate to judge the adequacy of the field concrete by comparison to laboratory concrete that continues to gain strength due to water curing.

Without the curing adjustment only 6 core-to-cylinder ratios exceed the 0.85 ACI 318 value. Although the curing adjustment significantly increased the average core-to-cylinder ratio from 0.65 to 0.75, only 11 out of 122 tests would pass the 0.85 ACI 318 value.

3.4.4 Internal Temperature Adjustment: As mentioned earlier in this Chapter, Section 3.3 of ACI 214.4R-10, “Guide for Obtaining Cores and Interpreting Compressive

Strength Results," refers to a strength loss of about 3% of the average strength in the specimen for every 10°F increase of average maximum temperature sustained during early hydration. Internal temperatures were measured in the cylinders and field concrete in this study. As expected, the cylinder temperatures increased by 1ºF or 2ºF. The average internal temperature of the field concrete increased by about 40ºF with a minimum and maximum increase in internal temperature of 27ºF and 54ºF, respectively.

Figure 3.7 shows the core-to-cylinder strength ratios using ACI 214.4R-10 strength loss information. The average core strength loss based on the average 40ºF increase in internal temperature would be about 12 percent. The actual strength loss for each field concrete tested was based on the measured internal temperatures shown in Table F14 of the Pankow Phase I report. Figure 3.7 shows that the core-to-cylinder ratio increased from 0.75 to 0.84 when an internal temperature adjustment was made. With the temperature adjustment, the total number of tests that would pass the 0.85 ACI 318 is 49 out of 122.

While ACI 214.4R-10 recognizes the strength loss due to an increase in internal temperature, the ACI 318 Commentary is silent on whether this adjustment should be considered when judging the adequacy of core strength test results. This adjustment could be a large factor in the decrease in core strengths because some internal temperature increases approach 100ºF.

3.4.5 Comparison to Bloem's Data: Table 4.2 summarizes the Bloem and Pankow data. The average and standard deviation of the core-to-cylinder ratio for the Bloem data were 0.80 and 0.10, respectively. The average and standard deviation of the core-to-cylinder ratio for the raw Pankow data were 0.64 and 0.12, respectively. The variability of the core-to-cylinder ratio as represented by the standard deviation is about the same for each study.

Based on the Bloem and Pankow raw (uncorrected) core data, about 20% of Bloem's core test results and only 5% percent of the Pankow core test results reached 85% of the standard-cured cylinder strength at the same age. While one major difference between the Bloem and Pankow tests was the use of SCM's for all but one of the mixtures tested, other differences such as mixture materials and proportions, differences in curing and temperature, and fresh and hardened concrete properties may also factor into the difference between the Bloem and Pankow data.

3.4.6 Comparison with ACI 363.2R-11 References: ACI 363.2R-11 "Guide to Quality Control and Assurance of High-Strength Concrete" provides core strength test results and conclusions with respect to that data and includes the following:

"A correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 4 in. in diameter) to the strength of specimens used for acceptance testing, that is, 6 by 12 in. or 4 by 8 in. cylinders. Then, if coring becomes necessary, the relationship has been established, agreed upon, and is ready for conclusive interpretation. In the absence of correlation data, the provisions of ACI 318 should be used."

"These data (see references below) indicate that the acceptance criteria for core strengths specified in ACI 318 are also applicable to high strength concretes."

- Cook, J. E., "10,000 psi Concrete," *Concrete International*, V. 11, No. 10, Oct. 1989, pp. 67-75
- Burg, R. G., and Ost, B. W., "Engineering Properties of Commercially Available High-Strength Concretes," *PCA Research and Development Bulletin RD104T*, 1992.
- Bickley, J. A.; Ryell, J.; Rogers, C.; and Hooton, R. D., "Some Characteristics of High-Strength Structural Concrete," *Canadian Journal of Civil Engineering*, V. 18, No. 5, 1991, pp. 885 -889.
- Bickley, J. A.; Ryell, J.; Rogers, C.; and Hooton, R. D., "Some Characteristics of High-Strength Structural Concrete: Part 2," *Canadian Journal of Civil Engineering*, V. 21, No. 6, 1994, pp. 1084-1087.
- Aïtcin, P.-C., and Riad, N., "Curing Temperature and Very High-Strength Concrete," *Concrete International*, V. 10, No. 10, Oct. 1988, pp. 69-72.

The information in this document is confusing and seems contradictory. The statements that an established correlation curve results in a relationship that "is ready for conclusive interpretation," implies that absent a correlation curve, core test results would lead to inconclusive interpretation. But the next sentence recommends that, in absence of a correlation curve, the provisions of ACI 318 should be used. This document also implies, but does not state, that the correlation curve is preferable to ACI 318 provisions. However, the document does not address suggested actions if the correlation curve results in a core-to-cylinder ratio for acceptance that is lower than the 0.*85f'c required* by ACI 318.

The document seems to contradict itself when it states that "these data" indicate that the acceptance criteria for core strengths in ACI 318 are also applicable to high strength concretes. If this were true, it would be unnecessary to establish a correlation curve. "These data" from ACI 363.2R-11 are shown and discussed below.

Cook 1989 — This data shows the range and average core-to-cylinder ratio at the same age. At 7 and 365 days, all cores exceed the ACI 318 limit. This is also reasonably true for the 28 day data where the lower core-to-cylinder ratio is stated at 0.84. However, the same is not true for the data at 56 or 180 days where the average core-to-cylinder ratio is close to the ACI 318 limit, but individual core-test results yielded core/cylinder ratios as low as 0.78. This would mean that 100% of the concrete represented by core strengths would be acceptable at 7, 28 and 365 days, but only about 50% of the concrete (based on a normal distribution) would be acceptable at 56 and 180 days. This anomaly of concrete being acceptable at one age but not another was also found in the Pankow study.

Table 5.2.1—Strength cores from 760 mm (30 in.) square columns (Cook 1989)

Age at test, days	Moist-cured cylinder strength at same age, percent	
	Range	Average
7	94 to 105	99
28	84 to 97	91
56	78 to 94	84
180	78 to 94	86
365	93 to 107	98

Notes: Cement: Type I -- 606 and 602 pcy
Water/cementitious ratio: 0.33, 0.29
Strength Level: 10,000 psi
Class C fly ash at 25 to 30% replacement
Admixtures: Type A and Type F
Core test condition unreported.

Burg and Ost 1992 – These data do not show core-to-cylinder data with both cores and cylinders tested at the same age. The data are for strengths of cores taken at 91 and 426 days and compared to strengths of 28-day-old moist-cured cylinders. In practice, cores are drilled almost immediately after a low-cylinder break is reported. It is not clear how this data can be used to suggest that the ACI 318 criteria applies to high-strength concrete.

Table 5.2.2—Strength of cores from 1220 mm (4 ft) cubes (Burg and Ost 1992)

Cementitious system	Age at test, days	28-day moist-cured 152 x 305 mm (6 x 12 in.) cylinder strength, percent	
		Range	Average
I	91	95 to 106	99
I + SF + FA		93 to 96	95
I + SF		85 to 90	88
I + SF		93 to 104	98
I + SF + FA		102 to 105	103
I + SF + FA		107 to 110	108
I + SF	426	109 to 123	117
I + SF + FA		104 to 106	105
I + SF		94 to 98	96
I + SF		100 to 111	107
I + SF + FA		104 to 113	109
I + SF + FA		122 to 124	123

*I = Type I portland cement; SF = silica fume; FA = fly ash.

Notes:
Water/cementitious ratios ranged from: 0.22 to 0.32
Strength Levels: 10,000 to 20,000 psi
Silica fume and fly ash replacement: 10 to 25%
Admixtures: HRWR and retarder
Core test condition unreported

Bickley et al. 1991, 1994 – This data compares cores tested at 1, 2 and 7 years with average 28-day moist-cured cylinder tests. Waiting this long to take cores is not practical for any ongoing construction. It is not clear how this data can be used to suggest that the ACI 318 criteria apply to high-strength concrete.

Table 5.2.3—Column core strength at later ages (Bickley et al. 1991, 1994)

Age at test, years	Average 28-day moist-cured cylinder strength, percent	
	Range	Average
1	90 to 109	97
2	91 to 107	100
7	97 to 100	99

Notes: Cement is CSA type 10 (Type I) -- 695 pcy
Cement replacement: 25% slag, 7.8% silica fume
Water/cementitious ratio: 0.31
Admixtures: WR and HRWR
Cores from 66.5 x 35.4 in columns
Cores tested dry.

Aitcin and Riad 1988 – This data also shows the results for cores taken at an extended time period, at 2 years. It compares the 2 year core strength to the 28-day moist-cured cylinder strengths.

"Aïtcin and Riad (1988) reported 2-year core strengths from columns made with Type I cement and silica fume. The average 2-year core strength was 97 percent of the strength of 28-day moist cured cylinders."

Notes: Cement is Type I -- 840 pcy
Silica fume replacement at 5.5%
Water-cementitious ratio is 0.26
Admixtures: HRWR and retarder
Cores from 44-in square columns
Cores test condition unreported.

Based on the preceding comments for the data cited, it is unclear how ACI Committee 363 concluded that that the "acceptance criteria for core strengths specified in ACI 318 are also applicable to high strength concretes." For four of the five references, this is true only if cores can be removed and tested at 3 months to 7 years and compared to the 28-day moist-cured cylinder strength. This is not a realistic construction expectation. For Cook's data, ACI 318 criteria works well at 7, 28 and 365 days but rejects 50% of the concrete at 56 and 180 days.

Strip 18- 24 hr. Air dry	**Table 3.1 Retest Strength and Variability of Cores from Field Constructed Blocks Core Testing by Central Concrete Supply and Independent Laboratory as Noted**							
Age About 280 days	Mix	#1, psi	#2, psi	#3, psi	Average, psi	Standard Deviation, psi	Coefficient of Variation, %	Comment
100% Cement	1	7786	6942	5872	6867	959	14.0%	Central core, cap and test
100% Cement	1	8440	7530	6280	7417	1084	14.6%	Central core and cap; Lab test
100% Cement	1	7330	6510	5900	6580	718	10.9%	Lab core, cap and test
70% Ternary	7	5472	6059	7412	6314	995	15.8%	Central core, cap and test
70% Ternary	7	4920	5920	7560	6133	1333	21.7%	Central core and cap; Lab test
70% Ternary	7	6540	5730	5420	5897	578	9.8%	Lab core, cap and test
70% Tern+ Low w/cm	8	8261	7834	6294	7463	1035	13.9%	Central core, cap and test
70% Tern+ Low w/cm	8	9030	8250	6450	7910	1323	16.7%	Central core and cap; Lab test
70% Tern+ Low w/cm	8	6450	6210	6080	6247	188	3.0%	Lab core, cap and test
70% Tern+ Ltwt Fines	10	6146	-----	-----	6146	-----	-----	Central core, cap and test
70% Tern+ Ltwt Fines	10	7410	5990	6410	6603	729	11.0%	Central core and cap; Lab test
70% Tern+ Ltwt Fines	10	6660	4600	4570	5277	1198	22.7%	Lab core, cap and test
15% Fly Ash 4000 psi	11	7415	6695	6617	6742	1035	15.4%	Central core, cap and test
15% Fly Ash 4000 psi	11	7170	6060	6990	6740	1323	16.7%	Central core and cap; Lab test
15% Fly Ash 4000 psi	11	5760	5350	5920	5677	188	3.0%	Lab core, cap and test

Table 3.2 Core-to-Cylinder Ratio Statistics				
Data Description	Number of tests	Average	Standard Deviation	Number of Tests Passing 0.85 ACI 318
Bloem 1965	27	0.78	0.09	11
Bloem 1968	56	0.81	0.11	6
Bloem total	83	0.80	0.10	17
Pankow raw data	122	0.64	0.12	6
Pankow sealed correction	122	0.75	0.12	11
Pankow sealed and temperature correction	122	0.84	0.13	49

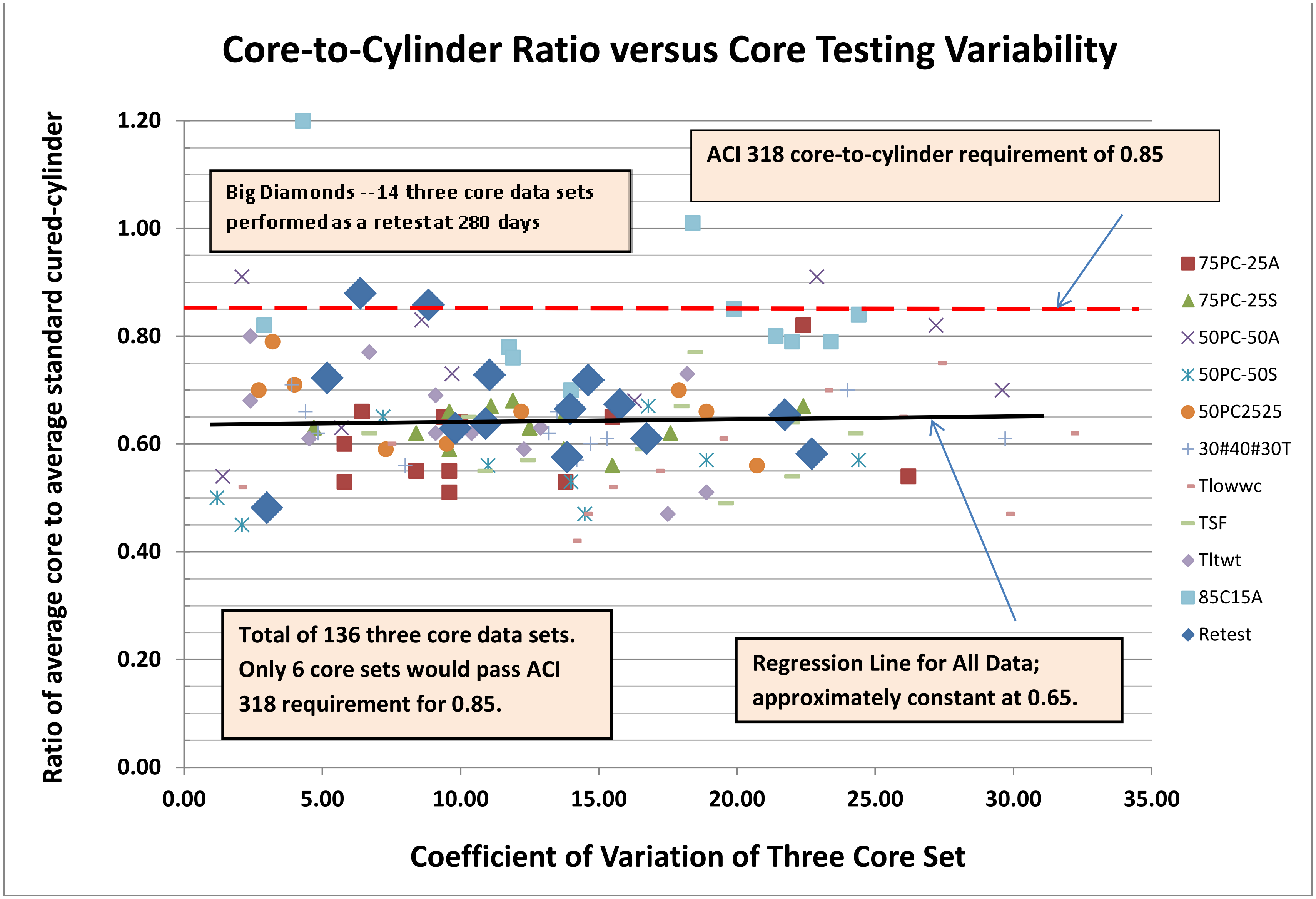


Figure 3.5 Raw (uncorrected) Core/Standard-Cure Cylinder Ratio vs Coefficient of Variation for All Tests at Ages Ranging from 28 to 280 days.

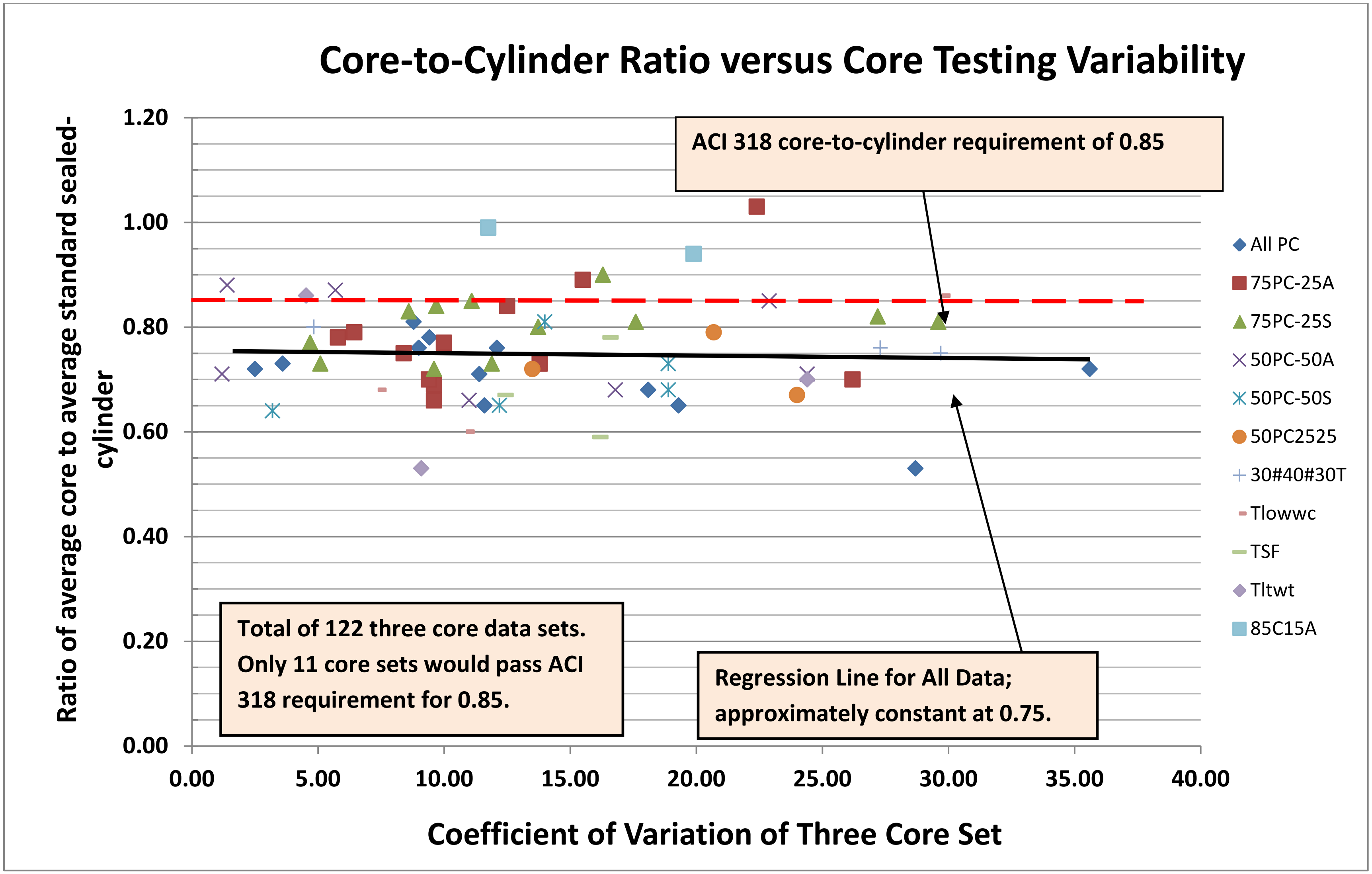


Figure 3.6 Raw (uncorrected) Core/Sealed-Cure Cylinder Ratio vs Coefficient of Variation for All Tests at Ages Ranging from 28 to 180 days.

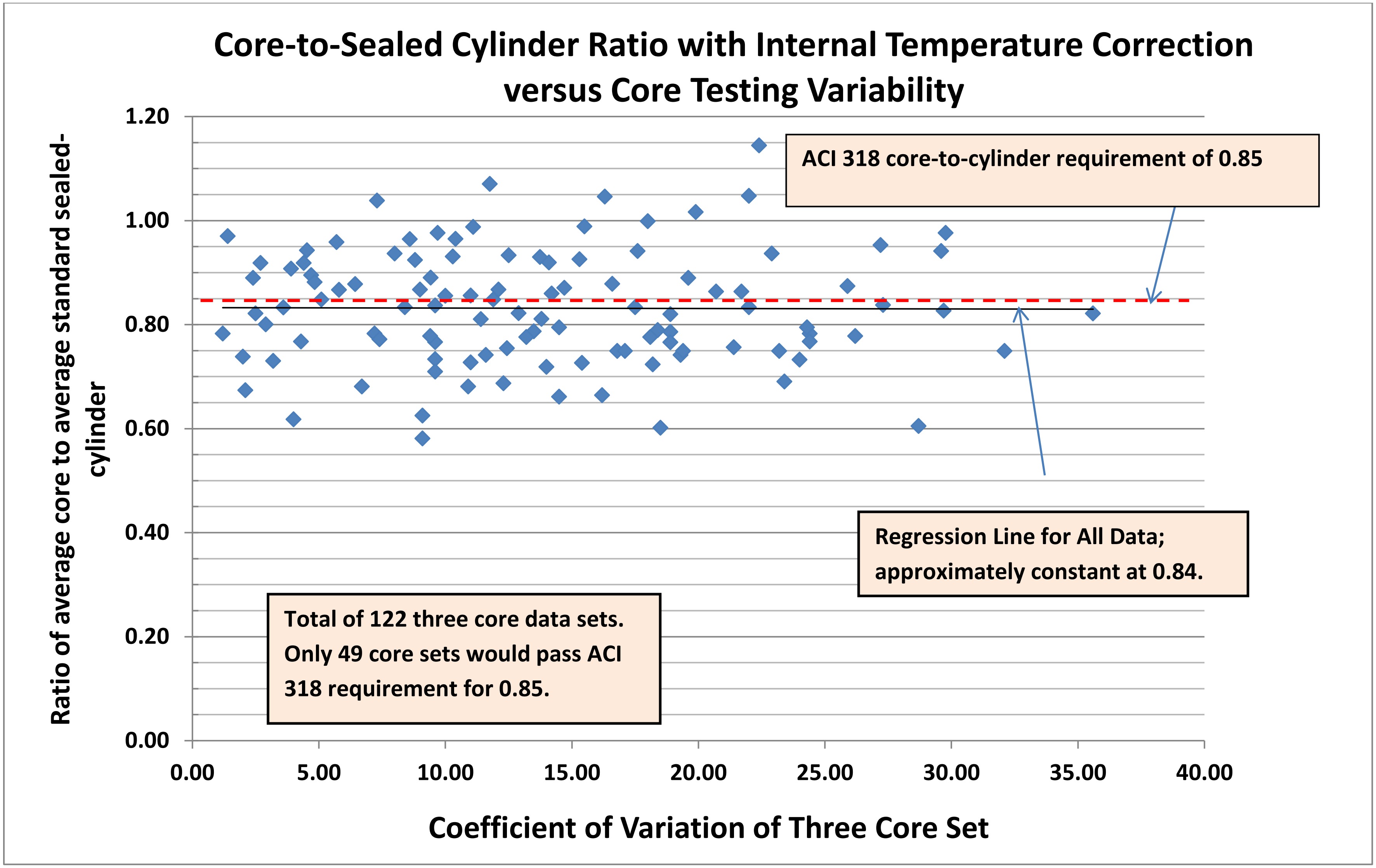


Figure 3.7 Core/Sealed-Cure Cylinder Ratio with Temperature Correction vs Coefficient of Variation for All Tests at Ages Ranging from 28 to 180 days.

3.5 References

Bartlett, F. Michael and MacGregor, James G., “Effect of Moisture Condition on Concrete Core Strengths”, *ACI Materials Journal*, May-June 1994, pp. 227-236.

Bartlett, F. Michael and MacGregor, James G., “In-Place Strength of High-Performance Concretes”, *High-Strength Concrete: An International Perspective, ACI SP 167*, March 1997, pp. 211-228.

Bloem, Delmar L., “Concrete Strength Measurement- Cores vs. Cylinders,’’ *ASTM Proceedings*, 1965, pp. 668-696.

Bloem, Delmar L., “Concrete Strength in Structures,” *ACI Journal Proceedings* V. 65, No. 3, Mar. 1968, pp. 176-187.

Malhotra, V. M., Testing Hardened Concrete: Nondestructive Methods, *ACI Monograph* No. 9, American Concrete Institute/Iowa State University Press, Detroit, 1976, 188 pp.

Malhotra, V. M., "Contract Strength Requirements – Cores Versus In Situ Evaluation," *ACI Journal Proceedings*, V. 74. No. 4, Apr. 1977. pp. 163-172.

Mindess, S., Young, J.F., and Darwin, D., *Concrete, 2nd ed.,* Pearson Education, Inc.,Upper Saddle River N.J., 2003, pp. 82-85.

Chapter 4 Early-Age Compressive Strength for Construction Operations

Specification compliance for concrete compressive strength is traditionally set at 28 days. For green concrete, as discussed in Chapter 2, specification compliance testing is often delayed until 56 or 90 days to allow a greater reduction in portland cement content. While the specification compliance testing requirement must be met, there are also early-age strength requirements needed by the contractor for construction operations. The cost and schedule for a project can be considerably altered if the concrete can't achieve the needed strength to sequence construction operations. These early-age strength requirements are first reviewed, discussed with respect to the Pankow data, and then considered with respect to green concrete mixtures in general.

4.1 Early-stage Construction Operations

The following list includes traditional early-stage construction operations that are typically completed within 3 days of placing concrete.

Vertical form removal -- Column and wall forms and beam side forms that don't support formwork for slab or beam soffits are traditionally removed the day after concrete placement. Published research indicates that the minimum compressive strength necessary to prevent mechanical damage to the concrete surface when stripping forms can be as low as about 300 psi or as high as about 450 psi (Malisch 2009). Some project specifications require a minimum strength of 500 psi for a field-cured cylinder to verify that vertical form removal can proceed. ACI 347-04 "Guide to Formwork for Concrete" includes an elapsed-time criteria for form stripping, as follows:

> "Because the minimum stripping time is a function of concrete strength, the preferred method of determining stripping time is using tests of job-cured cylinders or concrete in place. When the contract documents do not specify the minimum strength required of concrete at the time of stripping, however, the following elapsed times [12 hours for walls, columns, and beam sides that don't support formwork for slab or beam soffits] can be used. The times shown represent a cumulative number of… hours, not necessarily consecutive, during which the temperature of the air surrounding the concrete is above 50°F (10°C)."

During warm weather, 12 hours may be enough time to attain the necessary strength. In cold weather, more time may be needed. If forms are to be removed as early as possible to maximize form reuse, the maturity method can be used to determine when the desired strength level has been reached.

On one green concrete building project, the vertical form removal was delayed as long as two weeks to allow the time needed for the concrete to gain enough strength to permit form removal without damaging the concrete surface. This is not the norm, however. Cold weather effects on early-age strength gain for green concrete mixtures increase the possibility of damage to the formed surface during form stripping operations.

Early-age freezing -- ACI 306R-10 “Guide to Cold Weather Concreting” states that one of the objectives of cold weather concreting practices is to:

> “Prevent damage to concrete due to early age freezing. When no external water is available, the degree of saturation of newly placed concrete decreases as the concrete matures and the mixing water combines with cement during hydration. Under such conditions, the degree of saturation falls below the critical level (the degree of water saturation where a single cycle of freezing causes damage) at the approximate time the concrete attains a compressive strength of 500 psi (Powers 1962). At 50°F, most well-proportioned concrete mixtures reach this strength within 48 hours.”

The last statement in ACI 306R-10 is for traditional concrete mixtures with cement replacements by SCMs of less than 20 percent and designed for compressive strength compliance at 28 days. Many green concrete mixtures with cement replacements greater than 50 percent and cured at 50°F are unlikely to reach 500 psi within 48 hours.

Saw-cutting joints -- Sawcutting too early in concrete, before the concrete gains enough strength, causes unacceptable raveling. Most saw operators determine the earliest time to sawcut by judging the degree of raveling in trial cuts made in the slab. FHWA research (Suprenant 1995), however, provides the approximate minimum compressive strength of concrete required before joints can be sawcut with minimal raveling. The compressive strength for acceptable sawcuts varied from a low of 310 psi for rounded, soft coarse aggregates to 1,270 psi for crushed, hard coarse aggregates. While these were the lowest and highest strength values, the compressive strength range needed to produce acceptable sawcuts was between 500 to 1,000 psi for most concrete mixtures.

The American Concrete Pavement Association (ACPA) discusses the effect of using slag cement as a replacement on sawcutting in its R & T Update “Slag Cement and Concrete Pavements.” They state that:

> “For concrete pavements, slag cement is typically used in proportions of 25 to 35 percent. Joints need to be sawed after the concrete has achieved enough strength to keep the sawcut from raveling but before internal stresses in the

> concrete become great enough to initiate an uncontrolled crack. The earlier the concrete can be cut without raveling, the better the chances are that the concrete will not crack before saw cutting. As a rough guideline, for slag cements the time to saw cut is delayed approximately 30 minutes for every 10 percent of slag cement replacing portland cement."

Post-tensioning -- Post-tensioning tendons inside plastic ducts or sleeves, are positioned in the forms before the concrete is placed. Once the concrete has gained strength, but before the service loads are applied, the desired force in the tendons is applied by jacks to produce the required prestress before anchoring the tendons at the outer edges of the concrete member. <u>The Post-Tensioning Manual</u> published by the Post-Tensioning Institute (PTI) states that "when tests of field-cured cylinders indicate that the concrete has reached the proper strength (usually 3000 psi) the stressing operation may begin." In traditional concrete building projects, stressing is usually begun in the first 1 to 3 days.

Elevated form removal -- Supporting forms and shores should not be removed from floor and beam soffits until these structural units are strong enough to carry their own weight and any approved superimposed load. In no case should supporting forms and shores be removed from horizontal members before the concrete has achieved the strength specified by the engineer/architect. ACI 347-04 recommends that:

> "The engineer/architect should specify the minimum strength of the concrete to be attained before removal of forms or shores. The strength can be determined by tests on job-cured specimens or on in-place concrete." Specifications for traditional building projects set the concrete strength requirements at 75% *f'c*. This strength requirement usually allows form stripping and reshore placement to occur between 3 to 7 days.

It may take as long as one month however, to reach 75% *f'c* with green concrete mixtures when the test age for *f'c* is set at 56 or 90 days. Waiting a month for form removal and reshoring significantly increases cost and slows progress, which can put the concrete portion of the project behind schedule. Also note that ACI 301-10 "Specifications for Structural Concrete" defaults to an in-place strength of *f'c* or higher until formwork and shoring can be removed. If f'c is defined at 56 or 90 days, this ACI 301 provision could require leaving forms in place for up to 56 or 90 days.

Although ACI has defined shoring and reshoring design procedures set out in ACI 347.2R-05 "Guide for Shoring/Reshoring Multistory Buildings" some engineers and contractors still use a rule of thumb that it takes 2 floors of reshores and one floor of shores to support a newly placed concrete floor. This is a reasonable rule-of-thumb on most traditional building projects. Depending on the concrete strength at stripping, however, green concrete buildings may require 4 floors of reshores with one floor of shores.

Miscellaneous construction operations -- Contractors often set anchors in previously placed concrete, with temporary braces for forms and other work attached to the anchors. Anchor design is based on the concrete strength. To wait until green concrete reaches an appropriate strength, anchors may have to be drilled and installed at a later age than that for traditional concrete. Alternatively, more anchors than usual may be needed to offset the lower green concrete strength at an earlier age.

4.2 Pankow Early-age Compressive Strength Data

Fig. 4.1 shows the Pankow data for early-age compressive strength of standard-cured cylinders. Note that the compressive strengths range from about 500 to 1,750 psi, about 1,000 to 3,000 psi, and about 1,500 to 5,000 psi. at one, three, and seven days, respectively. The lowest strength at each age is for the concrete mixture with a 28-day design strength of 4000 psi and 15% of the portland cement replaced by fly ash. The green concrete mixes averaged about 6,700 psi at 28 days, 7,900 psi at 56 days and 8,600 psi at 90 days. See Tables L3 and F3 in the Phase I report for the compressive strength data at ages from 1 to 180 days.

The one-day compressive strength level of standard-cured cylinders indicates enough strength to permit vertical form removal, prevent early-age freezing, and allow sawcutting of joints. The three-day compressive strength of 2,500 to 3,500 psi needed to permit post-tensioning or elevated form removal was achieved by only the following 4 of the 11 mixtures:

- Replacement of 50% of the portland cement with slag cement
- Ternary mixture with a low w/cm
- 100% portland cement with no SCMs
- Replacement of 25% of the portland cement with slag cement

This is significant because the strengths of these mixtures are for laboratory-curing conditions. The compressive strengths of field-cured cylinders are lower than those of the laboratory-cured cylinders because of less than optimal curing conditions. This effect would be magnified during cold weather concreting.

The Pankow green concrete mixtures were designed for an *f'c* of about 8,000 psi at 90 days. It is expected that construction operations for these green concrete mixtures in buildings would be delayed as compared with traditional concrete building mixtures with *f'c* equal to about 8000 psi.

4.3 Project Experiences

Previous consulting experiences with green concrete mixtures in buildings in California has shown that relatively cold weather, in the range of ambient temperatures between 50ºF and 60ºF, dramatically affected early-age strength and construction operations. Accelerators were required in the green concrete mixtures to permit early-age construction operations. In a few cases, the green concrete mixture proportions were adjusted by reducing the cement replacement percentage from 50% to 20% in cold weather to avoid delaying early-age construction operations.

The *Concrete International* article, "Sustainability through Strength," (Stevenson and Panian 2009) discusses the impact of strength gain on post-tensioning for the 50% slag cement concrete mixture used at the David Brower Center in Berkeley California.

> "Although in many ways they are similar to conventional concrete, mixtures containing large amounts of slag cement have some unique properties that affect design and construction. These include rate of strength gain, finishing behavior, and ability to form fine details. The rate of strength gain can have a significant impact on the construction schedule. Because the elevated slabs were post-tensioned, the time between concrete placement and slab stressing was a critical-path item. Typically, a 5000 to 6000 psi post-tensioned slab is required to reach 3000 psi before the strands can be stressed. Most conventional mixtures, under typical conditions, can meet this criterion in 3 to 5 days. The 50% slag cement mixtures used in the Brower Center often reached stressing strength within 5 days, but in a number of instances required 7 to 10 days. Because construction continued from late autumn through late spring, a wide range of temperatures was encountered. Placements during colder weather were typically slower to reach strength. As the Brower Center has only four elevated decks and the adjacent plaza portion was on a separate construction track, the net impact on the construction schedule was minor."

Stevenson and Panian also reported that on the same project it was difficult to get sharp concrete corners and edges with the 50% slag cement concrete mixture when the formwork was removed. They reported that "This was problematic where reveals, sharp corners, or other fine features were required in exposed surfaces. Patching provided a good final appearance, but further investigation is needed to determine how to adjust the mixtures to correct this behavior."

4.4 The Need for Early-age Compressive Strength Data Prior to Bidding

The lower early-age compressive strength of green concrete mixtures can significantly impact the schedule and costs of a green concrete building. For traditional concrete buildings, contractors use their experience in understanding and adjusting to concrete mixtures for early-age construction operations. This experience however, may not be applicable for green concrete buildings. To submit a firm bid to the owner, the contractor needs to know the 1-, 3- and 7-day compressive strengths of the green concrete mixtures in order to plan the schedule. It would also be helpful to be able to estimate the effect of cold weather on the green concrete strength and the cost and benefits of accelerators and other green concrete mixture adjustments.

It was shown in section 4.2 that the Pankow early-age strength results would delay normal 3-day post-tensioning. These green concrete mixes were designed for an f'c of about 8000 psi at 90 days. Green concrete mixtures designed for 4000 to 6000 psi at 56 to 90 days will have even lower early-age strengths, creating delays that impact the schedules to a greater extent. The need for early-age strength data for concrete used in green buildings can't be over-emphasized. The data is needed so the contractor can prepare a realistic construction operations schedule that minimizes delays and the costs associated with them.

4.5 Flexible Engineering is Needed

Scattered through-out sections 4.2 and 4.3 are the implications of "flexible engineering" during construction. For the David Brower Center, the engineers adjusted the 50% slag cement concrete mixture to a 40% slag cement mixture when needed. They also recognized the need for patching of exposed concrete at the edges and corners. On other projects in California, green concrete mixtures have been adjusted during construction. As more projects strive to reach up to 70% cement replacement, adjustments may be needed during construction.

4.6 References

Malisch, Ward R., "Strength Needed for Stripping Forms Without Damaging the Concrete Surface," *ASCC Troubleshooting Newsletter No. 57,* American Society of Concrete Contractors, St. Louis, MO, October 2009.

American Concrete Pavement Association, "Slag Cement and Concrete Pavements", *R&T Update 4.03*, , Rosemont, IL, March 2003, 4 pp.

Post-Tensioning Manual 6th ed., Post-Tensioning Institute, Farmington Hills, MI.

Stevenson, Mark, and Panian, Leo, "Sustainability Through Strength," *Concrete International*, March 2009, pp. 34-39

Suprenant, Bruce A., "Sawcutting Joints in Concrete," *Concrete Construction*, January 1995, pp. 54-66.

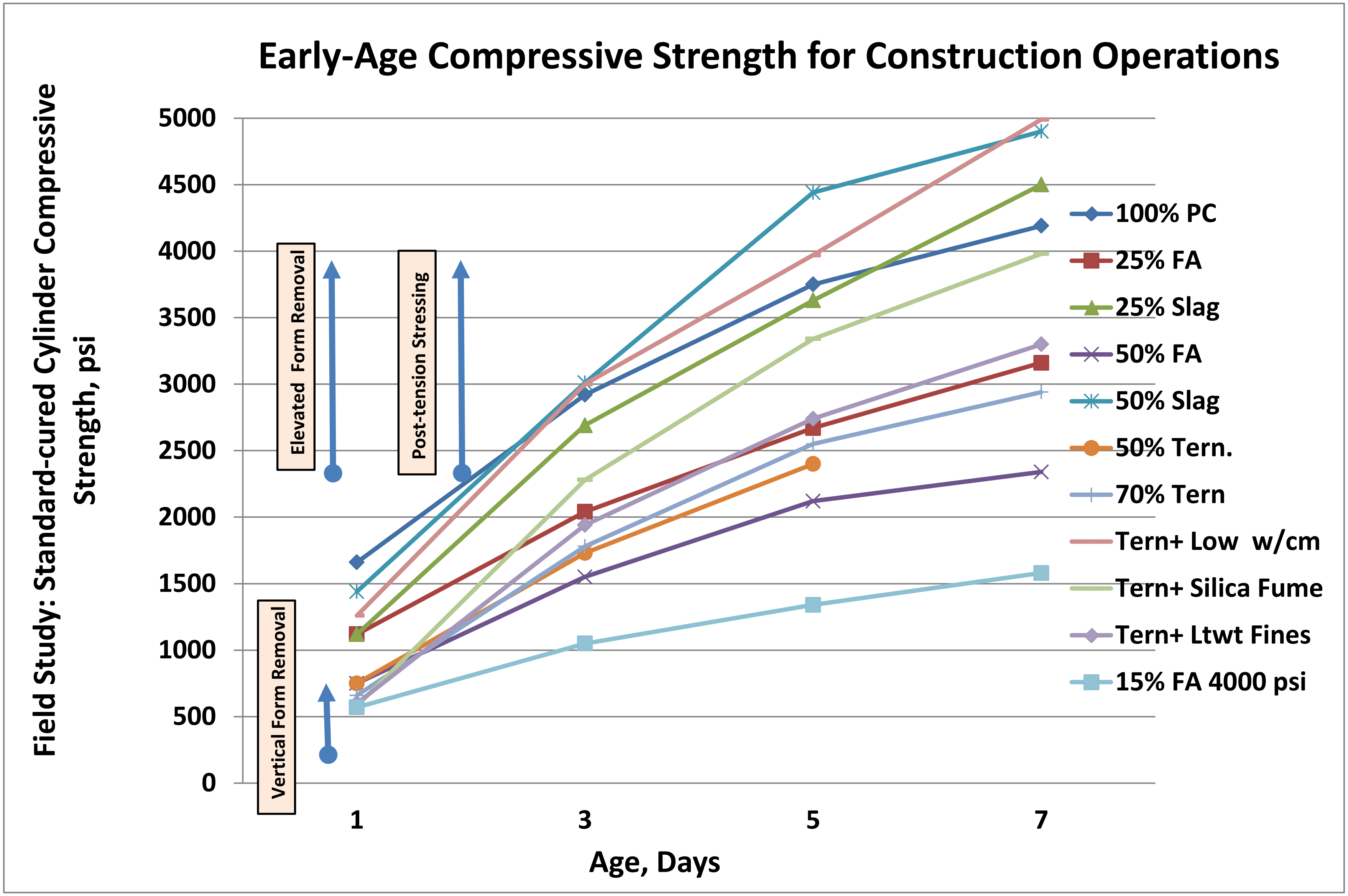


Figure 4.1 Early-age compressive strength of standard –cure, field cast cylinders from 11 Pankow research mixtures.

Chapter 5 Fresh Concrete Stiffening and Construction Operations

Specifications seldom address setting time, although this property of fresh concrete can affect construction operations in several ways when green concrete mixtures are used.

- Forming: Form pressures in walls and columns increase with increases in setting time. Increased form pressures increase forming costs because either the pour rate must decrease resulting in a longer wall placement or the wall must be placed in two separate formed pours.
- Consolidation: Fast setting can reduce the ability to thoroughly consolidate concrete, but slow setting is a more likely problem because it can result in settlement cracking in deep sections.
- Finishing: Again, slow setting is most likely to cause construction problems. Increased finishing costs are the result of delays in finishing caused by slow setting. Surface defects such as blisters, delamination, and plastic shrinkage cracking are often the result of a slow setting concrete.
- Curing: Initiation of initial and final curing can be delayed by slow setting. This too can result in plastic shrinkage cracking or in premature drying of the surface.

As indicated by the above bulleted list, cost for a project can increase considerably if the concrete sets too slowly. The effect of setting time on fresh concrete construction operations is first reviewed. Then the Pankow data on setting time is presented.

5.1 Fresh Concrete Construction Operations

The list below presents traditional fresh concrete construction operations, those typically completed while the concrete is still plastic.

Placing concrete in vertical forms (form pressures) -- Fresh concrete placed in wall or column forms acts like a fluid to exert a lateral pressure against the formwork. The formwork must be designed to withstand this lateral pressure. The maximum lateral pressure is equal to the height, h, of the fluid concrete times the unit weight, w, of the concrete – for normalweight concrete usually considered to be 150 pcf. ACI 347-04 “Guide to Formwork for Concrete” recommends that, unless other conditions are met, the formwork should be designed for a lateral pressure, $p = wh$. This equation considers lateral pressure to be a hydrostatic (fluid) pressure of concrete.

ACI 347-04 states that “The set characteristics of a mixture should be understood, and using the rate of placement, the level of fluid concrete can be determined.” The concrete set time determines the rate at which the full hydrostatic lateral pressure reduces due to concrete stiffening. As the concrete stiffens, the lateral pressure against the formwork decreases.

Concrete is usually placed in lifts of 4 ft. thickness or less. The hydrostatic lateral pressure against the formwork for the first lift is the height of that lift times the unit weight of the concrete. If the next lift is placed quickly, the maximum lateral pressure on the formwork is the total height of both lifts times the unit weight of the concrete. If the second lift placement is delayed, the concrete in the first lift stiffens and no longer exerts a full hydrostatic lateral pressure on the formwork. Typical industry practice is to place the lifts such that the formwork pressure is reduced to a value below maximum hydrostatic pressure. Thus, the set time or stiffening of the fresh concrete is an important factor when determining the formwork pressure used design.

ACI 347-04 indicates that "When working with mixtures using newly introduced admixtures that increase set time or increase slump characteristics, such as self-consolidating concrete, ….the maximum hydrostatic pressure… should be used until the effect on formwork pressure is understood by measurement." ACI 347-04 provides information on form pressures for concrete mixtures containing less than 70% slag or 40% fly ash. Without a formwork pressure measurement, ACI 347-04 recommends that for concrete mixtures that exceed these limits (more than 70% slag or 40% fly ash) the formwork should be designed for full hydrostatic pressures.

Consolidating concrete – Most concrete is consolidated by using immersion vibrators or external form vibrators while the concrete is still in a plastic state. If the concrete sets too fast, as it might when silica fume is used, it can't be adequately vibrated and a cold joint can form between successive placements. British Standard BS 5075 (Dodson 1994) uses a setting time measurement of 72 psi as the upper limit for placing and compaction of concrete. In other words, the faster this setting time value occurs the shorter time the contractor has to place and vibrate the concrete.

Slow setting is a more likely concern, because green concretes normally set more slowly than traditional concretes. This slower setting is a possible problem in deep sections of mat foundations, beams, or walls because the initial vibration doesn't fully consolidate the concrete. Further consolidation that occurs as a result of subsidence—settlement of solids—is likely in slow-setting mixtures. When restrained by reinforcing steel or other embedded items, settlement cracking may occur. Revibration is one method for reducing settlement cracking, but for large area placements such as base mats, it is seldom practical to revibrate the concrete. In addition, revibration increases form pressures by more than 40% above the ACI 347 formulas (Douglas et. al.) For such placements, if slow setting produces settlement cracks, a change in the concrete mixture may be appropriate.

Finishing concrete – After concrete floors or slabs are placed, finishing operations usually include screeding (sometimes accompanied by vibration), bullfloating, power floating and power troweling. The concrete must be plastic enough for screeding and bullfloating but must then stiffen prior to power floating and troweling. Setting time measurements can be used to estimate the amount of time available for finishing operations, and the measurements can also be used as a basis for needed mixture adjustments when concrete will be finished in hot or cold weather. Accelerating admixtures may be useful, especially in cold weather, to reduce setting time and the possibility of top-down setting, which can result in surface crusting and blistering or delamination.

Finishers observe loss of a bleedwater sheen and the depth of their footprint as rough measures of the time at which power floating should begin. Suprenant and Malisch (1988) used 6-in. thick by 4-ft-square slabs to check the depth of a finisher's footprint while also measuring setting time on a mortar sample tested in accordance with ASTM C 403. They found that a finisher's ¼-in.-deep footprint indentation corresponded to a penetration resistance of between 15 to 25 psi. Abel and Hover (2000) found that the decision to start brooming the concrete surface was when the penetration resistance was about 10 psi. Bury et al. (1994) found that the ¼-inch-deep footprint indentation occurred with penetration resistance less than 50 psi.

Curing during finishing – Fresh concrete loses moisture due to evaporation of bleed water. The longer the concrete remains plastic the more moisture it loses. When the evaporation rate exceeds the bleeding rate, plastic shrinkage cracking can occur. This occurs most often during hot weather concreting, but sometimes during cold weather as well. Slow setting exacerbates this problem because of increased bleeding duration and a longer time needed for the concrete to stiffen enough so finishers can start floating. Concretes containing supplementary cementitious materials (SCM's) usually set more slowly and may bleed less than straight portland cement mixtures. Thus, they are more susceptible to plastic shrinkage cracking. Spraying evaporation reducers on the fresh concrete surface assists in reducing moisture loss by evaporation and thus reduces the probability of plastic shrinkage cracking.

Final curing – Concrete floors or slabs are usually cured by spraying curing compounds on the surface or by using sheet materials such as plastic or specialty sheeting to reduces moisture loss or by. These curing activities take place when the concrete is hardened sufficiently so that no footprints are visible when workers walk on the surface. The Federal Highway Administration (Poole 2005) indicates that final curing should commence at initial set.

5.2 Understanding Time of Setting Measurements

Time of setting is determined with penetration resistance measurements on mortar sieved from the concrete mixture, as set forth in ASTM C 403-08 “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.” The test method includes a brief summary as follows:

> “A mortar sample is obtained by sieving a representative sample of fresh concrete. The mortar is placed in a container and stored at a specified ambient temperature. At regular time intervals, the resistance of the mortar to penetration by standard needles is measured. From a plot of penetration resistance versus elapsed time, the times of initial and final setting are determined.”

The information determined in this test method is plotted as shown in Figure 5.1 (from ASTM C 403-08). By definition, initial set and final set correspond to penetration resistances equal to 500 psi and 4000 psi, respectively. Tuthill and Cordon (1955) showed that the concrete is usually stiffer than the mortar being tested and that the 4000 psi final set determined by penetration resistance is approximately equal to a compressive strength of 100 psi.

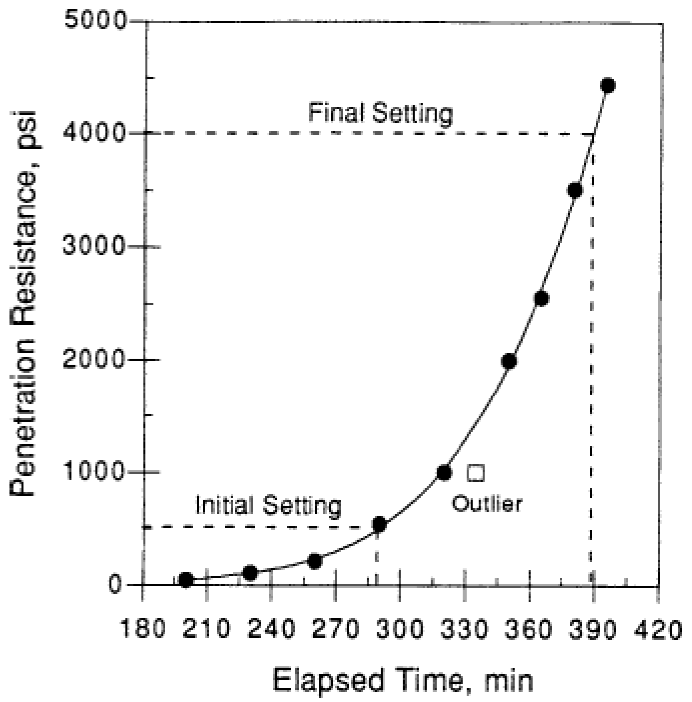


FIG. X1.1 Plot of Penetration Resistance Values Versus Elapsed Time and Hand Fit Curve Used to Determine Time of Setting (Note: Not drawn to actual scale)

Figure 5.1 Penetration resistance versus time showing initial and final set (from ASTM C 403).

Changes in the concrete mixture and the surrounding environment change the setting time. For instance, adding an accelerator to the concrete mixture speeds setting, while adding a retarder would slows setting. Water-reducing admixtures can be formulated from set neutral to acting as a retarder. Concretes containing SCM's are generally slow setting, but some admixtures can make the mixture set neutral. It's best to obtain setting time information for such mixtures from ASTM C 403 tests on samples with and without the admixture. Likewise, cold weather will slow setting time and hot weather will speed setting time. Most testing laboratories test concrete mixtures at about 70^{o}F so the effect at different temperatures needs to be evaluated. The next section gives a procedure for evaluating setting times at different temperatures.

5.3 Evaluating Time of Setting at Different Temperatures

FHWA (2005) notes that setting time measured in accordance with ASTM C 403 is conveniently done during mixture verification work prior to starting construction. The setting time is strongly affected by the concrete temperature, and therefore the field time of setting will differ from the laboratory-determined time if the two temperatures differ. This is important in field applications, since in-place concrete temperatures can differ significantly from laboratory concrete temperatures, and the effect can be substantial. Laboratory values can be adjusted for actual concrete temperature using the following equation.

$$TOS = TOS_{StdTemp} \bullet e^{R\left(\frac{1}{CT} - \frac{1}{StdTemp}\right)}$$

where:

- *TOS* = time of setting at temperature of in-place concrete, same units as in standard test
- $TOS_{StdTemp}$ = time of setting under standard conditions, any units
- *CT* = temperature of in-place concrete, *K*
- *StdTemp* = temperature of concrete during laboratory test, *K*
- *R* = constant

The constant, *R*, can be determined empirically, but a value of 5,000 Kelvins (K) works well. This equation can be programmed into a spreadsheet to simplify the calculation for use in exploratory work.

Temperature, F	Set Time Factor by Equation	Set Time Factor from Pankow Data	
40	2.78	Initial Set	Final Set
50	1.95	-----	
60	1.39	1.26	1.24
70	1.00	1.00	1.00
80	0.73	-----	----
90	0.54	0.63	0.65
100	0.40	-----	----

5.4 How Setting Time Influences Plastic Shrinkage Cracking

Poole's work for the FHWA describes how the combination of cumulative bleeding and cumulative evaporation affects the onset of plastic shrinkage cracking (PSC). "PSC occurs when concrete is still plastic (i.e. before time of initial setting), and when excessive loss of mixing water causes shrinkage sufficient to crack the plastic concrete. PSC may take the form of relatively large, parallel, well-spaced cracks that begin shallow but may penetrate deeply into the concrete. In other cases, PSC may take the form of a fine pattern of map cracks that penetrate only ½ to 1 inch into the concrete."

Figure 5.2 shows that bleed water rising to the surface offsets the evaporation loss. When cumulative bleeding exceeds cumulative evaporation, no plastic shrinkage cracks occur. When cumulative bleeding decreases and cumulative evaporation rate remains the same, a critical point can be reached at which plastic shrinkage cracks occur. When the concrete sets there is no more bleeding. The concrete can set before the fresh concrete reaches the critical bleed-evaporation point. If however, the concrete set time is delayed, the evaporation continues but the fresh concrete does not have enough bleed water to keep up with the evaporation rate. Thus the delayed set increases the potential for plastic shrinkage cracking.

To offset some of the delayed setting time resulting from reduced portland cement contents, green concrete mixtures are often proportioned at water-cementitious ratios below 0.40. This reduction in water-cementitious ratio reduces the amount of water in the concrete. Thus the longer the concrete remains plastic the more likely the bleed water needed to offset evaporation will be depleted. The combination of a lower water content and increased setting time makes green concrete mixtures more susceptible to plastic shrinkage cracking.

Fortunately, plastic shrinkage cracking is relatively harmless in reinforced concrete buildings.

5.5 Setting Time and Form Pressures

While the effect of setting time on form pressures is discussed in ACI 347-04, setting time is not used directly in any of the form pressure equations. Instead, ACI 347-04 modifies the form pressure equation based on concrete temperature, rate of placement, and concrete chemistry (mixture ingredients and quantities). The effect of these variables in combination could be more directly assessed by measuring setting time. In our literature search, however, we could find no research results in which an investigator included setting time as a variable in any proposed formwork pressure equation.

During construction, workers can estimate the degree of stiffening for each lift by inserting a #4 reinforcing bar into the top of the lift. If the bar penetrates more than 6 to 12 in. into the lift, the concrete has not stiffened enough to place the next lift. This field check more accurately estimates setting because form pressure calculations are based on anticipated, not actual, concrete temperature and rate of placement. Using the #4 bar test helps field personnel to evaluate form pressures under conditions that can differ from those assumed in formwork design.

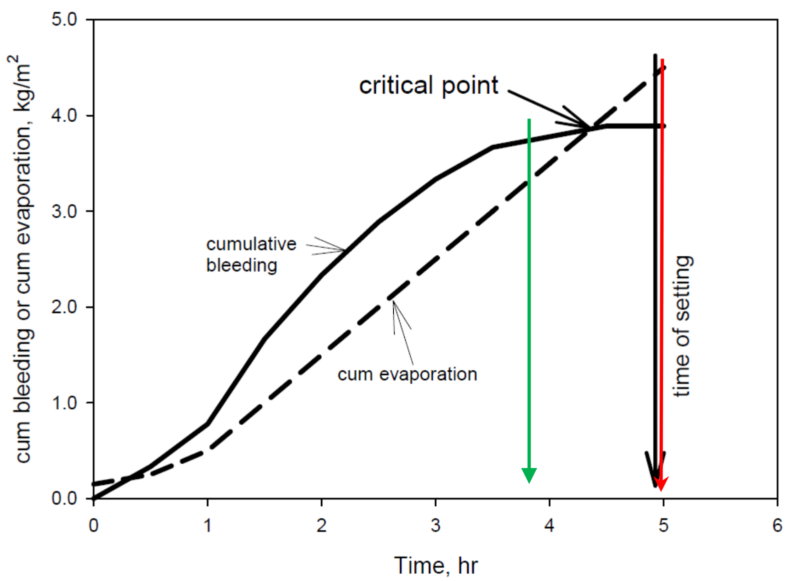


Figure 8. Graph. Plot of cumulative bleed and cumulative evaporation v. time.

Figure 5.2 Delaying the set time, moving from green to red line, can cause the concrete to reach a critical point where the cumulative evaporation exceeds the cumulative bleeding and plastic shrinkage cracks occur. (Modified from Poole 2005)

5.6 Evaluation of Pankow Setting Time Data

Table 5.1 shows the Pankow setting time data, developed in accordance with ASTM C 403 for concrete temperatures of 60°F, 72°F and 90°F. Figure 5.3 illustrates the effect of different concrete mixtures on the initial setting time. Figure 5.4 illustrates the effect of different mixtures on setting time: 100% portland cement, 50% fly ash and 70% ternary with low water-cementitious ratio. Note that the use of SCM's delayed setting.

As previously discussed, fresh concrete construction operations are influenced by concrete setting times below the 500 psi initial-set value. An example of the importance of cold and hot weather on initial setting times for the Pankow data is shown below. Note that at 60°F, the average setting times for all concrete mixtures were about 90 minutes greater than those at 72°F. And that at 90°F, the average setting times for all concrete mixtures were about 120 minutes less than those at 60°F. Note that the range of initial setting times at a cold temperature (60°F) varied by more than 240 minutes; while at a hot temperature (90°F) the variation was much smaller at about 40 minutes.

Initial Setting Times (500 psi) from Pankow Data

- At 60°F, setting time varies from 233 to 480 minutes; average is 360 minutes with a range of 247 minutes.
- At 72°F, setting time varies from 190 to 363 minutes; average is 286 minutes with a range of 173 minutes.
- At 90°F, setting time varies from 156 to 192 minutes; average of 175 minutes with a range of 41 minutes.

As expected the initial setting time for the 100% cement concrete mixture was the lowest at all three temperatures. The highest initial setting time was for the 70% ternary concrete mixture using a carbohydrate-based water-reducing admixture. This result was expected and was chosen to illustrate the importance of choosing a water-reducing admixture that does not retard set when the cementitious material is largely composed of SCMs. Because the large amount of SCM's typically used in green concrete mixtures delays setting, including admixtures that also delay setting can result in a concrete that is unsuitable for construction operations. As noted in this study, initial setting time for the 70% ternary concrete mixture using the carbohydrate-based water-reducing admixture exceeded 780 minutes (more than 13 hours). To show that this extraordinary setting time is primarily due to the high portland cement replacement percentage (70%), initial setting time was measured for another mixture containing 100% cement and the carbohydrate-based water-reducing admixture. This mixture had an initial setting time about 20 minutes slower than the 100% cement mixture containing a polycarboxylate admixture.

Table 5.1 Lab Study: Summary of ASTM C 403 Set Times at 60F, 72F and 90F

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern*	70% LW	75% Quad	70% In. C	5 sk 15% FA
	1	2	3	4	5	6	7	8	9	10	11
Initial Set Time, min											
60 F	233	333	250	397	380	357	>> 780	480	450	395	327
72 F	190	233	230	290	300	297	>> 780	333	363	357	270
90 F	156	170	163	170	171	175	197	180	185	188	192
Final Set Time, min											
60 F	357	450	400	535	510	510	>> 780	626	663	600	462
72 F	267	363	317	428	423	412	>> 780	478	527	537	388
90 F	228	240	235	262	260	253	300	289	286	300	281
*	Polycarboxylate water-reducing admixtures used except for the 70% Tern which used a carbohydrate admixture										

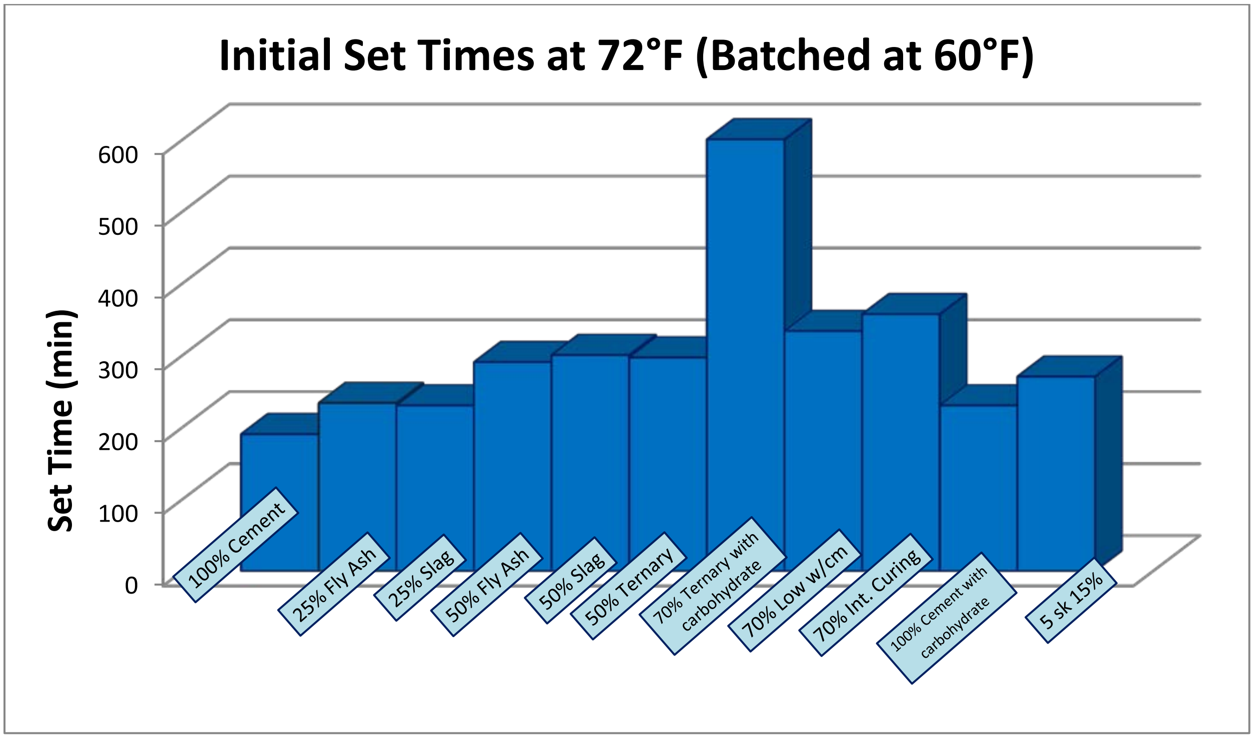


Figure 5.3 Initial setting times for concrete mixtures as measured by ASTM C 403. Initial setting times vary from a low of 190 minutes for the 100% cement mixture to greater than 780 minutes for the 70% ternary mixture with a carbohydrate-based admixture. Note that the carbohydrate-based admixture did not substantially increase initial setting time when used with the 100% cement mixture. All other concrete mixtures contained a polycarboxylate water-reducing admixture.

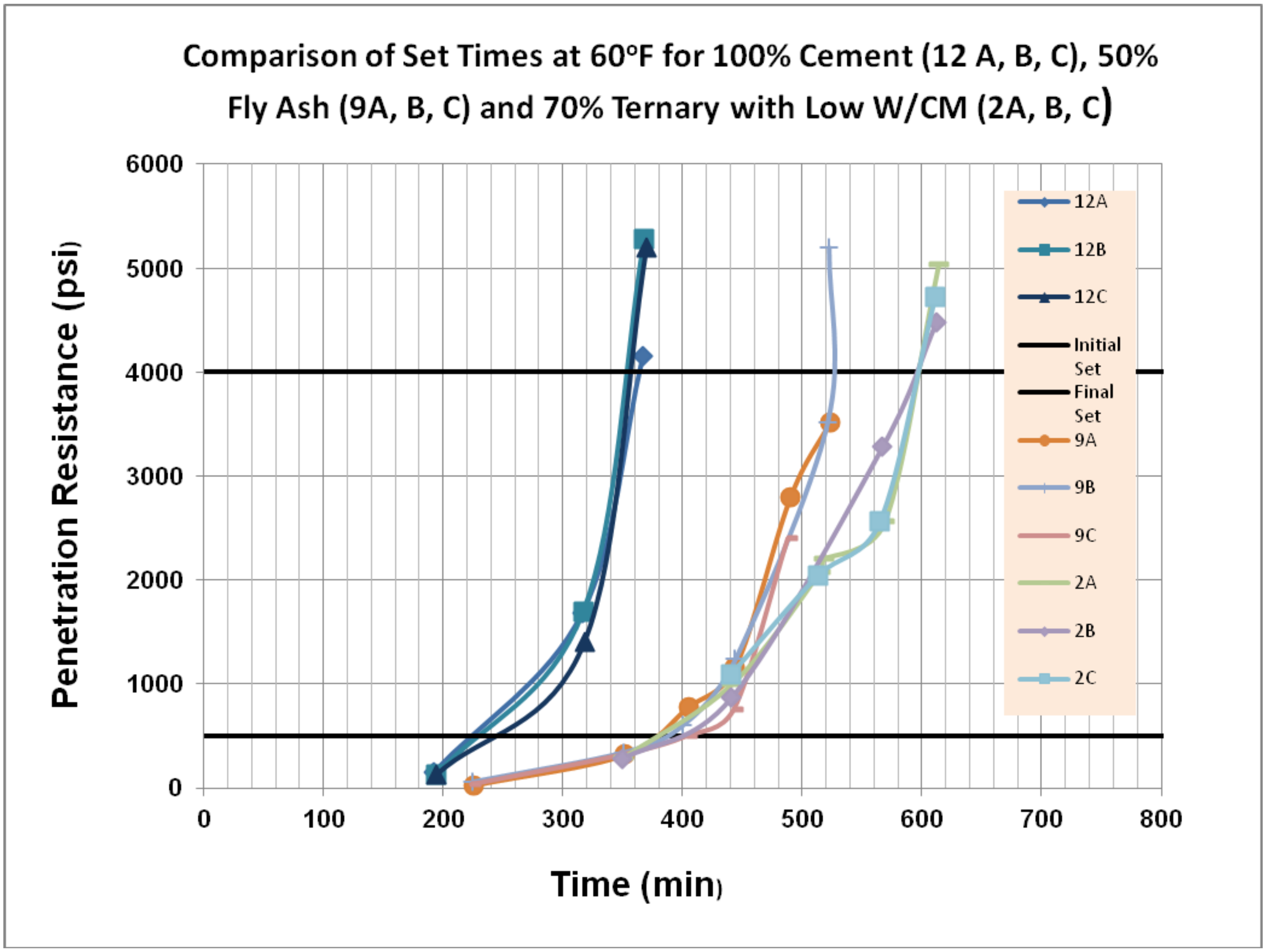


Figure 5.4 Penetration resistance versus time for three different mixtures at 60^{o}F: 100% portland cement, 50% fly ash and 70% ternary with low water-cementitious ratio. Note that the use of SCM's significantly delayed setting.

<u>Setting Times at 60^{o}F and 72^{o}F from Pankow Data</u>

- At 72^{o}F and 500 psi, setting time varies from 190 to 363 minutes; average is 286 minutes with a range of 173 minutes.
- At 72^{o}F and 100 psi, setting time varies from 155 to 277 minutes; average is 219 minutes with a range of 122 minutes.
- At 60^{o}F and 500 psi, setting time varies from 233 to 480 minutes; average is 360 minutes with a range of 247 minutes.
- At 60^{o}F and 100 psi, setting time varies from 189 to 321 minutes; average is 256 minutes with a range of 132 minutes.

As previously discussed most fresh concrete construction operations occur when the concrete penetration resistance is less than 100 psi as measured in accordance with ASTM C 403. The information above compares the setting time at 100 and 500 psi penetration resistance at a concrete temperature of 72°F and 60°F. Obviously the time to reach 100 psi penetration resistance is shorter than the time to reach 500 psi penetration resistance. At 72°F, the difference in times is about 60 minutes and at 60°F is about 90 minutes.

The important difference, however, is that caused by differences in mixture proportions. For a 100% cement mixture, the time to reach a penetration resistance of 100 psi at 60°F was 189 minutes. For the 50% fly ash and 50% slag mixtures, the time increased by up to 60 minutes. For other mixtures, for instance 70% low w/cm, the time is almost 120 minutes longer. During cold weather concreting, 60°F may not be the appropriate concrete temperature for determining setting time. ACI 306R-10 recommends that for concrete slab thickness of 12 inches or less, the concrete temperature as placed and maintained should be not less than 55°F. Using the previously cited equation for adjusting setting times based on temperature, it can be shown that at 55°F, the time to reach 100 psi penetration resistance with 100% cement is 320 minutes. For the 50% fly ash and 50% slag mixtures this time increases by slightly more than 60 minutes and the 70% low w/cm mixtures it increases by slightly more than 120 minutes.

Pankow Set Time Data		
Concrete Mixtures	Time to Reach 100 psi	
	At 60°F	At 72°F
100% cement	189	181
25% fly ash	217	197
25% slag	213	155
50% fly ash	254	218
50% slag	282	225
50% ternary	269	229
70% low w/cm	296	258
75% quad	305	277
75% ternary with WR	321	255
100% cement with carbohydrate	210	196
5 sack 15% fly ash	210	200

5.7 References

Abel, J.D. and Hover, K.C., “Field Study of the Setting Behaviors of Fresh Concrete”, *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 22. No. 2, December 200, pp. 95-102.

Bury, Mark A., Bury, Jeff R. and Martin, Dean, “Testing Effects of New Admixtures on Concrete Finishing,” *Concrete International*, January 1994.

Dodson, Vance H., “Time of Setting”, Chapter 11 Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP 169C, ASTM, West Conshohocken, PA., 1994.

Douglas, Bruce, Saiidi, Mehdi, Hayes, Robert and Holcomb, Grove, “Field Measurements of Lateral Pressures on Concrete Wall Forms”, *ACI Concrete International*, November 1981.

Suprenant, B.A. and Malisch, W.R., “Diagnosing slab delaminations – the role of top-down stiffening,” *Concrete Construction*, 1988.

Poole, Toy S., Guide for Curing of Portland Cement Concrete Pavements, Volume I, FHWA-RD-02-099, January 2005.

Poole, Toy S., Guide for Curing of Portland Cement Concrete Pavements, Volume II, FHWA-HRT-05-038, August 2006.

Tuthill, Lewis H. and Cordon, William, A., “Properties and Uses of Initially Retarded Concrete”, *Journal of the American Concrete Institute*, V. 27, No. 3, Nov, 1955, pp. 273-286.

Chapter 6 Recommendations for Using "Green" Concrete Mixtures

6.1 Background

Buildings are designed and constructed with knowledge, understanding, and expectations based on what we have called traditional concrete mixtures in this report. Concrete for building construction commonly contained only portland cement or portland fly-ash or blast-furnace slag cement blends as the binder until well into the 1960s. Expectations of designers and contractors were based on their having years of experience with this concrete and researchers having identified factors affecting properties such as setting behavior and strength gain. The 1963 ACI Building Code first allowed the use of fly ash as an admixture in 1963 and slag cement in 1989. The replacement percentage for building construction usually ranged from15% to 35%, and with portland cement contents above 400 lbs/cy. The concrete industry dealt with this change through a combination of research and experience that again set expectations for the effect of this level of SCMs on strength gain, internal heat generation, setting time, and other concrete properties. Based on these information sources, concrete buildings were successfully designed and constructed.

A new direction has emerged as evidenced by the increased concern with sustainability and, specifically, concrete's carbon footprint. While the carbon footprint is reduced by using the more traditional replacement levels of portland cement with SCMs, there is now an even greater emphasis on making concrete green by increasing these replacement levels. The new trend is for green concrete mixtures with SCMs replacing up to 70% of the cement and holding cement contents as low as 200 lbs/cy. As was the case when SCMs were first being used in building construction, the new green concrete mixtures must also be evaluated to determine their advantages and uses.

6.2 Recommendations

<u>Chapter 1</u>

1.1 Do not expect green concrete to cost less. Even though the total cost of cementitious materials *may* be lower because the unit cost of some SCMs is less than that of portland cement, there may be cost increases due to:

- Adding the production capacity (extra bins or silos) at the ready-mixed concrete plant
- Added quality control for additional cementitious ingredients
- Using more admixtures to balance longer setting times
- Other cost factors discussed in Chapters 2 through 5.

The only way to determine the cost of the green concrete is working with a contractor and concrete producer to assist in developing the concrete mixture and the associated costs. In other words, do not budget to save money because SCMs are being used unless that can be confirmed by the construction team.

1.2 Start with the industry information available from the American Concrete institute (ACI), American Society for Testing and Materials (ASTM), the National Ready Mixed Concrete Association (NRMCA), the American Coal Ash Association (ACAA) and others. Note however, that documents from these industry organizations may have a lag time of several years in publishing the information. The organizations do, however, publish magazines in which more recent trends are often reported.

1.3 Take advantage of the green concrete mixture proportions and test data provided in the Phase I report for this research project. Many concrete producers consider details of their green concrete mixtures to be proprietary information, so the mixture ingredients and quantities are not always available. The information in the Phase I report can be used as an aid in evaluating the ingredients and proportions for your project specific green concrete mixture along with expected fresh- and hardened-concrete properties. Note that the Phase I concrete mixtures were developed based on California experience, where the need for high-strength concrete in seismic regions was balanced with the desire for green concrete. Also note that the Phase I mixtures include cement, fly ash, slag, and silica fume from only one source. Results may differ with differing materials.

1.4 Be cautious with respect to concrete surfaces that will receive additional final finishes. There is some anecdotal evidence that concrete containing fly ash may not be suitable for surfaces to be painted, coated, or covered by flooring installed with adhesives. While there are some references to loss of adhesion in the literature, no proposed mechanisms such as slowed drying or an oily surface residue have been verified to explain the reasons for this phenomenon. It is also unclear if, or how, other SCMs may affect adhesion to a concrete substrate. Thus it is unclear as to how green concrete mixtures will perform with respect to drying and providing appropriate bonding for final finishes.

Chapter 2

2.1 Consider specifying compressive strength, f_c', at a designated test age greater than 28 days. Some green project specifications require compressive strengths to be achieved at 56 or 90 days so the slower rate of strength gain for green concrete mixtures can be accommodated.

2.2 Allow enough lead time for strength testing. The ACI Building Code requires trial laboratory or field mixtures when an acceptable record of field tests is not available to document acceptable strengths. This is often the case for green mixtures made with more than one type of cementitious material. When specifying compressive strengths at a designated test age of 56 or 90 days, the multiple trial batches needed substantially increase necessary lead times. Some specifiers for projects in California collaborate with the concrete producer a year in advance of starting construction.

2.3 Obtain more compressive strength information on green concrete mixtures than is usual for traditional concrete. Because of the construction operations and owner's schedule, contractors need data indicating early-age strength development. If the designated test age is 56 or 90 days, compressive- strength test results at 1, 3, 7, 14 and 28 days help the contractor estimate the time required for critical construction operations needed to stay on schedule. Consider obtaining compressive strength data for concrete that must be used for hot and cold weather concreting because high or low temperatures affect the concrete strength for each age. This additional information is useful to contractors during bidding so they can develop a time schedule and costs that meet the owner's requirements. Early-age strength requirements also provide a benchmark for early-age field tests that can be used as an early warning signal that 28-, 56- or 90-day specified strengths may not be reached.

2.4 Specify strength requirements and not time requirements or percentage of strength for construction operations. Time requirements assume curing conditions that may or may not be suitable for the concrete being placed. Also avoid specifying strengths required for construction operations as a percent of f_c'. For instance, the standard percentage for elevated formwork removal is 75% f_c'. *B*ut if f_c' is specified at 90 days, 75% of f_c' might not be reached until five to seven weeks after placement which must be considered in the schedule. For traditional concrete, 75% f_c', when f_c' is at 28 days, usually occurs in 3 to 7 days.

2.5 Have a plan for dealing with failure to achieve specified compressive strengths. If the designated age for acceptance testing is 56 or 90 days, there can be 4 or 5 floors on a mat foundation or on a lower floor level when strength test results are obtained. How will low strength-test results affect continued construction? Must construction stop? Must all floors be reshored? Early-age strength testing is recommended so action can be taken as soon as a potential problem is identified.

2.6 Use both standard-cure and sealed-cure cylinders in determining compressive strength during the laboratory trial mix-design phase. The Pankow data along with that of other investigators shows a 15% strength reduction when test cylinders are not cured by water immersion or in a moist room. Because the field concrete will not be cured in this manner, the engineer must determine if the design is to be based on water-cure or sealed-cure cylinder strengths.

2.7 Determine the effect of the standard-cure versus sealed-cure on other important design and construction considerations. These considerations include the ACI requirement for field curing in which field strength must be 85% of the companion laboratory-cured cylinders and core-strength acceptance requirement in which the average of three cores must equal at least 0.85 f_c'. If a 15% strength reduction is likely for sealed-cure laboratory cylinders, the effect in the field is likely to be larger.

Chapter 3

3.1 Determine the decision process needed if cylinders and cores for the same concrete are tested and cylinders test results meet ACI acceptance requirements but core test results do not meet ACI acceptance requirements. This has happened on some green concrete building projects and creates much confusion for the owners, designers and contractors.

3.2 Reevaluate Bloem's data, which was the ACI 318 basis for developing core-strength acceptance requirements. Bloem's concrete mixtures, specimen size, curing, and strength levels are unlikely to match those for green concrete projects. Consider developing a core-to-cylinder relationship during the laboratory trial-mixture phase for a project. Knowing this relationship in advance of cores being taken can save valuable time when a low-strength investigation is needed.

3.3 Evaluate the effect of internal heat generation on the strength of cores. ACI 318 is silent on this issue but ACI 214.4R-10 states that "… a strength loss of approximately 3% of the average strength in the specimen for every 10°F increase of average maximum temperature sustained during early hydration." The strength of cores removed from mat foundations and large columns or beams may be reduced due to this effect, which is not accounted for in the ACI 318 core-strength acceptance criteria. Thus when making specimens that will be cored for developing the core-to-cylinder relationship during the laboratory concrete mix design process, use specimen sizes that will reflect the effects of heat generation. If this isn't done, use the ACI 214.4R-10 strength-loss approximation of 3% to correct core strengths for the heat generated during curing in the structure.

3.4 Evaluate the effect of water- and sealed-curing on the strength of cores. ACI 318 is silent on this issue but the Pankow data and the data from other investigators indicates a possible15% strength reduction when green concrete is not cured with water. When making specimens that will be cored for developing the core-to-cylinder relationship during the laboratory concrete mix-design process, use the curing method that is required in the field.

3.5 Note the ACI 363.2R-11 recommendation that a "A correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 4 in. in diameter) to the strength of specimens used for acceptance testing, that is, 6 by 12 in. or 4 by 8 in. cylinders." However, this document also states that: "These data indicate that the acceptance criteria for core strengths specified in ACI 318 are also applicable to high-strength concretes". The cited ACI 363.2R-11 data includes core-to-cylinder strength ratios for cores taken and tested up to 7 years after the construction and cylinders tested at 28 days.

Chapter 4

4.1 Balance the compressive strengths needed at 1 to 7 days for timely construction operations with the desire for green concretes that dramatically reduce the carbon footprint attributable to portland cement replacement. This decision affects the owner's cost and schedule.

4.2 Provide the contractor with as much green concrete mixture data as possible to increase the likelihood of a bid that represents the construction operation sequence necessary for that concrete.

4.3 Stay flexible. Utilizing the green concrete mixtures with up to 70% replacement of portland cement by SCMs is likely to present some challenges. Engineers have sometimes adjusted strength and concrete mix-design requirements during building construction.

Chapter 5

5.1 Understand that formwork costs might increase slightly because some green concrete mixtures require that formwork be designed for full-hydrostatic pressure.

5.2 Measure setting times during the laboratory trial-mixture design process. Measured setting times (ASTM C 403) at temperatures representing hot and cold weather concreting would also be useful. Contractors can use this information to plan and schedule fresh concrete construction operations.

5.3 Be wary of the increased risk of plastic shrinkage cracking and settlement cracking that can occur as a result of green concrete mixtures setting more slowly than traditional concretes. Contractors need to consider construction practices to minimize these issues. Changes in the green concrete mixture design may also be necessary if these types of cracking are noted.

Preface

The American Society of Concrete Contractors submitted a proposal to the Charles Pankow Foundation for preparation of a *Users' Guide to "Green" Concrete in Building Construction.* In this context, "green" refers to concretes made with supplementary cementitious materials (SCMs) replacing varying amounts of portland cements to reduce the carbon footprint. As part of the preparation, several green concrete mixtures were tested and the data presented to provide information about mixture composition that is usually proprietary and not available to the industry or public. The relationship between cylinder strength and strength of cores from the same batch of concrete was of particular interest. The data was intended to supplement the limited amount of published data related to field experience with green concrete.

Bruce Suprenant and Ward Malisch, the authors of this report, became interested in this topic as a result of Suprenant's troubleshooting work on projects that utilized green concrete with acceptance testing done at 56 or 90 days rather than the standard 28 days. This later testing compensates for slower rates of strength gain when large amounts of portland cement are replaced by SCMs, but with a downside: more concrete has been placed when the test results become available at test ages greater than 28 days. If a strength test result is lower than allowed, and subsequent core testing indicates that the in-place strength is also lower than allowed, repair or removal and replacement generally costs more because of the larger volume of concrete in place. Schedule delays resulting from needed decisions on acceptance may also be more critical at this point.

Although the ACI 318 criteria for satisfactory core test results are based on the ratio of core strength to the design strength, f_c', we chose not to use that ratio in our research. Instead of estimating f_c' based on the average strength and standard deviation for our data, we used the ratio of core strength to standard-cured cylinder strength with both cores and cylinders tested at 28, 56, 90, and 180 days.

As our test results became available, we realized that the relationships between strengths of field-cast, wet-cured cylinders and cores from large blocks cast in the field were particularly puzzling. At ages of 28 to 180 days, the core/cylinder ratios ranged from about 0.40 to 0.90, with an overall average of about 0.65 for all but one of the 11 mixtures studied. Core/cylinder relationships for a control mixture containing no SCMs followed the same trend as those for fly ash, slag, ternary, and quaternary mixtures. This led to a literature search related specifically to the core/cylinder strength ratios for normal or high-strength concretes made with straight cements and varying SCM contents. That search resulted in questions concerning the ACI 318 code requirement that the average core strength of three cores must equal 0.85 times the design strength of the concrete, with no core in the set of three lower than 0.75 times the design strength.

As a result, we changed the title of our report to "Assessing the Impact of "Green" Concrete Mixtures on Building Construction." The report still covers construction rather than performance. But we acknowledge that our test results are for a combination of one cement, SCM, and admixture source and that, in field tests, the control mixture containing no SCMs performed similarly to mixtures made with varying percentages of SCMs. The scope for our field experiments did not include a factorial approach to evaluating the interactions between the cement and admixtures, nor do we suggest that the results of the field experiments can be generalized to include all green concretes. We do believe that, for confirmation, the results require further research of green concretes using differing cements and admixtures and in differing geographic regions. We also agree with the following recommendation in ACI 363.2R-11,"Guide to Quality Control and Assurance of High-Strength Concrete:"

"… a correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 4 in. [102 mm]) in diameter) to the strength of specimens used for acceptance testing, that is, 6 x 12 in. (152 x 305 mm) or 4 x 8 in. (102 x203 mm) cylinders. Then, if coring becomes necessary, the relationship has been established, agreed upon, and is ready for conclusive interpretation."

The correlation between core strength and the strength of specimens used for acceptance testing should be discussed at a preconstruction conference so the engineer of record, concrete producer, and concrete contractor are in agreement on steps to be taken when core tests are needed.

As the title of our original proposal implied, we were primarily interested in topics related to construction as opposed to performance of the green concrete after construction. Thus our testing program did not directly address durability because assessment of durability requires long-term testing or development of models for predicting durability, neither of which was within the scope of our proposal.

Bruce A. Suprenant
Ward R. Malisch

CHARLES PANKOW FOUNDATION
Building Innovation through Research

Lab and Field Data for

Assessing the Impact of “Green” Concrete Mixtures on Building Construction

Submitted By

ASCC Education, Research & Development Foundation

December 2013

EDUCATION, RESEARCH & DEVELOPMENT
ASCC
FOUNDATION
AMERICAN SOCIETY OF CONCRETE CONTRACTORS

PROVIDING THE MEANS TO ADVANCE CONCRETE CONSTRUCTION

Project Participants

Principal Investigator

- Ward R. Malisch, PhD, PE, FACI – Concrete Construction Specialist ASCC

Industry Champion

- Bruce A. Suprenant, PhD, PE, FACI

Authorized Organizational Representative

- Bev Garnant – Executive Director ASCC

Industry Collaborators

- Mike Donovan, Central Concrete Supply - A U.S. Concrete Company
- David Mar, Tipping Mar
- Phil Williams, Webcor Builders
- Tarek Khan, BASF

Funding

Charles Pankow Foundation
ASCC Education, Research & Foundation
ACI Concrete Research Council

PROVIDING THE MEANS TO ADVANCE CONCRETE CONSTRUCTION

Table of Contents

1. Introduction

2. Laboratory Studies
    - 2.1 Development of the plan
    - 2.2 Laboratory testing procedures
    - 2.3 Laboratory testing results

3. Field Studies
    - 3.1 Development of the testing plan
    - 3.2 Field study specimens
    - 3.3 Field study testing procedures
    - 3.4 Field study testing results
    - 3.5 Field study supplementary strength testing

Appendix A Concrete Mix Submittal Information (Cementitious Materials, Admixtures, Aggregates)

Appendix B Bibliography on “Green Concrete” Literature Review

Appendix C Industry Survey of ACI, ASCC and NRMCA Members on “Green Concrete”

List of Tables

List of Figures

List of Tables

Laboratory

Table L1 Lab Study: Mixture Ingredients, Proportions and Identification

Table L2 Lab Study: Fresh Concrete Mixture Properties

Table L3 Lab Study: Compressive Strength in psi for 4x8-in Cylinders with Standard, Sealed, and Air-Dried Curing

Table L4 Lab Study: Ratio of Sealed- and Air-Dry Cure 4x8-in. Cylinders to Standard Cure 4x8- in. Cylinders at 28, 56, 90 and 120 Days

Table L5 Lab Study: Shrinkage of 3x3x11.25-in. Prisms Cured and Dried per ASTM C 157

Field

Table F1 Field Study: Mixture Ingredients, Proportions and Identification

Table F2 Field Study: Fresh Concrete Mixture Properties

Table F3 Field Study: Compressive Strength in psi for 4x8-in.Cylinders with Standard, Sealed, Air Dried and Miscured Curing

Table F4 Field Study: Ratio of Sealed and Air-Dried Cure 4x8-in. Field-cast Cylinders to 4x8-in. Field-cast Standard Cured Cylinders at 7, 28, 56, 90, 120 and 180 Days

Table F5 Field Study: Within-test Coefficient of Variation for Field-cast 4x8-in Cylinders Tested at 28, 56, 90, 120 and 180 Days

Table F6 Field Study: Compressive Strength of 4-in Nominal Diameter Cores from 30x30x60-in. Field Cure 1 Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Table F7 Field Study: Compressive Strength of 4-in Nominal Diameter Cores from 30x30x60-in. Field Cure 2 Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Table F8 Field Study: Compressive Strength of 4-in Nominal Diameter Cores from 30x30x60-in. Field Cure 3 Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Table F9 Field Study: Shrinkage Data for 3x3x11.25-in. Prisms Dried per ASTM C 157

Table F10 Lab Study: Rapid Chloride Permeability Test Results at 28 and 56 days

Table F11 Lab Study: Summary of ASTM C403 Test Results at 60F
(concrete batched at 60F)

Table F12 Lab Study: Summary of ASTM C403 Test Results at 72°F
(concrete batched at 60F)

Table F13 Lab Study: Summary of ASTM C403 Test Results at 90°F

(concrete batched at 90F)

Table F14 Field Study: Internal Temperature Data for Field Constructed Blocks

Table F15 Field Study: Compressive Strength of 4-in Nominal Diameter Cores from standard and Sealed Cure 6x12-in. Field-cast Cylinders, Coefficient of Variation, and Ratio to Same-age and 56-day Strengths of Field-made Standard Cure and Sealed Cure 4x8-in. Cylinders

Table F16 Retest Field Study: Compressive Strength of 4-in. Nominal Diameter Cores Removed from Field-Cure 1 Block

List of Figures (Field)

Figure F1 Standard immersion-in-water cure for field-cast cylinders.

Figure F2 Concrete test cylinders incorrectly stored in the field without temperature control.

Figure F3 Forms for field-cast blocks. Note temperature data logger attached to tails of the lifting anchor.

Figure F4 Concrete truck discharge into the forms for field-cast blocks.

Figure F5 Consolidating field-cast block concrete with an internal vibrator.

Figure F6 Field-cast blocks covered with plastic sheeting and sand used to hold down the sheets and reflect the sun to limit temperature rise at the surface.

Figure F7 Approximate locations for cores drilled at 28, 56, 90, and 180 days .

Figure F8 Drilling 30-in.-long cores in field-cast blocks.

Figure F9 Moisture conditioning nominal 4x8-in. cylinders cut from 30-in.-long cores drilled in field-cast blocks.

Figure F10 Compressive strength vs age for concretes with 100% portland cement and replacements of 25% and 50% fly ash.

Figure F11 Compressive strength vs age for concretes with 100% portland cement and replacements of 25% and 50% slag.

Figure F12 Compressive strength vs age for Mixtures 1 (100% cement), 2 (50% ternary), and 3 (70% ternary).

Figure F13 Standard-cured cylinder compressive strength vs age for ternary concrete Mixtures 7-9. Adding silica fume or using a lower w/cm by adding more cement increased early and later-age strength.

Figure F14 Cylinder compressive strength vs age for ternary concrete Mixtures 7 and 10 with standard and sealed cure

Figure F15 Compressive strength vs age for standard-cure field- and lab-made concrete cylinders with Mixtures 1 and A, 7 and G and 11 and L.

Figure F16 Core drill set up for coring 6x12-in. hold cylinders at 182 days to produce 4x8-in. lab-cured cores.

Figure F17 The mounting plate for the 6x12 cylinders is bolted to a concrete block. Set screws similar to those on a Christmas tree stand prevent the cylinder from rotating while it's being cored.

Figure F18 Cores drilled from 6x12-in. cylinders before the cores were trimmed to a nominal 4x8-in. size and moisture conditioned.

1. Introduction

The Charles Pankow Foundation provided major funding to the American Society of Concrete Contractors Education, Research, and Development Foundation for development of "*Assessing the Impact of "Green" Concrete Mixtures on Building Construction"*. The term "green" concrete in this context refers especially to concrete containing supplementary cementitious materials (SCMs) that replace relatively large amounts of portland cement. In preparation for writing the *Guide*, a laboratory and field testing program was conducted to provide data that would supplement and illustrate construction challenges of green concrete that had been experienced on specific projects. This report summarizes the testing program results and includes all of the raw data that comprise the results.

Select results of both the laboratory and field studies will be presented in a condensed form in a "*Assessing the Impact of "Green" Concrete Mixtures on Building Construction",* the second publication being prepared under the terms of this research contract. In this second publication, we will briefly review the current state of knowledge regarding green concrete properties including setting time, shrinkage, rate of early and later strength gain, and durability. We will also further analyze the history of ACI building code requirements that are sometimes not met by green mixtures. Finally, we'll present a list of suggested best practices for specifying, proportioning, testing, curing, and evaluating green concrete construction and performance.

Many green concrete projects require reduction of concrete's carbon footprint by replacing as much as 80 percent of portland cement with SCMs such as fly ash and slag cement. This replacement can affect early and later strength gain, which can impact project schedules. In addition, durability, shrinkage, and setting time may be affected. Much of the lab and field data for green concrete mixes is considered proprietary. Thus, it is difficult for the industry to benefit and learn when information is not shared. The laboratory and field testing program was developed to provide data in the public domain that illustrates the challenges and potential solutions for potential green concrete construction problems.

Prior to initiating the testing program, a survey of owners, engineers, material suppliers, concrete producers, and concrete contractors was conducted. The major databases used for the survey were from the American Society of Concrete Contractors (ASCC), American Concrete Institute (ACI) and National Ready-Mixed Concrete Association (NRMCA). The primary survey focus was on users' perspectives related to issues involving green concrete. Users included:

- Building officials
- Design professionals
- Concrete and materials producers, and
- Contractors

Results of that survey are included in Appendix A.

As another part of the preliminary investigation, the Portland Cement Association conducted a literature search on green concrete and in particular the most commonly used SCMs and cement replacement levels. The annotated bibliography resulting from this search is included in Appendix B.

An Industry Advisory Committee was chosen to assist in direction and reviewing the study. Because of their experience, personnel from a concrete producer (Central Concrete Supply), concrete contractor (Webcor Concrete), structural designer (Tipping Mar), and an admixture manufacturer (BASF) were chosen. All of the Advisory Committee members had committed to ambitious sustainable goals for buildings being constructed in California. All of California is in seismic risk zones 3 or 4, and consequently the green concrete mixtures used there are often high performance concretes with design compressive strengths of 8000 psi or more—considerably higher than typical green concretes.

The study was conducted in two phases: an initial laboratory study with trial mixes followed by a field study in which 30-inch square concrete blocks were cast to simulate dimensions of typical field-cast concrete members. In the laboratory study, concrete was mixed in a central mixer and in the field study the concrete was mixed and delivered in ready mix trucks. Based on the laboratory study, some mixes were adjusted for use in the field study.

In the laboratory study, mixture proportions for the concretes tested were based on the survey results, literature search, and the extensive experience of industry advisor Mike Donovan of Central Concrete Supply, which has produced and tested green concrete mixtures for several concrete projects in California. Donovan was also instrumental in setting the variables to be studied in both the laboratory and field, plus the properties to be measured. Variables studied included:

- Type and amount of SCMs used in the concrete
- Aggregate additions (using some saturated lightweight aggregate for internal curing)
- Different laboratory and field curing methods
- Internal temperature of the blocks after placement
- Age at testing for compressive strength

Properties possibly affected by these variables included:

- Compressive strength at early (1 to 7 days) and later (up to 6 months) concrete ages
- Setting time at 60F, 72F, and 90F
- Free shrinkage
- Ability to resist chloride ion penetration

Slow setting and early strength gain of green concretes at low temperatures can be offset by modifying the concrete mixture with admixtures, changes in the water-cementitious materials ratio (w/cm) or with SCMs such as silica fume. Thus these variables were part of this study. Slower than normal strength gain is sometimes accommodated by specifying design strengths for cylinders tested at 56 or 90 days. To provide engineers with data regarding long-term compressive strength, cylinders and cores were tested at ages up to 6 months.

On some green concrete projects, low 56- or 90-day cylinder breaks for field-cast laboratory-cured cylinders have led to core testing that resulted in low core strengths. Some sets of three cores on these projects did not reach 85% of the specified 56-day design strength as required by ACI 318-11, even at ages of 90 days or more. Strength regression in shear wall and column cylinder strengths was also noted. When strength acceptance tests are not completed for 56 or 90 days and cores don't meet the ACI 318-11 requirements, construction has often progressed to the point that concrete removal and replacement are very expensive options. Thus, the field studies were designed to determine, among other properties, core-strength to cylinder-strength correlations at various ages.

The materials used in the study were typical for Northern California. Mill test certifications for all materials are given in Appendix C. Because some of the materials are specific to Northern California, and this climate differs from that of other regions, the general trends and concepts discussed in this study should be applied with engineering judgment to green concretes made with differing materials or under different climatic conditions.

2. Laboratory Studies

2.1 Development of the plan

The laboratory studies were intended to investigate the effects of varying types and amounts of SCMs upon concrete strength, free drying shrinkage, and electrical indication of ability to resist chloride ion penetration.

Ingredients, proportions and identification of 12 laboratory mixtures are shown in Table L1, while Table L2 lists the fresh concrete mixture properties. Note that one mixture had a portland cement content of 660 lb/cu yd and contained no SCMs. This was a control mixture used for comparison with the 11 other mixtures that contained varying amounts of SCMs. This concrete was a mixture with a nominal strength of 8000-psi at 56 days. Mixtures B through E were binary mixtures with fly ash or slag cement replacing some of the portland cement. Mixtures F and G were ternary mixtures containing portland cement plus both fly ash and slag cement.

Mixture G was the basic ternary mixture that was further modified as follows. To increase strength of the ternary mixture at early ages, some of the portland cement was replaced by silica fume (Mixture H) or the w/cm was decreased by adding more cement (Mixture K). Mixture I contained saturated 3/8-in. lightweight aggregate particles and Mixture J contained saturated lightweight fine aggregate. For both of these mixtures, the intent was to provide internal curing water for the relatively low w/cm ternary mixtures. Finally, Mixture L was a standard 4000-psi binary mixture with 15% of the portland cement replaced with fly ash. This mixture had a lower strength than the other 11 mixtures and was added to contrast a normal-strength concrete with the high-performance concretes used in the study.

2.2 Laboratory testing procedures

Test batches for each of the 12 mixtures were mixed in the laboratory using a 3 ft^3 mixer. Test specimens were prepared as follows:

- 4x8-in. test cylinders cast in accordance with ASTM C192, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory,” and stored under the following three curing regimes after one day in the molds:
  - -Standard cure—immersed in water at 73.5 ± 3.5ºF
  - -Sealed cure—cylinders kept in capped plastic molds sealed in plastic bags and left in capped molds at 73.5 ± 3.5ºF
  - -Air-dry cure—molds stripped at one day and stored at 50% relative humidity and 73.5 ± 3.5ºF
- 3x3x11.25-in. shrinkage-test prisms prepared and tested in accordance with ASTM C157, “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete,”

Compressive Strength: For the 11 mixtures containing SCMs, three cylinders for each curing regime were tested for compressive strength at 28, 56, 90, and 120 days, in accordance with ASTM C39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” and the results for each age were averaged. For the straight cement concrete, three standard-cured cylinders were also tested at 3 and 7 days.

Volume Change: For each of the 12 mixtures, three 3x3x11.25-in. prisms were prepared, cured, and stored in accordance with ASTM C157. The prism lengths were measured 24 hours after demolding and after 7, 14, 28, and 62 days of air storage in a room maintained at a relative humidity of 50 ± 4 % and a temperature of 73 ± 3°F.

2.3 Laboratory testing results

Strength: Compressive strength test results for cylinders subjected to all curing regimes are shown in Table 3L. Note the improvement in strength at 3 and 7 days under all curing regimes, as was expected, when silica fume was added to the basic ternary mixture or when the w/cm of the basic ternary mixture was lowered. Also note that under sealed curing conditions, the saturated lightweight fine aggregate was much more effective than the saturated 3/8-in. lightweight aggregate in increasing strength as a result of internal curing.

Sealed cylinder curing was believed to more closely resemble curing conditions for structural elements placed under field conditions because any external curing methods—even if water was added—were believed to affect only a thin layer of the surface concrete. Thus, the ratio of sealed-to-standard-cure cylinders was of special interest. Table 4L includes the ratio of compressive strengths for sealed and air-cured cylinders to strengths for standard-cured cylinders. Significant strength retrogression was noted for air-cured straight-cement concrete mixtures and for some ternary mixtures.

Volume change: Table 5L shows the results of ASTM C157 tests at drying durations up to 62 days. Note that the ternary mixtures containing saturated 3/8-in. lightweight aggregate and saturated lightweight fine aggregate exhibited virtually no shrinkage through 62 days of drying. Also, after 28 days of drying, all of the mixtures exhibited free drying shrinkage values less than 0.04% (400 microstrain), a maximum permitted value commonly cited in concrete performance specifications. While concrete with lower free shrinkage might be less likely to crack, the tendency of a concrete to exhibit shrinkage cracking is not a simple function of its free shrinkage. Other factors such as movement restraint, strength gain rate, thermal contraction, modulus of elasticity, and creep also have an effect on cracking tendency.

3. Field Studies

3.1 Development of the testing plan

The results of the laboratory tests formed the basis for choosing 11 mixtures that would be used in the field testing. After evaluating results from the laboratory studies, and in consultation with the Industry Advisory Committee, mixtures for use in a field study were chosen. Because the saturated 3/8-in. lightweight aggregate was less effective than the saturated lightweight fines in improving compressive strength of the sealed cylinders, only mixtures with the lightweight fines were used in the field studies. In addition, percentages of fly ash and slag in the binary mixtures were adjusted to include 25% and 50% replacement of both fly ash and slag. Proportions for the ternary mixtures, modified ternary mixtures, and the 4000-psi mixture remained the same as those used in the laboratory mixtures.

Central Concrete Supply furnished the personnel and equipment for batching, mixing, taking test samples, placing, and curing the field-study concrete. Three truck-mixed 5.0 yd^3 batches for each of the 11 different concretes were made on four different days. For one of the batches each day, aggregates were sampled as they were being batched and total moisture contents based on oven-dry weights were calculated. Using this calculation, the *as-batched* water/cementitious materials ratios (w/cm) were back calculated to account for aggregate free moisture contents (total moisture content minus aggregate absorption). The truck drivers were told not to add water because carefully measured aggregate moisture contents and material batching at the plant were expected to produce similar slumps at close to the design w/cm.

Proportions, and identification of field Mixtures 1 through 11 are shown in Table F1, while Table F2 lists the fresh concrete mixture properties including both design and actual w/c or w/cm.

The slump for Mixture 6 (50% ternary) in Table F2 is much higher than the others because one truck driver thought the concrete looked dry and added 2.5 gallons of water to the 5.0 yd^3 load.

The three batches for each of the 11 different concretes in Table F1 were used to mold:

- 825-4x8-in. test cylinders,
- 44-6x12-in. test cylinders,
- 66 3x3x11.25-in, prisms
- **33**-30-in.x30-in.x60-in. blocks in the field. Block placements were made on four different days. Cores with a nominal 4-in.diameter and drilled from the blocks each yielded three 4x8-in. segments for planned compressive strength testing at

28, 56, 91, and 180 days (total of 396 core tests). Further core testing at 282 days, as described later, resulted in an additional 43 core test results.

Central Concrete Supply personnel and equipment also did the initial testing of the cylinders and prisms, and drilling, conditioning, capping and testing of cores from the field-cast blocks. In addition, the personnel conducted setting time tests on mortar samples representing all of the mixtures except the one containing saturated lightweight fines. Setting time tests were also conducted on two other mortar mixtures in which a the polycarboxylate high-range water-reducing admixture indicated in Table F1 was replaced with a higher dosage of a carbohydrate-based water-reducing admixture meeting ASTM C494 requirements for Type A (water reducing), B (retarding), or D (water-reducing and retarding) admixtures.

3.2 Field study specimens

Cylinders cast concurrently with the blocks were made and initially cured in accordance with ASTM C31, then received the same curing treatments as the laboratory-cast cylinders:

- Strip molds in 24 hours and immerse cylinders in tank filled with limewater at 73.5 ± 3.5ºF—Standard cure (Fig. F1)
- After 24 hours, leave cylinders in molds with caps on, place in ziplock plastic bags, and store at 73.5 ± 3.5ºF—Sealed cure
- Strip molds in 24 hours and cure cylinders in air at 50% relative humidity and 73.5 ± 3.5ºF—Air cure

In addition, one set of three cylinders for each block received an improper initial cure by leaving them in the field for 3 days (Fig. F2) before curing them by immersion in water.

At ages 28 and 56 or 57 days, 2-in.-thick slices were cut from standard-cure cylinders to test for chloride ion penetration.

Three 30-in.x30-in.x60-in. blocks were cast in the field with each of the 11 different concretes and cured in three different ways as described below:

- Strip forms at 18-24 hours, then air dry (Block field cure 1)
- Cover with plastic sheets, strip forms after 18-24 hours, then spray curing compound on all six surfaces (Block field cure 2)
- Cover with plastic sheets, strip forms after 72 hours, then air dry (Block field cure 3)

Fig. F3 shows the mold used to form the blocks and Figs. F4 and F5 show the blocks being cast and consolidated. For each of the 11 mixtures, one block contained a data logger that continuously measured internal temperature near the center of the block.

Fig. F6 shows the blocks covered with plastic sheets and sand that was used to hold down the sheets and reflect the sun to limit temperature rise at the surface.

Sets of three 4x4x11-in. prisms for each of the 11 mixtures were prepared in the field, then cured, and stored in accordance with ASTM C157 and SEAOC Supplementary Recommendations for Control of Shrinkage of Concrete, **ref** respectively.

To determine initial and final setting time, sets of three prepared mortar samples with the same proportions as Mixtures 1 through 9 and 11 (see Table F1) were batched at either 60F or 90F. These were placed in 6-in. deep layers in rigid, nonabsorptive, watertight 6x12-in. plastic cylinder molds. The samples batched at 60F were stored at 60F and 72F and the samples batched at 90F were stored at 90F, all in a room at 50% relative humidity. Four sets of three mortar samples were batched at 60F with the same proportions as Mixture 1 and Mixture 7 except that the polycarboxylate-based high-range water-reducer was replaced with a carbohydrate-based water-reducing admixture. Two of the sets were stored at 60F and two at 72F, also in a room at 50% relative humidity.

Cores that were 30-in.long, with a nominal 4 in. diameter were drilled in the direction of casting and in accordance with ASTM C42 (Figs. F7 and F8). The core barrel needed to produce a 30-in.-long core was too long to fit in the coring rig so a shorter barrel was used to drill to a depth of about 14 in., then removed and replaced with a longer barrel to finish the drilling. The long cores removed from the blocks were sawed into three sections with nominal dimensions of 4x8 in. for strength testing and a 2-in.-long section used for chloride ion penetration testing. The 4x8-in. cores were moisture conditioned in accordance with ASTM C42 (Fig. F9).

3.3 Field study testing procedures

Cylinder Compressive Strength: Each set of three 4x8-in. field-cast cylinders with the standard cure was tested in accordance with ASTM C39 at 1, 3, 5, 7, 14, 28, 56, 90, 120, and 180 days. Each set of 4x8-in. cylinders with a sealed or air-dry cure was tested at 7, 28, 56, 90, and 180 days.

Core Compressive Strength: Each set of three 4x8-in.cores taken from the 33 blocks at ages 28, 56, 90, and 180 days was capped with sulfur caps and tested in accordance with ASTM C42. Additional coring and strength testing, as described on page 22, were carried out at later ages to confirm the accuracy of the original testing.

Drying Shrinkage: The 4x4x11-in. prisms were tested in accordance with ASTM C157 and SEAOC methods, respectively, for measuring free drying shrinkage. When using the ASTM C 157 method, specimen length changes are measured after storage in water for 28 days and storage in air for varying time periods. When using the SEAOC method, specimen length changes are measured after storage in water for 7 days.

Initial and Final Setting Time: Mortar samples were tested for penetration resistance in accordance with ASTM C403.

Chloride Ion Penetration: 2-in.-thick cylinders with a nominal diameter of 4 in. were cut from standard-cured cylinders and field-block cores before testing them at ages of 28 and 56 days after conditioning, all in accordance with ASTM C1202.

Internal Block Temperature: Temperatures at the approximate center of 11 blocks representing each mixture were recorded with Engius software used for maturity testing.

3.4 Field study testing results

Cylinder Strengths: Compressive strength test results for field-cast cylinders subjected to the four curing regimes are shown in Table F3. Strength regression is indicated by asterisks in the table, but the strength loss in these instances was not as pronounced as for the laboratory-cast and tested cylinders.

Note again the improvement in 3-, 7-, or both 3 and 7-day ages when silica fume was added to the basic ternary mixture or when the w/cm of the basic ternary mixture was lowered. Note also, however, that one day after field casting of cylinders for mixtures with a standard cure, the addition of silica fume did not increase strength while the lower w/cm almost doubled strength, from 660 psi to 1260 psi. Figs. F10, through F13 compare the strength vs age relationship for several different mixtures.

Adding saturated lightweight fine aggregate to the basic ternary mixture did not increase strength as much after sealed curing of the field-cast cylinders as it had after adding saturated lightweight fine aggregate to the basic ternary laboratory-cast cylinders. Fig.F14 illustrates the differences in strength for the laboratory- and field-cast basic ternary-mix cylinders with and without saturated lightweight aggregate.

Fig. F15 shows strength vs. age for standard-cured of field-cast and laboratory-cast Mixtures 1(A), 7(G), and 11(L), each pair having the same nominal composition. The pattern of field-cast cylinder strength gain is similar to that of the laboratory-cast cylinders, but field-cast cylinder strengths were less than those of the laboratory-cast cylinders for the three mixtures shown.

As was true for the laboratory study, the ratio of sealed-to-standard-cure field-cast cylinders was of special interest. Table F4 includes the ratio of compressive strengths for sealed and air-cured cylinders to strengths for standard-cured cylinders.

Table F5 shows the within-test coefficient of variation (COV) for the field-cast cylinders. Based on Table 4.4 values in ACI 214R-11, “Guide to Evaluation of Strength Test Results of Concrete,” **t**his data indicates excellent control in 50 of the 52 results, with 2 COVs in the fair control range.

Miscuring the field-cast cylinders resulted in lower strength-test results at 56- and 90-day ages for all of the concretes except the 4000-psi binary mixture. The 56- and 90-day strengths for this mixture were essentially unaffected by the poor curing. For the straight cement mixture and all four 70% ternary mixtures, miscured field-cast cylinders exhibited strength decreases at 56 or 90 days ranging from 810 psi to 1920 psi.

Core Strengths: Tables F6, F7, and F8 show the following:

- Individual and average compressive strengths for cores removed from field constructed blocks treated by Field Cures 1, 2, and 3, respectively
- Within-test coefficient of variation for each of the core sets
- Ratio of average core strength to standard-cure average cylinder strength at the same age

Some strength regression with age was noted as indicated in Tables F6, F7, and F8. In addition, the within-test coefficient of variation for the core-test averages varied over a wide range. Note that for all of the core sets tested, in only three did the ratio of average strength cores reach or exceed 85% of the average strength for standard-cured 4x8-in. field-cast cylinders tested at the same age.

Drying Shrinkage: Table F9 shows free drying shrinkage results for the 11 mixtures measured in accordance with ASTM C157 after 7, 14, 28, 56, and 154 days. It also shows drying shrinkage values for the same mixtures, but measured in accordance with SEAOC Modified method after 21, 28, 56, 84, 112, and 175 days. Note that the 70% ternary and 70% ternary plus silica fume mixtures exhibited only expansion when tested in accordance with ASTM C157. As was noted in the laboratory studies, all of the 11 mixtures exhibited free drying shrinkage values less than 0.04% (400 microstrain), a maximum permitted value commonly cited in concrete performance specifications.

When tested in accordance with the SEAOC Modified method, all of the free shrinkage results after 21 days of drying were less than the 0.048% (480 microstrain) permissible maximum limit for field-cast specimens stated in the SEAOC document.

Chloride Ion Penetration: Table F10 shows the results of testing specimens from both standard cured cylinders and drilled cores in accordance with ASTM C1202. The chloride penetrability categories listed are from Table X1.1 in the Appendix of ASTM C1202**.**

Setting Time: Tables F11, F12, and F13 summarize the average initial and final setting times for the 12 mortar samples tested at 60F, 72F and 90F. Note that replacing the polycarboxylate water-reducing admixture with a higher dosage of the carbohydrate-based water-reducing admixture had no effect on setting time of Mixture 1 (100% cement) but severely retarded the set of Mixture 7 (70% ternary).

Internal block temperature: Table F14 includes the starting temperature, maximum temperature, and the temperature increase based on these values for the 11 blocks cured by Field cure 1 (Strip forms 18-24 hours after casting and air dry).

3.5 Field study supplementary strength testing

A comparison of strengths of cores taken from laboratory-cured 6x12-in. cylinders with strengths of laboratory-cured 4x8-in. cylinders was of interest because this minimizes the effects on core strength of differences in consolidation and curing for the field-placed blocks. At an age of 182 days, 44-6x12-in. hold cylinders representing the 11 different mixtures were core drilled to produce nominal 4-in.-diameter cores as illustrated in Figs. F16 through F18. Half of the cylinders had received a standard cure and the other half had received the sealed cure. The cores were trimmed to produce a nominal 4x8-in. dimension, before testing. Three cores were damaged and could not be tested.

Results from strength tests on the remaining 41 cores were compared with results from testing 180-day-old 4x8-in.cylinders receiving either the standard or sealed cure. Results of the testing, plus the compositions of the 11 mixtures tested are shown in Table F15. Note that of the eight ratios of core-to-cylinder strengths calculated for standard-cured concrete, only one exceeded 0.85. When comparing sealed-cure cores and cores from sealed-cure cylinders, note that four of the eight ratios of core-to-cylinder strengths exceeded 0.85.

To investigate the accuracy of our core testing five more 30-in.-long cores were drilled from Field cure 1 blocks containing mixtures 1, 7, 8, 10, and 11 at an age of 282 days. Each 30-in. core was to be treated as follows:

- Concrete Central Supply cored, sawed, conditioned, capped, and tested specimens (15-4x8-in. cores)
- Concrete Central Supply cored, sawed, conditioned, and capped specimens, which Inspection Services Inc. (a privately owned laboratory) tested (15-4x8-in. cores)
- Inspection Services Inc. cored, sawed, conditioned, capped, and tested specimens (15-4x8-in. cores)

The results are given in Table F16. One of the cores from mixture 11 was defective and yielded only one specimen for testing. Note that the coefficient of variation ranged from 3.00% to 22.7%, with the lowest values for four of the five blocks corresponding to the specimens cored, sawed, conditioned, capped, and tested by Inspection Services. In two cases, however, the average strengths for the Central Concrete Cores were more than 1000 psi higher than those from Inspection Services and in two other cases the average strengths were within about 300 to 400 psi of each other. This confirms that there was not a systematic error in Central Concrete's procedures that resulted in lower core strengths.

Select results of both the laboratory and field studies will be presented in a condensed form in a *Users' Guide to "Green" Concrete in Building Construction,* the second publication being prepared under the terms of this research contract. In this publication, we will briefly review the current state of knowledge regarding green concrete properties including setting time, shrinkage, rate of early and later strength gain, and durability. We will also further analyze the history of ACI building code requirements that are sometimes not met by green mixtures. Finally, we'll present a list of suggested best practices for specifying, proportioning, testing, curing, and evaluating green concrete construction and performance.

Table L1 Lab Study: Mixture Ingredients, Proportions and Identification

Mix Proportions	100% PC	20% FA	30% FA	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Silica Fume	Tern+ 3/8-in. Ltwt	Tern+ Lwt Fines	Tern+ Low w/cm	15% FA 4000 psi
	A	B	C	D	E	F	G	H	I	J	K	L
Cement, lb/cy	660	528	462	330	330	330	198	163	198	198	234	400
Slag cement, lb/cy	-----	-----	-----	-----	330	198	264	264	264	264	312	-----
Fly Ash, lb/cy	-----	132	198	330		132	198	198	198	198	234	70
Silica Fume, lb/cy	-----	-----	-----	-----	-----	-----	-----	35	-----	35	-----	-----
#57 Stone, lb/cy	1450	1450	1450	1450	1450	1450	1450	1450	1450	1450	1450	1450
Lightweight, lb/cy	-----	-----	-----	-----	-----	-----	-----	-----	260	315	-----	-----
#8 Pea Gravel, lb/cy	225	225	225	225	225	225	225	225	-----	-----	225	225
Sand, lb/cy	1480	1420	1400	1380	1470	1440	1440	1430	1290	1024	1326	1621
Admixture	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Polycar-boxylate	Carbo-hydrate Lignin blend

Table L2 Lab Study: Fresh Concrete Mixture Properties

Fresh Concrete Properties	**100% PC**	**20% FA**	**30% FA**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Silica Fume**	**Tern+ 3/8-in. Ltwt**	**Tern+ Ltwt Fines**	**Tern+ Low w/cm**	**15% FA 4000 psi**
	A	B	C	D	E	F	G	H	I	J	K	L
Slump, in	5.25	5.00	4.75	4.50	-----	-----	-----	-----	-----	-----	-----	-----
Air Content, %	2.6%	2.5%	2.4%	2.6%	2.7%	2.5%	2.8%	2.9%	2.5%	3.2%	2.5%	2.8%
Temperature, F	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Unit Weight, pcf	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Design w/cm	0.42	0.41	0.40	0.38	0.40	0.39	0.37	0.38	0.37	0.37	0.31	0.57
Batched w/cm	0.42	0.40	0.38	0.38	0.39	0.38	0.36	0.36	0.37	0.37	0.31	0.57

Table L3 Lab Study: Compressive Strength in psi for 4 x 8 in. Cylinders with Standard, Sealed, Air Dried Curing

	100% PC	20% FA	30% FA	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Silica Fume	Tern+ 3/8-in. Ltwt	Tern+ Ltwt Fines	Tern+ Low w/cm	15% FA 4000 psi
Standard	A	B	C	D	E	F	G	H	I	J	K	L
3	3370	3000	2600	1680	2490	2020	1740	2960	2520	2880	3790	1490
7	5160	4010	3690	2470	4530	3400	3380	4720	4370	4680	5650	1630
28	7780	6720	6720	5520	8280	7230	6870	6500	6720	7440	8910	4990
56	8730	8220	8040	6950	9170	7840	8050	7550	7610	8880	10190	5920
90	9370	9090	8330	7830	9450	8990	8750	7820	8310	9680	10880	6560
120	9440	9440	9350	7900	9450	9320	9140	8680	8010	10330	11070	6970
Seal												
28	6360	6000	5400	5020	7150	6180	5830	5770	5860	7550	7770	4680
56	7260	6090	6370	5700	7840	7020	6740	6620	6920	8710	9140	5560
90	7250	7270	6660	6220	8420	7410	6980	7550	6990	9440	9570	6050
120	7490	6840	7150	6600	8170	7980	7520	7230	7170	9590	9740	6200
Air												
28	6110	4730	4590	3820	5870	4750	4700	4850	4950	6270	6270	3810
56	6040	4930	4980	3730	6710	5540	5750	4490	5270	7070	8050	4110
90	4660	4670	4540	3470	7100	5580	4910	4670	5810	6740	8160	4250
120	5310	4400	3790	3360	6010	4920	4830	5700	4540	6920	8180	4430

Note: Each strength result is the average of three cylinders.

Table L4 Lab Study: Ratio of Sealed- and Air-dry Cure 4x8-in. Cylinders to Standard Cure 4x8-in. Cylinders at 28, 56, 90, and 120 days

	100% PC	20% FA	30% FA	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Silica Fume	Tern+ 3/8-in. Ltwt	Tern+ Ltwt Fines	Tern+ Low w/cm	15% FA 4000 psi			
28 Days	A	B	C	D	E	F	G	H	I	J	k	l			
													Min	Max	Average
Sealed/Standard	0.82	0.89	0.80	0.91	0.86	0.85	0.85	0.89	0.87	1.01	0.87	0.94	0.80	0.91	0.88
Air/Standard	0.79	0.70	0.68	0.69	0.71	0.66	0.68	0.75	0.74	0.84	0.70	0.76	0.66	0.79	0.77
56 Days															
													Min	Max	Average
Sealed/Standard	0.83	0.74	0.79	0.82	0.85	0.90	0.84	0.88	0.91	0.98	0.90	0.94	0.74	0.91	0.86
Air/Standard	0.69	0.60	0.62	0.54	0.73	0.71	0.71	0.59	0.92	0.80	0.79	0.69	0.54	0.92	0.70
90 Days															
													Min	Max	Average
Sealed/Standard	0.77	0.80	0.80	0.79	0.89	0.82	0.80	0.97	0.84	0.98	0.88	0.92	0.77	0.97	0.86
Air/Standard	0.50	0.51	0.55	0.44	0.75	0.62	0.56	0.60	0.70	0.70	0.75	0.65	0.44	0.75	0.61
120 Days															
													Min	Max	Average
Sealed/Standard	0.72	0.76	0.84	0.86	0.86	0.82	0.83	0.90	0.72	0.93	0.88	0.89	0.72	0.90	0.83
Air/Standard	0.47	0.41	0.43	0.64	0.53	0.53	0.66	0.57	0.47	0.67	0.74	0.64	0.41	0.66	0.56

Table L5 Lab Study: Shrinkage of 3x3x11.25-in. Prisms Cured and Dried per ASTM C157

Shrinkage Data (percent)	**100% PC**	**20% FA**	**30% FA**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Silica Fume**	**Tern+ 3/8-in. Ltwt**	**Tern+ Ltwt Fines**	**Tern+ Low w/cm**	**15% FA 4000 psi**
ASTM C 157	A	B	C	D	E	F	G	H	I	J	K	L
7 Day Dry	0.000	0.002	0.002	0.003	-0.003	0.001	0.017	0.007	0.016	0.011	0.006	0.003
14 Day Dry	-0.070	-0.006	-0.006	-0.008	-0.009	-0.005	0.004	0.000	0.012	0.007	-0.004	-0.007
28 Day Dry	-0.020	-0.019	-0.019	-0.019	-0.016	-0.016	-0.006	-0.007	0.008	0.006	-0.009	-0.017
62 Day Dry	-0.028	-0.029	-0.029	-0.027	-0.026	-0.027	-0.018	-0.015	0.001	-0.001	-0.015	-0.027

Note: Positive numbers indicate expansion and negative numbers indicate shrinkage

Table F1 Field Study: Mixture Ingredients, Proportions and Identification

Mix Proportions	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi
	1	2	3	4	5	6	7	8	9	10	11
Cement, lb/cy	660	495	495	330	330	330	198	234	163	198	400
Slag cement, lb/cy	-----	-----	165	-----	330	165	264	312	264	264	0
Fly Ash, lb/cy	-----	165	-----	330	-----	165	198	234	198	198	70
Silica Fume, lb/cy	-----	-----	-----	-----	-----	-----	-----	-----	35	-----	-----
#57 Stone, lb/cy	1450	1450	1450	1450	1450	1450	1450	1450	1450	1450	1450
#8 Pea Gravel, lb/cy	225	225	225	225	225	225	225	225	225	225	225
C33 Sand, lb/cy	1332	1498	1404	1376	1498	1448	1447	1326	1444	1024	1621
Ltwt Fines, lb/cy	-----	-----	-----	-----	-----	-----	-----	-----	-----	315	-----
Polycarboxylate, oz/cwt	3.0	3.0	1.5	3.0	1.5	3.0	3.0	3.0	3.0	3.0	---
Workability retention oz/cwt	---	---	1.5	---	1.5	---	---	---	---	---	---
Carbohydrate-lignin blend oz/cwt	---	---	---	---	---	---	---	---	---	---	3.0

Table F2 Field Study: Fresh Concrete Mixture Properties

Fresh Concrete Properties	**100% PC**	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**
	1	2	3	4	5	6	7	8	9	10	11
Slump, in	3.50	5.50	4.00	4.50	4.00	7.50	5.00	3.25	3.75	4.50	4.50
Air Content, %	2.5%	2.0%	1.8%	1.7%	2.1%	1.2%	1.5%	2.1%	2.9%	2.1%	2.1%
Temperature, F	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Unit Weight, pcf	149.4	149.0	150.6	150.6	150.4	150.4	149.0	150.2	147.9	144.4	150.2
Design w/cm	0.40	0.39	0.40	0.38	0.39	0.38	0.37	0.31	0.37	0.37	0.57
Batched w/cm	0.39	0.38	0.42	0.40	0.43	0.41	0.40	0.34	0.40	0.39	0.58

Table F3 Field Study: Compressive Strength in psi for 4x8 in. Cylinders with Standard, Sealed, Air Dried, and Miscured Curing

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern.	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi
Standard	1	2	3	4	5	6	7	8	9	10	11
1	1660	1120	1120	750	1440	750	660	1260	580	600	570
3	2920	2040	2690	1550	3010	1730	1780	3000	2280	1940	1050
5	3750	2670	3630	2120	4440	2400	2550	3970	3340	2740	1340
7	4190	3160	4500	2340	4900	2920	2940	4990	3980	3300	1580
14	6040	4640	5980	3500	6510	3890	4630	6570	5560	4860	1750
21	6640	5600	7090	4480	7590	5060	5530	7630	6560	5880	3370
28	7490	6310	7760	5070	7860	5760	6130	8060	6940	6140	4040
56	8420	7940	8380	6450	9090	6840	7130	9410	8090	7540	5030
90	8810	8880	8930	7350	9710	7590	7720	10310	9010	8210	5560
120	8910	9200	9180	8100	9570	8060	8170	9890	9210	8190	5800
180	9290	9380	9070	-----	-----	-----	8440	11670	10230	8160	7070
Seal											
7	4030	3000	4190	2310	4420	2920	3240	4570	3880	3520	1730
28	5760	5270	6010	4780	6470	4820	5130	6980	5700	5530	3420
56	6510	6170	6840	6650	7160	5740	5930	7650	6820	6670	4300
90	7150	6510	7200	6540	7880	6350	6250	8080	7340	7210	4880
120	7170	7000	7260	6690	8140	6740	6950	8070	7370	7450	5050
180	7780	7500	6880	-----	-----	-----	7570	8610	8120	8100	6200
Air											
7	3720	2920	3770	2290	4130	2870	2760	4600	3330	3020	1660
28	4820	3940	4890	3390	5150	4090	3790	5420	4180	4020	2260
56	5060	3630	5140	3340	5870	4090	3710	5500	4170	4590	2260
90	5150	4010	5180	3720	5460	3500	3980	5500	4080	4820	2290
120	4800	3790	4850	-----	-----	-----	3680	5250	3750	4480	2120
180	4780	3820	5150	-----	-----	-----	3960	5320	4130	4560	2240
Miscured											
7	3760	3140	4270	2300	4480	2990	2760	4600	3330	3320	1770
28	6500	5620	6790	5060	7200	5540	5070	6910	6290	5740	4110
56	7440	7000	7870	6220	8420	6560	6000	7860	6950	6730	4960
90	7520	7870	8390	6910	8740	7340	6490	8390	7220	7110	5540
120	8240	8280	8740	-----	-----	-----	6510	8660	8040	7460	6020
180	8500	8850	8730	-----	-----	-----	7280	9290	7930	7030	6470

Table F4 Field Study: Ratio of Sealed and Air-Dried Cure 4x8 Field-cast Cylinders to 4x8 Field-cast Standard-Cure Cylinders at 7, 28, 56, 90, 120 and 180 Days

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern.	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi			
7 Days	1	2	3	4	5	6	7	8	9	10	11			
												Min	Max	Average
Sealed/Standard	0.96	0.95	0.93	0.99	0.90	1.00	1.10	0.92	0.97	1.07	1.09	0.90	1.10	0.99
Air/Standard	0.89	0.92	0.84	0.98	0.84	0.98	0.94	0.92	0.84	0.92	1.05	0.84	1.05	0.92
28 Days														
												Min	Max	Average
Sealed/Standard	0.77	0.84	0.77	0.94	0.82	0.84	0.84	0.87	0.82	0.90	0.85	0.77	0.94	0.84
Air/Standard	0.64	0.62	0.63	0.67	0.66	0.71	0.62	0.67	0.60	0.65	0.56	0.56	0.71	0.64
56 Days														
												Min	Max	Average
Sealed/Standard	0.77	0.78	0.82	1.03	0.79	0.84	0.83	0.81	0.84	0.88	0.85	0.77	1.03	0.84
Air/Standard	0.60	0.46	0.61	0.52	0.65	0.60	0.52	0.58	0.52	0.61	0.45	0.45	0.65	0.56
90 Days														
												Min	Max	Average
Sealed/Standard	0.81	0.73	0.81	0.89	0.81	0.84	0.81	0.78	0.81	0.88	0.88	0.73	0.89	0.82
Air/Standard	0.58	0.45	0.58	0.51	0.56	0.46	0.52	0.53	0.45	0.59	0.41	0.41	0.59	0.51
120 Days														
												Min	Max	Average
Sealed/Standard	0.80	0.76	0.79	0.83	0.85	0.84	0.85	0.82	0.80	0.91	0.87	0.76	0.91	0.83
Air/Standard	0.54	0.41	0.53	-----	-----	-----	0.45	0.53	0.41	0.55	0.37	0.37	0.55	0.47
180 Days														
												Min	Max	Average
Sealed/Standard	0.84	0.80	0.76	-----	-----	-----	0.90	0.74	0.79	0.99	0.88	0.74	0.99	0.84
Air/Standard	0.51	0.41	0.57	-----	-----	-----	0.47	0.46	0.40	0.56	0.32	0.32	0.57	0.46

Table F5 Field Study: Within-test Coefficient of Variation for Field-cast 4x8-in. Cylinders Tested at 28, 56, 90, 120 and 180 Days

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Low w/c	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi			
28 day strength, psi	1	2	3	4	5	6	7	8	9	10	11			
#1	7520	6340	7810	5020	8410	5660	6230	7810	6850	6050	3990			
#2	7540	6290	7580	5220	7500	5820	6080	8270	6940	6050	4040	All Mixes at 28 days		
#3	7400	6300	7900	4980	7680	5800	6080	8100	7020	6330	4080	Min	Max	Average
Average, psi	7487	6310	7763	5073	7863	5760	6130	8060	6937	6143	4037	4037	8060	6506
Standard Deviation, psi	76	26	165	129	482	87	87	233	85	162	45	26	482	143
Coefficient of Variation, %	1.0%	0.4%	2.1%	2.5%	6.1%	1.5%	1.4%	2.9%	1.2%	2.6%	1.1%	1.4%	6.1%	2.1%
56 day strength, psi	1	2	3	4	5	6	7	8	9	10	11			
#1	8600	8050	8560	6670	9210	7120	7400	9700	8200	7600	5040			
#2	8230	7850	8320	6550	8850	6860	6760	9350	7830	7410	4930	All Mixes at 56 days		
#3	8430	7910	8250	6140	9220	6550	7220	9170	8240	8241	5110	Min	Max	Average
Average, psi	8420	7937	8377	6453	9093	6843	7127	9407	8090	7750	5027	5027	9407	7684
Standard Deviation, psi	185	103	163	278	211	285	330	270	226	435	91	91	435	234
Coefficient of Variation, %	2.2%	1.3%	1.9%	4.3%	2.3%	4.2%	4.6%	2.9%	2.8%	5.6%	1.8%	1.3%	5.6%	3.1%
90 day strength, psi	1	2	3	4	5	6	7	8	9	10	11			
#1	8660	9010	8560	7450	9750	7840	7650	10080	9220	8120	5660			
#2	8830	8770	8320	7360	9660	7300	7850	10140	8860	8280	5510	All Mixes at 90 days		
#3	8950	8860	8230	7240	9720	7620	7660	10710	8940	8220	5520	Min	Max	Average
Average, psi	8813	8880	8370	7350	9710	7587	7720	10310	9007	8207	5563	5563	10310	8320
Standard Deviation, psi	146	121	171	105	46	272	113	348	189	81	84	46	348	152
Coefficient of Variation, %	1.7%	1.4%	2.0%	1.4%	0.5%	3.6%	1.5%	3.4%	2.1%	1.0%	1.5%	0.5%	3.6%	1.8%

Table F6 Field Study: Compressive Strength of 4-in Nom. Dia. Cores from 30x30x60-in. Field Cure 1 Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Stripped 18- 24 hrs Air Dry	**100% PC**	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**			
28 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4539	4006	5488	3066	4537	2935	3936	5551	4314	4509	2967			
#2	4875	3961	4680	4212	6007	4054	4113	4534	3832	4937	3760	All Mixes at 28 days		
#3	4036	4443	4186	4907	5216	4463	4335	8029	3360	4746	3419	Min	Max	Average
Average, psi	4483	4137	4785	4062	5253	3817	4128	6038	3835	4731	3382	3382	6038	4423
Standard Deviation, psi	422	266	657	930	736	791	200	1798	477	214	398	200	1798	626
Coefficient of Variation, %	9.42%	6.44%	13.74%	22.89%	14.00%	20.72%	4.84%	29.77%	12.44%	4.53%	11.76%	4.5%	29.8%	13.7%
Core/Cylinder Ratio	0.60	0.66	0.62	0.80	0.67	0.66	0.65	0.75	0.55	0.77	0.84	0.55	0.84	0.69
56 day	1	2	3	4	5	6	7	8	9	10	11			
#1	5,790	3,658	5,138	3,977	4,434	4,312	3,291	4,800	4,983	3,721	3,138			
#2	5,188	4,035	5,447	4,909	4,590	3,501	4,160	5,187	4,619	3,692	4,694	All Mixes at 56 days		
#3	4,875	4,435	4,301	4,246	4,727	4,572	5,884	5,568	6,289	3,154	4,258	Min	Max	Average
Average, psi	5284	4043	4962	4377	4584	4128	4445	5185	5297	3522	4030	3522	5297	4533
Standard Deviation, psi	465	389	593	480	147	559	1320	384	878	319	803	147	1320	576
Coefficient of Variation, %	8.8%	9.6%	11.9%	11.0%	3.2%	13.5%	29.7%	7.4%	16.6%	9.1%	19.9%	3.2%	29.7%	12.8%
Core/Cylinder Ratio	0.63	0.51	0.59	0.68	0.50	0.60	0.62	0.55	0.65	0.47	0.80	0.47	0.80	0.60
90 day	1	2	3	4	5	6	7	8	9	10	11			
#1	5,258	4,820	5,425	3,344	4,422	3,083	3,669	5,291	5,160	4,461	3,876			
#2	4,394	4,518	5,385	5,317	5,501	4,809	4,459	4,267	3,866	4,163	4,878	All Mixes at 90 days		
#3	5,485	5,331	4,942	5,310	5,516	4,896	6,216	5,028	4,025	6,412	4,522	Min	Max	Average
Average, psi	5046	4890	5251	4657	5146	4263	4781	4862	4350	5012	4425	4263	5251	4789
Standard Deviation, psi	576	411	268	1137	627	1023	1304	532	706	1222	508	268	1304	756
Coefficient of Variation, %	11.4%	8.4%	5.1%	24.4%	12.2%	24.0%	27.3%	10.9%	16.2%	24.4%	11.5%	5.1%	27.3%	16.0%
Core/Cylinder Ratio	0.57	0.55	0.59	0.63	0.53	0.56	0.62	0.47	0.48	0.61	0.80	0.47	0.80	0.58
182 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,700	7,186	6,241	7,271	6,805	6,137	3,945	9,114	5,526	5,878	4,517			
#2	5,010	9,630	6,819	6,745	6,749	6,598	4,493	6,945	4,314	6,115	4,874	All Mixes at 180 days		
#3	8,610	6,296	3,710		7,728	5,277	7,046	6,599	5,057	5,777	5,366	Min	Max	Average
Average, psi	6107	7704	5590	7008	7094	6004	5161	7553	4966	5923	4919	4949	7704	6184
Standard Deviation, psi	2173	1726	1654	372	550	670	1655	1363	611	174	426	174	2173	1034
Coefficient of Variation, %	35.6%	22.4%	29.6%	5.3%	7.7%	11.2%	32.1%	18.0%	12.3%	2.9%	8.7%	2.9%	35.6%	16.9%
Core/Cylinder Ratio	0.66	0.82	0.62	---	---	---	0.61	0.66	0.49	0.73	0.70	0.49	0.82	0.66

Table F7 Field Study: Compressive Strength of 4-in Nom. Dia. Cores from 30x30x60-in. Field Cure 2 Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Stripped 18- 24 hrs Curing Compound	**100% PC**	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**			
28 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,048	3,635	4,318	4,082	3,822	4,244	3,789	4,741	4,034	5,036	4,402			
#2	4,257	4,067	4,725	3,968	5,319	4,522	3,603	5,960	6,320	4,331	4,046	All Mixes at 28 days		
#3	4,149	4,443	3,896	4,427	3,973	4,911	4,671	6,233	5,612	5,316	6,042	Min	Max	Average
Average, psi	4,151	4,048	4,313	4,159	4,371	4,559	4,021	5,645	5,322	4,894	4,830	4,021	5,645	4,574
Standard Deviation, psi	105	404	415	239	824	335	571	794	1170	508	1065	105	1,170	584
Coefficient of Variation, %	2.5%	10.0%	9.6%	5.7%	18.9%	7.3%	14.2%	14.1%	22.0%	10.4%	22.0%	2.5%	22.0 %	12.4%
Core/Cylinder Ratio	0.55	0.64	0.56	0.82	0.56	0.79	0.66	0.70	0.77	0.80	1.20	0.55	1.20	0.73
56 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,584	3,521	4,492	3,660	6,057	3,393	4,502	4,806	5,453	5,366	3,865			
#2	4,897	3,783	6,414	4,878	5,348	5,189	4,632	5,203	6,418	3,992	4,814	All Mixes at 56 days		
#3	4,856	5,591	5,817	5,062	4,120	4,981	5,891	7,618	4,311	3,947	3,757	Min	Max	Average
Average, psi	4,779	4,298	5,574	4,533	5,175	4,521	5,008	5,876	5,394	4,435	4,145	4,145	5,876	4,885
Standard Deviation, psi	170	1127	984	762	980	982	767	1522	1055	807	582	170	1,522	885
Coefficient of Variation, %	3.6%	26.2%	17.6%	16.8%	18.9%	21.7%	15.3%	25.9%	19.6%	18.2%	14.0%	3.6%	26.2%	18.0%
Core/Cylinder Ratio	0.57	0.54	0.67	0.70	0.57	0.66	0.73	0.62	0.67	0.59	0.82	0.54	0.82	0.65
91 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,207	4,912	4,180	4,680	4,919	3,809	3,719	4,462	4,162	4,829	4,086			
#2	5,697	6,700	7,353	4,567	5,813	4,770	3,610	5,016	5,025	5,260	4,115	All Mixes at 91 days		
#3	4,076	5,737	6,115	4,620	5,842	4,885	5,362	3,446	4,782	5,111	4,913	Min	Max	Average
Average, psi	4,660	5,783	5,883	4,622	5,525	4,488	4,230	4,308	4,656	5,067	4,371	4,230	5,883	4,872
Standard Deviation, psi	900	895	1599	57	525	591	982	796	445	219	469	57	1,599	680
Coefficient of Variation, %	19.3%	15.5%	27.2%	1.2%	9.5%	13.2%	23.2%	18.5%	9.6%	4.3%	10.7%	1.2%	27.2%	13.8%
Core/Cylinder Ratio	0.53	0.65	0.66	0.63	0.57	0.59	0.55	0.42	0.52	0.62	0.79	0.42	0.79	0.59
182 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,071	5,231	5,115	6,748	4,699	5,984	4,699	7,858	7,124	6,363	5,376			
#2	3,546	5,613	7,122	6,105	7,532	4,835	4,624	6,804	5,761	6,263	6,519	All Mixes at 182 days		
#3	6,018	4,627	6,359	5,279	7,054	4,218	6,191	6,468	5,069	4,236	6,165	Min	Max	Average
Average, psi	4,545	5,157	6,199	6,044	6,428	5,012	5,171	7,043	5,985	5,621	6,020	4,545	7,043	5,748
Standard Deviation, psi	1302	497	1013	736	1517	896	884	725	1046	1200	585	497	1,517	946
Coefficient of Variation, %	28.7%	9.6%	16.3%	12.2%	23.6%	17.9%	17.1%	10.3%	17.5%	21.4%	9.7%	9.6%	28.7%	16.7%
Core/Cylinder Ratio	0.49	0.55	0.68	---	---	---	0.61	0.60	0.59	0.69	0.85	0.49	0.85	0.63

Table F8 Field Study: Compressive Strength of 4-in Nom. Dia. Cores from 30x30x60-in. Field Cure 1Blocks, Coefficient of Variation, and Ratio to Same-age Field-made Standard Cure Cylinders

Stripped 72 hrs Air Dry	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi			
28 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,064	4,523	5,568	4,176	5,106	4,176	4,357	4,378	4,802	4,503	4,250			
#2	4,317	4,083	4,482	4,281	5,049	4,068	4,038	4,567	3,851	4,405	3,513	All Mixes at 28 days		
#3	4,838	3,751	5,329	4,178	5,257	3,955	4,738	5,685	4,291	3,529	4,421	Min	Max	Average
Average, psi	4,406	4,119	5,126	4,212	5,137	4,066	4,378	4,877	4,315	4,146	4,061	4,061	5,137	4,440
Standard Deviation, psi	395	387	571	60	107	111	350	706	476	536	483	60	706	380
Coefficient of Variation, %	9.0%	9.4%	11.1%	1.4%	2.1%	2.7%	8.0%	14.5%	11.0%	12.9%	11.9%	1.4%	14.5%	8.6%
Core/Cylinder Ratio	0.59	0.65	0.66	0.83	0.65	0.71	0.71	0.61	0.62	0.68	1.01	0.59	1.01	0.70
56 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,251	4,835	5,193	5,098	4,483	4,829	4,342	4,017	4,089	3,486	3,962			
#2	5,356	5,054	5,526	4,544	4,148	4,926	4,264	5,364	6,260	3,819	4,607	All Mixes at 56 days		
#3	5,182	4,504	5,038	4,484	4,241	4,570	5,495	5,262	4,785	4,181	3,415	Min	Max	Average
Average, psi	4,930	4,798	5,252	4,709	4,291	4,775	4,700	4,881	5,045	3,829	3,995	3,829	5,252	4,655
Standard Deviation, psi	594	277	249	339	173	184	689	750	1109	348	597	173	1,109	483
Coefficient of Variation, %	12.1%	5.8%	4.7%	7.2%	4.0%	3.9%	14.7%	15.4%	22.0%	9.1%	14.9%	3.9%	22.0%	10.3%
Core/Cylinder Ratio	0.59	0.60	0.63	0.73	0.47	0.70	0.66	0.52	0.62	0.51	0.79	0.47	0.79	0.62
91 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,168	4,986	6,104	4,159	4,799	5,090	3,401	4,514	5,621	4,518	4,094			
#2	5,240	5,226	6,362	3,293	4,803	5,556	5,053	5,139	5,875	6,268	4,222	All Mixes at 91 days		
#3	4,568	3,991	5,373	4,377	3,455	5,324	4,334	5,004	5,853	4,749	4,314	Min	Max	Average
Average, psi	4,659	4,734	5,946	3,943	4,352	5,323	4,263	4,886	5,783	5,178	4,210	3,943	5,946	4,843
Standard Deviation, psi	542	655	513	573	777	233	828	329	141	951	110	110	951	514
Coefficient of Variation, %	11.6%	13.8%	8.6%	14.5%	17.9%	4.4%	19.4%	6.7%	2.4%	18.4%	2.6%	2.4%	19.4%	10.9%
Core/Cylinder Ratio	0.53	0.53	0.67	0.54	0.45	0.70	0.55	0.47	0.64	0.63	0.76	0.45	0.76	0.59
182 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4,794	5,205	5,559	7,271	6,513	5,295	5,099	5,623	4,458	4,028	4,925			
#2	5,627	4,312	6,390	6,745	5,756	5,260	5,122	4,822	5,481	6,384	5,626	All Mixes at 182 days		
#3	6,867	5,519	5,329		5,004	3,807	4,938	7,668	6,534	4,879	5,611	Min	Max	Average
Average, psi	5,763	5,012	5,759	7,008	5,758	4,787	5,053	6,038	5,491	5,097	5,387	4,787	7,008	5,559
Standard Deviation, psi	1043	626	558	372	755	849	100	1468	1038	1193	400	100	1,468	764
Coefficient of Variation, %	18.1%	12.5%	9.7%	5.3%	13.1%	17.7%	2.0%	24.3%	18.9%	23.4%	7.4%	2.0%	24.3%	13.9%
Core/Cylinder Ratio	0.62	0.53	0.63	---	---	---	0.60	0.52	0.54	0.62	0.76	0.52	0.76	0.60

Table F9 Field Study: Shrinkage Data for 4x4x11-in. Prisms Dried per ASTM C 157

Shrinkage Data	**100% PC**	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern.**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**
SEAOC Modified	1	2	3	4	5	6	7	8	9	10	11
21 Day Dry	-0.028	-0.021	-0.037	-0.025	-0.034	-0.038	-0.037	-0.027	-0.035	-0.027	-0.035
28 Day Dry	-0.033	-0.033	-0.053	-0.025	-0.034	-0.042	-0.042	-0.036	-0.046	-0.028	-0.038
56 Day Dry	-0.049	-0.054	-0.061	-0.040	-0.045	-0.060	-0.060	-0.028	-0.049	-0.038	-0.049
84 Day Dry	-0.052	-0.037	-0.048	-0.038	-0.054	-0.070	-0.050	-0.053	-0.047	-0.037	-0.069
112 Day Dry	-0.061	-0.064	-0.070	-0.058	-0.066	-0.082	-0.047	-0.034	-0.056	-0.051	-0.070
175 Day Dry	-0.070	-0.058	-0.075	-0.035	-0.062	-0.066	-0.062	-0.045	-0.056	-0.056	-0.072
ASTM C 157											
7 Day Dry	-0.020	0.001	-0.003	0.018	0.001	0.012	0.157	-0.001	0.045	0.015	-0.001
14 Day Dry	-0.024	-0.008	-0.011	0.001	-0.007	0.006	0.187	0.000	0.044	0.015	-0.013
28 Day Dry	-0.026	-0.014	-0.017	-0.012	-0.015	-0.007	0.150	-0.011	0.037	-0.001	-0.026
56 Day Dry	-0.057	-0.037	-0.039	-0.022	-0.033	-0.027	0.142	-0.01	0.036	-0.014	-0.041
154 Day Dry	-0.068	-0.053	-0.05	-0.036	-0.039	-0.045	0.132	-0.031	0.008	-0.032	-0.057

Note: Positive numbers indicate expansion and negative numbers indicate shrinkage

Table F10 Field Study: Chloride Ion Penetrability Test Results at 28 and 56 days

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi
28 days	1	2	3	4	5	6	7	8	9	10	11
Cylinder	4,868	3,350	4,023	2,913	2,212	3,637	1,058	1,171	913	992	5,084
Chloride ion penetrability Per ASTM C1202	High	Mod	High	Mod	Mod	Mod	Low	Low	Very low	Very low	High
56 days											
Cylinder	4,057	1,714	3,720	1,404	1,124	1,557	788	907	526	324	3,531
Chloride ion penetrability Per ASTM C1202	High	Low	Mod	Low	Low	Low	Very low	Very low	Very low	Very low	Mod
Core - stripped after 1 day, air dry	4,275	2,328	2,904	1,267	1,139	1,988	895	582	465	415	4,785
Chloride ion penetrability Per ASTM C1202	High	Mod	Mod	Low	Low	Low	Very low	Very low	Very low	Very low	High
Core - stripped after 1 day, curing compound	4,547					1,656	754		813	587	
Chloride ion penetrability Per ASTM C1202	High					Low	Very low		Very low	Very low	
Core - stripped after 3 days, air dry	6,460					2,025	780		735	621	
Chloride ion penetrability Per ASTM C1202	High					Mod	Very low		Very low	Very low	

Table F11 Lab Study: Summary of ASTM C403 Test Results at 60F (Concrete batched at 60F)

Concrete Mix	Cylinder ID	Initial Set Time (min)	Average Initial Set Time (min)	Final Set Time (min)	Average Final Set Time (min)
100% Cement	12A	230	233	360	357
	12B	230		355	
	12C	240		355	
25% Fly Ash	11A	340	333	450	450
	11B	320		460	
	11C	340		440	
25% Slag	10A	250	250	390	400
	10B	250		410	
	10C	250		400	
50% Fly Ash	9A	390	397	530	535
	9B	390		540	
	9C	410		-----	
50% Slag	8A	430	380	540	510
	8B	370		510	
	8C	340		500	
50% Ternary	7A	370	357	500	510
	7B	340		510	
	7C	340		520	
70% Ternary with carbohydrate admixture	1A	Sometime after 13 hours		Sometime after 13 hours	
	1B				
	1C				
Ternary+ Low w/cm	2A	390	395	600	600
	2B	400		600	
	2C	-----		600	
Ternary+ Silica Fume	3A	450	450	690	663
	3B	450		640	
	3C	450		660	
70% Ternary	4A	480	480	610	626
	4B	480		657	
	4C	480		610	
100% cement with carbohydrate admixture	5A	280	280	420	420
	5B	280		420	
	5C	280		420	
15% Fly Ash 4000 psi	6A	340	327	460	462
	6B	320		460	
	6C	320		465	

Table F12 Field Study: Summary of ASTM C403 Test Results at 72°F (Concrete batched at 60F)

Concrete Mix	Cylinder ID	Initial Set Time (min)	Average Initial Set Time (min)	Final Set Time (min)	Average Final Set Time (min)
100% Cement	12A	190	190	260	267
	12B	190		280	
	12C	190		260	
25% Fly Ash	11A	240	233	360	363
	11B	240		360	
	11C	230		370	
25% Slag	10A	230	230	320	317
	10B	230		310	
	10C	230		320	
50% Fly Ash	9A	290	290	440	428
	9B	290		420	
	9C	290		425	
50% Slag	8A	300	300	420	423
	8B	300		420	
	8C	300		430	
50% Ternary	7A	290	297	410	412
	7B	300		410	
	7C	300		415	
70% Ternary with carbohydrate admixture	1A	Sometime after 13 hours		Sometime after 13 hours	
	1B				
	1C				
Ternary Low w/cm	2A	330	333	480	478
	2B	330		480	
	2C	340		475	
Silica Fume	3A	380	363	520	527
	3B	355		540	
	3C	355		520	
70% Ternary	4A	355	357	530	537
	4B	355		542	
	4C	360		540	
100% Cement with carbohydrate admixture	5A	230	230	350	350
	5B	230		350	
	5C	230		350	
15% Fly Ash 4000 psi	6A	270	270	395	388
	6B	270		375	
	6C	270		395	

Table F13 Lab Study: Summary of ASTM C403 Test Results at 90°F (Concrete batched at 90F)

Concrete Mix	Cylinder ID	Initial Set Time (min)	Average Initial Set Time (min)	Final Set Time (min)	Average Final Set Time (min)
100% Cement	12A	160	156	260	228
	12B	155		211	
	12C	154		212	
25% Fly Ash	11A	170	170	245	240
	11B	170		245	
	11C	170		229	
25% Slag	10A	160	163	235	235
	10B	170		235	
	10C	160		235	
50% Fly Ash	9A	170	170	255	262
	9B	170		266	
	9C	170		266	
50% Slag	8A	172	171	280	260
	8B	169		245	
	8C	172		255	
50% Ternary	7A	185	175	255	253
	7B	170		255	
	7C	170		250	
70% Ternary with carbohydrate admixture	1A	182	197	290	300
	1B	220		305	
	1C	190		304	
Ternary+ Low w/cm	2A	190	180	295	289
	2B	190		275	
	2C	160		297	
Ternary+ Silica Fume	3A	190	185	290	286
	3B	190		298	
	3C	175		270	
70% Ternary	4A	200	188	304	300
	4B	182		295	
	4C	182		300	
15% Fly Ash 4000 psi	6A	190	192	302	281
	6B	195		260	
	6C	190		280	

Table F14 Field Study: Internal Temperature Data for Field Constructed Blocks

	100% PC	25% FA	25% Slag	50% FA	50% Slag	50% Tern	70% Tern	Tern+ Low w/cm	Tern+ Silica Fume	Tern+ Ltwt Fines	15% FA 4000 psi
	1	2	3	4	5	6	7	8	9	10	11
Field Cure 1											
Starting Temperature, F	90	90	73	86	88	84	86	93	84	88	88
Maximum Temperature, F	137	127	127	117	129	115	120	138	126	120	115
Temperature Increase, F	47	37	54	34	41	31	34	45	42	32	27

Table F15 Field Study: Compressive Strength of 4-in Nom. Dia. Cores from Standard and Sealed Cure 6x12-in. Field-Cast Cylinders, Coefficient of Variation, and Ratio to Same-age and 56-day Strengths of Field-made Standard Cure and Sealed Cure 4x8-in. Cylinders

Standard Cure Cylinders	**100% PC**	**25% FA**	**25% Slag**	**50% FA**	**50% Slag**	**50% Tern**	**70% Tern**	**Tern+ Low w/cm**	**Tern+ Silica Fume**	**Tern+ Ltwt Fines**	**15% FA 4000 psi**			
182 day	1	2	3	4	5	6	7	8	9	10	11			
#1	7074	7071	6958	6776	10868	7090	6158	5170	6118	5307	5150	All Mixes at 182 days		
#2	6658	6343	9596	5245	6045	-----	5098	6947	6151	5375	6290	Min	Max	Average
Average, psi	6866	6707	8277	6010	8456	7090	5628	6058	6134	5341	5720	5341	8457	6572
Standard Deviation, psi	294	515	1865	1083	3410	-----	750	1257	23	48	806	23	3410	1005
Coefficient of Variation, %	4.3%	7.7%	22.5%	18.0%	40.3%	-----	13.3%	20.7%	0.4%	0.9%	14.1%	0.4%	40.3%	14.2%
Core/Cyl Std Cure 182 day	0.74	0.72	0.91	---	---	---	0.67	0.52	0.60	0.65	0.81	0.91	0.52	0.70
Sealed Cure Cylinders														
182 day	1	2	3	4	5	6	7	8	9	10	11			
#1	4970	4680	7676	5496	8319	6981	7242	7213	8353	7040	3982	All Mixes at 182 days		
#2	7289	7597	7516	5443	7449	-----	-----	6763	7836	6910	4153	Min	Max	Average
Average, psi	6130	6139	7596	5470	7884	6981	7242	6988	8095	6975	4068	4068	8095	6688
Standard Deviation, psi	1640	2063	113	37	615	-----	-----	318	366	92	121	37	2063	596
Coefficient of Variation, %	26.8%	33.6%	1.5%	0.7%	7.8%	-----	-----	4.6%	4.5%	1.3%	3.0%	0.7%	33.6%	9.3%
Core/Cylinder Seal Cure	0.79	0.65	1.10	---	---	---	0.96	0.81	1.00	0.86	0.66	0.65	1.10	0.85

Table F16 Retest Field Study: Compressive Strength of 4-in. Nom. Dia. Cores Removed from Field-Cure 1 Blocks

Field Cure 1 Strip 18- 24 hrs Air dry	**Retest Strength and Variability of Cores from Field Constructed Blocks Core Testing by Central Concrete Supply and Independent Laboratory as Noted**							
Age About 280 days	Mix	#1, psi	#2, psi	#3, psi	Average, psi	Standard Deviation, psi	Coefficient of Variation, %	Comment
100% Cement	1	7786	6942	5872	6867	959	14.0%	Central core, cap and test
100% Cement	1	8440	7530	6280	7417	1084	14.6%	Central core and cap; Lab test
100% Cement	1	7330	6510	5900	6580	718	10.9%	Lab core, cap and test
70% Ternary	7	5472	6059	7412	6314	995	15.8%	Central core, cap and test
70% Ternary	7	4920	5920	7560	6133	1333	21.7%	Central core and cap; Lab test
70% Ternary	7	6540	5730	5420	5897	578	9.8%	Lab core, cap and test
70% Tern+ Low w/cm	8	8261	7834	6294	7463	1035	13.9%	Central core, cap and test
70% Tern+ Low w/cm	8	9030	8250	6450	7910	1323	16.7%	Central core and cap; Lab test
70% Tern+ Low w/cm	8	6450	6210	6080	6247	188	3.0%	Lab core, cap and test
70% Tern+ Ltwt Fines	10	6146	-----	-----	6146	-----	-----	Central core, cap and test
70% Tern+ Ltwt Fines	10	7410	5990	6410	6603	729	11.0%	Central core and cap; Lab test
70% Tern+ Ltwt Fines	10	6660	4600	4570	5277	1198	22.7%	Lab core, cap and test
15% Fly Ash 4000 psi	11	7415	6695	6617	6742	1035	15.4%	Central core, cap and test
15% Fly Ash 4000 psi	11	7170	6060	6990	6740	1323	16.7%	Central core and cap; Lab test
15% Fly Ash 4000 psi	11	5760	5350	5920	5677	188	3.0%	Lab core, cap and test

Appendix A

Concrete Mix Information

Cementitious Materials

Portland Cement Type II-V, Low Alkali, ASTM C 150 Test Report

Class F Fly Ash, ASTM C 618 Test Report

GGBFS (Slag Cement), Grade 100-120, ASTM C 989 Test Report

Silica Fume, ASTM C 1240 Test Report

Admixtures

High-Range Water-Reducing Admixture, GLENIUM 7500, Data Sheet

Water-Reducing Admixture, POZZOLITH 200 N, Data Sheet

Water-Reducing Admixture, POZZOLITH 322 N, Data Sheet

Aggregates

1 inch (Size #4) Concrete Aggregate, ASTM C 33 Test Report

3/8 inch (Size #8) Concrete Aggregate, ASTM C 33 Test Report

Concrete Sand, ASTM C 33 Test Report

Lightweight Aggregate Here, ASTM C 330 Test Report

LEHIGH
HEIDELBERGCEMENT Group

TECHNICAL SERVICES SALES & MARKETING
12667 Alcosta Blvd., Suite 400
San Ramon, CA 94583
Telephone (925) 244 6500
FAX (925) 244 6586

AASHTO R18

PERMANENTE PLANT
24001 Stevens Creek Blvd.
Cupertino, CA 95014-5659
Telephone (408) 996-4033
FAX (408) 996-4033

CEMENT TEST REPORT

Cement: Permanente Type II-V, Low Alkali; ASTM C 150-09

Production Period: April 2012 | **Report Date:** 5/16/2012

STANDARD CHEMICAL REQUIREMENTS ASTM C 114	TEST RESULTS	ASTM C 150-09 SPECIFICATIONS TYPE II	TYPE V
Silicon Dioxide (SiO_2), %	21.2	20.0 Min	----
Aluminum Oxide (Al_2O_3), %	3.8	6.0 Max	----
Ferric Oxide (Fe_2O_3), %	3.8	6.0 Max	----
Calcium Oxide (CaO), %	65.4	----	----
Magnesium Oxide (MgO), %	1.4	6.0 Max	6.0 Max
Sulfur Trioxide (SO_3), %	3.4	3.0 Max	2.3[B] Max
Loss on Ignition (LOI), %	1.4	3.0 Max	3.0 Max
Insoluble Residue, %	0.43	0.75 Max	0.75 Max
Alkalies (Na_2O equivalent), %	0.34	0.60 Max	0.60 Max
Tricalcium Silicate (C_3S), %	65	----	----
Dicalcium Silicate (C_2S), %	12	----	----
Tricalcium Aluminate (C_3A), %	4	8 Max	5 Max
Tetracalcium Aluminoferrite (C_4AF), %	11	----	----
2 (C_3A) + C_4AF, %	19	----	25 Max
PHYSICAL REQUIREMENTS			
(ASTM C 1038) Expansion @ 14 days,%	0.003	0.020 Max	0.020 Max
(ASTM C 452) Expansion @ 14 days,%	0.021	----	0.04 Max
(ASTM C 430) -325 Mesh, %	98.9	----	----
(ASTM C 204) Blaine, m2/kg	387	280 Min	280 Min
(ASTM C114) Limestone, max, %	2.1	5 Max	5 Max
(ASTM C114) Limestone, %CaCO3	75.8	----	----
(ASTM C114) Cement, %CO2	0.71	----	----
(ASTM C 191) Time of Setting - Initial (Vicat)	144	45 Min	45 Min
(ASTM C 191) Time of Setting - Final (Vicat)	271	375 Max	375 Max
(ASTM C 451) False Set, %	89	50 Min	50 Min
(ASTM C 185) Air Content, %	6.6	12 Max	12 Max
(ASTM C 151) Autoclave Expansion, %	0.00	0.80 Max	0.80 Max
(ASTM C 187) Normal Consistency, %	25.6	----	----
(ASTM C 109) Compressive Strength, psi (MPa)			
1 Day	1717	----	----
3 Day	3215	1500 (10.3) Min	1160 (8.0) Min
7 Day	4281	2500 (17.2) Min	2180 (15.0) Min
28 Day (previous month)	6298	----	3050 (21.0) Min

This cement meets the requirements of specification:

ASTM C150-09 Type II-V, Low Alkali
[a] Adjusted per ASTM C-150-09 Section A1.6
Caltrans Section 90-2.01 - Type II-V Modified
ASTM C 1157 Portland Cement Type HS
AASHTO Practice R18 accredited laboratory

Alan Sabawi, Quality Control Manager

Applicable ASTM C 150 Notes:

Note B: There are cases where the optimum SO3 (using Test Method C563) for a particular cement is close to or in excess of the limit in this specification. In such cases where properties of a cement can be improved by exceeding the SO3 limit stated in this table it is permissible to exceed the values in the table, provided it has been demonstrated by Test Method C1038 that the cement with the increased SO3 will not develop expansion in water exceeding 0.020% at 14 days. When the manufacturer supplies cement under this provision, he shall, upon request, supply supporting data to the purchaser.

Note C: Limestone addition as per C 150-09 Item 5.1.3

Salt River Materials Group

PHOENIX CEMENT

Central Concrete Supply Co Inc
Attn: Kelly Idiart
830 W Elkhorn Blvd
Rio Linda, CA 95673-3006

Corporate Headquarters
8800 E Chaparral Rd, Ste 155
Scottsdale, AZ 85250
Phone: 480-850-5757
Fax: 480-850-5758

Cement Manufacturing
601 N Cement Plant Rd
Clarkdale, AZ 86324
Phone: 928-634-2261
Fax: 928-634-3543

19th Avenue Facility
1802 W Lower Buckeye Rd
Phoenix, AZ 85007
Phone: 602-253-9149
Fax: 602-253-9160

Lower Buckeye Facility
1941 W Lower Buckeye Rd
Phoenix, AZ 85009
Phone: 602-258-7798
Fax: 602-525-3362

21st Avenue Facility
1325 N 21st Avenue
Phoenix, AZ 85009
Phone: 602-254-3824
Fax: 602-254-3825

Mesa Community Storage
Dobson & McKellips
Mesa, AZ 85211
Phone: 480-990-7847

Cholla Fly Ash Facility
P O Box 380
Joseph City, AZ 86032
Phone: 928-288-1661
Fax: 928-288-1663

Four Corners Fly Ash Facility
P O Box 1007
Fruitland, NM 87416
Phone: 505-598-8657
Fax: 505-598-8633

San Juan Fly Ash Facility
San Juan Generating Station
Waterflow, NM 87421
Phone: 505-598-7546
Fax: 505-598-7547

Escalante Fly Ash Facility
CR19 / P O Box 620
Prewitt, NM 87405
Phone: 505-285-4590
Fax: 505-285-4667

Gallup Fly Ash Facility
9001/4 N 9th St.
Gallup, NM 87305

Product: ASTM C618 Class F, Four Corners Fly Ash
AASHTO M295

6-18-12 — **POZZOLAN TEST REPORT** — Ctl#: 64166

Lot: 6137	Results	Specifications
Chemical Analysis (C311 / C114 / D4326)		
Silicon Dioxide, SiO_2	63.13 %	---
Aluminum Oxide, Al_2O_3	25.13 %	---
Ferric Oxide, Fe_2O_3	4.40 %	---
$SiO_2+Al_2O_3+Fe_2O_3$	92.66 %	70.00 Min
Calcium Oxide, CaO	2.07 %	---
Magnesium Oxide, MgO	1.27 %	---
Sulfur Trioxide, SO_3	0.18 %	5.00 Max
Moisture Content	0.03 %	3.00 Max
Loss on Ignition	0.36 %	5.00 Max
Available Alkalis as Na_2O	0.34 %	---
Alkalis (%Na_2O + 0.658% K_2O)	2.04 %	---
R Factor (%CaO -5) / (%FeO)	-0.67 %	---
Physical Analysis		
Fineness, amount retained on		
#325 sieve, % (C430)	24.50	34.00 Max
variation, points from average	1.87	5.00 Max
Density, g/cm^3 (C188)	1.96	---
Variation from average, %	0.01	5.00 Max
Strength Activity Index		
with Portland Cement (C311 / C109)		
at 7 days, % of cement control	75.37	---
at 28 days, % of cement control	81.98	75.00 Min
Water Requirement (C311)		
% of cement control	94.21	105.00 Max
Soundness, autoclave expansion (C311 / C151)		
or contraction, %	-0.01	0.80 Max

All tests have been made in strict accordance with the current standards of the American Society for Testing and Materials covering the type of material specified.

Lee Gorby

Lee Gorby, Quality Assurance Manager
31 OCT 2012

LEHIGH
HEIDELBERGCEMENT Group

Lehigh Southwest Cement Company

SALES & MARKETING
12667 Alcosta Blvd, Suite 400
San Ramon, CA 94583
Telephone (925) 244-6562
FAX (925) 244-6586

PLANT LOCATION
Port A Harbor Road
Port of Stockton, CA 95203
Telephone (209) 465-1921
FAX (209) 465-1083

ALLCEM GGBFS (SLAG CEMENT) TEST REPORT

Specification: ASTM C 989-05 Grades 100 & 120 **Report Date:** May-13

STANDARD CHEMICAL AND PHYSICAL REQUIREMENTS	TEST RESULTS	ASTM C 989 SPECIFICATIONS Grade 100	Grade 120
Sulfur Trioxide (SO_3), %	2.03	4.0 Max	4.0 Max
Sulfur Sulfide (S),%	0.824	2.5 Max	2.5 Max
Chloride (Cl),%	0.005	----	----
(ASTM C 204) Blaine Fineness, m^2/km	502	----	----
(ASTM C 430) 325 Mesh, % Passing	99.98	80 Min	80 Min
Density	2.92	----	----
(ASTM C 185) Air Content, %	7.5	12 Max	12 Max
SLAG ACTIVITY INDEX, %			
7 Day Individual	137	70 Min	90 Min
7 Day Average of last 5	139	75 Min	95 Min
28 Day Individual	146	90 Min	110 Min
28 Day Average of last 5	148	95 Min	115 Min
REFERENCE CEMENT			
Total Alkali, %	0.74	0.60 - 0.90	0.60 - 0.90
(ASTM C 204) Blaine Fineness, m^2/km	355	----	----
C_3S, %	64	----	----
C_2S, %	11	----	----
C_3A, %	8.3	----	----
C_4AF,%	7.5	----	----
COMPRESSIVE STRENGTH, psi			
7 Day Reference Cement	4420	----	----
28 Day Reference Cement	5170	5000 psi Min	5000 psi Min
7 Day Slag and Cement Reference	6050	----	----
28 Day Slag and Cement Reference	7530	----	----

This GGBFS meets the requirements of ASTM C 989-05 (Grade 100 and Grade 120)
AASHTO M 302

Alan Sabawi, Quality Control Manager

BASF
The Chemical Company

3/4	03 30 00 03 40 00 03 70 00 04 05 16	**Product Data** Cast-in-Place Concrete Precast Concrete Mass Concrete Masonry Grouting

GLENIUM® 7500

High-Range Water-Reducing Admixture

Description

GLENIUM® 7500 high-range water-reducing admixture is based on the next generation of polycarboxylate technology found in all of the Glenium 7000 series products. This technology combines state-of-the-art molecular engineering with a precise understanding of regional cements to provide specific and exceptional value to all phases of the concrete construction process.

GLENIUM 7500 admixture is very effective in producing concrete mixtures with different levels of workability including applications that require self-consolidating concrete (SCC). The use of GLENIUM 7500 admixture results in faster setting characteristics as well as improved early age compressive strength. GLENIUM 7500 admixture meets ASTM C 494/C 494M compliance requirements for Type A, water-reducing, and Type F, high-range water-reducing, admixtures.

Applications

Recommended for use in:

- Concrete with varying water reduction requirements (5-40%)
- Concrete where control of workability and setting time is critical
- Concrete where high flowability, increased stability, high early and ultimate strengths, and improved durability are needed
- Production of Rheodynamic® Self-Consolidating Concrete (SCC) mixtures
- 4x4™ Concrete for fast-track construction
- Pervious Concrete mixtures

Features

- Excellent early strength development
- Controls setting characteristics
- Optimizes slump retention/setting relationship
- Consistent air entrainment
- Dosage flexibility

Benefits

- Faster turnover of forms due to accelerated early strength development
- Reduces finishing labor costs due to optimized set times
- Use in fast track construction
- Minimizes the need for slump adjustments at the jobsite
- Less jobsite QC support required
- Fewer rejected loads
- Optimizes concrete mixture costs

Performance Characteristics

Concrete produced with GLENIUM 7500 admixture achieves significantly higher early age strength than first generation polycarboxylate high-range water-reducing admixtures. GLENIUM 7500 admixture also strikes the perfect balance between workability retention and setting characteristics in order to provide efficiency in placing and finishing concrete.

Guidelines for Use

Dosage: GLENIUM 7500 admixture has a recommended dosage range of 2-15 fl oz/cwt (130-975 mL/100 kg) of cementitious materials. For most applications, dosages in the range of 5-8 fl oz/cwt (325-520 mL/100 kg) will provide excellent performance. For high performance and Rheodynamic Self-Consolidating Concrete mixtures, dosages of up to 12 fl oz/cwt (780 mL/100 kg) of cementitious materials can be utilized. Because of variations in concrete materials, jobsite conditions and/or applications, dosages outside of the recommended range may be required. In such cases, contact your local BASF Construction Chemicals representative.

Mixing: GLENIUM 7500 admixture can be added with the initial batch water or as a delayed addition. However, optimum water reduction is generally obtained with a delayed addition.

Master Builders

BASF
The Chemical Company

3	03 30 00 03 40 00 03 70 00	**Product Data** Cast-in-Place Concrete Precast Concrete Mass Concrete

Description

Pozzolith 200 N ready-to-use, liquid admixture is used for making more uniform and predictable quality concrete. It meets ASTM C 494/C 494M requirements for Type A, water-reducing, Type B, retarding, and Type D, water-reducing and retarding, admixtures.

Applications

Recommended for use in:

- Prestressed concrete
- Precast concrete
- Reinforced concrete
- Shotcrete
- Lightweight concrete
- Pumped concrete
- 4x4™ Concrete
- Pervious Concrete
- Rheodynamic® Self-Consolidating Concrete (SCC)

POZZOLITH® 200 N

Water-Reducing Admixture

Features

- Reduced water content required for a given workability
- Controlled setting characteristics – normal or retarded

Benefits

- Improved workability
- Reduced segregation
- Improved finishing characteristics for flatwork and cast surfaces
- Increased compressive and flexural strength

Guidelines for Use

Dosage: Pozzolith 200 N admixture is recommended for use at a dosage of 3-4 fl oz/cwt (195-260 mL/100 kg) of cementitious materials for Type A applications and up to 6 fl oz/cwt (390 mL/100 kg) for Type B and D requirements. Because of variations in job conditions and concrete materials, dosages other than the recommended amounts may be required. In such cases, contact your local sales representative.

Product Notes

Corrosivity – Non-Chloride, Non-Corrosive: Pozzolith 200 N admixture will neither initiate nor promote corrosion of reinforcing steel in concrete. This admixture does not contain intentionally-added calcium chloride or other chloride-based ingredients.

Compatibility: Pozzolith 200 N admixture may be used in combination with any BASF admixtures. When used in conjunction with other admixtures, each admixture must be dispensed separately into the mix.

Storage and Handling

Storage Temperature: If Pozzolith 200 N admixture freezes, thaw at 35 °F (2 °C) or above and completely reconstitute by mild mechanical agitation. ***Do not use pressurized air for agitation.***

Shelf Life: Pozzolith 200 N admixture has a minimum shelf life of 18 months. Depending on storage conditions, the shelf life may be greater than stated. Please contact your local sales representative regarding suitability for use and dosage recommendations if the shelf life of Pozzolith 200 N admixture has been exceeded.

Master Builders

BASF
The Chemical Company

3 | 03 30 00
03 40 00
03 70 00

Product Data
Cast-in-Place Concrete
Precast Concrete
Mass Concrete

Description

Pozzolith 322 N ready-to-use, liquid admixture is used for making more uniform and predictable quality concrete. It meets ASTM C 494/C 494M requirements for Type A water-reducing, Type B retarding, and Type D retarding and water-reducing admixtures.

Applications

Recommended fo use in:

- Prestressed concrete
- Precast concrete
- Reinforced concrete
- Shotcrete
- Lightweight or standard weight concrete
- Pumped concrete
- 4x4™ Concrete
- Pervious Concrete
- Rheodynamic® Self-Consolidating Concrete (SCC)

POZZOLITH® 322 N

Water-Reducing Admixture

Features

- Reduced water content required for a given workability
- Normal setting characteristics

Benefits

- Improved workability
- Reduced segregation
- Superior finishing characteristics for flatwork and cast surfaces
- Increased compressive and flexural strength

Performance Characteristics

Mix Data: 400 lb/yd^3 (237 kg/m^3) of Type I cement; slump 5 inches (125 mm); non-air-entrained concrete; concrete temperature 76 °F (24 °C); ambient temperature 74 °F (23 °C).

Setting Time

Mix Design	Initial Set (h:min)	Difference (h:min)
Plain Concrete	5:20	REF
Pozzolith 322 N admixture @		
3 fl oz/cwt (195 mL/100 kg)	5:15	-0:05
5 fl oz/cwt (325 mL/100 kg)	5:40	+0:20
7 fl oz/cwt (460 mL/100 kg)	6:20	+1:00

Compressive Strength

	7 Days			28 Days		
Mix Design	psi	MPa	%	psi	MPa	%
Plain Concrete	2150	14.8	100	3070	21.2	100
Pozzolith 322 N admixture @						
3 fl oz/cwt (195 mL/100 kg)	2820	19.4	131	3970	27.4	129
5 fl oz/cwt (325 mL/100 kg)	3160	21.8	147	4100	28.3	134
7 fl oz/cwt (460 mL/100 kg)	3190	22.0	148	4390	30.3	143

Note: The data shown is based on controlled laboratory tests. Reasonable variations from the results shown here may be experienced as a result of differences in concrete-making materials and jobsite conditions.

Setting time of concrete is influenced by the chemical and physical composition of the basic ingredients of the concrete, the temperature of the concrete and the climactic conditions. Trial mixes should be made with job site materials to determine the dosage required for specified setting time and a given strength requirement.

Master Builders

Graniterock
350 Technology Drive; Watsonville, CA 95076
Baldrige Award Winner
Research-Technical Services Ph. (831) 768-2330
FAX (831) 768-2403

Wilson Quarry Material Certification
Aromas, CA

Product: Wilson 1" x #4 Concrete Aggregate SMARA# 91-35-0012 (#003) **Date: July 26, 2012**

Contractor: Central Concrete

Attn: Patrick Rawley

Graniterock conducts regular sampling and testing of its materials, in accordance with ASTM or other applicable standards. The results listed below are average results derived from these tests. Based on the testing conducted, Graniterock certifies that the material identified on this certificate typically has the following physical properties, and meets the specification shown below.

Gradation : Cumulative Percent Passing (CT 202)

Sieve Sizes inches	mm/um	Wilson 1" x #4"	Caltrans Sec. 90
1 ½"	38.1 mm	100	100
1	25mm	100	88-100
¾	19mm	76 (x= 85)	x +/- 15
½	12.5mm	26	---
3/8	9.5mm	14 (x= 18)	x +/- 15
#4	4.75mm	6	0-16
#8	2.36 mm	3	0-6

Aggregate Quality Test Results:

Abrasion Loss (L.A. Rattler) (CT 211):	30.0% @ 500 rev.	≥45%
Cleanness Value (CT 227):	86	≥ 75
Sodium Sulfate Soundness (ASTM C 88):	1.4%	≤10%
Specific Gravity (CT 216):	2.81	
Absorption (CT 216):	0.9%	

Submitted by:

Gregory A. Wilkinson
Representative, LEED AP BD+C
Research Technical Services

Vulcan Materials Company

PLEASANTON PLANT
SMARA 91-01-0010

May 25, 2012

To: Mike Donovan, Central Concrete Supply Co., Inc.

Project: 3/8" Concrete Aggregate Used in Ready Mix Concrete

Please find below the laboratory test results. We certify that the aggregate produced at our Pleasanton operation meets the requirements of the American Society of Testing and Materials, ASTM C 33 size #8, and Caltrans Section 90. Our most recent test results presented for your review:

3/8" CONCRETE AGGREGATE

GRADATION			
SIEVE SIZE	PERCENT PASSING	ASTM SIZE #8 SPECIFICATION	CALTRANS SEC. 90
½" (12.5 mm)	100	100	100
⅜" (9.5 mm)	91	85 – 100	70 – 100 (X=85)
#4 (4.75 mm)	17	10 - 30	0 – 25
#8 (2.36 mm)	1	0 – 10	0 – 6
#16 (1.18 mm)	1	0 - 5	-

PHYSICAL PROPERTIES

ASTM STANDARD	COARSE AGGREGATE ASTM C 33
Specific Gravity (SSD)	2.68
Absorption	1.4%
Cleanness Value	94
Dry Rodded Unit Weight	102.0 lbs/cu. Ft.
ASTM C 88 – Sodium Sulfate Soundness	.21% Loss
ASTM C 117 – Material Finer Than #200	.4%
ASTM C 131 – Los Angeles Abrasion (500 Revs)	22% Loss
ASTM C 142 – Clay Lumps & Friable Particles	. 5%
ASTM C123 Light Weight Particles	0 %

If you require any additional information, please do not hesitate to call.

Respectfully,
Vulcan Materials Company

Philip Reid
Technical Services Regional Manager

Hanson
HEIDELBERGCEMENTGroup

December 2, 2011

Hanson Aggregates
West Region
12667 Alcosta Blvd. #400
San Ramon, CA 94583
Tel 925 244-6560

SECHELT CONCRETE SAND

The Sechelt Concrete Sand supplied by Hanson Aggregates meets the requirements of the referenced specifications. This aggregate is produced at the Sechelt, B.C. plant and is distributed at Hanson's Bay area facilities. Concrete aggregates from this plant have been used in concrete for more than twenty years with no known incidence of alkali reactivity or cement incompatibility. The typical physical properties of the aggregate are as follows.

Gradation:	Percent Passing		
	Sechelt	Caltrans Spec.	ASTM
Sieve Size	Conc.Sand	Sec. 90	C 33 Spec.
9.50 mm (3/8")	100	100	100
4.75 mm (#4)	99	95 - 100	95 - 100
2.36 mm (#8)	86	65 - 95	80 - 100
1.18 mm (#16)	66 (68)	58 - 78 (X ± 10)	50 - 85
600 µm (#30)	40 (43)	34 - 52 (X ± 9)	25 - 60
300 µm (#50)	16 (20)	14 - 26 (X ± 6)	5 - 30
150 µm (#100)	4	2 - 12	0 - 10
75 µm (#200), C 117	1.5	0 - 8	
	(X-value)		
Fineness Modulus	2.90	-	2.3 - 3.1
Specific Gravity, Bulk S.S.D.	2.65	-	-
Absorption, %	0.9	-	-
Dry Rodded Unit Wt., pcf	114.6	-	-
Sand Equivalent	92	75 Min.	-
Organic Impurities, C 40	Clear	S	Clear
Rel. Mortar Strength, C 87	130%	95% Min.	-
Sod. Sulfate Sound., C 88	3.9%	10% Max.	10% Max.
Fine Durability, d_f	86	60 Min.	-
Water Sol. Chlorides	n.d.	-	-
Deleterious Substances			
Clay & Friables, C 142	0.3%	-	3.0% Max.
Shale & Chert, C 295	0.2%	-	-
Lt. Wt. Particles, C 123	None	-	0.5% Max.
Alkali Reactivity			
ASTM C 295	Innocuous	I	I
ASTM C 1260	0.045%	0.15%	0.10%
ASTM C 1293	0.022%	0.04% Max.	0.04% Max.
Resistivity (Ohm-cm)	96,812		

Should you have questions regarding this aggregate material, please do not hesitate to call your Sales Representative.

LEHIGH HANSON

Bruce W. Carter, P.E.
Regional Director, QC/QA

Appendix B

Industry Survey

To assist in developing the *User's Guide to "Green" Concrete in Building Construction*, ASCC surveyed members of the American Concrete Institute, National Ready Mixed Concrete Association, and American Society of Concrete Contractors for input on their challenges and concerns for the use of green concrete in building construction. The main focus was on effects of carbon footprint reduction as related to replacement of large amounts of portland cement with supplementary cementitious materials (SCMs).

Many of the survey questions were based on a 2006 Canadian qualitative assessment of the use of SCMs. The assessment was conducted by the EcoSmart Foundation, which was commissioned by the Government of Canada through Natural Resources Canada.

The purpose of our survey was twofold:

- To obtain an approximate ranking of the key concerns, primarily regarding use of SCMs in "green" concrete, related to economic and technical challenges.
- To get input, through questions with open-ended response vehicles, that could add to our knowledge gained from the literature review.

The survey questions were as follows:

Input Survey to Assist in Developing a *User's Guide to "Green" Concrete in Building Construction*

The American Society of Concrete Contractors (ASCC) Education Foundation received a grant from the Charles Pankow Foundation (CPF) to develop a *User's Guide to "Green" Concrete in Building Construction*. As part of the development process, ASCC is surveying partners in the concrete community to determine their challenges and concerns for the use of green concrete in building construction. Please help ASCC by responding to the survey below. We thank you for your time and input. For more information on this project or to contribute more, contact Ward R. Malisch, PhD, PE, FACI, ASCC technical director at (800) 331-0668 or wmalisch@ascconline.org.
****

Check one or more boxes or add comments for each question shown below:

1. Identify your role as a stakeholder in green concrete building construction:
   - ☐ Architect ☐ Engineer ☐ Contractor ☐ Producer ☐ Supplier ☐ Test lab
   - ☐ Other/Comments: ____ __________
2. Identify any policy barriers in implementing green concrete building construction:
   - ☐ Code restrictions ☐ Prescriptive specifications ☐ Concern with possible EPA rules on fly ash
   - ☐ Other/Comments: ____
3. Identify any market or regulatory drivers that may be advancing/advocating greener concrete building construction
   - ☐ Code requirements ☐ LEED specifications ☐ Client sustainability policy ☐ Competitive pressures
   - ☐ Other/Comments:____
4. Identify any economic barriers in implementing green concrete building construction:
   - ☐ Increased concrete cost ☐ Lengthened construction schedule ☐ Increased design cost ☐ Increased testing/inspection
   - ☐ Other/Comments: ____
5. Identify any economic stimulus or assistance that may be impacting choices for greener concrete construction
   - ☐ Higher profit for green ☐ Market differentiation ☐ Better performing concrete with SCM's
   - ☐ Other/Comments: ____

6. Identify any technical barriers in implementing green concrete building construction:
- ☐ Increased set times ☐ Delayed strength gain ☐ Curing/protection time increases ☐ Difficulty in hard trowel finish
- ☐ Other/Comments: ____________________

7. Identify specific design challenges in green concrete building construction:
- ☐ Delayed availability of strength test results ☐ Acceptance of concrete when strength tests are low ☐ Architectural Concrete
- ☐ Other/Comments: ____________________

8. Identify specific concrete mix design challenges in green concrete building construction:
- ☐ Trial mix required ☐ Inconsistent slumps ☐ Variation in set times ☐ Early-age strength ☐ Later-age strength
- ☐ Other/Comments: ____________________

9. Identify specific material supply challenges in green concrete building construction:
- ☐ Availability ☐ Variability ☐ Admixture incompatibility ☐ Storage of several supplementary cementitious material
- ☐ Other/Comments: ____________________

10. Identify specific construction challenges in green concrete building construction:
- ☐ Delayed formwork removal ☐ Increased curing time ☐ Delay in post-tensioning ☐ Placing & finishing difficulties
- ☐ Other/Comments: ____________________

11. Identify specifications for material in green concrete building construction:
- ☐ Limit Portland cement content ☐ Minimum percent of SCMs per mix ☐ Minimum percent of SCM's per project
- ☐ Other/Comments: ____________________

12. Tell us about any other challenges and how you dealt with them:
____

Summary charts, comments made, and analyses are attached as Appendix B, with ranking results in bar graphs, and a summary of the rankings by source. All answers to open ended questions are included in Appendix C.

Based on non-open-ended responses:

- The leading policy barrier to green concrete is prescriptive specifications.
- The leading market/regulatory driver is LEED specifications
- The leading economic barrier is increased concrete cost
- The leading economic stimulus is market differentiation
- The leading technical barrier is delayed strength gain
- The leading design challenge is acceptance of low strength tests
- The leading mix design challenge is early-age strength
- The leading material supply challenge is availability of SCMs
- The leading construction challenge is delayed form removal
- The leading type of “green” concrete specification is a minimum limit on SCMs in the concrete

The different viewpoints in open-ended written responses highlight the need for:

- Better education of owners, engineers/specifiers, concrete producers, and contractors so all share the same general knowledge
- More cost information, including differences in cost for different environmental exposure conditions
- More information about performance of “green” concrete, and the differences in performance that can be expected for different structural members and different exposures in service.

Industry Survey Analyses and Summary Charts

Input survey results

The top choices in questions 2 through 11 were remarkably similar in results from ACI, NRMCA and ASCC members. The rankings of checked responses were as follows for the three organizations:

Response Rankings to Green Survey Questions (1 highest)

Question 2	**ACI**	**NRMCA**	**ASCC**	**Composite Rank**
Policy barriers				
Code restrictions	3	3	3	3
Prescriptive specifications	1	1	1-2 tie	1
EPA fly ash ruling	2	2	1-2 tie	2
Question 3				
Market/Regulatory drivers				
Code requirements	4	4	4	4
LEED specifications	1	1	1	1
Client sustainability policy	2	2	2	2
Competitive pressure	3	3	3	3
Question 4				
Economic barriers				
Increased concrete cost	1	1	1	1
Longer construction schedule	2	2	2	2
Increased design cost	4	4	3-4 tie	4
Increased testing/inspection	3	3	3-4 tie	3
Question 5				
Economic stimulus				
Higher profit	3	3	3	3
Market differentiation	1	2	1	1
Better performance with SCMs	2	1	2	2
Question 6				
Technical barriers				
Increased set time	3	3	1	1
Delayed strength gain	1	1	2	3
Curing/protection time inc.	2	2	3	2
Difficulty in hard troweling	4	4	4	4
Question 7				
Design challenges				
Late str. test results	3	2	2-3 tie	2
Acceptance of low str. tests	1	1	1	1
Architectural concrete	2	3	2-3 tie	3
Question 8				
Mix design challenges				
Trial mix required	2	2	5	2
Inconsistent slumps	4	5	2-3 tie	4
Variation in set times	3	3	2-3 tie	3
Early-age strength	1	1	1	1
Later-age strength	5	4	4	5

Question 9

Material supply challenges

Availability	1	2	1-2 tie	2
Variability	3	3	1-2 tie	3
Admixture incompatibility	4	4	4	4
Storage limitations	2	1	3	1

Question 10

Construction challenges

Delayed form removal	1	1-2 tie	1-2 tie	1
Increased curing time	2	3	1-2 tie	2
Delay in post-tensioning	3	1-2 tie	4	3
Placing and finishing	4	4	3	4

Question 11

Specifications

Limit PC content	2	2-3 tie	2	2
Minimum % SCMs/mix	1	1	1	1
Minimum % SCMs/project	3	2-3 tie	3	3

As would be expected, the composite ranking closely mirrored the ACI ranking because the ACI survey resulted in the most responses. One exception to this was the agreement between ACI and NRMCA that storage limitations were the number one material supply challenge. For ternary mixtures, at least three silos are needed for portland cement, fly ash, and slag cement..

Open-ended response results

For each of the first eleven questions the “Other” category allowed for open-ended responses and Question 12 was completely open ended, asking for any other challenges and how they were dealt with. The most striking result in the open-ended questions was the number of contradictory responses from different industry segments. The most evident was a belief by many that the industry already knows how to solve problems related to slow setting time and early strength gain, difficulty in hard trowel finish, and increases in curing and protection times. Some examples of this follow. Numerals refer to the survey questions, which are briefly summarized.

Understanding of green concrete properties, advantages, and disadvantages

Limited or No knowledge (Problems are real)

2. Policy barriers in implementing green construction
    - Knowledge of code officials
    - Limited knowledge of long term impact and ROI
    - Architects and engineers not understanding anything about ggbfs and fly ash and therefore being afraid to allow the use of it
    - Lack of knowledge on how to implement green building processes
    - Lack of knowledge on what constitutes sustainable construction
4. Economic barriers to green concrete
    - Lack of knowledge of owners and design professionals
    - Lack of familiarity of engineers with green mix performance vs. normal mix performance
    - Lack of understanding of process
    - Understanding the use of green materials and specifications
5. Economic stimulus impacting choices for green concrete
    - SCMs are widely available but engineers lack familiarity and flexibility

6. Technical barriers to implementing green concrete

Specifiers lack sufficient knowledge; longevity suffers as a result
General ignorance regarding the requirements for green concrete
Lack of knowledge of impact of green techniques on long-term durability
Some lack of understanding about green
Lack of knowledge
Learning to work with new product
Lack of training
Educational barriers
Lack of specifier knowledge
Poor product knowledge

7. Design challenges in green concrete construction

Lack of knowledge
Misunderstanding of strength gain patterns
Insufficient designers' knowledge of green concrete materials
Lack of understanding by specifiers and contractors
Understanding all possible materials available
Specifier knowledge of green concrete performance parameters
Lack of knowledge of expected service life
Lack of understanding about strength gain with SCMs and possible improvements with new admixture technology

8. Mix design challenges in green concrete construction

Challenge is NOT the materials, it's the specifiers' lack of sufficient knowledge
Lack of knowledge

All the knowledge needed (Problems are perceived, not real)

6. Technical barriers to implementing green concrete

No technical barriers
No barriers that can't be overcome pretty easily through use of admixtures
None of these [the choices listed] are barriers as these are all chemically adjustable
None worth mentioning
As a supplier with extensive technical resources at its disposal, the above barriers are solvable. It is the Code and prescriptive specifications that become the most difficult barriers to overcome.
Good quality construction practices and communication between designer, concrete producer, and contractor would mitigate any of the "technical barriers" listed.
All of the above [the choices listed] are technical perceptions often advanced by ASCC, not technical barriers
None
All of the above [the choices listed] have solutions, but are perceived as problems
None, only perceived problems
All of the above [the choices listed] can be mitigated by correct use of proportioning and training
All of the above [the choices listed] can often be offset with mix design changes
None. Really…just a question of correct product development
Highly sustainable concrete mixtures can be developed with a wide range of performance characteristics
None of the above [the choices listed] for qualified finishers
Most of the above [the choices listed] are problems that are being solved depending on whether the requirements are reasonable

Many of these [the choices listed] can be overcome with some proficiency

Workmanship could be the problem. Resources available for the first three items listed [the choices listed in the question]

None of the above [the choices listed]

I can't see any barriers

All of the above can be overcome with proper mix design development.

There were also differences of opinion about the cost of "green concrete.

Effect on short-or long-term costs

No cost increase or a cost decrease

3. Regulatory drivers that may be advancing greener concrete

    Interest in cost savings

4. Economic barriers in implementing green concrete

    No real cost increase. The fallacy that green is a huge cost increase. More publicity needs to be out there clearing the facts that cost increase is not really true

    Perceived additional costs that may not be real

    No economic barriers

    The discrete cost to purchase the concrete per yard could be higher , but the installation cost per yard could be lower, resulting in overall lower costs. Unfortunately, we do not look at construction costs this way, and we should.

    Perceived price difference

5. Economic stimulus impacting choices for green concrete

    Reduced cost of concrete due to reduced cement, increased fly ash

    Lower material cost

    The owners here don't seem to take a sufficiently long term view. Short term economics generally dominate.

Cost increase

2. Policy barriers in implementing green construction

    Cost

4. Economic barriers in implementing green concrete

    Increased cost of conforming to green requirements

    Increased construction costs

    Market resistance to increased cost and inconvenience

    Increased cost to owners

    Concrete finishing costs have gone up 30%

And finally, performance of green concrete was a contentious issue.

Effect of SCMs on performance

Negative effect

2. Policy barriers in implementing green construction

    Does it really work and does it last?

    Concrete quality

    Concern about performance

    Substandard green product quality

4. Economic barriers to green concrete

    Increased risk to designers if concrete doesn't perform

    Increased risks due to serviceability/performance

5. Economic stimulus impacting choices for green concrete

    I see no economic stimulus

6. Technical barriers to implementing green concrete

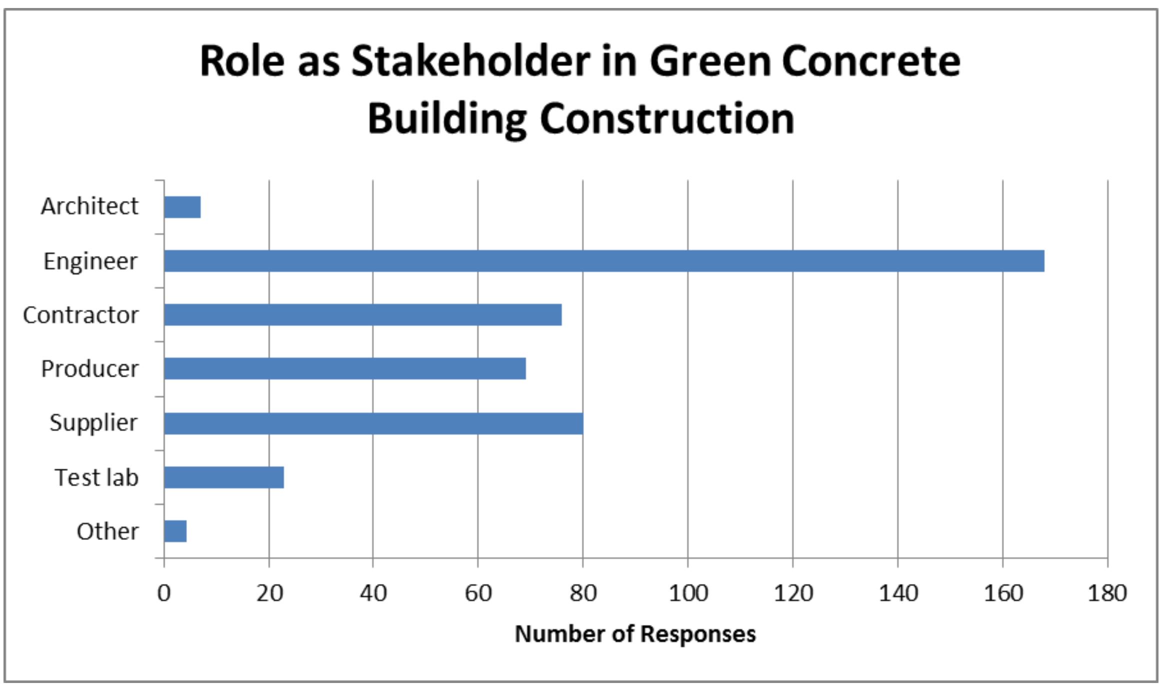
Durability and long-term performance
High % GGBFS causes scaling issues
Quality of final product
Uncertainty with respect to durability
Lack of knowledge of impact of green techniques on long-term durability

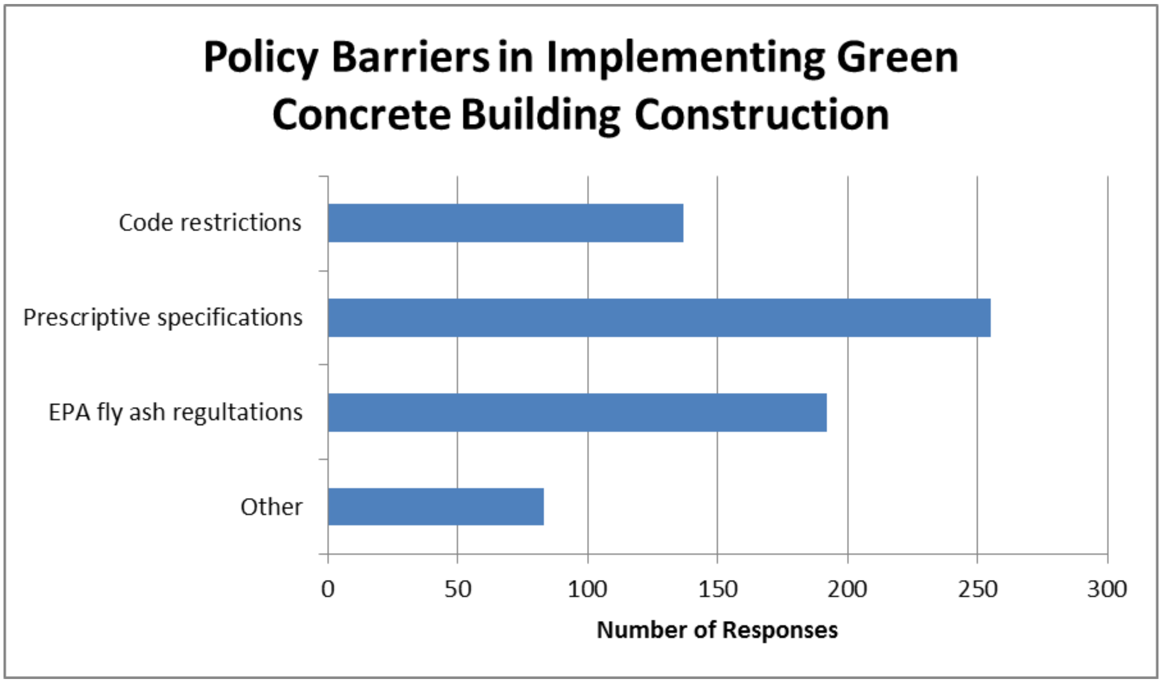
7. Design challenges in green concrete
   Durability

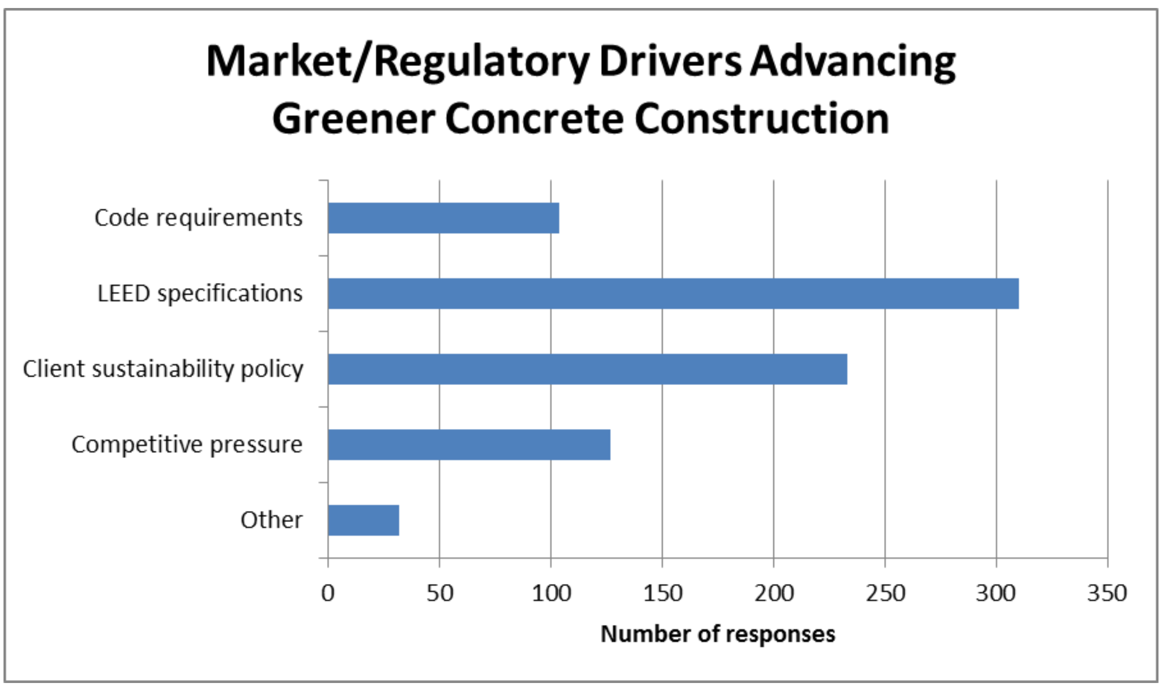
Positive effect

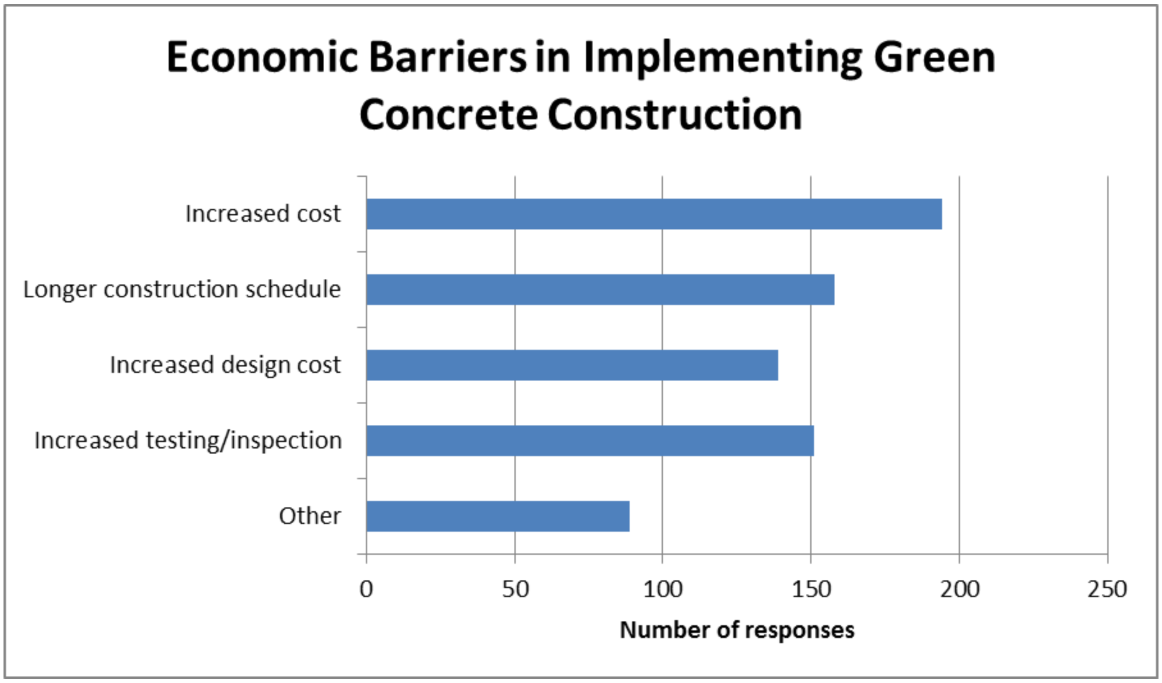
3. Regulatory drivers that may be advancing greener concrete
   Concurrent benefits from green concrete such as higher durability
   Ash and other SCMs improve concrete
   Higher performance concrete using cement replacement
5. Economic stimulus impacting choices for green concrete
   SCMs required for durability and high strength concrete
   The industry is geared to look at capital costs and does not look at structure in terms of cradle-to-grave costs

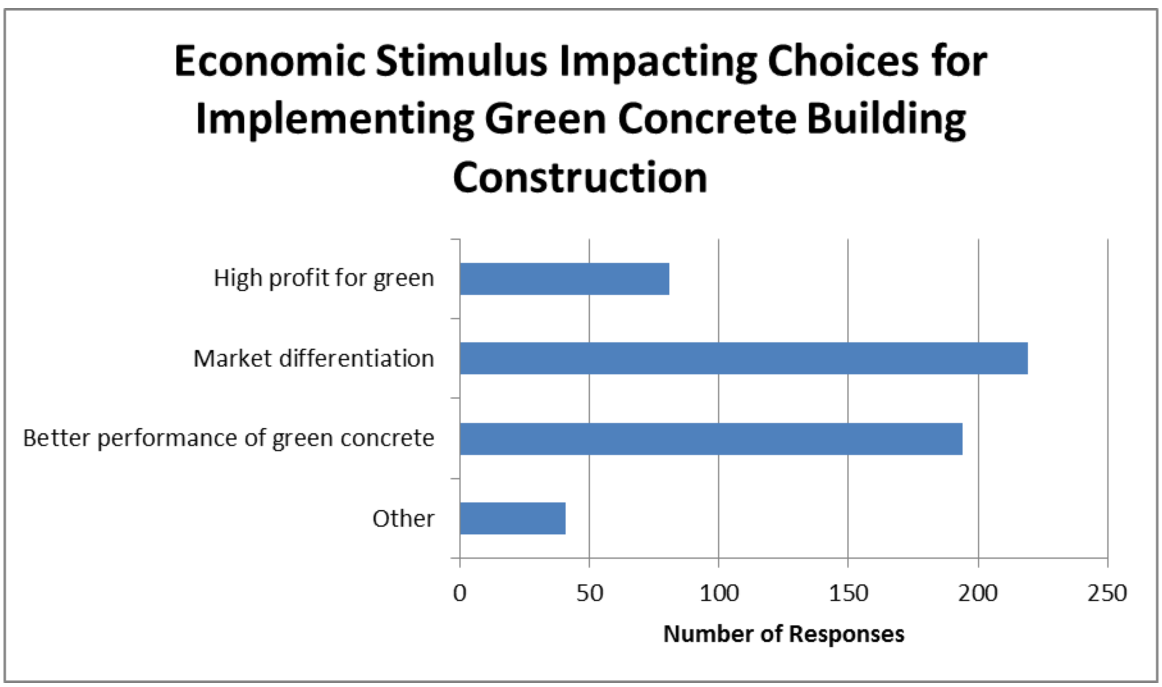
Industry Survey Summary Charts

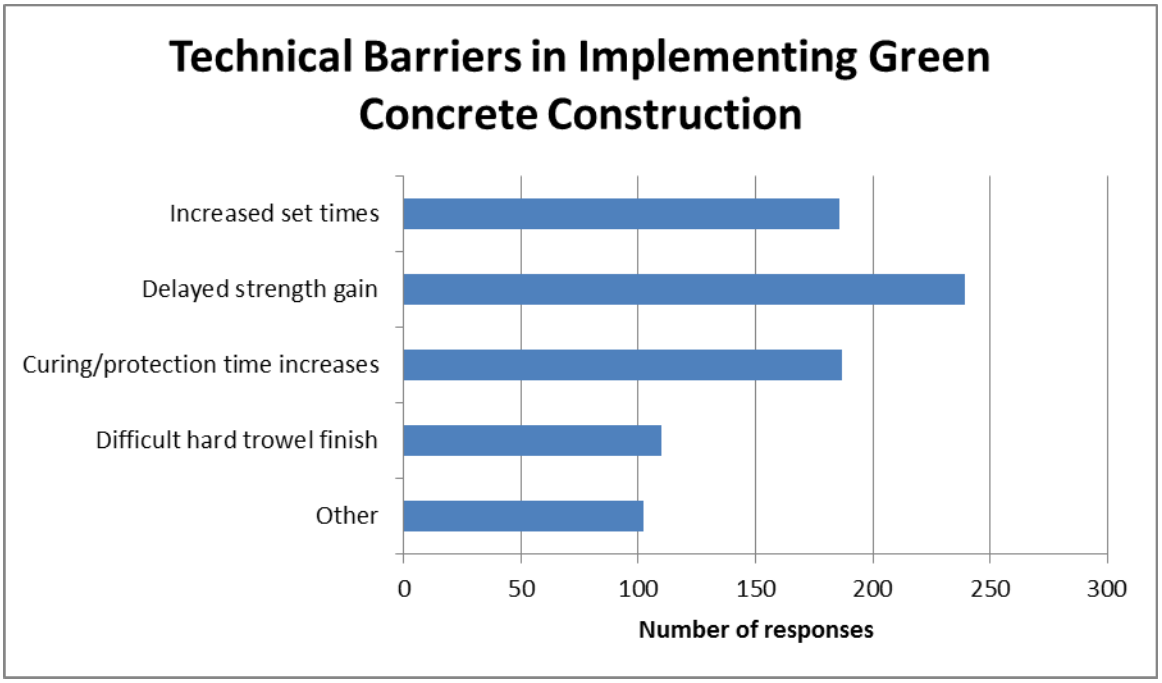


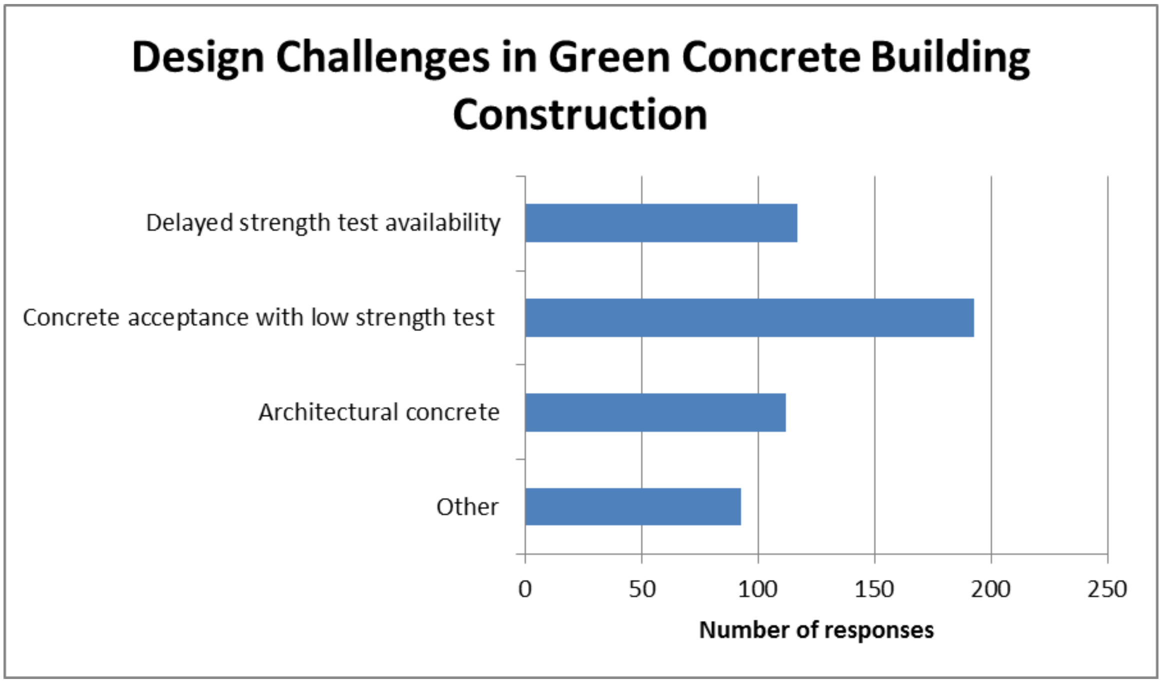

Policy Barriers in Implementing Green Concrete Building Construction
Code restrictions
Prescriptive specifications
EPA fly ash regultations
Other
0
50
100
150
200
250
300
Number of Responses

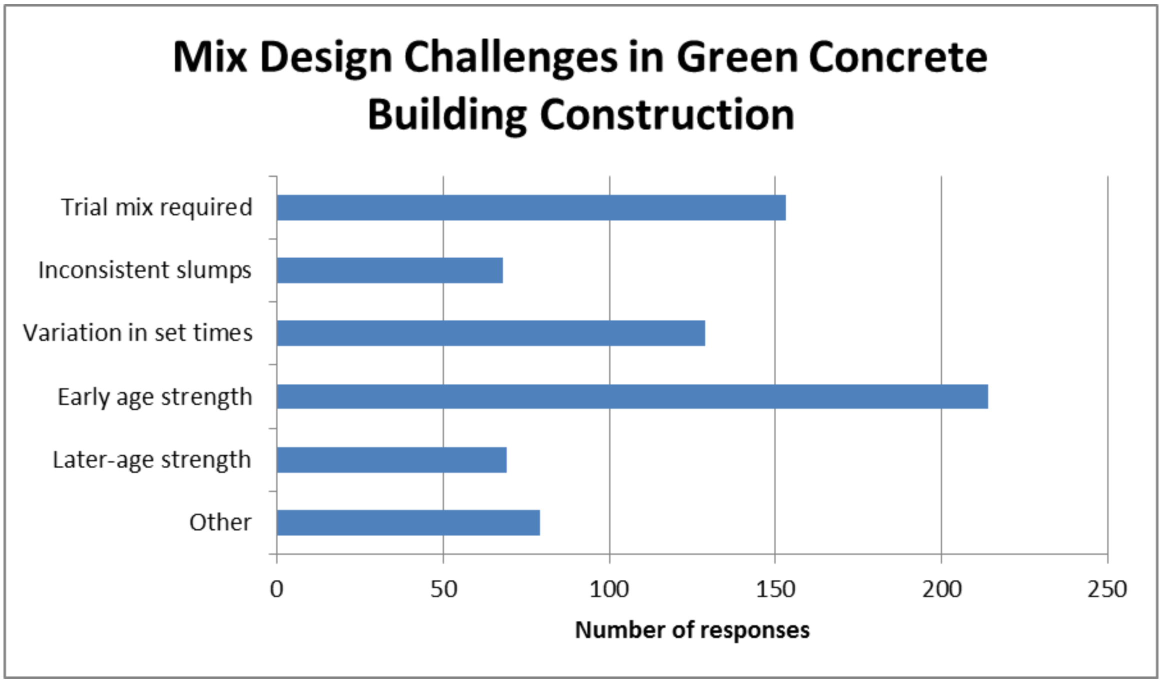

Market/Regulatory Drivers Advancing Greener Concrete Construction
Code requirements
LEED specifications
Client sustainability policy
Competitive pressure
Other
0
50
100
150
200
250
300
350
Number of responses


Economic Barriers in Implementing Green Concrete Construction
Increased cost
Longer construction schedule
Increased design cost
Increased testing/inspection
Other
0
50
100
150
200
250
Number of responses

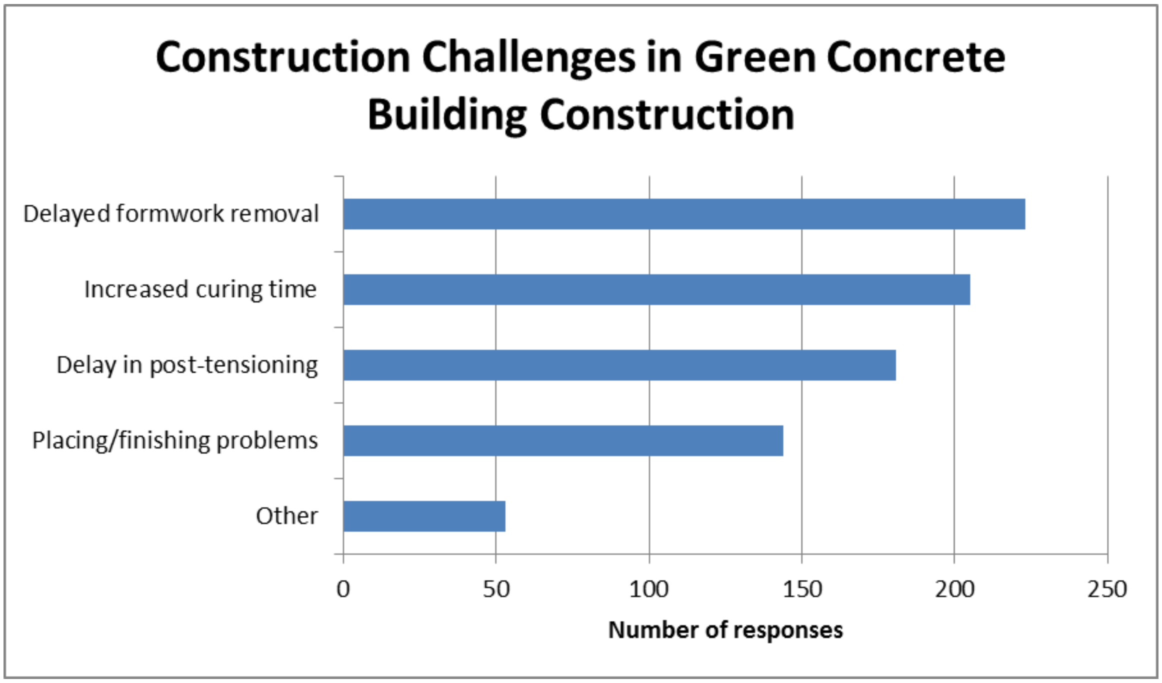

Economic Stimulus Impacting Choices for Implementing Green Concrete Building Construction
High profit for green
Market differentiation
Better performance of green concrete
Other
0
50
100
150
200
250
Number of Responses

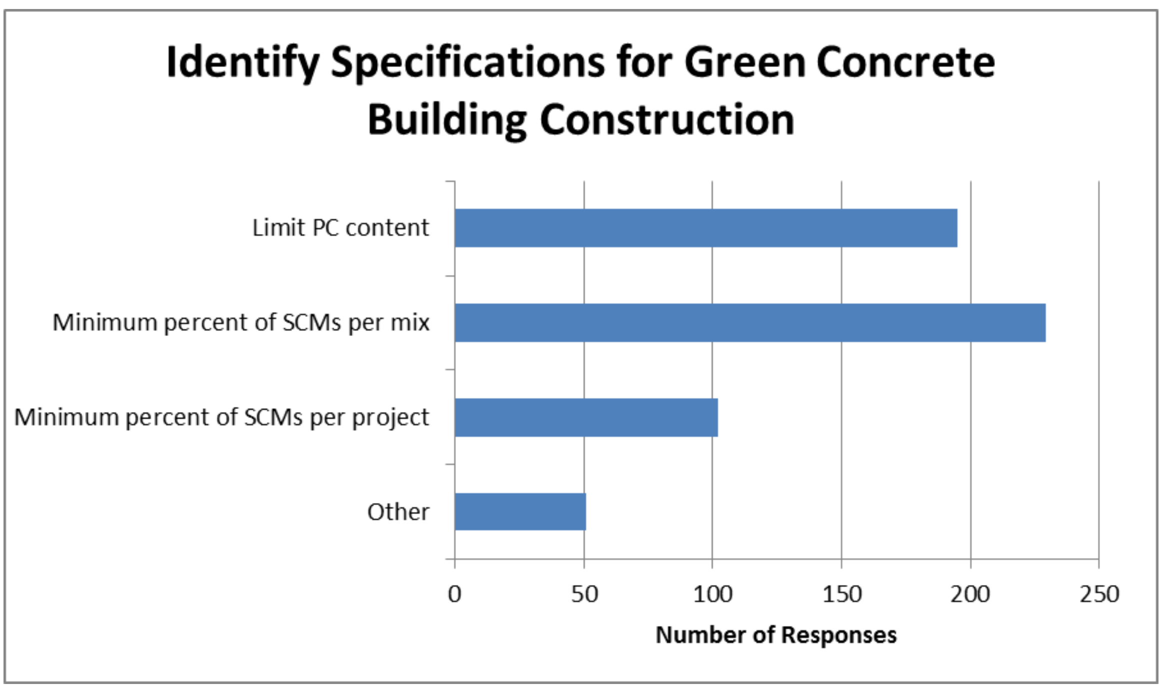

Technical Barriers in Implementing Green Concrete Construction
Increased set times
Delayed strength gain
Curing/protection time increases
Difficult hard trowel finish
Other
0
50
100
150
200
250
300
Number of responses


Design Challenges in Green Concrete Building Construction
Delayed strength test availability
Concrete acceptance with low strength test
Architectural concrete
Other
0
50
100
150
200
250
Number of responses


Mix Design Challenges in Green Concrete Building Construction
Trial mix required
Inconsistent slumps
Variation in set times
Early age strength
Later-age strength
Other
0
50
100
150
200
250
Number of responses


Material Supply Challenges in Green Concrete Building Construction
Availability
Variability
Admixture incompatibility
Storage for several SCMs
Other
0
50
100
150
200
250
Number of responses


Construction Challenges in Green Concrete Building Construction
Delayed formwork removal
Increased curing time
Delay in post-tensioning
Placing/finishing problems
Other
0
50
100
150
200
250
Number of responses


Identify Specifications for Green Concrete Building Construction
Limit PC content
Minimum percent of SCMs per mix
Minimum percent of SCMs per project
Other
0
50
100
150
200
250
Number of Responses

Answers to Open-ended Questions

1. Identify your role as a stakeholder in green concrete building construction:

1	University professor (educator, researcher)
	Materials consultant
3	Highway research engineer into green pavements and other transportation structures.
4	Forensic analysis / long-term maintenance
5	Building owner / engineer
6	R&D
7	Marketing consultant, freelance writer.
8	I mainly work on bridge structures rather than buildings.
9	Raw material supplier
10	Concrete consultant
11	Association (Producer)
12	Precast manufacturer
13	Trade Association
14	Huxter
15	Research Officer
16	Educator
17	Researcher
18	Educator
19	Contractor, educator
20	Educator, researcher
21	Executive Director, Industry Trade Association
22	Concrete specialist engineer
23	SCM - Silica Fume
24	Federal government researcher
25	Reinforcing steel supplier
26	Ill. Ready Mixed Concrete Assoc.
27	Educator, engineer
28	Trade Association
29	Moisture remediation concrete supplier
30	Trade association
31	Leed AP Building Design+Construction
32	Construction project manager consultant
33	Concrete consultant
34	Concrete contractor
35	Industry representative
36	Consulting services
37	University professor
38	Concrete construction consultant
39	Consultant
40	Engineering professor and consultant
41	Consultant
42	Industry Association
43	Educator
44	Educator
45	Forensic Consultant
46	Design/Builder

2. Identify any policy barriers in implementing green concrete building construction:

1	Local knowledge of code officials
2	Policies are not enforced, people can provide false statistics with no consequence.
3	Chloride accelerator limitations
4	Does it really work and does it last
5	Specific characterization needed to use recycled materials
6	NA
7	Snake oil salesmen
8	None
9	Moisture RH values in concrete being compatible w/ New LEED flooring products.
10	Concrete quality
11	Limited knowledge of long-term impact and ROI
12	Confusion between LEED and truly better total environmental choices
13	Owner restrictions
14	Cold weather concrete and 2 day cycle
15	Education
16	Percent in trowel finished slabs
17	None
18	Not allowing the use of slag cement
19	Disclosure of proprietary materials
20	Conservatism of market
21	Defining what is "green", education, slow pace of change in construction
22	Failure to address serviceability
23	Architect's & engineer's not understanding anything about ggbfs and fly ash therefore being afraid of it and refusing to allow the use of it.
24	LEED scorecard inadequately addresses green concrete
25	Economics, substandard green product quality
26	Lack of knowledge on how to implement green building processes
27	Over simplification of complex issue, like trying to design Freedom One empirically.
28	Set times and schedule
29	Less experiences in Japan
30	I prefer pink or purple
31	pH
32	The lack of definition of "green concrete".
33	I've not come against any.
34	Strength gain characteristics for form removal and loading purposes.
35	Cost
36	Construction schedule
37	Resistance to replacing cement with ash - slows down curing
38	Restrictions from my agency
39	Cost
40	Concern about performance
41	Lack of knowledge on what constitutes sustainable construction
42	Cost
43	Cost to owner
44	DOT restrictions
45	LEED provides no points for slab on ground or pavement designs that reduce either the amount of steel in the slab or the cross sectional area.
46	Cost
47	Construction schedules. Green friendly mixes may take longer to finish and/or gain strength.
48	Risk of products not proven by test of time (or 2 new products never used together)
49	None, we are moving ahead on all fronts. Could be mercury in SCM's as an issue with owners.
50	High SCM content pushed by LEED credits
51	User concerns with impact on placement/finishing (not policy)
52	None that aren't manageable.
53	Lack of performance data being provided by producer's
54	Contractor reluctance to try anything new, i.e. don't try and tell me how to lay concrete.
55	ASTM C94 requirements related to ACI
56	Strength and setting times
57	Lack of legislation that results in mandatory requirements in Codes.
58	This is mostly a designers issue / fly ash is from coal burning - how is this green ?
59	As a contractor, lack of input. Lack of references to use to recommend alternates.
60	Identifying actual green compliance
61	ACI 318 building code
62	Price
63	Material quantities
64	Confidence of contractors
65	Using pulverized limestone as a cement replacement not being inter-ground. Why can't the producer use it like a cement and meter it in.
66	Lack of clarity in what it is and how to judge it
67	Performance and cost
68	None, really
69	NA
70	"Green" is a broad term with a wide variety of interpretations
71	Consumer knowledge
72	None in our segment, except for lack of sufficient appreciation
73	To the extent that the goals of being green are in direct contradiction to the aims of the flooring industry to deflect warranty claims, codes and prescriptive specification both are barriers
74	

3. Identify any market or regulatory drivers that may be advancing/advocating greener concrete building construction:

1	Industry trend towards going green to impress clients
2	Clients that don't realize the risks and issues
3	Concurrent benefits from green concrete such as higher durability
4	Personal preference
5	Peer pressure
6	Local codes and standards
7	Research and development, education, competition from non-concrete products
8	Owners and developers using green as a marketing tool. These progressive thinkers are forcing the others to step up when I don't believe they would have otherwise. The same goes for the straggler architect's & engineer's.
9	General public awareness of environmental impacts
10	Standards and government programs (such as Energy Star, EPA environmentally preferable products, etc.) and private sector labeling (such as GreenGuard, ICC-ES, etc.)
11	Some idiots like green color things.
12	Interest in cost savings
13	Ash and other scm's improve concrete
14	Cost
15	Demand from the public
16	Cost
17	Government regulations and orders
18	Political direction
19	General focus on green and initiatives by competing building materials
20	Architects
21	LEED is NOT advancing concrete, but stepping it back - see the current and upcoming guidelines
22	Higher performance concrete using cement replacement

4. Identify any economic barriers in implementing green concrete building construction:

1	Liquid head pressures on formwork design
2	Durability and long-term performance
3	Increased testing to ensure it will work
4	Lack of knowledge
5	High % GGBFS cause scaling Issues !!!
6	Variation
7	Shrinkage and durability
8	Misunderstanding of requirements vs. performance
9	Not all batch plants can accommodate multiple silos for different SCM's
10	As you know fly ash or slag delays set in winter
11	Getting Engineers/Architects to be innovative in designing green. Stop the cut and paste design used today.
12	Unknown
13	None
14	Quality of final product
15	Availability of fly ash

16	All of the above have solutions but are perceived as a problem due to specifying Type F fly ash, etc.
17	Uncertainty with respect to durability
18	None, only perceived problems.
19	None
20	Specifiers lack sufficient knowledge, longevity suffers as a result
21	Whoever wrote these questions seem to be thinking very narrowly about concrete.
22	The only real increase in set times/strength gains comes in the winter. The other times of the year it is simply a misperception that people don't change their mind about.
23	Lack of accepted performance specs in private sector
24	General ignorance regarding the requirements for green concrete. What does it include? How do I comply? How do these affect concrete production and cost? Etc.
25	Lack of knowledge of impact of green techniques on long-term durability
26	SCMs not a solution for all concrete: white, pigmented, cast stone, decorative, etc. etc. etc. Too much focus on carbon footprint without overall environmental footprint, resilience, or long-term or intended performance.
27	Some lack of understanding about green requirements
28	Industrial side in which I work is not embracing.
29	Longer formwork in place time due to delay stripping strength
30	What's a technical barrier?
31	Don't know
32	All of the above can be mitigated by correct use of proportioning and training.
33	Contractor knowledge
34	High sustained surface pH impacting flooring limitations
35	Integral color dosage rates
36	Lack of knowledge
37	Practical information on all aspects of non-Portland cement based systems
38	Concrete contractors not willing to introduce and test green mixes
39	Economics ... can't get credit economically because of materials availability.
40	Proper testing methods
41	Language, cultural knowledge transfer challenges
42	Risk aversion
43	Application?????????
44	Drying shrinkage of room temp. curing mixes.
45	Good concrete paving practices may be too technical for contractors and DOT in the state of KY
46	Learning to work with new product
47	Don't know
48	All of the above can often be offset with mix design changes
49	Lack of training
50	None, really...just a question of correct product development
51	The Hassle Factor - extra work...
52	Educational barriers
53	Highly sustainable concrete mixtures can be developed with a wide range of performance characteristics
54	Surface dries before concrete gets hard and pulls a part when trying to finish
55	Cost
56	Again none of the above for qualified finishers
57	Concrete contractors/finishers adding too much water to concrete on the job!
58	Too much attention paid to cement replacement as the only way to make concrete 'green' and not enough on designs that increase service life, reduce total concrete used (section) or the amount of steel used in the design.
59	Service life tests not designed for non-Portland cement materials
60	Lack of specifications and experience
61	Specs/codes must permit/support 56 day test age
62	Most of the above are problems that are being solved depending upon whether the requirements are reasonable
63	County and State Acceptance
64	Increased potential for carbonation induced corrosion
65	Willingness of contractors/specifiers to adopt new methods of construction
66	Many of these can be overcome with some proficiency
67	Lack of good sounds performance measures, both in the lab and field
68	Need for handling/installing materials differently than with conventional materials
69	Workmanship could be the problem. Resources available for first three items.
70	ASTM C94 requirement that all concrete be designed for 1 failure in 100 tests even for on grade slabs.
71	The industry geared to look at capital costs and does not look at structure in terms of cradle to grave cost.
72	Green is not easier, it is more complicated (and necessary too)
73	Lack of specifier knowledge
74	Need better understanding of end results
75	None of the above
76	Durability in different climates
77	I can´t see any barriers
78	Winter concrete work required more heat for a

	longer time
79	Using only 28 days strength for acceptance, need 56 or 90 days
80	Poor product knowledge
81	DOT specifications based on PC that do not apply to SCM'as.
82	All of the above can be overcome with proper mix design development.
83	Ready mix supply chain

5. Identify any economic stimulus or assistance that may be impacting choices for greener concrete construction:

1	Reduced cost of concrete due to reduced cement, increased fly ash
2	Lower material cost
3	Logistics of nearby recycled materials. may drive choices
4	Item 3 above is true for concrete performance but frequently at the expense of time for fast track projects
5	Higher strength, faster curing, and whiter concrete using slag cement and can contribute to LEED credit
6	Tax return for use of green product
7	SCM's required for durability and high strength concrete
8	None
9	Public perception of owner
10	In concrete, "green" practices have been already used for years
11	Poorly written questions and responses.
12	Green is what consumers want. developers are moving to greener builders to increase their market share. I don't think most are doing it to save the planet but even if they are doing it just for profit, the planet thanks them.
13	Cost
14	Public demand
15	Note SCMs were in place and used before "green," it's just good concrete.
16	Energy requirements
17	It's too cheap.
18	Improved performance and durability.
19	The owners here don't seem to take a sufficiently long term view. Short term economics generally dominate. The result is generally that LEED is too expensive.
20	Many initially think high SCM content will be cheaper
21	Consumer awareness
22	Broad recognition and agreement of benefits, and acceptance of inconvenience, of reducing cement content
23	Don't know
24	Lower operating cost for many 'green' buildings, also easier to lease out
25	Total in-place cost
26	Improved site safety
27	Better understanding/information of green concrete
28	Desire to recycle and not fill up landfills
29	I see no economic stimulus
30	SCM's are widely available but engineers lack familiarity and flexibility
31	Popularity of LEED certified projects, becoming industry standard.
32	Focus by public entities and politics
33	Demand from market / code agencies for reduction of green house gas emission is emerging.
34	Lower life cycle costs for the owner
35	Monetary rewards for engineers and architects to do more complex design
36	Responsibility for our actions and impact on our environment
37	LEED

6. Identify any technical barriers in implementing green concrete building construction:

1	Liquid head pressures on formwork design
2	Durability and long-term performance
3	Increased testing to ensure it will work
4	Lack knowledge
5	High % GGBFS cause scaling Issues !!!
6	Variation
7	Shrinkage and durability
8	Misunderstanding of requirements vs. performance
9	Not all batch plants can accommodate multiple silos for different SCM's
10	As you know fly ash or slag delays set in winter

11	Getting Engineers/Architects to be innovative in designing green. Stop the cut and paste design used today.
12	Unknown
13	None
14	Quality of final product
15	Availability of fly ash
16	All of the above have solutions but are perceived as a problem due to specifying Type F fly ash, etc.
17	Uncertainty with respect to durability
18	None, only perceived problems.
19	None
20	Specifiers lack sufficient knowledge, longevity suffers as a result
21	Whoever wrote these questions seem to be thinking very narrowly about concrete.
22	The only real increase in set times/strength gains comes in the winter. The other times of the year it is simply a misperception that people don't change their mind about.
23	Lack of accepted performance specs in private sector
24	General ignorance regarding the requirements for green concrete. What does it include? How do I comply? How do these affect concrete production and cost? Etc.
25	Lack of knowledge of impact of green techniques on long-term durability
26	SCMs not a solution for all concrete: white, pigmented, cast stone, decorative, etc. etc. etc. Too much focus on carbon footprint without overall environmental footprint, resilience, or long-term or intended performance.
27	Some lack of understanding about green requirements
28	Industrial side in which I work is not embracing.
29	Longer formwork in place time due to delay stripping strength
30	What's a technical barrier?
31	Don't know
32	All of the above can be mitigated by correct use of proportioning and training.
33	Contractor knowledge
34	High sustained surface pH impacting flooring limitations
35	Integral color dosage rates
36	Lack of knowledge
37	Practical information on all aspects of non-Portland cement based systems
38	Concrete contractors not willing to introduce and test green mixes
39	Economics ... can't get credit economically because of materials availability.
40	Proper testing methods
41	Language, cultural knowledge transfer challenges
42	Risk aversion

43	Application?????????
44	Drying shrinkage of room temp. curing mixes.
45	good concrete paving practices may be too technical for contractors and DOT in the state of KY
46	Learning to work with new product
47	Don't know
48	All of the above can often be offset with mix design changes
49	Lack of training
50	None, really...just a question of correct product development
51	The Hassle Factor - extra work...
52	Educational barriers
53	Highly sustainable concrete mixtures can be developed with a wide range of performance characteristics
54	Surface dries before concrete gets hard and pulls a part when trying to finish
55	Cost
56	Again none of the above for qualified finishers
57	Concrete contractors/finishers adding too much water to concrete on the job!
58	Too much attention paid to cement replacement as the only way to make concrete 'green' and not enough on designs that increase service life, reduce total concrete used (section) or the amount of steel used in the design.
59	Service life tests not designed for non-Portland cement materials
60	Lack of specifications and experience
61	Specs/codes must permit/support 56 day test age
62	Most of the above are problems that are being solved depending upon whether the requirements are reasonable
63	County and State Acceptance
64	Increased potential for carbonation induced corrosion
65	Willingness of contractors/specifiers to adopt new methods of construction
66	Many of these can be overcome with some proficiency
67	Lack of good sounds performance measures, both in the lab and field
68	Need for handling/installing materials differently than with conventional materials
69	Workmanship could be the problem. Resources available for first three items.
70	ASTM C94 requirement that all concrete be designed for 1 failure in 100 tests even for on grade slabs.
71	The industry geared to look at capital costs and does not look at structure in terms of cradle to grave cost.
72	Green is not easier, it is more complicated (and

	necessary too)
73	Lack of specifier knowledge
74	Need better understanding of end results
75	None of the above
76	Durability in different climates
77	I can´t see any barriers
78	Winter concrete work required more heat for a longer time
79	Using only 28 days strength for acceptance, need 56 or 90 days
80	Poor product knowledge
81	DOT specifications based on PC that do not apply to SCM'as.
82	All of the above can be overcome with proper mix design development.
83	Ready mix supply chain

7. Identify specific design challenges in green concrete building construction:

1	Lack knowledge
2	Blemishes, variability
3	item #2 correct if acceptance is at Early ages? 3-7-14 days?
4	Misunderstanding of strength gain patterns
5	I believe all challenges can be met by proper pre-planning
6	cracking and long-term behavior
7	Unknown
8	Concrete RH Moisture Values.
9	durability
10	Limited knowledge of long-term impact and ROI
11	LEED documentation raises costs to contractors and specifiers
12	None
13	Insufficient designers' knowledge of green concrete materials
14	convincing the owner to deviate from their tried and true concrete
15	None, only perceived problems.
16	new products like calcium carbonate and other are unknown
17	Recognizing strength gain characteristics
18	again, specifiers lack sufficient knowledge, longevity suffers as a result
19	acceptance of lesser quality finishes
20	Always done it the old way, why change.
21	ditto. What does testing have to do with "design". Architectural concrete is by definition a design challenge.
22	finishes, color variations
23	none that I can think of except cold weather strength gains.
24	Lack of real time testing regimens for certain performance spec properties
25	Preparing new mix designs and getting them approved.
26	Lack of a consistent means of comparing competing products
27	Not sure if decorative and cast stone are considered in architectural
28	overcome cost when non-green systems are compared
29	Making it look good when combined with better colors.
30	don't know
31	Quality Control
32	Lack of understanding by specifiers and contractors.
33	Training of Technical Staff
34	decorative flatwork finishes such as a washed finish
35	Performance specs are not adequate
36	Temperature matched strength data for HVFA massive elements
37	Concrete contractors unwilling to use slag cement when fly ash is limited to a certain %
38	understanding all possible materials available
39	most prescribe, not design
40	understanding LEED recycled content versus fly ash percentage
41	depends on application
42	Larger strength standard deviation
43	specifiers who believe asphalt is superior to concrete, no matter what. Many DOTs restrict fly ash and slag between Nov and April, regardless of actual weather conditions
44	Cold weather construction/concrete protection with high SCM replacement
45	Don't know
46	Specifier knowledge of 'green' concrete performance parameters
47	structural design methodology
48	Not sure I see any
49	designs with durability in mind
50	none
51	none
52	Air Barrier testing
53	delayed slab drying affecting floor finishes?
54	Color variation will occur
55	approving concrete mix-designs to meet leed.
56	lack of knowledge of expected service life

57	early strengths
58	specifiers are generally not familiar with local mix design practices and the application of green mixes is new territory to them also.
59	The West coast has overcome most of the above challenges
60	Fear on the new or lack of familiarity with the product
61	Calculating total costs of a job instead of individual product costs.
62	Perception on slower rate of strength gain - maturity methods might be useful for formwork scheduling
63	SCM's are no longer readily available providing less real benefit.
64	Lack of performance data
65	exotic expectations on the part of the architect/engineer
66	finishing times, discoloration
67	none
68	Acceptance of concrete when early strength tests are low.
69	Concrete's value for sustainability beyond simple material issues
70	As part of my job I review work of other firms and find a general reluctance to specify SCMs.
	Codes need to allow performance-based specification of concrete and the industry needs to develop a Performance-Based Specification equivalent to ACI 301.
71	concrete cracking - durability
72	None of the above
73	lack of understanding about strength gain with SCM's and possible improvement with new admixture technology
74	paper work
75	Strength in general and additional material safety.
76	Durability
77	none noted
78	Understanding sustentaible concept
79	Not sure that concrete suppliers can deliver on their promises
80	defining what it is - where is the "box" drawn?
81	All of the above can be overcome with proper mix design development.
82	Establishing appropriate specifications
83	Designer reluctance to spend more than the minimum amount of time

8. Identify specific concrete mix design challenges in green concrete building construction:

1	Controlling variation through QC
2	Variation in density of components
3	Early age issue, even worse in cold temperatures
4	Captive to the ready mix supplier - not enough independent information available
5	Unprepared ready mix plants
6	Unknown
7	None
8	None
9	Site testing for correct design mix performance and slump or flow
10	None
11	Potential incompatibility issues
12	None, only perceived problems.
13	"Normal" set required for floors, slabs & toppings
14	Challenge is NOT the materials, it's the specifiers' lack of sufficient knowledge
15	Data requested for all slight variations in dosage, materials and percentage/blend of cementitious material
16	All of the above
17	Ggbfs and fly ash are great additives that increase concrete performance and reduce cost. The only challenge is changing people's antiquated thinking.
18	Producers want to keep their mix designs "secret"
19	All can be a concern. Testing requirements for acceptance can also be challenging, such as the variability of RCPT tests for permeability.
20	Impacts of and on admixtures, difficulties producing required workability
21	Core strengths
22	Inconsistency of available fly ash
23	Don't like green buildings, pink and purple are better.
24	Don't know
25	Control of variations in recycled aggregate
26	Robustness and compatibility between cementitious materials and chemical admixtures
27	Pozzalons
28	Lack of knowledge
29	All the above
30	Varying fly ash percentages requiring new mix designs
31	Working time in hot weather
32	Intermediate and final curing requirements are similar to HPC; contractors are unfamiliar and unprepared
33	Don't know

34	Consistent availability of 'green' raw materials (fly ash, recycled aggregate, etc.)
35	Consistency in general - image of poorer product
36	Adequate protection
37	Does not bleed, surface dries before concrete gets hard and pulls a part
38	None
39	Need to get chemical analysis from SCM supplier to make sure that the material behavior will match trial mix properties
40	Water cement ratio!
41	Inconsistent set; difficult to finish.
42	Usual durability tests are fairly meaningless for high fly ash concrete
43	Requirement of high SCM without due regard to contractor schedule
44	Understanding all of the different admixtures
45	Long-term durability
46	Nothing that cannot be overcome with appropriate proficiency. The lack of proper evaluation can be an issue.
47	Reproducible, predictable performance
48	None
49	Design professionals refusal to allow green materials
50	Adequate consideration or understanding of plasticizers and retardants as the affect SCMs - may compound effects of delayed set and add to flowability unnecessarily for mass concrete.
51	General lack of knowledge by specifiers of what increases sustainability of concrete.
52	Green concrete is not finisher friendly - but it could be if the RM industry tried
53	Use of recycled materials which haven't been proven
54	Durability
55	Delayed set time
56	None of the above
57	Durability
58	When strengths are out of spec it is harder to track down the problem and resolve it
59	Should not be a problem.
60	Access to and storage of any supplemental materials

9. Identify specific material supply challenges in green concrete building construction:

1	Increased number of mix designs due to customization of each mix type
2	Batch plants aren't set up for it, and are scared so they put risk on others
3	Storage/batching of more aggregates as well
4	Getting the materials specified.
5	Tracking material sourcing to meet Leeds record requirements
6	Batch plant design mixes not tested to include green solutions
7	In some cases, demand far exceeds supply resulting in ridiculous costs for nil longevity gain
8	All of the above
9	No material challenges other than limited markets using ggbfs and engineers stuck on 20 % limit on fly ash (both C & F)
10	Ability to determine the best combination of materials without extensive testing
11	You can get it at any paint store.
12	Don't know
13	Need for careful quality control of materials and mixes.
14	Lack of knowledge
15	Few suppliers of low cost pre-batched materials.
16	Gap graded mixes are the norm, even when specs prohibit them
17	Material supply challenges are specific to regions of the country
18	Cost
19	Increased batch times because of more SCM's
20	Some ready mix producers will charge more by labeling it, a boutique Concrete
21	Non-potable mixing water
22	Small market suppliers usually do not have extra silos for slag, fly ash or silica fume
23	Not aware of any
24	Storage and bin space for recycled aggregates
25	Most plants have one or maybe two SCM's - we typically have only one when two or three are permitted on green projects
26	None
27	Storage and use of additional components
28	Maintaining consistent performance with associated separate variability's
29	Slag & fly ash
30	Acceptance of SCM by design community.
31	Unable to comment
32	Use on non-specified materials
33	Quality control of supplemental binders
34	None of the above
35	Urban ready mix plants have limited storage capability
36	None found so far unless EPA fly ash ruling is unfavorable.

10. Identify specific construction challenges in green concrete building construction:

1	Insuring QA
2	Item #4 when coupled with incompatibility, and low temps, and contractor lack of experience with high SCM percentage mixes
3	Dealing with variability in mix performance
4	Again except in cold weather all challenges can be dealt with proper pre-planning
5	Unknown
6	None, only perceived problems.
7	Many are just perception and can be overcome with mix adjustment
8	No real construction challenges
9	Additional work require additional cost which is conflict with owners budgets
10	Depending upon the mix design, all of the above can become a challenge.
11	Haven't used so can't answer
12	Why delay; do it now!
13	Don't know
14	Need for training of producers and contractors so these items are not problematic.
15	Increasing awareness of opportunity
16	Proper material information
17	Sensitive to temperature, especially low temp.
18	Mixtures should be designed to achieve set and strength expectations; contractors usually don't allow enough time to generate custom mixtures with these properties, and producers may not have enough data for approval
19	Don't know
20	Just a question of good planning
21	Delayed setting and strength development are not a given when using a more sustainable concrete mixture
22	Cost
23	Educating finishers
24	None of the above with proper trial mix study
25	None, just again monitoring the contractor/finisher not to add too much water on the job!
26	Invalid perceptions due to prior problems
27	Assuring durability - tests are inadequate
28	SCM's are sensitive to weather and are especially sensitive to initial curing
29	All of the above if not taken into consideration in establishing a reasonable mix design for a specific need
30	Color of initial and final finishes
31	Increased carbonation induced corrosion due to high SCM content
32	Ability to gage appropriate set time of concrete
33	Many of these can be overcome with proper evaluation. Perception of changes in finishability will impact flatwork finishing.
34	None of the above apply as they are easily overcome
35	Needing to divide work into smaller areas, due to set time and finishing time delays.
36	Contractors unwilling to take ownership of specifying fresh characteristics.
37	Lack of disclosure by ready mix producer on protection requirements - they care about 28 days and not how difficult the concrete is to work with
38	None of the above
39	None
40	I can´t see any barriers
41	The above items should not be a challenge. These concerns can be addressed with innovative planning and design.
42	Continuing education of people involved
43	Delayed floor finishing due to increased set times

11. Identify specifications for material in green concrete building construction:

1	Lack of understanding by design professionals
2	Use performance specs
3	Maximize SCMs, alternative cements, recycled aggregates.
4	Quest unclear to me, I'd like to see a minimum OPC % for durability, and then use SCM's at elevated % but without loss of performance (fresh or hardened)
5	Unprepared architects or engineers
6	Unknown
7	Eliminate prescriptive specifications.
8	Carbon footprint over life of structure. Not initial.
9	Materials resourcing and batch plant location within 500 miles of project
10	None
11	Percent of SCM's can be higher in formed

	members then in floors and slabs
12	Not sure what these choices mean. Provide good guidelines and people will follow.
13	Performance based specification, not prescriptive
14	Don't understand question
15	Use of more fly ash
16	Limit maximum amount of water
17	Note these are flawed as SCM or PC limits are totally inappropriate. Use good mix design for the intended use and application in accordance with acceptable practice such as PCA EB001
18	No green; use pink and purple.
19	Don't know
20	Performance specs are not adequate for this job
21	Maximum cementitious content. Non-Portland cement systems
22	Reinforcement
23	Geopolymer cements
24	Polymer concrete
25	Define "green". Need LCA
26	Specify immediate protection of concretes
27	Use SCM from local sources, fly ash from regional power plant, slag from regional manufacturing facility
28	Water cement ratio.
29	Recycled content of reinforcing, low-VOC admixtures, sealers or form release agents
30	Eliminate steel reinforcement in slabs and pavements. Reduce pavement section by decreasing joint spacing and warping (curling).
31	Don't know this one
32	Need reasonable requirements
33	Do not see many - typically reduce carbon footprint, use high min SCM, Do not exceed some level of Portland cement
34	Don't fence me in or out, tell me what you want, and stay out of the way
35	FSC lumber specified for formwork, and recycling of waste products.
36	Adjustments to schedule to allow greater curing time and better curing conditions.
37	I don't understand what you are asking in this question
38	Extend the f'c date (stop requiring "28 days")
39	Minimizing cement only produces concrete which is impossible to finish - eg: 3500 psi with only 400 pounds of cement/CY
40	Limited green construction specifications
41	Specifications should be purely performance based.

12. Tell us about any other challenges and/or how you dealt with them:

1	High percentages of fly ash in flatwork, had to utilize a HVFA (High-Volume Fly Ash) in vertical work to meet FF/FL requirements for slabs, which is too difficult to achieve once you hit 20% FA in a mix.
2	I just want to reiterate that challenges associated with using Fly Ash or other SCM's in Cold Weather environments. This makes our lives very difficult.
3	Clients want "green concrete" but don't realize associated costs, efforts, delays, risks, etc. I think we need gradual increases in requirements, not overnight increases. EPA needs to stop delaying their decision and take the handcuffs off of fly ash.
4	Had big problems with too much GGBFS- scaling problems. Likely caused from de-icing salts.
5	A Web site you might look at -- http://www.sustainablehighways.org/ -- "Pilot Test Version of INVEST, the FHWA Sustainable Highways Self-Evaluation Tool This website represents a significant revision of the FHWA Sustainable Highways Self-Evaluation Tool that was released as a Beta Version in the Fall of 2010. Called the "Infrastructure Voluntary Evaluation Sustainability Tool", INVEST is a practical, web-based, collection of best practices that allow states to integrate sustainability into their transportation projects. The use of the tool is voluntary and can be used by states or other project sponsors to measure the sustainability of their projects."
6	-Batching error that doubled already high SCM replacement rates. -No admix. incompatibility testing -No trials at colder temps (I recommend SCM replacement% occasionally be reduced (5-10%) in colder weather. - Abuse of Evaporative retardants (repeatedly used as a finishing "aid") on mixes that appear stickier to finish due to higher SCM% Great Topic, coming to the seminar at WOC! GW Seegebrecht
7	Aside from contractors misunderstanding what green means, strength gain concerns, the biggest issue I see is a misunderstanding of mix design. Often green means 50% fly ash to a contractor. To get around the 50% requirements, they are requesting higher strengths. the LEED method of calculating cement content DOES NOT WORK!!!!!! Concrete is a local material and what should be supported and promoted is an efficient concrete mix.
8	The specifications for green concrete all over the board. Need consistency based on proper data.
9	Steel scrap is almost impossible to accurately Identify, from where it was actually sourced, by the time it is acquired and mixed for use in making new reinforcing and structural steel components.
10	Placing elevated decks on a concrete frame structure with intent to achieve early-age for lessen shoring time with low W/C ratios (0.41 to 0.43) and yet be compatible to moisture RH values within the concrete prior to flooring installations. This has been my biggest challenge where the flooring industry does not match well with concrete practice. Also, water based curing compounds lead to compatibility issues with flooring material manufacturers. Again, the flooring industry does not match well with good sound concrete construction quality practices.
11	The issue is Political Correctness overriding common sense.
12	Preventing "cooked" concrete from being installed or brought to site too late in the day to allow proper saw cut and curing procedures (Reject truck) Requiring proper placement of less than 0.02 perm underslab vapor retarder. Proper 3-7 day curing using evaporation retarders and sheet curing membrane. Not allowing curing/sealers on horizontal slabs that may interfere with subsequent finishes and result in drying of top of slab (resulting in curling)
13	Cultural resistance to change is the biggest problem is such cases, particularly in developing countries.
14	The industry (construction companies) don't feel obligated to shift to greener concrete and the risk they would need to take to start using greener concrete is too high considering relatively insignificant reward (e.g., LEED points). Unless there are specific code requirements putting limits on carbon footprint associated with a concrete mix, or if contracts are awarded to greenest contractors (which would force competition), nothing will change.
15	In middle east and Arabian countries they used imported Pozzolan from west or east , that will increase the cost of green concrete by 75 % for each cubic meter comparing to our local ip cement that had 20% natural Pozzolan type and 80% Portland . cement. The use of imported Pozzolan will increase the carbon foot print for each ton by 100 to 155 kg of carbon for each ton of Pozzolan.
16	LEED needs to consider product with CO2 emission versus cement like calcium carbonate fines not just recycled content. The idea is to

	reduced energy consumed to make concrete, place concrete, finish concrete.
17	Focus on overall benefits for durability and impermeability while lowering the carbon footprint.
18	Suggesting something out of the ordinary often raises suspicions in clients and contractors.
19	Due to weather variations the projects limiting mix design changes to adjust for hot or cold weather have a great impact on cost, set, strength loss and rate of strength gain.
20	There are a number of challenges in green concrete construction, but they are not necessarily negatives they just require different thinking and processes than in the past. Most of the green concrete practices result in better performing concrete but may require some compromise in scheduling, forming etc. and will require some understanding from the design community.
21	minimize scm's in exposed flatwork and slabs, and maximize them in elements where aesthetics and tolerances matter less.
22	Ward, feel free to call me to discuss these issues, or how to design better surveys. 818 774 0003 -- or, look for me at World of Concrete. Michael Chusid
23	Client tolerance for cracking, deflection and other defects have become much lower. Particularly PT and SDI do not rationally address serviceability.
24	people are very confused about cures. most gc's think your cure counts but it does not since it is not "permanent". Same applies to bond breakers and releases. more education on this. Also, formwork. Most don't know that formwork is not counted unless ALL temp wood is and further, getting form lumber from sustainable forests, tracked sources is not available in many parts of the US so people need to know it is not possible in many cases.
25	Green concrete gets no play on the LEED scorecard, so there is little push by Owners because you cannot get points...So there is little impetus to pushing for green concrete.
26	The variability of test results from the RCPT can be avoided by the use of the Rapid Migration test, a variation of the RCPT which avoids the problems created by current flow through concrete with mix constituents that affect the flow rate.
27	Contractor usually stops use due to lack of knowledge of producer capabilities. Need performance specifications.
28	How to write specifications that encourage the use of advanced concrete technology while not restricting access by companies with little technical capability.
29	concept is flawed, it presumes that high PC content is not green. Good mix design for the intended placement, long-term use, and performance is far more important than short-term (time of construction) savings on carbon content. Cut carbon in half and replace or repair three times instead once might be green initially but surely is not sustainable. Focus should be on viable alternatives to achieve the desired performance, moisture energy, fire, structural acoustical, aesthetic, durability, longevity, recyclability, etc. Industry needs to recognize that because of durability and ability to be multi-functional concrete is inherently green and sustainable with or without SCMs. Steel is re-cycled, wood is bio-mass, and concrete is durable and multi-functional.
30	We substituted slag for fly-ash due to supply and quality issues in fly-ash.
31	I avoid green and besides concrete is gray.
32	don't know
33	1. Obtain aggregates and materials from the project. 2. Prepare mix design meeting or exceeding requirements for the project. 3. Perform field test to assure finishing and set time requirements are met. 4. Perform ongoing QC for the project.
34	Since we are a research lab we can deal with all the above challenges regarding the mix design of green concrete.
35	None
36	N/A
37	Replacement of cement with fly ash, pozzalons and post consumer materials results in a higher sustained surface PH. This condition inhibits the installation of most flooring systems. Carbonation does not compensate for this condition when cement replacements are as high as 40 percent or more. Typically the only solution is a PH/Vapor Barrier, the cost of which can seriously impact the construction budget.
38	Architects will need to be educated. That is a challenge for them to gain an understanding of how "green" affects aesthetics and the properties of concrete. They typically are only interested in obtaining LEED certification for their project.
39	The industry is not technically aware of what can (and cannot) be done to make concrete that is both durable with adequate service life. In Australia the 4 C's are not understood and green technologists cannot make ANY concrete - let alone GREEN CONCRETE
40	No GGBFS in Raleigh, NC market Haven't actually had much pressure to use green concrete
41	Economic comments above, Anchorage, Alaska

42	proper education on all the possibilities and products that can be used.
43	It is difficult to change general and practical knowledge in concrete construction while producing an important change in concrete performance, specially fresh concrete and delayed strength gain.
44	To educate the contractor & testing companies on the differences in concrete with SCM's verses typical concrete. We hold training classes.
45	Make knowledge on SCM's easily available for contractors and engineers through ACI.
46	we need to go to performance concrete, Strength, Air and workable.
47	competitive costing versus product knowledge
48	Use of recycled concrete aggregate and other recycled materials
49	Making user friendly geoploymer mixes that are consistent and set well at room temperature. Limited supply of raw materials.
50	Good start. If we can get some help in presentation material for Green Concrete. I have been asked to make presentation to the Clients (overseas), where the market is much more than in the US and export of technology possibilities along with education. Keep me posted of results of survey, (gms@sabnis.com). Thanks.
51	Specifying Green Concrete for Pad-Footings, Piles, D-Walls, Rafts, Machine Foundations and the like was accepted by the Contractors and implemented with success as it did not impose delivery issues.
52	The recycled content of a concrete mixture is often restricted to its fly ash content, without consideration to recycled materials used in making cement, recycled water used in batching, and partial replacement using recycled aggregates. Many specs prohibit or severely restrict the use of these materials by imposing unreasonable requirements on these alternate materials, instead of a performance spec on the hardened concrete. LEED worksheets request material pricing information, which ought to be confidential, and has no bearing on any aspect of the LEED program.
53	Limited Design Engineering knowledge
54	Concern is cost. Education.
55	Just the general acceptance. Too many people think of it as unattainable and too costly. Need more education on the benefits of going green.
56	Code guidance not specifically provided
57	Convincing the customers for benefits
58	NA
59	Use of maturity meters significantly increases confidence level when early formwork removal or tendon stressing is desired.
60	The client has to be motivated by the long term profits, like accumulation of energy use and social responsibility
61	Fear is the main challenge - that the concrete will be poor, not perform as well as 'real' concrete. This can only be overcome with education and examples. Some of the best projects in the world have been built using SCMs in binary ternary and quaternary blends - it is a case of showing that this works!
62	Admixtures & fly ash finishing issues especially on slab on grades over vapor retardant
63	The challenge is in educating the community to new products that will allow a truly sustainable surface and longevity..
64	Most difficulties are in specifications - what they allow. The cement industry could provide materials that are vastly more sustainable then those in current use with little effort if specifications allowed and standards called for these materials to be used. Issues with set and early strength are the two major problems with most sustainable mixtures. These issues are largely temperature dependent and many can be overcome with admixture adjustments.
65	I feel that sometimes we try to go green to quick with too many admixtures, fly ash and slag and sometimes get poor concrete that is almost un-workable, and the result is a less than perfect job, with increased time finishing. As we refine mix designs, and learn what works I hope we will see an improvement.
66	Getting finishers that understand how these "GREENER" mixes set and why they are more susceptible to certain weather conditions.
67	"Green" concrete goes beyond limiting Portland cement. Other factors that should be considered are the potential toxicity of admixtures, curing agents, and form-release agents; avoiding excess steel reinforcement; designing for durability; recycled concrete aggregates; design for component reuse (applies mostly to precast); thermal mass benefits for building use-phase energy savings; minimizing thermal bridging, such as at cantilevered balcony slabs.
68	We are now facing maximum cement factors of 400#/YD/N.Y.C. Building code
69	As an engineer, I stay current with availability of SCMs in current project locations. This allows me to be able to offer options depending upon the project/client requirements or expectations.
70	NO ONE SHOULD DICATE OR REQUIRE THE CONCRETE REDI-MIX SUPPLIER QC MANAGER HOW TO DESIGN A MIX OR ANYTHING ELSE. HE KNOWS MORE ABOUT MIXES AND RAW MATERIALS THEN ANYONE ELSE. HIS/HERS EXPERTIZE!
71	I don't have much experience in green concrete.

	In my design experience, I found some criticism on green concrete, I have indicated those.
72	There are many design professionals who are not well educated regarding cement and concrete.
73	The premise of "green" building is flawed. Mandating "green" tech is the wrong way to go. "green" materials should be allowed as alternatives and allow the true green standard, cost, to determine whether or not they are used. The green hippies may want a project or building that they can use to show off how much "greener" they are than their hippie friends, no matter how much that green costs.
74	We must be careful that being Green doesn't supersede performance and cost.
75	I don't have much experience with green concrete
76	There is not any standardization for calculating the value of the "green materials" incorporated into a mix design. Each and every project wants the information reported in a different format. This has become very time consuming for concrete producers.
77	Fortunately I am given the opportunity to lunch/learn local engineers on subject and try to maintain some "order" in the use of scm's by local engineers. I think the local ready mix industry has been very responsive to the market, but the early strength issue for heavy commercial concrete construction is something we have to be proactive about. I think most LEED points are being achieved by other than the mix design.
78	Greenwash vs. Green - We may need some self-policing.
79	It has been very challenging to get a new technology adopted. The initial testing and codes were prevent smaller size companies from having the resources. The technical side of the concrete industry seems more willing to explore new methods while the producers and contractors are sometimes more hesitate. To answer these challenges we tried to assess the right tests and work with acknowledged experts in their fields when validating the technology.
80	We would love to see real advancement in aggregate recycling and use of non-potable water. Too many people focus only on SCM's that are no longer readily available and that are in their own right by-products of environmentally damaging processes. Focus should be on reduction of (or elimination) of the use of raw aggregate and potable water.
81	Air Quality
82	Each market is a bit different in the tools and talents available. For example, what is working in Seattle will not and cannot work in New Orleans. Too often designers fail to understand the realities of the market in which the project will be built.
83	When using class C we limit use to 25% for exposed concrete because of discoloration and slow setting times, use higher percent in foundations. Use class F at higher percentages if available at the plant. Some plants cannot use additional silos because of permitting issues
84	Need to be thinking about systems not just the concrete mix. Using sandwich wall panels may be more significant than adding fly ash. Have an energy efficient building envelope is a significant part of "green" construction.
85	We are making concrete better through the use of SCM's because of permeability.
86	When working as a subcontractor, I find a general lack of knowledge amongst other subcontractors, and general contractors that are receiving bids. As a result, I have lost work by providing a bid based on the requirements that others simply ignore.
87	Primary challenges are getting design professionals to accept or learn about fly ash and slag cement and to then permit them in projects.
88	Most constrictions related to delayed set times for SCMs are artificial, and could be more flexible in order to gain greater concrete quality and durability. Work around and better scheduling can address this, and ad-mixes or adjusted mix designs can minimize the impact.
89	getting good quality fly ash for all projects
90	Lack of willingness of designers in particular to accept any other concretes but traditional 100% Portland cement based.
91	how about light reflective floors - this is a very green solution. how about determining the maximum SCM cement replacement without requiring any changes in protection (eg: max 10% fly ash or 20% slag). how about designing concrete floors for finishability instead of lowest cement or highest SCM content.
92	there is a mis-conception within the design community that "high fly ash" mixes benefit the overall ability to achieve LEED points. Not only is this incorrect, the latest version(s) of LEED no longer allow this and have reduced concrete's ability to achieve SRI credit without costly proof tests and long-term assurance requirements. The USGBC is slanting away from fact and truth and towards supporting an adverse political agenda.
93	It appears contractor are fighting Green Building instead of using it to differentiate concrete from other building materials.
94	none
95	Lack of education/knowledge about green concrete construction on the part of engineers,

	as well as architects
96	If it improves economics it is good. If it is done for political correctness it is a waste.
97	education of architect
98	Cannot use a pulverized limestone as a filler in concrete due to the fact there is NOT an ASTM to support it. It's not a pozzolan, if it was classed as fine aggregate, it puts the Fineness Modulus out of specification with the combined gradation.
99	Not sure what green concrete does to creep and shrinkage properties so not clear about how much minimum steel is required to control cracks, and uncertain how to adjust deflection predictions.
100	Poor supply chain for slag in the west.
101	as an impendent testing lab I am having to assist and educate on those that are trying to replace OPC with fly ash and other materials. The hardest hurdle is how to satisfy DOT requirements that were designed fro other material. What there needs to be assistance to this market for selection and development of appropriate testing to evaluate a product in a way that the DOT will accept or consider its use.
102	As with many new technologies and ideas, it is difficult in the beginning because most of us apply the means and methods that we have been accustomed to in our own past experience. Most of the concerns expressed in this survey have already been addressed and overcome. I would recommend that you pursue those people and companies that have been on the front lines of green building technologies to develop specification requirements and standards that are appropriate for green concrete construction and not conventional concrete construction. Some of the best performing concrete that I have seen consisted of ternary blends of cementitious materials. They have exhibited some of the best early and ultimate strength gain characteristics.
103	Delayed strength gains cause payments on the project to be delayed.
104	For widespread changes to take hold, I believe they have to come from the cement companies. Alternate cements such as Portland Limestone cement that could be used in everyday mixes could have a big impact.
105	Engineers not taking the time to understand the benefits and behavior of SCM. Promote by conducting seminars in offices of engineers, architects and contractors.

Appendix C

Annotated Bibliography

(2001). "Hollywood stays green using underground water tanks." Water Engineering and Management **148**(Compendex): 14-15.

The construction of two of the world's largest underground water tanks, the Toyon tanks, in the mountains of Hollywood is described. DN Concrete Pumping was the exclusive pumping contractor for the project. The concrete tank construction involved the use of a 36-Meter Putzmeister boom pump and a Putzmeister 14000 HP-D high-pressure and high-volume trailer pump with a slick line between the pumps. Work was handled in sections. The pumps used for the construction of the Hollywood pump station, a bypass tunnel and concrete wall are described. The tanks will not be visible to local residents.

(2003). "Quality work defeats corrosion." Civil Engineers Australia **75**(Compendex): 59-60.

The Patterson River Bridge was constructed in 1994/1995 with high-quality standards using supplementary cementitious materials, protective coatings and volume of permeable voids (VPV) testing. All materials were protected against chloride contamination prior to concrete placement. The columns, crossheads, pile caps, pre-stressed concrete beams, wing walls and abutments were constructed using VicRoads grade VR 470/55 concrete. The results of all testing show that there is no evidence of structural weakening or corrosion, and for at least 10 years and beyond there is little likelihood of corrosion activity starting.

(2005). "The ICAR plan." Rock Products **108**(Compendex): 32-35.

The research plan of the International Center for Aggregates Research is discussed. The plan strives to advance the product knowledge that will facilitate superior aggregate performance and improve application quality and durability. The research in Portland Cement Concrete investigates performance including constructability, hardened concrete properties, green concrete and special concretes. Another project focuses on developing a device for measuring the rheological properties in contrast with most other proposed methods.

(2006). Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential**:** 92p.

This study presents estimates of embodied primary energy usage and global warming potential over a 50 year "life cycle" for the construction and maintenance of comparable flexible asphalt and rigid Portland cement concrete pavement structures across the following road types and regions: typical Canadian arterial roadways; typical Canadian high volume highways; a Quebec urban freeway and; a section of the Highway 410 freeway in Ontario.

national block specifications regarding strength and appearance.

(2009). 10th ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issues. 10th ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issues, October 14, 2009 - October 16, 2009, Seville, Spain, American Concrete Institute.

The proceedings contain 21 papers. The topics discussed include: durability of

ultra-high-performance concrete; shrinkage reducing effect of a combination of internal curing and shrinkage compensating agents on high-performance concrete; geo-polymer concrete - sustainable cementless concrete; structural synthetic fibers for three-dimensional reinforcement of concrete; slab-on-ground case studies about synthetic fiber-reinforced concrete; rheology and pumping of self-compacting concrete; optimization of self-consolidating pastes containing limestone powder and chemical admixtures; shear friction of reinforced self-compacting concrete members; effect of different fibers and mineral additions on the performance of FRSCC; investigation of the type of supplementary cementing materials on the durability of self-compacting concrete; and a brief history of pullout testing with particular reference for Canada - a personal journey.

(2009). Concrete: The Sustainable Material Choice - Session at the ACI Spring 2009 Convention. ACI Spring 2009 Convention, March 15, 2009 - March 19, 2009, San Antonio, TX, United states, American Concrete Institute.

The proceedings contain 7 papers. The topics discussed include: performance-based specifications for concrete to advance sustainable development; supplementary cementitious materials for sustainability; cementitious blends and their impact on sustainable construction; performance-based specifications and sustainable development using slag cement; use of slag cement for improved durability in Virginia department of transportation structures; achieving sustainable goals with architectural concrete; and sustainable bridges - Otay river bridge case study.

(2009). Slag Cement Concrete**:** 136p.

This Special Publication (SP) contains eight papers sponsored by ACI Committee 233 that provide insight on recent slag cement concrete developments in academia, the concrete industry, and in real life applications of slag cement concrete. Topics include materials aspects related to the benefits of adding slag in concrete to prevent alkali-silica reactions, reducing drying shrinkage, and reducing the potential for thermal cracking during the curing period. Also covered are high-volume applications of slag cement in: concrete for transportation structures, high-performance concrete pavements, mass concrete, and high-density concrete.

(2011). "Developing eco-friendly cements." Indian Concrete Journal **85**(Compendex): 3-5.

A number of studies have been conducted to demonstrate the potential of creating sustainable cements. A study from VDZ provided information on the performance of cements containing limestone as a filler material. The study used binary and ternary blends of cement with limestone and other supplementary cementitious materials, such as granulated slag and fly ash. The investigations were focused on Portland-limestone containing up to 35 mass percent limestone and on cements containing 10 mass percent to 25 mass percent of limestone combined with granulated blast furnace slag or siliceous fly ash. The study

included the exposure of the concrete made with such cement to outdoor conditions, calculating service life based on the fib Bulletin 34 Model Code for Service Life Design and analyzing CO2abatement potential. The calculations of service life showed that there was no need to fear any adverse effect on the durability of concretes made with such cements.

Abbasl, A., G. Fathifaz, et al. (2007). Durability of green concrete. Annual Conference of the Canadian Society for Civil Engineering 2007: Where the Road Ends, Ingenuity Begins, June 6, 2007 - June 9, 2007, Yellowknife, NT, United states, Canadian Society for Civil Engineering.

It is expected that during the next two decades, a large amount of concrete, resulting from the demolition of buildings and structures in Canada, will be available for either disposal or for being recycled for reuse as concrete aggregates. However, only a very small portion of the concrete waste is reused in building construction with most being used as highway base or sent to landfills for disposal. There are several reasons why recycled concrete aggregates (RCA) are not widely used in concrete. Among them are the lack of technical data and specifications, as well as the lack of quality control and quality assurance guidelines in the processing of RCA and in the production of green concrete (GC) mixes prepared with RCA. In orderte ensure the wide use of GC as a structural material in Canada, we need to gain confidence in its short- and long-term mechanical, physical and durability properties. Currently in Canada, there are no established design specifications or guidelines for producing structural-grade GC with satisfactory durability properties. The main objective of this research is to establish these guidelines so that the use of RCA in Canada can be a feasible alternative to conventional concrete. The paper will specifically present the outcome of two durability properties of GC: the vulnerability to freeze/thaw action and chloride permeability. The comprehensive experimental study whose overview is presented in this paper demonstrates that the design and production of durable structural-grade GC is feasible alternative to conventional concrete.

Abd-El.aziz, M. A., S. Abd.el.aleem, et al. (2012). "Physico-chemical and mechanical characteristics of pozzolanic cement pastes and mortars hydrated at different curing temperatures." Construction and Building Materials **26**(Compendex): 310-316.

The effect of elevated curing temperature on the properties of cement mortars is vital for heat resistance. Addition of pozzolanas, such as slag, to type I cement is known to increase heat resistance. In this study, OPC was partially substituted by two types of slag (WCS and ACS) in the ratios of 10, 20, 30, 40 and 50 wt.%. The cement mortars were cured for 120 days at different curing temperature from 25 to 100 C. The results show that, elevated curing temperatures improves the early age strength in the all cement mortars. Also, the results indicated that, the pozzolanic cement mortars gives higher compressive strength than the plain cement mortars, especially at curing temperatures above 35 C. Therefore, slag pozzolanic cement mortars can be beneficially used in the hot conditions. 2011 Elsevier Ltd. All rights reserved.

Abd-El-Aziz, M. A. and M. Heikal (2009). "Characteristics and durability of cements containing fly ash and limestone subjected to caron's lake water." Advances in Cement Research **21**(Compendex): 91-99.

In most countries, limestone and pozzolanas are widely used in Portland cement because such additions increase the chemical resistance to sulfate and/or chloride attack, impermeability and lower the heat of hydration of concrete. This study aimed to investigate the effect of fly ash (FA) and limestone (LS) on the hydration and durability of ordinary Portland cement (OPC) subjected to Caron's Lake water. The results revealed that the increase of LS content increased the water of consistency (normal consistency) of cement pastes, whereas the initial and final setting times were reduced by up to 30. The portlandite contents of mixtures containing FA decreased. At the same time, an increase of LS content from 10 to 20 decreased the portlandite content by up to 90 days. On the other hand, the portlandite content of 30 LS increased by up to 90 days. Cement pastes containing FA had the lower values of total sulfate and chloride contents than sulfate-resisting cement pastes. The compressive strength of mixture M.10 (20 FA and 10 LS) showed higher compressive strength values than the other cements when immersed in both curing media, namely tap and Caron's Lake water. It is recommended that cements that are to be used for underground concrete structures or marine structures that are exposed to sulfate-containing seawater do not contain more than 10-20 of LS. 2009 Thomas Telford Ltd.

Adam, A. A., T. C. K. Molyneaux, et al. (2008). Strength of mortar containing activated slag. 4th International Structural Engineering and Construction Conference, ISEC-4 - Innovations in Structural Engineering and Construction, September 26, 2007 - September 28, 2007, Melbourne, VIC, Australia, Taylor and Francis/Balkema.

The strength development of Portland cement mortar, blended cement-slag mortars and alkali activated slag (AAS) mortars was investigated. Variables were the level of slag replacement in the blended cement-slag mortars, and activator concentration and alkali modulus (AM) in the AAS mortar. In addition the effect of heat curing on AAS mortars was also investigated. Mortars prepared using alkali activated slag as binder had greater early strength than ordinary Portland cement mortar and blended cement-slag mortars of the same water/binder ratio. All AAS mortars gained strength more rapidly at heat curing however at later age the heat curing reduced the ultimate strength compared to normal curing specimens. 2008 Taylor Francis Group.

Agarwal, S. K., I. Masood, et al. (2000). "Compatibility of superplasticizers with different cements." Construction and Building Materials **14**(Compendex): 253-259.

The incompatibility between cement and chemical admixtures has increased over the last decade. Specifications calling for the use of admixtures in concrete often results in strange occurrences, i.e. rapid set, retardation, accelerated stiffening, etc. This paper presents the observations of a study on the effect of different superplasticizers with respect to the setting behavior and compressive strength. The hydration behavior of different cements at different time intervals (1,3,7,28 and 360 days) in the presence of superplasticizers has also been analyzed by differential thermal analysis (DTA). The 33 grade ordinary Portland cement has shown retardation with naphthalene-based superplasticizer at the recommended dose (2%) of manufacturer, where as 43 grade OPC has shown retardation with blended polymer-based superplasticizer. Portland Slag Cement and 53 grade OPC has been found to be compatible with all the superplasticizers studied in the present investigation.

Ahmadi, B. and M. Shekarchi (2010). "Use of natural zeolite as a supplementary cementitious material." Cement and Concrete Composites **32**(Compendex): 134-141.

Natural zeolite, a type of frame-structured hydrated aluminosilicate mineral, is used abundantly as a type of natural pozzolanic material in some regions of the world. In this work, the effectiveness of a locally quarried zeolite in enhancing mechanical and durability properties of concrete is evaluated and is also compared with other pozzolanic admixtures. The experimental tests included three parts: In the first part, the pozzolanic reactivity of natural zeolite and silica fume were examined by a thermogravimetric method. In this case, the results indicated that natural zeolite was not as reactive as silica fume but it showed a good pozzolanic reactivity. In the second part, zeolite and silica fume were substituted for cement in different proportions in concrete mixtures, and several physical and durability tests of concrete were performed. These experimental tests included slump, compressive strength, water absorption, oxygen permeability, chloride diffusion, and electrical resistivity of concrete. Based on these results, the performance of concretes containing different contents of zeolite improved and even were comparable to or better than that of concretes prepared with silica fume replacements in some cases. Finally, a comparative study on effect of zeolite and fly ash on limiting ASR expansion of mortar was performed according to ASTM C 1260 and ASTM C 1567. Expansion tests on mortar prisms showed that zeolite is as effective as fly ash to prevent deleterious expansion due to ASR. 2009 Elsevier Ltd. All rights reserved.

Ahmed, S. F. U. and M. Maalej (2007). Fracture Toughness of Cement Mortar Containing High Volume Fly Ash.

In this paper experimental evaluation on the effect of high volume fly ash as partial replacement of cement on fracture toughness of cement mortar are presented. The fly ash replacement level was 50%, 60% and 70% by weight of cement. Three-point bend notch beams were used to measure the fracture toughness of mortar. Results show that the use of 50% fly ash as partial replacement of cement reduces the fracture toughness values between 38% and 58% compared to that without fly ash. Reduction of compressive strength and Young’s modulus in mortar containing 50% fly ash as partial replacement of cement compared to that without fly ash is also observed in this study. The use of 60% and 70% fly ash as partial replacement of cement is found to have negligible effect on the reduction of fracture toughness of cement mortar. Long term effects of high volume fly ash (50% cement replacement) on fracture toughness, compressive strength and Young’s modulus of cement mortar are also evaluated in this study. Tests were conducted at 28, 56 and 91 days and at

5, 7, 10 and 12 months. Results show that the rate of increase of fracture toughness of cement mortar containing 50% fly ash with time is very slow. Compressive strength and Young’s modulus also increase with time.

Ahmed, S. F. U., M. Maalej, et al. (2007). "Flexural responses of hybrid steel-polyethylene fiber reinforced cement composites containing high volume fly ash." Construction and Building Materials **21**(Compendex): 1088-1097.

Strain hardening and multiple cracking behavior of hybrid fiber reinforced cement composites containing different hybrid combinations of steel and polyethylene (PE) fibers under four-point bending are reported. The total volume fraction of fibers was kept constant at 2.5% to maintain a workable mix. Effects of increase in fly ash content as partial replacement of cement beyond 50%, such as 60% and 70% on the flexural response of hybrid steel-PVA (polyvinyl alcohol) and steel-PE fiber composites are also evaluated here. Among composites with different volume ratios of steel and PE fibers, the composite with 1.0% steel and 1.5% PE was found to show the highest flexural strength and that with 0.5% steel and 2.0% PE exhibited highest deflection and highest flexural toughness. Generally, the steel-PE hybrid composites exhibited lower flexural strength but higher deflection capacity than steel-PVA hybrid composites. The rate of strength loss after peak load in steel-PE hybrid composites was found low compared to steel-PVA hybrid system. The 50% replacement of cement by fly ash is found to be an optimum fly ash content in hybrid fiber composites. 2006 Elsevier Ltd. All rights reserved.

Ahmed, S. F. U., M. Maalej, et al. (2006). "Assessment of corrosion-induced damage and its effect on the structural behavior of RC beams containing supplementary cementitious materials." Progress in Structural Engineering and Materials **8**(Compendex): 69-77.

This paper reports the results of an experimental program on the effect of steel loss and corrosion induced-damage (cracking, delamination, spalling, etc.) on the post-corrosion flexural response of reinforced concrete beams incorporating supplementary cementing materials (fly ash, slag and silica fume) used as partial replacement of ordinary Portland cement. Eight reinforced concrete beams measuring 2.5 m in length and 210 300 mm in cross-section were cast, four of which were subjected to accelerated corrosion. Among all specimens incorporating supplementary cementing materials (SCM), the specimen containing fly ash showed the best performance in terms of the highest residual load carrying capacity at failure. Its best performance was also evident from the lowest measured steel loss, the least corrosion-induced cracking and the lowest tendency for the concrete cover to delaminate as measured by a concrete-embeddable fiber optic strain sensor (FOSS). Correlation between the amount of steel loss and the reductions in load carrying at failure was also established. Copyright 2006 John Wiley Sons, Ltd.

Ahnberg, H. (2006). "Consolidation stress effects on the strength of stabilised Swedish soils." Ground Improvement **10**(Compendex): 1-13.

Common estimates of the design strength of soft soils stabilised by deep mixing do not take into account the effect of the confining stresses on the behaviour of the material. This is largely an effect of the limited knowledge of how different consolidation stresses affect the strength of such soils. Furthermore, an increasing variety of binders is used nowadays in deep mixing of soils, and it is uncertain whether these affect the stress dependence in different ways. To gain increased insight into this aspect, a series of triaxial compression tests, unconfined compression tests and oedometer tests has been performed on soils stabilised with cement, lime, cement-lime, cement-slag, cement-fly ash and slag-lime. The results show that both the drained and the undrained strength are dependent on the confining stresses. The extent of this stress dependence is affected by the stress and strength level. The type of binder used affects the achieved strength level to a great extent, but in principle is of less importance for the response of the material. The results provide a set of parameters for rough estimates of the stress dependence for both the undrained and drained strength of stabilised soils. By applying the concept of quasi-preconsolidation pressures, an improved method of modelling the strength of stabilised soils is proposed. 2006 Thomas Telford Ltd.

Aimin, X. and S. L. Sarkar (1991). "Microstructural study of gypsum activated fly ash hydration in cement paste." Cement and Concrete Research **21**(Compendex): 1137-1147.

The addition of 3 to 6% gypsum to a low alkali, low C3A cement blended with low (30%) and high (60%) volume of a Class F fly ash (FA) led to a distinct increase in strength in comparison to the blends without additional gypsum. This is discussed in terms of the reaction of the FA with cement and gypsum. The role of FA alkalies is also described. The investigation included scanning electron microscopy/energy dispersive X-ray analysis (SEM/EDXA) to study the microstructural development of FA replacement pastes with progressive hydration, and X-ray diffraction (XRD) for mineralogical identification of hydrated phases.

Aitcin, P.-C. (1988). "CURING TEMPERATURE AND VERY HIGH STRENGTH CONCRETE." Concrete International **10**(Compendex): 69-72.

The effects of early temperature rise in very high strength concrete used in structural elements are investigated. The compressive strengths of specimens are tested and compared to each other and to that of core samples taken from instrumented, experimental columns. Variables affecting the laboratory specimens include cement content, the addition of silica fume, and the curing process.

Aitcin, P. C. and M. Page (2005). Admixtures and sustainability. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

It is imperative to foresee the development of any material and civil engineering structure within a sustainable development perspective. Up to now, admixtures have only been considered as chemical products that can improve certain physico-chemical aspects of fresh or hardened concrete. It is now time to consider the significant role that such chemicals can play in reducing greenhouse gas emissions and increasing the life cycle of concrete structures. When properly used, the contribution of admixtures can be as significant as that of supplementary cementitious materials in reducing the emission of green house gases and in increasing the life cycle of concrete structures. In this paper, the benefits of using dispersants (water-reducers, midrange water-reducers and superplasticizers), as well as air entraining agents will be emphasized.

Akin Altun, I. and I. Yilmaz (2002). "Study on steel furnace slags with high MgO as additive in Portland cement." Cement and Concrete Research **32**(Compendex): 1247-1249.

In this study, usability of Basic Oxygen Process (BOP) slags of Kardemir Iron and Steel Plant, Karabuk, Turkey as an additive into cement was investigated. Slags were ground to 4000 and 4700 cm2/g levels, and added in ratios 15, 30 and 45 wt.%. Volume expansion, setting time, compressive strength and bending strength tests were measured according to Turkish standards. Due to impurities of the slags, the 2- and 7-day compression strengths decrease with increase in amount of Mn, but this decrease is lower in the 28-day compression strength, 30 wt.%. It is observed that the physical and mechanical properties of the resulting concrete were acceptable in the Turkish Standards Institute (TSE). 2002 Elsevier Science Ltd. All rights reserved.

Akkaya, Y., M. Konsta-Gdoutos, et al. (2004). The pore structure and autogenous shrinkage of high-performance concrete with ternary binders. Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete (SP-221), , American Concrete Institute.

Most high performance concretes contain supplementary cementitious materials such as silica fume, slag or fly ash. However, highly reactive silica fume adversely affects the autogenous shrinkage properties and increases the risk of cracking at early ages. To compensate for the adverse effects of silica fume, ultrafine fly ash was also incorporated into the binder phase of the concrete. Part of cement and part of silica fume were replaced by ultrafine fly ash and early age properties of the mixtures with these ternary binders were compared. Testing showed that ternary binders can decrease autogenous shrinkage strains while keeping early strength gain at a comparable level.

Akkaya, Y., C. Ouyang, et al. (2007). "Effect of supplementary cementitious materials on shrinkage and crack development in concrete." Cement and Concrete Composites **29**(Compendex): 117-123.

The autogenous and drying shrinkage of Portland cement concrete, and binary and ternary binder concretes, were measured and compared. The binary and ternary binder concretes were formed by replacing part of the cement with fly ash, very fine fly ash and/or silica fume. Restrained shrinkage test was also performed to evaluate the effect of binder type on early age cracking. After the cracking of the restrained ring samples, crack widths were measured and compared with the results of an R-curve based model, which takes post-peak elastic and creep strains into account. The incorporation of fly ash and very fine fly ash decreased the autogenous shrinkage strain but increased the drying shrinkage strain. Since the total shrinkage strains of both the ternary and the binary concrete mixtures were similar, the strength development became an important factor in the cracking. The lower strength of the concrete with ternary binders led to earlier cracking compared to the binary binder concrete. Portland cement concrete cracked the earliest and had the greatest crack width. Measured crack widths were in accordance with the crack widths calculated with the R-curve model. 2006 Elsevier Ltd. All rights reserved.

Al-Amoudi, O. S., M. Maslehuddin, et al. (2007). "Shrinkage of plain and silica fume cement concrete under hot weather." Cement and Concrete Composites **29**(9): 690-699.

Supplementary cementing materials (SCMs) are widely used these days to improve the durability of concrete. Silica fume has gained world wide acceptance due to its high pozzolanic reactivity compared to other SCMs. While silica fume cement concrete has several advantages over other blended cement concretes its main draw back is increased plastic and drying shrinkage, particularly under hot weather conditions. This paper reports results of a study conducted to assess these properties of plain and silica fume cement concrete specimens cast and cured in the field under hot weather conditions. The effect of specimen size and method of curing on plastic and drying shrinkage and some of the mechanical properties of silica fume and plain cement concrete specimens were evaluated. Results indicated that the type of cement significantly affected both the plastic and drying shrinkage of concrete in that these values in the silica fume cement concrete specimens were more than those in the plain cement concrete specimens. As expected, the shrinkage strains in both the plain and silica fume cement concrete specimens cured by continuous water-ponding were less than that in similar concrete specimens cured by covering them with wet burlap. The results point to the importance of selecting a good quality silica fume and good curing for avoiding cracking of concrete due to plastic and drying shrinkage, particularly under hot weather conditions. (A) “Reprinted with permission from Elsevier”.

Al-Amoudi, O. S. B., M. Maslehuddin, et al. (2011). "Performance of blended cement concretes prepared with constant workability." Cement and Concrete Composites **33**(Compendex): 90-102.

The use of supplementary cementing materials, such as silica fume, fly ash, blast furnace slag, and natural pozzolans, has been promoted by their technical and economic advantages. However, in certain parts of the world, where these materials are not available locally, their utilization is solely based on their technical superiority. The practice in such regions is to replace part of the cement with the selected supplementary cementing materials while maintaining constant water-to-cementitious materials ratio. In such cases, the advantage of a reduction in the water requirement of certain materials is not utilized. In the reported study, fly ash, silica fume, or a highly reactive finely pulverized fly ash replaced part of the cement. The concrete mixtures were designed for a constant workability of 75-100 mm slump. The performance of ordinary Portland cement (OPC) and silica fume (SF), fly ash (FA) and very fine fly ash (VFFA) cement concretes was evaluated by measuring the compressive strength development and reduction in both compressive strength and pulse velocity after exposure to moisture and thermal variations, and sulfate (SO4- = 1%, 2%, and 5%) solutions. The effect of curing regime, namely water ponding and application of a curing compound, was also evaluated. It was noted that the water requirement of FA cement concretes was less than that of OPC and SF cement concretes. Consequently, the mechanical properties and durability characteristics of the former cements were better than those of the latter cements. It was also noted that a longer curing period, prior to the application of a curing compound, is beneficial to OPC, SF, FA, and VFFA cement concretes. Curing with water tended to improve the quality of OPC, SF, FA, and VFFA cement concretes; and as the curing period increased the quality improved further. 2010 Elsevier Ltd.

Al-Amoudi, O. S. B., M. Maslehuddin, et al. (2007). "Shrinkage of plain and silica fume cement concrete under hot weather." Cement and Concrete Composites **29**(Compendex): 690-699.

Supplementary cementing materials (SCMs) are widely used these days to improve the durability of concrete. Silica fume has gained world wide acceptance due to its high pozzolanic reactivity compared to other SCMs. While silica fume cement concrete has several advantages over other blended cement concretes its main draw back is increased plastic and drying shrinkage, particularly under hot weather conditions. This paper reports results of a study conducted to assess these properties of plain and silica fume cement concrete specimens cast and cured in the field under hot weather conditions. The effect of specimen size and method of curing on plastic and drying shrinkage and some of the mechanical properties of silica fume and plain cement concrete specimens were evaluated. Results indicated that the type of cement significantly affected both the plastic and drying shrinkage of concrete in that these values in the silica fume cement concrete specimens were more than those in the plain cement concrete specimens. As expected, the shrinkage strains in both the plain and silica fume cement concrete specimens cured by continuous water-ponding were less than that in similar concrete specimens cured by covering them with wet burlap. The results point to the importance of selecting a good quality silica fume and good curing for avoiding cracking of concrete due to plastic and drying shrinkage, particularly under hot weather conditions. 2007 Elsevier Ltd. All rights reserved.

Aldea, C. M., B. Cornelius, et al. (2008). High-volume slag-blended cement concrete for high-density concrete at mid-range temperatures. ACI Fall 2008 Convention, November 2, 2008 - November 6, 2008, St. Louis, MO, United states, American Concrete Institute.

Synopsis: The experimental program presented in this paper was a technical evaluation of an alternative cement and high-density (HD) concrete mixture design for HD concrete at mid-range temperature to meet specific target properties. The cement industry has moved away from manufacturing 'special use' portland cements, which were approved for some applications of mass HD concrete, for which temperature rise in the concrete is of importance. Potential replacement of these 'special use' portland cements by blending varying amounts of supplementary cementitious materials (SCMs) with 'general use' portland cement to provide 'blended cements' was investigated. The paper focuses on experimental results obtained in the laboratory showing the effect of the addition of high volume slag blended cement for HD concrete on temperature rise, as well as on mechanical properties and microstructure after aging and mid-range temperature exposure. Slag-blended cement was evaluated and determined to have acceptable properties in HD concrete, meeting or exceeding performance requirements.

Aldea, C.-M., B. Cornelius, et al. (2009). "High-Volume Slag-Blended Cement Concrete for High-Density Concrete at Mid-Range Temperatures." pp 95-110.

This paper will present an experimental that was a technical evaluation of an alternative cement and high-density (HD) concrete mixture design for HD concrete at mid-range temperature to meet specific target properties. The cement industry has moved away from manufacturing ‘special use’ portland cements, which were approved for some applications of mass HD concrete, for which temperature rise in the concrete is of importance. Potential replacement of these ‘special use’ portland cements by blending varying amounts of supplementary cementitious materials (SCMs) with ‘general use’ portland cement to provide ‘blended cements’ was investigated. The paper focuses on experimental results obtained in the laboratory showing the effect of the addition of high volume slag blended cement for HD concrete on temperature rise, as well as on mechanical properties and microstructure after aging and mid-range temperature exposure. Slag-blended cement was evaluated and determined to have acceptable properties in HD concrete, meeting or exceeding performance requirements.

Aldea, C.-M., B. Shenton, et al. (2009). Performance-based specifications and sustainable development using slag cement. ACI Spring 2009 Convention, March 15, 2009 - March 19, 2009, San Antonio, TX, United states, American Concrete Institute.

In recent years, human sustainability has been increasingly associated with the integration of economic, social, and environmental spheres. The concrete industry is committed to minimizing any negative impact it may contribute to the natural environment. When performance-based specifications are used, performance requirements are stated in measurable terms. They promote a better use of materials, including supplementary cementitious materials, provided that the finished product meets performance requirements. Slag is an industrial by-product, which when used in concrete has engineering, economical, and ecological benefits; therefore it makes concrete a more sustainable product. In this paper, performance-based specifications and sustainable development are defined in the context of the concrete industry, and examples of two projects,

where performance-based specifications, sustainable development and high volumes of slag were successfully used: 50% slag replacement was used to mitigate the alkali-silica reaction of local fine aggregate for use in making concrete for the construction of DeBeers diamond mine facilities in Northern Ontario, Canada; 50% slag replacement was used to limit the heat-generation capacity of high-density concrete during the initial period of curing and subsequent cooling to avoid thermal cracking for high level used nuclear fuel waste storage containers.

Al-Dulaijan, S. U., D. E. Macphee, et al. (2007). "Performance of plain and blended cements exposed to high sulphate concentrations." Advances in Cement Research **19**(Compendex): 167-175.

The sulphate resistance of plain (ASTM C150 Type I and Type V) cements and cements blended with silica fume, fly ash, blast furnace slag or Superpozz, a new generation of supplementary cementing materials, exposed to sodium sulphate solutions was evaluated in this study. Cement mortar specimens were exposed to sulphate concentrations of up to 25 000 ppm. The sulphate resistance of the selected cements was evaluated by visual examination and measuring expansion and reduction in the compressive strength. Morphological changes in cements, due to sulphate exposure, were evaluated by scanning electron microscopy. The mineralogical changes in cements exposed to a solution with 15 000 ppm sulphate were evaluated. Cracks were noted in Type I and silica fume cement mortar specimens exposed to a sulphate concentration of 15 000 ppm or more. In Type V cement, the sulphate tolerance was 25 000 ppm. Cracks were not noted in the blast furnace slag, fly ash, and Superpozz cement mortar specimens exposed to 25 000 ppm sulphate solution. It is suggested to use Type V cement or Type I cement blended with fly ash, blast furnace slag or Superpozz in sulphate-bearing environments.

Alexander, M. G. and B. J. Magee (1999). "Durability performance of concrete containing condensed silica fume." Cement and Concrete Research **29**(Compendex): 917-922.

The paper describes a short-term study carried out to examine the durability performance of various condensed silica fume (CSF) concretes in comparison to portland cement (PC) and PC/ground granulated blast furnace slag (GGBS) controls up to the age of 28 days. Mix proportions were designed to provide 28-day strengths of 30, 40, and 50 MPa for the PC controls and these were used for all binder combinations considered. Concrete durability was inferred from a suite of durability index tests designed to measure concrete resistance to gas, liquid, and ion transport mechanisms. It is shown that concrete durability is dramatically improved through the use of CSF. Optimum performance was achieved through the use of CSF as a 10% addition by mass to the initial binder content. The work also confirms CSF's effectiveness when used in ternary binder blends with PC and GGBS, with these mixes out-performing the controls and selected binary-blended PC/CSF mixes.

Alhassan, M. A. and M. A. Issa (2009). Simplified shrinkage-prediction model applicable to high performance concrete. 8th International Conference on Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures, September 30, 2008 - October 2, 2008, Ise-Shima, Japan, CRC Press.

This study proposes a simplified shrinkage-prediction model that can be applied to moist-cured High Performance Concrete (HPC) and normal strength concrete. The principal goal is to provide a model that gives a better prediction of the shrinkage for HPC that rapidly develops at early age. The proposed model derives its roots from the ACI Committee 209-1992 taking into account the value of the concrete compressive strength. The effect of the compressive strength was introduced in a normalized fashion with respect to the compressive strength of normal strength concrete, which is assumed to be 28 MPa (4 ksi). Formulation of the model was based on shrinkage data of ready-mixed HPC mixtures containing silica fume, fly ash, and/or slag. These mixtures received moist curing for 7 days and have w/cm ratio of 0.37 and a 28-average compressive strength of 52 MPa (7.5 ksi). The model was then verified based on shrinkage data obtained from the literature. It was concluded that the proposed model can be used to predict the shrinkage of HPC, especially at early ages. In addition, it was found mat the current ACI Committee 209-1992 shrinkage prediction model underestimates the shrinkage of HPC at early ages and overestimates it at later ages. 2009 Taylor Francis Group.

Al-Khaiat, H. and N. Fattuhi (2001). "Long-term strength development of concrete in arid conditions." Cement and Concrete Composites **23**(Compendex): 363-373.

A long-term investigation into the development of the compressive strength of various concretes, subjected to Kuwait hot and arid environmental conditions is reported. The main parameters investigated included, w/c ratio, cement type and content, and admixture type and its dosage. Other parameters investigated included the effects of using different water curing periods, curing compounds, and casting season. Forty-seven different mixes were placed on the roof of the laboratory building and were exposed to the environment. Compression tests on 100 mm cubes were carried out over a period in excess of five years. The results generally showed that the compressive strength of the concrete increased with age. The gain in strength at 1800 days above that at 28 days varied considerably depending on the concrete constituents and curing procedure. Concretes made with white Portland cement achieved higher compressive strengths than those made with ordinary or sulphate resisting Portland cements. Also, the type and dosage of admixture influenced the compressive strength of concrete. An increase in the water-curing period was more effective in improving the 28-day compressive strength than the 1800-day strength. The use of curing compounds or silica fume appeared to influence the early age strength more than the long-term strength. Compression test results from selected mixes at the age of 10 years indicated that there was little or no increase in strength during the previous five years. 2001 Elsevier Science Ltd. All rights reserved.

Al-Khattat, I. (2008). "Light Prestressed Segmented Arch (LPSA) Bridges: A

Demonstration of Sustainable Engineering." STRUCTURAL ENGINEERING INTERNATIONAL **18**(1): 62-66.

A jointing method combining slide-fitting with tension-induced compression is presented. It eliminates the "analysis black box" at each node of a timber structure. Mathematical and computational modeling is further enhanced by the use of small diameter timber (SDT), due to its more predictable natural growthring structure. This is the core concept of the LPSA (light prestressed segmented arch) structural system as applied to timber-in-the-round. It represents a significant leap forward in the sustainable use of timber in construction, offering a sustainable alternative to steel and concrete, especially for bridges. The slidefitting jointing mechanism produces a unique property of harmless distortion energy dissipation via internal rigid-body motion. Therefore, LPSA structures have inherent resistance to the actions of earthquakes, hurricanes and flooding. The LPSA structuralsystem outlines a framework for an urgently needed research, design and innovation field of sustainable engineering, in a world on the verge of environmental instability. SDT is a vast, untapped, sustainable resource. Itsuse as a premium construction material could provide a recipe for saving what remains of the world's forests and for profitable sustainable development. Two 19,5 m LPSA bridges have recently been constructed, using black locust (Robinia pseudoacacia) SDT. This is a least desirable but decay-resistant species with twoto-three times the crushing strength of concrete. (A)

Allahverdi, A., E. N. Kani, et al. (2011). "Effects of blast-furnace slag on natural pozzolan-based geopolymer cement." Ceramics - Silikaty **55**(Compendex): 68-78.

A number of geopolymer cement mixes were designed and produced by alkali-activation of a pumice-type natural pozzolan. Effects of blast-furnace slag on basic engineering properties of the mixes were studied. Different engineering properties of the mixes such as setting times and 28-day compressive strength were studied at different amounts of blast-furnace slag, sodium oxide content, and water-to-cement ratio. The mix comprising of 5 wt.% blast-furnace slag and 8 wt.% Na_2O with a water-to-dry binder ratio of 0.30 exhibits the highest 28-day compressive strength, i.e. 36 MPa. Mixes containing 5 wt.% of ground granulated blast furnace slag showed the least efflorescence or best soundness. Laboratory techniques of X-ray diffractometry (XRD), fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) were utilized for characterizing a number of mixes and studying their molecular and micro-structure. Investigations done by scanning electron microscopy confirm that smaller blast-furnace slag particles react totally while the larger ones react partially with alkaline activators and contribute to the formation of a composite microstructure.

Aly, T. and J. G. Sanjayan (2008). "Factors contributing to early age shrinkage cracking of slag concretes subjected to 7-days moist curing." Materials and Structures/Materiaux et Constructions **41**(Compendex): 633-642.

The objective of this study was to investigate all the factors contributing to early age shrinkage cracking in concrete, namely, shrinkage, tensile creep, tensile elastic modulus, tensile strength of concretes, and to study the effect of slag as a binder on these factors. The above-mentioned factors were measured in early age concretes made with 0, 35, 50 and 65% level replacement of ordinary Portland cement by slag. All the concretes studied were moist cured for 7-days. It was found that, at lower slag replacement levels (0, 35 and 50%), the tensile strength decreased with increasing slag replacement. However, this is more than compensated by decreasing tensile elastic modulus and shrinkage. There was no significant change found in tensile creep with the changing slag levels. The study shows that the influence of the tensile elastic modulus is a major consideration for early age cracking of slag concretes. 2007 RILEM has copyright.

Aly, T. and J. G. Sanjayan (2008). "Shrinkage cracking properties of slag concretes with one-day curing." Magazine of Concrete Research **60**(Compendex): 41-48.

The current paper presents the results of a restrained shrinkage test that captures the shrinkage, tensile creep and tensile stress plotted against strain behaviour of early-age concretes. Four types of concrete mixes were studied: concretes made with ordinary Portland cement (OPC) and slag-blended cements with 35%, 50% and 65% replacement of OPC Two identical specimens of each mix were tested: one subjected to fully restrained conditions and the other allowed to shrink freely, both under the drying conditions of 23C and 50% relative humidity at the age of 24 h. Indirect tensile tests were also performed in the same concretes to monitor the tensile strength development. With increasing slag contents, the tensile strength decreased, which is detrimental to crack resistance. However, with increasing slag contents, the elastic modulus also decreased, which is beneficial to crack resistance. The slag content levels did not significantly influence the shrinkage and creep characteristics. Increasing slag levels did not significantly alter the time to cracking behaviours owing to the compensating effects of decreasing tensile strength and elastic modulus. 2008 Thomas Telford Ltd.

Anastasiou, P. E. (2010). "Production of high-strength concrete using high volume of industrial by-products." Construction and Building Materials **24**(8): 1412-1417.

The production of a high-strength, high performance concrete using high volumes of industrial by-products is tested in laboratory mixtures. The by-products used are high-calcium fly ash and ladle furnace slag as binders and electric arc furnace slag as aggregates. Fly ash is used as 50% by mass of the total binder and ladle furnace slag as 30% by mass of the total binder. Slag aggregates are used in replacement of coarse aggregate or in replacement of both fine and coarse aggregates. In the mixtures containing both supplementary cementitious materials and slag aggregates the produced concrete shows high-strength (>70 MPa), good abrasion resistance and fracture toughness. (A) Reprinted with permission from Elsevier.

Anderson, D., A. Roy, et al. (2000). "Preliminary assessment of the use of an amorphous silica residual as a supplementary cementing material." Cement and

Concrete Research **30**(Compendex): 437-445.

An amorphous silica (AS) by-product was investigated as a possible supplementary cementing materials (SCM). Standard ASTM tests for the SCM as well as specific surface area measurement, electron microscopy, Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD), 29Si nuclear magnetic resonance (NMR) spectroscopy, thermal analysis, and cement paste and mortar cube strength studies were conducted. A 10:90 AS:OPC paste (w/cm of 0.4) and mortar cubes (w/cm = 0.50 to 0.60) were prepared. AS is a white amorphous materials (x = 29 9 (1) nm) with a surface area of 95,000 m2/kg, the latter resulting in a high water demand. All of the AS in 10:90 AS:OPC paste reacted by 7 days, consuming more than 50% of the calcium hydroxide. The compressive strength of OPC paste remained unchanged with the addition of AS but that of mortar increased.

Andrews-Phaedonos, F. (2001). THE PERFORMANCE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS) AND WATERPROOFING ADMIXTURES.

Supplementary cementitious materials (SCMs), that is, slag, fly ash and silica fume, are now recognised as an integral part of concrete technology and construction, due to their ability to enhance the properties of fresh and hardened concrete. Since their introduction in 1993 into the VicRoads concrete specification, a number of major structures have been successfully constructed utilising these cement replacement materials. An investigation was undertaken to evaluate their suitability under various curing regimes, including moist curing, polyethylene sheeting, curing compounds and wet/dry curing. The study has confirmed previous research results in that the use of SCMs in concrete results in significant reductions in the volume of permeable voids (VPV). The greatest VPV reductions occurred in concrete containing moderate single combinations of silica fume followed by fly ash and finally slag. Based on the efficiencies of the curing techniques with respect to strength development and VPV reduction, it has been recommended that polyethylene sheeting and curing compounds not be allowed for curing of concrete with high replacement of SCMs. (a) For the covering entry of this conference, please see ITRD E204173.

Anita, M., A. Vanita, et al. (2010). "Durability aspect of fly ash concrete." International Journal of Earth Sciences and Engineering **3**(Compendex): 572-581.

The challenge for civil engineering community in the coming days will be development of high performance, materials, produced at reasonable cost with the lowest possible environment impact. Taking view of sustainable development it is imperative that the supplementary cementing materials may be used to replace large amount of cement in concrete. However concrete has certain disadvantages as well; like low tensile strength, not entirely impervious to moisture and containing soluble salts which may cause efflorescence, liable to disintegrate by alkali and sulphate attack, unstable crack propagation, limited durability. Fly ash is one such admixture, which exhibits pozzolanic activity and contributes largely to enhance the workability of fresh concrete, reduces the water requirement at given consistency and increases the durability of hardened concrete which results in a product which has similar or even greater ultimate strength. Several research investigations conducted in past have clarified the effect of fly ash on different properties of concrete, but more research is still needed to study its effect on durability. The aim of present research is to investigate the effect of some aggressive chemicals on the compressive strength of fly ash concrete by replacing cement with fly ash in different percentages. The study includes the variation in the strength after immersion in the two different chemicals i.e. is sodium chloride and sulphuric acid. The objectives of using fly ash in concrete are to reduce heat of hydration and Cement content to reduce costs, secondly to improve durability and workability. 2010 CAFET-INNOVA TECHNICAL SOCIETY. All rights reserved.

Antiohos, S., D. Giakoumelos, et al. (2004). Strength development of ternary blended cement with high-calcium fly ash and amorphous silica. Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete American Concrete Institute.

The work presented is a laboratory study on the mechanical properties of ternary blended cement built with various combinations of two different high calcium (ASTM Class C) fly ashes and an amorphous silica. Amorphous silica was added to the fly ash-cement system to compensate for shortfalls associated with the presence of high lime ashes and to provide a benchmark for utilizing supplementary cementing material rich in active silica. The generated ternary blends were examined for compressive strength development, efficiency factors (k-values) and strength gain. Results showed up to 10% amorphous silica addition accelerated strength development

Antiohos, S., K. Maganari, et al. (2005). "Evaluation of blends of high and low calcium fly ashes for use as supplementary cementing materials." Cement and Concrete Composites **27**(Compendex): 349-356.

The present paper outlines the results of a research attempt aimed at developing and evaluating the performance of ternary blended cements, incorporating mixtures of two different types of fly ash (of high and low calcium content). The main target of this study was to investigate whether and by what means, the introduction of a certain type of fly ash into a fly ash-cement (FC) matrix containing a different type of ash, can improve the performance of the initial binary system. For achieving this, new pozzolans were prepared by mixing, in selected proportions, a high lime fly ash with an ash of lower calcium content. The efficiency of the new materials was examined in terms of active silica content, pozzolanic activity potential, strength development, k-values and progress of the pozzolanic action by means of fixed lime capabilities. The results obtained demonstrated that the mixtures containing equal amounts of each fly ash were the most effective for moderate cement substitution, whilst for higher replacements the intermixture possessing the highest active silica content shows supremacy at almost all hydration ages. The superior performance of the ternary fly ash blends was mainly attributed to synergistic effects detected for all the ashes utilized. These were quantified in each case and almost linear correlations were obtained with the k-values of the most efficient ternary mixes. 2004 Elsevier Ltd. All rights reserved.

Antiohos, S. K., V. G. Papadakis, et al. (2007). "Improving the performance of ternary blended cements by mixing different types of fly ashes." Cement and Concrete Research **37**(Compendex): 877-885.

For overcoming certain drawbacks characterizing both basic types of fly ashes (of high and low calcium content), different ash intermixtures consisting of two types of fly ashes were prepared. The principal idea lying beneath the effort presented herein is that beneficial assets of the one type of ash could compensate for the shortcomings of the other. Compressive strength development, pozzolanic activity potential and nature of hydration products of all ternary cements were closely monitored and presented in comparison to the respective properties of the initial binary blends. Moreover, efficiency factors were calculated for all new systems and were further used to validate previously reported expressions describing Binary Fly ash-Cement (BFC) systems. In accordance with previous works, ternary fly ash systems examined here outperformed the respective binary systems almost throughout the curing period. Synergy between the different types of fly ashes was considered the main reason for the excellent performance of the ternary mixtures. Results obtained indicate that previously developed analytical expressions, correlating active silica of SCMs and k-values, can be applied in the case of multicomponent ash systems as well. 2007 Elsevier Ltd. All rights reserved.

Antiohos, S. K., D. Papageorgiou, et al. (2007). "Mechanical and durability characteristics of gypsum-free blended cements incorporating sulphate-rich reject fly ash." Cement and Concrete Composites **29**(Compendex): 550-558.

To accommodate the wide variations among the different types of fly ash and the growing need for its greater utilization in the construction sector, relevant standards have been established that differentiate the appropriate qualities from the unacceptable ones. Unfortunately, potentially reject fly ashes (rFA), which do not comply with standard requirements, comprise a significant part of the total amount produced in coal or lignite burning stations. High-sulphate fly ash (HSFA) is a typical example of reject material, since all relevant standards (both European and ASTM) clearly define that sulphur trioxide should be kept under a certain low limit (approximately 3-5% depending on the standard) or else concrete's durability may be threatened. The aim of this work was to design, produce and monitor the properties of a series of blended cements prepared by mixing clinker with a fly ash of high-sulphate content. No gypsum was added in the mixtures, since it is believed that sulphate ions necessary for the prolongation of the setting process (commonly provided by gypsum) could be provided by fly ash enriched in sulphates. All samples tested exhibited satisfactory initial and final setting times as well as decent compressive strength values when compared to the reference specimen containing only gypsum and no fly ash. Additionally, this paper reports on the performance aspects of blended pastes exposed to chloride binding tests and aggressive (a) 2% H2SO4 and (b) simulated marine environment solutions. Results revealed that waste materials not up to relevant standards could still contribute to the production of quality products of energy and economical efficiency. 2007 Elsevier Ltd. All rights reserved.

Antiohos, S. K. and S. Tsimas (2007). "A novel way to upgrade the coarse part of a high calcium fly ash for reuse into cement systems." Waste Management **27**(Compendex): 675-683.

Reject fly ash (rFA) represents a significant portion of the fly ashes produced from coal-fired power plants. Due to the high carbon content and large particle mean diameter, rFA is not utilized in the construction sector (for example, as supplementary cementing material) and is currently dumped into landfills, thus representing an additional environmental burden. Recently, the feasibility of using rFA in a relatively small number of applications, like solidification/stabilization of other wastes, has been investigated by different researchers. However, as the overall amount of fly ash utilized in such applications is still limited, there is a need to investigate other possibilities for rFA utilization starting from a deeper understanding of its properties. In the work presented herein, mechanical and hydration properties of cementitious materials prepared by blending the coarse fraction of a lignite high-calcium fly ash with ordinary cement were monitored and compared with the respective ones of a good quality fly ash-cement mixture. The results of this work reveal that a relatively cheap, bilateral classification-grinding method is able to promote the pozzolanic behavior of the rFAs, so that the overall performances of rFA containing cements are drastically improved. The evaluation of these results supports the belief that appropriate utilization of non-standardized materials may lead to new environmental-friendly products of superior quality. 2006 Elsevier Ltd. All rights reserved.

Anwar, M. (2004). The effects of type of cement and curing methods on the pore structure of concrete. First International Conference on Computational Methods in Materials Characterisation, MATERIALS CHARACTERISATION, November 5, 2003 - November 7, 2003, Santa Fe, NM, United states, WITPress.

The resistance of cementitious materials to chemical attack or physical degradation is related to the mechanical properties of the material, but more importantly the chemical and microstructural characteristics and particularly the pore structure of the hardened material. Given information about pore structure, Mercury Intrusion Porosimetiy (MIP) is a technique that can provide such information which has improved significantly in pressuring capacity and in operational convenience. By measuring the amount of mercury intruded into the pores of a solid sample, the porosimeters give valuable data from which cumulative volume and pore size distribution, porosity as well as pore surface area can be determined. In this work, five concrete mixtures are prepared with water/cementitious material ratio 0.4 to investigate the effect of using different types of supplementary cementing materials and curing methods on the pore structure of concrete. The measured properties of fresh concrete include slump, air content and unit weight while the measured properties of hardened concrete include compressive strength, flexural strength, tensile strength, pulse velocity and dynamic young's modulus as well as the pore structure characteristics which involve, porosity, cumulative intrusion volume, pore surface area, and pore size distribution. These properties are measured according to the specifications provided by Japanese Industrial Standard (JIS) after 28 days of curing.

Arangelovski, T., P. Babamov, et al. (2003). Cements for obtaining high performance concrete. Role of Cement Science in Sustainable Development - International Symposium Celebrating Concrete: People and Practice, September 3, 2003 - September 4, 2003, Dundee, United kingdom, Thomas Telford Services Ltd.

In mix proportioning of concrete ordinary Portland cement remains a basic hydraulic binder. Because of more and more frequent use of high-performance criteria for quality of concrete there is a need to improve mechanical, rheological and durability properties of cement. For this purpose, concrete technology today uses materials that have filler effect and puzzolanic action known as mineral admixtures. The properties of mineral admixtures improve cement matrix on microstructure level during the hydration of cement. European Standards, EUROCODE-2, part1 and ENV 197-1, Cement, composition, specification and criteria of correlation (acceptance) part1 ordinary cement give us directions for use of silica fume and fly ash in chemical composition of cement. An experimental programme was carried out to determine the influence of silica fume on properties of cement. Silica fume was added as a cementitous replacing material in dosage of 5, 8 and 12% by mass cement to obtain a convenient hydraulic binder for production of high-performance concrete. All relevant properties related to physical and mechanical performance: standard consistency, setting time, flexural strength and compressive strength were analyzed. In order to investigate optimum dosage for the concrete mix design, varying content of superplasticizer and silica fume was used.

Arturo, G. C., M. R. Homero, et al. (2010). Concrete in the inner circuit, a sustainable solution for Mexico City. Green Streets and Highways 2010: An Interactive Conference on the State of the Art and How to Achieve Sustainable Outcomes, November 14, 2010 - November 17, 2010, Denver, CO, United states, American Society of Civil Engineers.

In one of the largest cities in the world, the concern to prevent and reverse the environmental damage caused by a disorganized and uncontrolled planning process, becomes a primary focus on the development of a city. The specific options that concrete gives us in terms of sustainability according to their physical and mechanical characteristics enabled the Government of Mexico City to create a sustainable solution for one of the largest thoroughfares of this city, the Inner Circuit. Sustainable benefits were reported in three areas, the social, economic and environmental improvement over other materials performance in durability, safety, energy conservation, heat island effect and others. The repaving project of Inner Circuit of Mexico City, not only involves the incorporation of a sustainable material in the pavement but all works carried out on alternate result of the project, such as empowerment of green areas, recreational areas along the 42 kilometers that make up the circuit, the use of sustainable alternatives and innovative recycled materials and waste. Now, the Inner Circuit in Mexico City is an example of sustainable project on highways and streets. 2010 ASCE.

Assaad, J. and K. H. Khayat (2004). "Assessment of Thixotropy of Self-Consolidating Concrete and Concrete-Equivalent-Mortar - Effect of Binder Composition and Content." ACI Materials Journal **101**(Compendex): 400-408.

A comprehensive research program was undertaken to determine the influence of thixotropy on the development of formwork pressure of self-consolidating concrete (SCC). Ten concrete and concrete-equivalent-mortar (CEM) mixtures were evaluated using different types of binder, including a Type 10 and Type 30 CSA cements and three other blended cements containing various combinations of supplementary cementitious materials (SCM). The binder content varied from 400 to 550 kg/m3. The paper aims at presenting test protocols to quantify the degree of thixotropy and attempts to correlate such response determined for SCC and CEM mixtures. The influence of binder type and content on the degree of thixotropy and pseudoplasticity are also investigated. For a given binder content, the degree of thixotropy is shown to be significantly affected by the type of binder; mixtures made with Type 30 cement exhibit a greater degree of thixotropy compared to those prepared with binary or ternary cement. On the other hand, SCC and CEM mixtures made with a quaternary cement containing 50% SCM or those with Type 10 cement without any SCM exhibit lower degree of thixotropy. For a given binder type, the increase in binder content is shown to increase thixotropy in the case of CEM mixtures. This is related to the increased degree of restructuring resulting from higher binder content. Conversely, in the case of SCC, the degree of thixotropy increases with the decrease in the binder content. This is attributed to the relative increase in coarse aggregate volume that can lead to a greater level of internal friction. Such phenomena seem to overshadow the restructuring process resulting from the use of higher binder content in the case of SCC.

Assaad, J. and K. H. Khayat (2005). "Formwork pressure of self-consolidating concrete made with various binder types and contents." ACI Materials Journal **102**(Compendex): 215-223.

An experimental program was carried out to determine the effect of binder type and content on variations in lateral pressure of self-consolidating concrete (SCC). The mixtures were prepared with five binder types incorporated at various contents varying from 400 to 550 kg/m3. The influence of thixotropy, determined from concrete and concrete-equivalent-mortar (CEM) mixtures, on the variations of lateral pressure development was investigated. Test results show that, for a given binder content, the initial lateral pressure and rate of pressure drop with time are significantly affected by the binder type in use. Self-consolidating concrete made with 450 kg/m3 of Type 10 CSA cement (GU) and no supplementary cementitious materials exhibited the highest initial pressure corresponding to 98% of hydrostatic pressure. Mixtures made with quaternary,

binary, and ternary cements of similar content developed lower initial relative pressures of 95, 94, and 90%, respectively. For a given binder type, the initial lateral pressure was found to increase with the binder content. This is attributed to the relatively lower coarse aggregate volume that reduces internal friction leading to greater lateral pressure. Test results also indicate that the rate of pressure drop following casting is dependent on the degree of increase in cohesion. Therefore, an increase in binder content resulted in a greater rate of gain in cohesiveness and a sharper drop in lateral pressure with time. Test results show that the increase in the degree of thixotropy of SCC and CEM can lead to lower initial pressure. For the monitoring of pressure drop with time, which is mainly dependent on the development of cohesion, thixotropy determined using CEM mixtures should be used to estimate the rate of variation in lateral pressure rather than those determined from SCC mixtures. This is because the increase in thixotropy determined from concrete mixtures is highly affected by internal friction resulting from the presence of coarse aggregate. This can overshadow the development of cohesion resulting from the binder phase that controls the rate of pressure drop with time. Copyright 2005, American Concrete Institute. All rights reserved.

Assaad, J., K. H. Khayat, et al. (2003). "Assessment of thixotropy of flowable and self-consolidating concrete." ACI Materials Journal **100**(Compendex): 99-107.

An experimental investigation was carried out to determine the influence of thixotropy on the development of formwork lateral pressure. Five self-consolidating concrete (SCC) mixtures prepared with different combinations of cementitious materials and two flowable mixtures of different stability levels were evaluated. This article seeks to quantify the thixotropy of fresh concrete by evaluating the variations in yield stress and the evolution of the structural breakdown curves. Changes to the impeller of a modified Tattersall concrete rheometer are proposed for the protocol used to assess thixotropy. Instead of the H-shaped impeller that rotates in a planetary motion, a four-bladed vane impeller rotating coaxially around the main shaft was used. This resulted in less slip flow of fresh concrete and an increase in the sheared surface during rotation. Test results show that thixotropy is not an inherent property of SCC of a given slump flow consistency of 650 10 mm. The concrete exhibits a high degree of thixotropy when proportioned with ternary cement containing 6% silica fume and 22% fly ash compared with similar concrete made with 4% silica fume and no fly ash. The incorporation of set-accelerating and set-retarding agents resulted in greater and lower degrees of thixotropy, respectively. In the case of flowable concrete with 200 mm slump, the addition of a viscosity-modifying admixture is shown to significantly increase the thixotropy compared with similar concrete made without any viscosity-modifying admixture.

Atis, C. D. (2003). "High-volume fly ash concrete with high strength and low drying shrinkage." Journal of Materials in Civil Engineering **15**(Compendex): 153-156.

In this work, a laboratory investigation was carried out to evaluate the strength and particularly the shrinkage properties of concrete containing high volumes of

fly ash. The concrete mixtures made with 50 and 70% replacement (by mass) of ordinary portland cement (OPC) with fly ash were prepared. Water-cementitious material ratios ranged from 0.28 to 0.34. Some concrete mixtures were also made with superplasticizer. The strength and shrinkage properties of the concrete mixtures cured at 20C temperature with 65% relative humidity are reported. The laboratory test results show that high-volume fly ash (HVFA) concrete attained satisfactory compressive and tensile strength at 1 day of age. It also showed that 50% replacement HVFA concrete developed higher strength than OPC concrete at 28 days and beyond. The inclusion of high volumes of fly ash in concrete with a low water-cementitious material ratio resulted in a reduction in the shrinkage values of up to 30% when compared to OPC concrete. The concrete mixtures made with superplasticizer showed higher shrinkage values of up to 50% when compared to the concrete made with no superplasticizer.

Atis, C. D. (2005). "Strength properties of high-volume fly ash roller compacted and workable concrete, and influence of curing condition." Cement and Concrete Research **35**(Compendex): 1112-1121.

A laboratory investigation was carried out to evaluate the strength properties of high-volume fly ash (HVFA) roller compacted and superplasticised workable concrete cured at moist and dry curing conditions. Concrete mixtures made with 0%, 50% and 70% replacement of normal Portland cement (NPC) with two different low-lime Class F fly ashes, good and low quality, were prepared. Water-cementitious material ratios ranged from 0.28 to 0.43. The compressive, flexural tensile and cylinder splitting tensile strengths were measured and presented. The relationship between the flexural tensile and compressive strengths was discussed. The influence of loss on ignition (LOI) content of fly ash on water demand and the strength of concrete was also discussed. The influence of moist and dry curing conditions on the high-volume fly ash (HVFA) concrete system was assessed through a proposed simple efficiency factor. The study showed that producing high-strength concrete was possible with high-volume fly ash content. LOI content increased the water demand of fresh concrete. HVFA concrete was found to be more vulnerable to dry curing conditions than was NPC concrete. It was concluded that HVFA concrete was an adequate material for both structural and pavement applications. 2004 Elsevier Ltd. All rights reserved.

Austin, S. A. and A. A. Al-Kindy (2000). "Air permeability versus sorptivity: Effects of field curing on cover concrete after one year of field exposure." Magazine of Concrete Research **52**(Compendex): 17-24.

There is substantial interest in the air permeability and sorptivity tests as potential indicators of concrete quality. This paper reports on part of a research programme that investigated the effects of field exposure and curing on the penetrability properties of the cover region of concrete. The air permeability and sorptivity profiles indicated that curing generally affected the penetrability properties of concrete to a depth of 20 mm from the exposed surface; however, the curing-affected zone varied widely depending on concrete type and strength as well as exposure conditions. Curing with wet hessian improved the penetrability properties of the cover region of the concrete. The air permeability test was more sensitive to variations in curing than the sorptivity; however, the difference between the two measured parameters was insignificant for concretes characterized by coarser pore systems (young and poorer-quality concrete). Slag concrete had higher sensitivity to inadequate curing and exhibited higher carbonation depths than plain Portland cement concrete. There was a good agreement of the air permeability and sorptivity results with the carbonation results, with the air permeability displaying better correlation.

Austin, S. A. and P. J. Robins (1997). "Influence of early curing on the sub-surface permeability and strength of silica fume concrete." Magazine of Concrete Research **49**(Compendex): 23-24.

The effects of curing duration, method (water and polyethylene), and environment (temperate and hot) on three strength grades of condensed silica fume (CSF) concrete are reported. The curing duration, method and climate have great influence on CSF's permeability and durability, in terms of resisting carbonation and ingress of other aggressive mediums such as chlorides. The CSF responded favourably to the hot climate after two days of moist curing at lower strength grades.

Austin, S. A., P. J. Robins, et al. (1992). "Influence of curing methods on the strength and permeability of GGBFS concrete in a simulated arid climate." Cement and Concrete Composites **14**(Compendex): 157-167.

Problems are frequently encountered in producing good-quality concrete in hot climates. Inadequate curing results in early cracking or porous and permeable concrete, or both; these effects, in turn, make structures prone to reinforcement corrosion and other processes of degradation. This research compares the development of strength and permeability of ordinary Portland cement (OPC) and ground granulated blast furnace slag (GGBFS)-modified concretes which were cured in a simulated arid climate. This was achieved with an environmental room in which temperature and humidity were cycled to imitate a typical Algerian Sahara climate. Four curing regimes were investigated to encompass the range of practical methods encountered on site. Specimens were placed in the hot environment immediately after casting and conditioned for up to 28 days. The strength of the GGBFS concretes was higher than that of the OPC control concrete at all test ages (7, 14 and 28 days) when good curing was provided. Partial cement replacement with GGBFS therefore offers the potential to produce stronger and more durable concrete in hot climates. The disadvantage of GGBFS concretes is that they proved to be more sensitive to poor curing than OPC concrete. In this case, both their strength and permeability, and hence their durability, were seriously impaired. Therefore, special care must be taken when using this type of concrete, especially on site, where the working conditions and the application of curing are not as easy to control as in the laboratory.

Awad, K. W., H. Mazen, et al. (2002). EXTREME CONCRETE.

This paper describes extreme concrete properties in 2 particular projects in Saudi Arabia, demonstrating how the local concrete industry has used specific measures to produce high-performance concrete in very hot weather. It was concluded that controlling the temperature of fresh concrete in hot weather should be primarily based on parameters related to cost, workability retention, and long-term strength. In addition, cited examples show how use of admixtures in hot weather can be very beneficial, even if the dosage considered did not comply with ASTM C494 requirements and manufacturer's standard recommendations.

Babu, K. G. and D. S. Babu (2003). "Behaviour of lightweight expanded polystyrene concrete containing silica fume." Cement and Concrete Research **33**(Compendex): 755-762.

Lightweight concrete can be produced by replacing the normal aggregate with lightweight aggregate, either partially or fully, depending upon the requirements of density and strength. The present study covers the use of expanded polystyrene (EPS) beads as lightweight aggregate both in concretes and mortars containing silica fume as a supplementary cementitious material. The main aim of this project is to study the strength and the durability performance of EPS concretes. These mixes were designed by using the efficiency of silica fume at the different percentages. The resulting concretes were seen to have densities varying from 1500 to 2000 kg/m3, with the corresponding strengths varying from 10 to 21 MPa. The rate of strength gain for these concretes shows that an increase in the percentage of silica fume increases the 7-day strength. This was observed to be about 75%, 85%, and 95% of the corresponding 28-day strength at the silica fume replacement levels of 3%, 5%, and 9%, respectively. The results of absorption, at 30 min and the final absorption, show that the EPS mixes made with sand have lower levels of absorption compared to the mixes containing normal aggregates. Further, the absorption values were seen to be decreasing with increasing cementitious content. The performance of these concretes, in terms of their chloride permeability and corrosion resistance, even at the minimal silica fume content level was observed to be very good. 2002 Published by Elsevier Seicence Ltd.

Badogiannis, E., G. Kakali, et al. (2005). "Metakaolin as supplementary cementitious material : Optimization of kaolin to metakaolin conversion." Journal of Thermal Analysis and Calorimetry **81**(Compendex): 457-462.

In this paper the optimization of the kaolin calcination is studied, aiming at using the produced metakaolin as supplementary cementitious material. Representative samples of poor Greek kaolin (Milos island) and a high purity commercial kaolin were tested. Samples were heated at different temperatures during different times. The optimization of calcination conditions was studied by DTA-TG and XRD analysis of the raw and thermal treated kaolin samples, by pozzolanic activity analysis of metakaolins and finally by strength development analysis of cement-metakaolin mixtures. This approach showed that heating at

650C for 3 h is efficient to convert poor kaolins with low alunite content to highly reactive metakaolins. However in the case of kaolin with a high alunite content, thermal treatment at 850C for 3 h is required in order to remove undesirable SO3. Evidence was found that poor kaolins can be efficiently used for the production of highly reactive metakaolins. 2005 Akademiai Kiado, Budapest.

Badr, A. and A. K. Platten (2006). "Effect of silica fume and fly ash on fatigue and impact strength of fibre-reinforced concrete." PROCEEDINGS OF THE 5TH INTERNATIONAL CONFERENCE ON RESEARCH AND PRACTICAL APPLICATIONS USING WASTES AND SECONDARY MATERIALS IN PAVEMENT ENGINEERING HELD 22-23 FEBRUARY 2006, LIVERPOOL, UK - VOL 1 - DAY ONE, VOL 2 - DAY TWO: 9p.

The utilisation of by-products such as silica fume and fly ash in the production of concrete produces concrete with desirable performance characteristics. However, these materials can also impair the ability of concrete to resist dynamic loading, a property that can be restored using fibre reinforcement. This paper reports the results from a programme of laboratory research, which has been conducted to investigate the effect of silica fume and fly ash on the fatigue strength and impact resistance of fibre-reinforced concrete. In this work, six mixtures were investigated. The control mix was produced without fibre or cement replacement materials. The other five mixes were reinforced with 1% (by volume) steel fibres. The effects of fly ash and silica fume were investigated at two replacement levels on a weight-to-weight basis. For fly ash, the replacement levels were 25% and 50%, whereas the replacement percentages for silica fume were 5% and 10%. The results suggested that the effect of steel fibre on the flexural fatigue strength was more significant than the effect of the cement replacement materials. The use of silica fume and fly ash slightly improved the flexural fatigue behaviour. As a conservative approach, it was concluded that the fatigue strength of mixes containing silica fume or fly ash is at least comparable to that of Portland cement FRC. The use of steel fibre had a negligible effect on the first-crack impact resistance, yet it enhanced the ultimate impact resistance by more than 200%. The mix including silica fume exhibited a 50% increase in both first-crack and ultimate impact resistance of the FRC. The effect of fly ash on the impact resistance was insignificant. For the covering abstract see ITRD E145817

Baert, G., A. M. Poppe, et al. (2005). Evaluation and comparison of mechanical characteristics and durability of concrete with different cement replacement levels by fly ash. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

To determine the activity index of different types of fly ash, mortars with 25% cement replacement by fly ash were made. At 90 days the compressive strength was similar for the mortars with only cement as hydraulic binder and for the mortars with low-calcium fly ash from the combustion of coal and twice as high as the compressive strength of the mortars made with Municipal Solid Waste

Incineration fly ash. After 90 days the splitting tensile strength for the mortar with MSWI fly ash was significantly lower than for the two other mortars. Secondly concrete samples with 10%, 40% and 60% replacement of cement by fly ash were produced, using an appropriate amount of (super)plasticizer to obtain good workability. The compressive strength of the mixes at young age decreased with increasing cement replacement level. Inclusion of 40% fly ash allowed to halve thickness changes in lactic/acetic acid, weight loss in sulphuric acid and chloride diffusion coefficients during accelerated experiments. The resistance to frost/thaw cycles was similar for fly ash and reference concrete (without air entrainments agents). The carbonation depth after 9 weeks in a 10% CO2 environment was much higher for the 60% fly ash mixture. High volumes fly ash decreased the resistance against the combined action of frost and de-icing salts (3% NaCl solution).

Baert, G., A.-M. Poppe, et al. (2008). "Strength and durability of high-volume fly ash concrete." Structural Concrete **9**(Compendex): 101-108.

The effects of replacing 10, 40 or 60% of the cement content by low-calcium fly ash on the compressive strength and durability of the concrete were investigated. An appropriate amount of (super)plasticiser was added to the mix to obtain good workability. At an early age the compressive strength decreases with increasing level of cement replacement. After 28 days the compressive strength increased relatively more for high-volume fly ash concrete than for the control concrete. Concrete with fly ash performed better in lactic/acetic and sulphuric acid during accelerated experiments. The chloride diffusion coefficients resulting from accelerated chloride migration tests were significantly lower for concrete with fly ash than for the control concrete, except for the mixture with 60% replacement of the cement content. The resistance to frost/thaw cycles was similar for all concrete mixtures. The carbonation depth after 9 weeks in a 10% carbon dioxide (CO2) environment increased with increasing fly ash content. High volumes of fly ash also decreased significantly the resistance against the combined action of frost and de-icing salts (3% sodium chloride (NaCl) solution). From these results it can be concluded that high-volume fly ash concrete has a potential for commercial use in particular applications. 2008 Thomas Telford and fib.

Bakharev, T., J. G. Sanjayan, et al. (1999). "Effect of elevated temperature curing on properties of alkali-activated slag concrete." Cement and Concrete Research **29**(Compendex): 1619-1625.

This investigation is focused on the effect of curing temperature on microstructure, shrinkage, and compressive strength of alkali-activated slag (AAS) concrete. Concrete prepared using sodium silicate and hydroxide as the activator had greater early and flexural strength than ordinary Portland cement concrete of the same water/binder ratio, but it also had high autogenous and drying shrinkage. Heat treatment was found to be very effective in reducing drying shrinkage of AAS concrete and promoting high early strength. However, strength of AAS concrete at later ages was reduced. Microstructural study revealed an inhomogeneity in distribution of hydration product in AAS concrete that can be a cause of strength reduction. Pretreatment at room temperature before elevated temperature curing further improved early strength and considerably decreased shrinkage in AAS concrete.

Bakharev, T., J. G. Sanjayan, et al. (2000). "Effect of admixtures on properties of alkali-activated slag concrete." Cement and Concrete Research **30**(Compendex): 1367-1374.

This paper reports the results of an investigation on concrete that incorporated alkali-activated slag (AAS) as the only binder. The activators were liquid sodium silicates (4-7% Na, mass of slag) and a multi-compound activator (NaOH+Na2CO3) (8% Na, mass of slag). AAS utilizes industrial by-products and develops high early strength. However, some of its properties such as high shrinkage and poor workability impede its practical application. Admixtures used for ordinary portland cement (OPC) were tested to improve these properties of AAS concrete. Superplasticizer based on modified naphthalene formaldehyde polymers (S), air-entraining agent (AEA), water-reducing (WRRe), shrinkage-reducing (SHR) admixtures at dosages of 6-10 ml/kg, and gypsum (G) (6% of slag weight) were used. The paper presents the study of workability in the fresh state, shrinkage and compressive strength of AAS concrete, and the effect of admixtures and type of activator on these properties. Concrete activated by liquid sodium silicate had the best mechanical properties. AEA, SHR, and G significantly reduced its shrinkage. AEA also improved workability and had no negative effect on compressive strength. On the basis of this investigation, AEA was recommended for use in AAS concrete.

Balasubramanian, K., T. S. Krishnamoorthy, et al. (2004). "Bond characteristics of slag-based HPC." Indian Concrete Journal **78**(Compendex): 39-44.

The bond between steel and concrete is necessary to ensure composite interaction between two materials and is very critical. It is necessary not only to ensure an adequate level of safety, by allowing the two materials (concrete and steel) to work together, but it also controls the structural behaviour, by providing an adequate level of ductility. At the serviceability limit state, it serves to control the crack width and deflection and at ultimate limit state, strength of laps and anchorages depends on bond. In addition, bond characteristics of flexural reinforcement will influence the rotation capacity of plastic hinges. However, very few documented studies are available in India on the bond behaviour of high performance concrete containing supplementary cementitious materials. In order to study the bond behaviour of high performance concrete with ground granulated blast furnace slag (GGBS) as cement replacement material (CRM), experimental investigations were conducted on M60 grade of concrete and three CRM levels (0,40 and 70 percent). Three types of reinforcing bars, namely, mild steel, high strength deformed(HSD), thermo mechanically treated (TMT) of diameters 10 mm and 20 mm were investigated. The bond strength was evaluated by employing static pullout test as per IS 2770: 1967. The results of this investigation arc presented in this paper.

Ballester, P., A. Hidalgo, et al. (2009). "Effect of Brief Heat-curing on Microstructure and

Mechanical Properties in Fresh Cement Based Mortars." Cement and Concrete Research **39**(7): pp 573-579.

The effect of temperature on fresh mortar and cement paste was evaluated by simulating the curing conditions of external structural plastering applied under extremely hot weather. The specimens were heated at controlled temperatures in the 40-80°C range by exposure to IR radiation over short periods. The effect of soaking for a short time was also examined. The results of compressive strength tests, scanning electron microscopy, infrared spectroscopy, and mercury porosimetry helped to characterize the mechanical and physico-chemical properties of the studied sample. Early age behavior (28 days) in neat cement was barely affected by the temperature. By contrast, exposure to high temperatures caused significant microstructural changes in the mortar. However, successive soaking over short periods was found to reactivate the mechanism of curing and restore the expected mechanical properties. Based on the results, application of cement based mortar at high temperatures is effective when followed by a short, specific soaking process.

Ballim, Y. and P. C. Graham (2009). "The effects of supplementary cementing materials in modifying the heat of hydration of concrete." Materials and Structures/Materiaux et Constructions **42**(Compendex): 803-811.

This paper is intended to provide guidance on the form and extent to which supplementary cementing materials, in combination with Portland cement, modifies the rate of heat evolution during the early stages of hydration in concrete. In this investigation, concretes were prepared with fly ash, condensed silica fume and ground granulated blastfurnace slag, blended with Portland cement in proportions ranging from 5% to 80%. These concretes were subjected to heat of hydration tests under adiabatic conditions and the results were used to assess and quantify the effects of the supplementary cementing materials in altering the heat rate profiles of concrete. The paper also proposes a simplified mathematical form of the heat rate curve for blended cement binders in concrete to allow a design stage assessment of the likely early-age time-temperature profiles in large concrete structures. Such an assessment would be essential in the case of concrete structures where the potential for thermally induced cracking is of concern. 2008 RILEM.

Banfill, P. and M. Frias (2007). "Rheology and conduction calorimetry of cement modified with calcined paper sludge." Cement and Concrete Research **37**(Compendex): 184-190.

This paper considers calcined paper sludge as an alternative source of metakaolin, an established supplementary cementitious material. Calcination of the sludge generated in the recycling of newsprint paper at 700C yields a product with pozzolanic properties. The effects of this recycled metakaolin on the rheology and conduction calorimetry of cement pastes have been studied and compared to the effects of commercial metakaolin. The effects are similar and the results show that calcined paper sludge has the potential to be used as a supplementary cementitious material. This offers a route for utilising this waste material, as an alternative to the increased environmental burden associated with the production of metakaolin from natural kaolinite resources. 2006 Elsevier Ltd. All rights reserved.

Baraett, S. J., M. N. Soutsos, et al. (2005). The effect of ground granulated blastfurnace slag on the strength development and adiabatic temperature rise of concrete mixes. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

The strength development of concretes containing ground granulated blastfurnace slag (GGBS) has been investigated under standard and adiabatic curing conditions. Concretes with cement replacement levels varying from 0 to 70%, and water/binder ratios from 0.25 to 0.80 have been investigated. For a given water/binder ratio, the 28-day strength is approximately the same, irrespective of the level of cement replacement. However, the early age strengths of GGBS concrete are lower than those of Portland cement concrete. The adiabatic temperature rises of concretes with target mean strength of 70N/mm2 at 28 days and cement replacement levels of 0, 35, and 70% have been measured. Their strength development under adiabatic conditions has been determined and compared with the strength development under standard curing conditions. For higher cement replacement levels, the adiabatic temperature rise is slower and the peak temperature reached is lower. Concretes containing GGBS show a much greater improvement in early age strength than PC concrete, even though the adiabatic temperature rise is lower, with 2-day strengths as high as 21/2 times the standard cured strength.

Barna, L. A., P. M. Seman, et al. (2009). Extending the Season for Concrete Construction and Repair — The Next Phase.

The Corps of Engineers is embarking on the next phase, Phase III, of Cold Weather Admixture Systems (CWAS). CWAS is an innovative approach to conventional cold weather concreting. Since its inception several years ago, the Corps continues to develop this technology to benefit the user and change the approach to winter concreting. Chemical admixtures are routinely used to accelerate cement hydration and promote early strength gain in fresh concrete. To date, no single admixture, when used within the manufacturer's recommended dosage, is capable of preventing fresh concrete from freezing. External heating is still required to maintain a curing environment. This necessitates additional resources (time and money) and is expensive, given volatile energy prices. To fill this void, CWAS uses an `off-the-shelf' approach of suites of admixtures that, when used in combination, protect fresh concrete to an internal concrete temperature of −5°C. The cement hydrates and the concrete gains strength even when the temperature is below freezing. Phase I showed the feasibility of the CWAS approach and uncovered potential long-term durability benefits. Phase II further investigated CWAS formulations using elevated dosages of chemical admixtures. Throughout this time period, numerous field demonstrations have been conducted to introduce the CWAS approach to State

Departments of Transportation and the U.S. Army. CWAS is catching on. The next phase seeks to optimize the admixture combinations tailoring the mixes to site-specific conditions based on the geometry and forecasted weather conditions. This capability makes CWAS a powerful tool providing users greater flexibility for winter concrete construction projects.

Barnett, S. J., M. N. Soutsos, et al. (2006). "Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies." Cement and Concrete Research **36**(Compendex): 434-440.

The strength development of mortars containing ground granulated blast-furnace slag (ggbs) and portland cement was investigated. Variables were the level of ggbs in the binder, water-binder ratio and curing temperature. All mortars gain strength more rapidly at higher temperatures and have a lower calculated ultimate strength. The early age strength is much more sensitive to temperature for higher levels of ground granulated blast-furnace slag. The calculated ultimate strength is affected to a similar degree for all ggbs levels and water-binder ratios, with only the curing temperature having a significant effect. Apparent activation energies were determined according to ASTM C1074 and were found to vary approximately linearly with ggbs level from 34 kJ/mol for portland cement mortars to around 60 kJ/mol for mortars containing 70% ggbs. The water-binder ratio appears to have little or no effect on the apparent activation energy. 2005 Elsevier Ltd. All rights reserved.

Bassuoni, M. T. and M. L. Nehdi (2009). "Durability of self-consolidating concrete to different exposure regimes of sodium sulfate attack." Materials and Structures/Materiaux et Constructions **42**(Compendex): 1039-1057.

This study investigates the durability of a wide scope of self-consolidating concrete (SCC) mixture designs to sodium sulfate attack. The mixture design variables included the type of binder (single, binary, ternary and quaternary), air-entrainment, sand-to-aggregate ratio and hybrid fibre reinforcement. Since current standard test methods (e.g. ASTM C 1012) generally do not address various sulfate attack exposure scenarios that may exist under field conditions, three different sulfate attack exposure regimes (full immersion, wetting-drying and partial immersion) were investigated in the current study. In the wetting-drying and partial immersion exposure regimes, results of the physico-mechanical properties revealed performance risks associated with some SCC mixture designs. Such risks were not captured by the full immersion exposure. Thermal, mineralogical and microscopy studies elucidated the complexity of degradation mechanisms, which in some cases varied at different locations of the same specimen. Findings from this study emphasize the need for performance standard tests that can better simulate various realistic field exposure regimes in order to achieve a more reliable and comprehensive evaluation of the resistance of concrete to sulfate attack. 2008 RILEM.

Bassuoni, M. T., M. L. Nehdi, et al. (2006). "Enhancing the reliability of evaluating chloride ingress in concrete using the ASTM C 1202 rapid chloride penetrability test." Journal of ASTM International **3**(Compendex).

The rapid chloride penetrability test (RCPT-ASTM C 1202) is commonly used to evaluate the resistance of concrete to chloride ions ingress owing to its simplicity and rapidity. However, it has been criticized for various shortcomings such as giving favorable results to supplementary cementitious materials (e.g., silica fume), and bias against calcium nitrite corrosion inhibitors (CNI). Based on the ASTM C 1202 induced voltage concept, this study aims at enhancing the reliability of rapidly evaluating concrete resistance to chloride ions ingress. It is proposed that upon test termination, not only the passing charges are recorded, but the depth of chloride front migrating into concrete is also measured. Concrete mixtures herein were prepared incorporating selected materials (silica fume and CNI) that have been known to cause misleading results for the RCPT test. The effects of silica fume and CNI dosages on RCPT results were investigated and correlated to porosity trends evaluated by mercury intrusion porosimetry (MIP). The study reveals that measuring the migrating chloride front in concrete subsequent to the ASTM C 1202 test can eliminate the bias induced by electrolysis conductivity resulting from silica fume and/or CNI. This improves the reliability of assessing concrete resistance to chloride ions penetration using the RCPT procedure. Copyright 2006 by ASTM International.

Basu, P. C. (2001). "NPP containment structures: Indian experience in silica fume-based HPC." Indian Concrete Journal **75**(Compendex): 656-664.

Changes in construction methods due to use of silica fume based high performance concrete (HPC) in building nuclear power plant (NPP) containment structures were discussed. Initial curing of surface for extended reinforcement construction joint preparation was performed by application of surface retarder followed by high pressure air water jet green curing. Defining of HPC, selection of ingredients, mix design, field trials and mock-up studies were the stages involved in the development of HPC for inner containment domes. Several measures were adopted for the protection, transportation, placement, compaction and curing of HPC in the construction process of NPP.

Basu, P. C. and S. Saraswati (2006). "Are existing IS codes suitable for engineering of HVFAC?" Indian Concrete Journal **80**(Compendex): 17-21.

The suitability of the Indian Standard (IS) codes for prescribing the required specifications for engineering concrete structures using high volume fly ash concrete (HVFAC) is discussed. HVFAC is a type of high performance concrete (HPC), which is used in higher quantity as supplementary cementitious material replacing Ordinary Portland Cement (OPC). The existing code IS 3812 (Part-I and II): 2003 allows the use of fly ash in concrete both as pozzolana and mineral admixture. Both the parts of this IS code specify detailed requirements on physical and chemical characteristics of fly ash. The code categorizes fly ash into siliceous fly ash (SFA) having reactive calcium oxide content less than 10 percent and calcareous fly ash (CFA) having reactive oxide content between 10 percent to 25 percent. The code specifies that the HVFAC should be produced in mechanized batching plant or ready mix concrete (RMC) plant under necessary quality control. The fly ash should restrain LOI to 5 percent.

Beal, D. L. and H. L. Brantz (1992). Assessment of the durability characteristics of triple blended cementitious materials. Fourth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete: , Istanbul, Turkey.

This investigation evaluated the durability aspects of the triple blends which at a previous research project were identified as economic alternatives to the normal replacement of cement with fly ash in normal portland cement concrete. The blends containing fly ash, ground granulated blast furnace slag and normal Portland cement were tested in the 20 MPa and 40 MPa concrete strength levels. Concrete specimens were cast and exposed to suitable and controlled environments to assess chloride diffusion in the fully immersed state and also in the simulated splash zone. Similarly other specimens were assessed for resistance to sulphate attack, carbonation and alkali aggregate reaction. The commonly used 25% fly ash blend concrete was used as control.

Becknell, N. K. and W. M. Hale (2005). Ternary concrete mixtures containing ground granulated blast furnace slag and fly ash. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

Ground granulated blast furnace slag (GGBFS) and fly ash (FA) are two common supplementary cementitious materials used in concrete mixtures. The Arkansas Highway and Transportation Department (AHTD) limits the use of GGBFS and FA in the Standard Specifications for Highway Construction. These limits are lower than those being used successfully in other parts of the United States and the world. The amount of replacement of cement by weight allowed for GGBFS is 25% and for FA is 20%, while no ternary mixtures are allowed. Research was done to determine, using materials common and native to Arkansas, if the limits could be changed and to what extent of change is reasonable.

Bellmann, F. and J. Stark (2009). "Activation of blast furnace slag by a new method." Cement and Concrete Research **39**(Compendex): 644-650.

Blast furnace slag is used as supplementary cementing material for the production of blended cement and slag cement. Its latently hydraulic properties can be activated by several methods. Most applications employ the use of high pH values in the pore solution (13.0) to accelerate the corrosion of the glass network of the slag. It is shown in this work that activation is also possible by lowering the pH to a range between 11.8 and 12.2 by the addition of calcium hydroxide and soluble calcium salts. Among the salts investigated in this study are calcium chloride, calcium bromide, calcium nitrate, calcium formate, and calcium acetate. Other salts can be used alternatively as long as they are able to increase the calcium ion concentration and thus reduce the pH in the pore solution via the calcium hydroxide equilibrium. Complex formation of organic anions with calcium ions in the pore solution is a serious handicap when using organic calcium salts. This concept was tested on a particular slag improving its

early compressive strength. It was possible to increase the strength of mortar bars produced from the pure slag from 3MPa to 25MPa after seven days by adding calcium hydroxide, calcium carbonate and calcium acetate. The early strength of slag cement containing 80% slag was increased from 6 to 16MPa after two days by adding calcium chloride. The final strength was increased from 36 to 53MPa after 28days (water/cement-ratio = 0.40, 20C). Analytical data is included to demonstrate that application of the aforementioned concept is able to increase heat liberation and degree of slag consumption. 2009 Elsevier Ltd. All rights reserved.

Bentz, D. P. and C. F. Ferraris (2010). "Rheology and setting of high volume fly ash mixtures." Cement and Concrete Composites **32**(Compendex): 265-270.

While high volume fly ash (HVFA) concretes can be designed and produced to meet 28-d strength requirements and often even exceed the durability performance of conventional concretes, a persistent problem is the potentially long delay in setting time that produces concurrently long delays in finishing the concrete in the field. Previous isothermal calorimetry studies on two different powder additions, namely calcium hydroxide and a rapid set cement, have shown that these powders can mitigate excessive retardation of the hydration reactions. In this paper, rheological measurements and conventional Vicat setting time studies are conducted to verify that these powder additions do indeed reduce setting times in paste systems based on both ASTM Class C and ASTM Class F fly ashes. The reductions depend on the class of fly ash and suggest that trial mixtures would be a necessity to apply these technologies to each specific fly ash/cement/admixture combination being employed in the field. Potentially, for such screening studies, the rheological measurement of yield stress may provide a faster indication of setting (and finishability) than conventional Vicat needle penetration measurements on pastes.

Bentz, D. P., C. F. Ferraris, et al. (2010). "Mixture proportioning options for improving high volume fly ash concretes." International Journal of Pavement Research and Technology **3**(Compendex): 234-240.

High volume fly ash (HVFA) concretes are one component of creating a more sustainable infrastructure. By replacing 50 % or more of the Portland cement with fly ash, a significant reduction is achieved in the carbon footprint of the in place concrete. While HVFA mixtures can be proportioned to produce equivalent long term performance as conventional (cement-only) mixtures, performance problems are often encountered at early ages, including low early-age strengths, long delays in finishing, and potentially greater susceptibility to curing conditions. In this paper, a variety of mixture proportioning options to mitigate these deficiencies are investigated within the framework of a proposed mixture proportioning methodology. Variables examined in laboratory studies include cement type, fly ash class, the provision of internal curing, and the addition of either calcium hydroxide or a rapid set cement to the binder. Switching from a Type II/V to a Type III cement enhanced one-day compressive strengths by over 50 %. Using a Class C fly ash produced a mixture with a higher calcium-to-

silicate ratio than a comparable Class F fly ash and increased the measured 7-day compressive strength. However, in this study, sulfate balance was a problem in the Class C HVFA mixtures, requiring 2 % additional gypsum to provide a proper sulfate balance. Internal curing was found to significantly reduce autogenous deformation by 50 % or more, with a concurrent 13% decrease in compressive strength. Excessive retardations of 3 to 4hrs were observed in both mixtures with the Class C and the Class F fly ashes; powder additions of either a rapid set cement or calcium hydroxide were found to be effective in reducing this retardation (and setting time delays) in pastes and mortars. Chinese Society of Pavement Engineering.

Bentz, D. P., A. S. Hansen, et al. (2011). "Optimization of cement and fly ash particle sizes to produce sustainable concretes." Cement and Concrete Composites **33**(Compendex): 824-831.

In the drive to produce more sustainable concretes, considerable emphasis has been placed on replacing cement in concrete mixtures with more sustainable materials, both from a raw materials cost and a CO2 footprint perspective. High volume fly ash concretes have been proposed as one potential approach for achieving substantial reductions in cement usage, but their usage is sometimes hampered by reduced early age strengths and dramatically increased setting times. One limitation of the current industry practice is that portland cements are generally only optimized for their performance in a pure cement, as opposed to a blended cement, system. In this paper, a new approach of optimizing the particle sizes of the cement and fly ash for achieving desired performance in a blended product will be presented. By appropriately selecting the particle size distributions of cement and fly ash, equivalent 1 d and 28 d strengths may be achieved with about a 35% volumetric replacement of cement with fly ash, while maintaining the same volume fraction of water in the mixture, thus providing an actual 35% reduction in cement content.

Beretka, J., B. de Vito, et al. (1993). "Hydraulic behaviour of calcium sulfoaluminate-based cements derived from industrial process wastes." Cement and Concrete Research **23**(Compendex): 1205-1214.

The manufacture of cements based on calcium sulfoaluminate (C4A3S) requires lower firing temperatures and lower grinding energy, as compared to ordinary Portland cements (OPC). Some of these low-energy cements can be formulated in order to develop high early strength and other performances similar to OPC. Further interest towards these types of cements relies on the possibility of using industrial process wastes as raw materials for their manufacture. It has been found that a number of industrial wastes and by-products such as phosphogypsum, bauxite fines, fly ash and blast furnace slag, can be employed without negatively affecting the hydraulic behaviour of cements of planned C4A3S:-C2S:CS weight ratio 1.5:1:1. Blast furnace slag and fly ash can also be advantageously used as blending components of the fired products.

Bergstrom, M. and B. Taljsten (2006). Degradation of structural performance -

Experiment introduction and expected results. 3rd International Conference on Bridge Maintenance, Safety and Management - Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost, July 16, 2006 - July 19, 2006, Porto, Portugal, Taylor and Francis/Balkema.

Much effort has been put on investigating degradation of concrete structures, repair and upgrading separately, as can be read in numerous publications, i.e., Green et. al. (2003), Morgan (1995) and Taljsten (2004). However, an overall view has not been taken where the whole life cycle of a concrete structure is considered. In particular, no laboratory tests have been presented in the literature to the author's knowledge. A structure passes several stages during its life. Normally two major stages are discerned, the service limit state (SLS) and the ultimate limit state (ULS). Concrete structures are designed for both these stages. In the SLS normally the deformation and crack widths are controlled. Deformation due to comfort demands and crack widths due to durability demands. In the ULS the structure is designed for its ultimate capacity - which for civil and building structures almost never is reached. From a safety aspect the ULS is most important; however, for the client the SLS with regard to maintenance, repair and upgrading are most costly. If the SLS was better understood, in particular from a rehabilitation point of view, more robust and cost effective repair and upgrading system could be developed. (Figure Presented). This paper is also a part of "Sustainable bridges". "Sustainable bridges" is a European project which focus is to preserve bridges throughout Europe and create unanimous codes for all participating countries. The project presented in this paper, Degradation of Structural Performance (DOSP), will investigate the behaviour of concrete beams which will endure a simulated life cycle procedure. The test program will direct the beams from full strength of the intact beam through degradation, repair and upgrading with FRP plate bonding to its original strength again or near. The cross-sectional strain distribution will be monitored during the test using Fibre Bragg Grating (FBG) Strain Sensors as well as traditional strain gauges. This gives the possibility of comparing results in between the two monitoring techniques over proportionately long time span. An accelerated corrosion procedure is used to corrode the flexural tensile reinforcement. The cycle may be divided into seven stages, a to g, presented shortly in Figure 1, Horrigmoe (1998) and Sand 2001. This life cycle is possible in the real case scenario for bridges or other concrete structures which are subjected to chlorides, i.e. de-icing salt or sea water. 2006 Taylor Francis Group.

Berry, E. (1980). "Strength development of some blended cement mortars." Cement and Concrete Research **10**(1): 1-11.

Development of compressive strength of mortars made from blends of slag, fly ash and portland cement was examined. No apparent interactions were found between granulated slag and fly ash used together. An examination of the effects of supplementary cementing materials on entrapped air showed that one of the fly ash samples caused significant air reduction in the non-air-entrained, fresh mortars. A modification of Feret’s equation was applied to estimate the contribution made by this fly ash to cementing activity at early ages.

Berry, M., D. Cross, et al. (2009). Changing the environment: An alternative "green" concrete produced without Portland cement. 3rd World of Coal Ash, WOCA Conference, May 4, 2009 - May 7, 2009, Lexington, KY, United states, Unavailable.

The benefits of using 100% fly ash concrete are at least two fold: reduced environmental impacts from the production of cement, and reduced need for stockpiling of common waste-streams. Previous research at MSU has clearly demonstrated the use of 100% fly ash concrete with conventional aggregates and recycled pulverized glass aggregates for use in structural (and non-structural) applications. The fly ash concretes made throughout this research program have had slumps from 102 to 216 mm (4 to 8.5 in), set times of approximately 120 minutes, and 28 day unconfined strengths on the order of magnitude of at least 28 MPa (4,000 psi). With a few exceptions, the equations available to characterize the behavior of Portland cement based concrete were found to apply to the fly ash concretes. These new concretes offer good durability relative to ASR and freeze-thaw resistance. Reinforced structural elements made with fly ash concrete behaved as would be expected based on design equations for conventional Portland cement based concrete. Specifically, element behavior with respect to strength and ductility closely match that expected for similar Portland cement concrete elements. Thus, existing flexural design procedures can generally be employed when using these materials. This research program has moved beyond the laboratory, and has been used in multiple pilot projects. These pilot projects used conventional equipment to batch the alternate concrete, and were successful at validating this concrete as an alternative to conventional Portland cement based concrete. However, these projects revealed several obstacles that must be overcome prior to widespread use of this material, a majority of which are related to human factors and the tendency of contractors, batch plan operators, and concrete finishers to underestimate the importance of differences between this material and traditional concrete. Current work is focused on simplifying the batching process and developing educational materials to distribute to all those involved in using these new materials. These educational materials will emphasize the importance of subtle, yet important differences between these materials. This material is not intended to replace conventional Portland cement concrete; however it is a viable environmentally attractive option in appropriate situations. Additionally, this work was performed with a very specific fly ash from the Corette Power Plant near Billings, MT. More work is required and currently underway to expand the scope of this material to encompass other types of ashes.

Bhanumathidas, N. and N. Kalidas (2001). INFLUENCE OF SULFATE ON CEMENT MIXTURES CONTAINING FLY ASH OR BLAST-FURNACE SLAG.

Both fly ash and granulated blast-furnace slag contain reactive alumina, the strength potential of which can be tapped through addition of gypsum. This has resulted in the development of cementitious mixture of fly ash, lime and gypsum, called FaL-G. In the presence of gypsum, some fly ash-lime mixtures render 3 to 6 times strength enhancement at all ages. The authors have found that high-volume fly ash blended portland cements also increase in strength with the addition of gypsum or anhydrite. Similar behavior is observed in ground granulated blast-furnace slag blended portland cements also. This improved strength is attributed to the formation of additional calcium sulfoaluminate hydrates. The research findings are highly significant from the standpoint of conservation of agricultural soils, minerals and energy, and better utilization of fly ashes and blast-furnace slag in tropical climates.

Bharatkumar, B. H., B. K. Raghuprasad, et al. (2005). "Effect of fly ash and slag on the fracture characteristics of high performance concrete." Materials and Structures/Materiaux et Constructions **38**(Compendex): 63-72.

The premature deterioration of concrete structures in aggressive environments has necessitated the development of high performance concrete (HPC). The major difference between conventional concrete and HPC is essentially the use of chemical and mineral admixtures. The improved pore structure of HPC achieved by the use of chemical and mineral admixtures causes densification of paste-aggregate transition zone, which in turn affects the fracture characteristics. Hence, studies were taken up to investigate the effect of fly ash and slag on the fracture characteristics of HPC. Beam specimens (geometrically similar and single size variable notch) with locally available fly ash (25%) and slag (50%) as cement replacement materials were prepared and tested in a servo-controlled Universal Testing Machine (UTM) under displacement control. From the value of the peak load for each beam, various fracture parameters were calculated. The results show that there is a reduction in the fracture energy due to addition of fly ash or slag, which can be attributed to the presence of unhydrated particles of size larger than that of normal flaws in concrete. Also due to densification, Jtoe post peak behaviour is steeper for the fly ash or slag based HPC mixes. The results of the investigation are presented in this paper. 2004 RILEM. All rights reserved.

Bhatty, J. and P. Taylor (2006). Sulfate Resistance of Concrete Using Blended Cements or Supplementary Cementitious Materials**:** 21p.

This report briefly discusses the mechanism of sulfate attack and the role of selected supplementary cementitious materials (SCMs) in reducing this attack in concrete. The relationship between sulfate resistance and the chemical, physical, and mineralogical composition of SCMs has been elucidated. Based on a number of bench-scale studies, several of models predicting sulfate resistance in fly ash-containing concretes have been cited and discussed. The report has also discussed sulfate resistance of concrete that contained SCMs interground and optimized at the cement plant as compared to that mixed at the concrete batch plant. From the very limited data available on the subject, use of interground SCMs with clinker have shown improved sulfate resistance for concrete, primarily attributed to finer and better particle size distribution that enhance the reactivity and reduce the permeability in concrete. The report also recommends that the optimization of sulfate should be based on 3-day strength instead of 1-day strength as in ASTM C 563. This may require a higher sulfate addition that can potentially improve sulfate resistance as the porosity of the system would be markedly reduced.

Bhatty, J. I., P. C. Taylor, et al. (2006). Sulfate Resistance of Concrete Using Blended Cements or Supplementary Cementitious Materials. Skokie, Illinois, USA, Portland Cement Associaiton.

This report briefly discusses the mechanism of sulfate attack and the role of selected supplementary cementitious materials (SCMs) in reducing this attack in concrete. The relationship between sulfate resistance and the chemical, physical, and mineralogical composition of SCMs has been elucidated. Based on a number of bench-scale studies, several of models predicting sulfate resistance in fly ash-containing concretes have been cited and discussed. The report has also discussed sulfate resistance of concrete that contained SCMs interground and optimized at the cement plant as compared to that mixed at the concrete batch plant. From the very limited data available on the subject, use of interground SCMs with clinker have shown improved sulfate resistance for concrete, primarily attributed to finer and better particle size distribution that enhance the reactivity and reduce the permeability in concrete. The report also recommends that the optimization of sulfate should be based on 3-day strength instead of 1-day strength as in ASTM C 563. This may require a higher sulfate addition that can potentially improve sulfate resistance as the porosity of the system would be markedly reduced.

Bhatty, M. S. Y. (1986). Properties of Blended Cements made with Portland Cement, Cement Kiln Dust, Fly Ash, and Slag. 8th International Congress on the Chemistry of Cement, Rio de Janeiro–Brasil.

Bilek, V., M. Urbanova, et al. (2007). Alkali-Activated Slag Concrete—Development for Practical Use.

Alkali-activated slag concretes (AASC) are relatively well-known composites. For practical application various different problems must be solved. For example, they are the optimum content of alkaline activator and its nature; the composition of the activator for optimum setting and hardening time, the design of concrete for good workability, for the reaching of the smallest volume exchanges, and for maximum strength and for high durability. These problems are discussed in this paper. Water glass and/or natrium hydroxide were chosen as the best type of activator and the optimum ratio of Na2O and SiO2 were found. Calorimetry, MAS NMR (27Al and 29Si), SEM and other methods were used for the characterization of the mixes. The concrete mixes are designed as self compacting for easier introduction of these materials into practice. Strengths, volume changes and their time development were measured during the aging of the mixes. Some elements will be produced from the concretes in 2005 and 2006 (elements for cable pipe-lines).

Bilodeau, A., N. Bouzoubaa, et al. (2004). "Development of ternary blends for high-performance concrete." ACI Materials Journal **101** (1): 11.

The purpose of this study is to develop ternary blends with optimum amounts of fly ash and silica fume to be used in high-performance concrete. Two series of air-entrained concrete mixtures were investigated in this study: Series 1 included concretes with a total cementitious materials content (CM) of 350 kg/m/sup3/ and a water-cementitious material ratio (w/cm) of 0.40, and Series 2 included concretes with a total CM of 450 kg/m/sup3/ and a w/cm of 0.34. In each series, one silica fume and three fly ashes were used; these consisted of two ASTM Class F and one ASTM Class C fly ashes. Properties of the fresh and hardened concrete such as slump, air content, bleeding, setting time, autogenous temperature rise, plastic shrinkage, compressive strength, and the resistance to chloride-ion penetration were determined. The results have shown that the combined use of fly ash and silica fume in concrete are more advantageous in terms of the following parameters: the dosage of high-range water-reducing admixture (HRWRA), plastic shrinkage, and chloride-ion penetrability.

Bilodeau, A. and V. M. Malhotra (2000). "High-volume fly ash system: Concrete solution for sustainable development." ACI Materials Journal **97**(Compendex): 41-48.

The challenge for the civil engineering community in the near future will be to realize projects in harmony with the concept of sustainable development, and this involves the use of high-performance materials produced at reasonable cost with the lowest possible environmental impact. Portland cement concrete is a major construction material worldwide. Unfortunately, the production of portland cement releases large amounts of CO2 into the atmosphere, and because this gas is a major contributor to the greenhouse effect and the global warming of the planet, the developed countries are considering very severe regulations and limitations on the CO2 emissions. In view of the global sustainable development, it is imperative that supplementary cementing materials be used to replace large proportions of cement in the concrete industry, and the most available supplementary cementing material worldwide is fly ash, a by-product of thermal power stations. To considerably increase the utilization of fly ash that is otherwise being wasted, and to have a significant impact on the production of cement, it is necessary to advocate the use of concrete that will incorporate large amounts of fly ash as replacement for cement. Such concrete, however, must demonstrate performance comparable to that of conventional portland cement concrete, and must be cost effective. In 1985, CANMET developed a concrete incorporating large volumes of fly ash that has all the attributes of high-performance concrete, that is, one that has excellent mechanical properties, low permeability, superior durability, and that is environmentally friendly. This paper gives an overview of the properties of this type of concrete that is believed to be a very promising alternative for the industry seeking to meet the sustainable development objectives.

Bilodeau, A., V. Sivasundaram, et al. (1994). "Durability of concrete incorporating high volumes of fly ash from sources in the U.S." ACI Materials Journal **91**(Compendex): 3-12.

This paper presents the results of investigations to determine the various durability aspects of high-volume fly ash concrete using eight fly ashes and two portland cements from U.S. sources. Briefly, in high-volume fly ash concrete, the water and cement content are kept low at about 115 and 155 kg/m3 of concrete, respectively, and the proportion of fly ash in the total cementitious materials content ranges from 55 to 60 percent. The durability aspects investigated included resistance to the repeated cycles of freezing and thawing (ASTM C 666 Procedure A), the deicing salt-scaling resistance (ASTM C 672), the resistance to the chloride-ion penetration (AASHTO T 277-83) and the determination of water permeability coefficient. Based upon the test results, it is concluded that regardless of the type of fly ash and the cements used, the air-entrained high-volume fly ash concrete exhibited excellent durability characteristics in the tests investigated. The only exception was the deicing salt-scaling test in which the performance of the concretes investigated was less than satisfactory.

Binici, H. (2010). "Durability of heavyweight concrete containing barite." International Journal of Materials Research **101**(Compendex): 1052-1059.

The supplementary waste barite aggregates deposit in Osmaniye, southern Turkey, has been estimated at around 500 000 000 tons based on 2007 records. The aim of the present study is to investigate the durability of concrete incorporating waste barite as coarse and river sand (RS), granule blast furnace slag (GBFS), granule basaltic pumice (GBP) and &le4 mm granule barite (B) as fine aggregates. The properties of the fresh concrete determined included the air content, slump, slump loss and setting time. They also included the compressive strength, flexural and splitting tensile strengths and Young's modulus of elasticity, resistance to abrasion and sulphate resistance of hardened concrete. Besides these, control mortars were prepared with crushed limestone aggregates. The influence of waste barite as coarse aggregates and RS, GBFS, GBP and B as fine aggregates on the durability of the concretes was evaluated. The mass attenuation coefficients were calculated at photon energies of 1 keV to 100 GeV using XCOM and the obtained results were compared with the measurements at 0.66 and 1.25 MeV. The results showed the possibility of using these waste barite aggregates in the production of heavy concretes. In several cases, some of these properties have been improved. Durability of the concrete made with these waste aggregates was improved. Thus, these materials should be preferably used as aggregates in heavyweight concrete production. 2010 Carl Hanser Verlag, Munich, Germany.

Binici, H., O. Aksogan, et al. (2005). "A study on cement mortars incorporating plain Portland cement (PPC), ground granulated blast-furnace slag (GGBFS) and basaltic pumice." Indian Journal of Engineering and Materials Science **12**(6): 214-220.

In this paper, an experimental investigation on the effect of ternary blending on the various properties of cement paste and mortar has been reported. The ternary blended cements have been prepared by using one type of clinker and two types of pozzolans. Two types of grinding techniques, two different fineness values and varying amounts of additives have been employed. Besides these, control pastes and mortars are prepared. The influence of fineness, different grinding techniques and other parameters on the strength of the ternary blended cements has been evaluated. The chemical compositions of the pozzolans are consistent with the requirements given in both the TS 25 (a Turkish standard) and ASTM C 168 standards. The results indicate that the basaltic pumice used in this study, taken from the Osmaniye-Adana province (Southern Turkey), can be used as an admixture in cement production. SEM, XRD and thin section analyses showed that a large quantity of sheet-like CSH was formed when a combination of basaltic pumice and slag were incorporated in the mortar.

Binici, H., T. Shah, et al. (2008). "Durability of concrete made with granite and marble as recycle aggregates." Journal of Materials Processing Technology **208**(Compendex): 299-308.

The ornamental stone industries in Turkey produce vast amount of by-product rock waste (marble, granite) that could be used in concrete production suitable for construction purposes. In this work we have highlighted some technical aspects concerning the use of these waste materials. Durability of concrete made with granite and marble as coarse aggregates was studied. River sand and ground blast furnace slag (GBFS) were used as fine aggregates. The results were compared with those of conventional concretes. Slump, air content, slump loss and setting time of the fresh concrete were determined. Furthermore, the compressive strength, flexural- and splitting-tensile strengths, Young's modulus of elasticity, resistance to abrasion, chloride penetration and sulphate resistance were also determined. Control mortars were prepared with crushed limestone as coarse aggregates. The influence of coarse and fine aggregates on the strength of the concrete was evaluated. Durability of the concrete made with marble and GBFS was found to be superior to the control concrete. In the specimens containing marble, granite and GBFS there was a much better bonding between the additives and the cement. Furthermore, it might be claimed that marble, granite and GBFS replacement provided a good condensed matrix. These results illustrate the prospects of using these waste by-products in the concrete production. 2008 Elsevier B.V. All rights reserved.

Bisaillon, A., M. Rivest, et al. (1994). "Performance of high-volume fly ash concrete in large experimental monoliths." ACI Materials Journal **91**(Compendex): 178-187.

Presents comparative data on high-volume fly ash concrete made with ASTM Type 1 cement, and control concrete for mass concrete applications made with ASTM Type I and a modified version of ASTM Type II cements. The concrete was supplied by a ready-mix concrete producer for casting five large rectangular monoliths, each measuring 2.5 4.0 5.0 m. The maximum and effective temperature rises were measured, and in situ strength was determined by testing drilled cores. Also, the mechanical properties and durability of the concrete for the monoliths were determined. The adequate strength development and low temperature rise characteristics of high-volume fly ash concrete, combined with the ability to place the concrete in one 5-m continuous lift, make this type of material a possible alternative to conventional concrete used for mass concreting applications. The high-volume fly ash concrete had excellent resistance to freezing and thawing cycling when tested in accordance with ASTM C 666, and no difficulty was experienced in entraining air in the system.

Blair, B. (2009). Cementitious blends and their impact on sustainable construction. ACI Spring 2009 Convention, March 15, 2009 - March 19, 2009, San Antonio, TX, United states, American Concrete Institute.

Today, the demand for high-performance building materials continues to grow along with the demand for "green" product manufacturing and sustainable building practices. Supplementary cementitious materials (SCMs) and blended cements offer sustainable and performance advantages for those who build and occupy structures of all kinds. The growing use of these environmentally friendly materials is due to several performance factors, including low permeability, resistance to chlorides and sulfates, mitigation of alkali silica reaction, greater strength, lower temperatures for mass concrete, and improved workability. The use of cementitious blends not only results in stronger, more durable, high-performance concretes but also helps reduce global climate impact by lowering energy consumption and greenhouse gas emissions. In fact, each ton of portland cement that is replaced by SCMs reduces CO2 emissions by approximately 0.8 ton (0.7 metric ton). Using cementitious blends also reduces solid waste disposal because SCMs are by-products from other industries. These environmental benefits are increasingly important to project developers and owners.

Blair, B. (2009). "Performance Blend: Supplementary Materials Can Extend Concrete Life and Produce Longer-Lasting Bridges." Roads & Bridges **47**(1): pp 44-46, 64.

This article describes current trends in the use of optimized concrete mixes using supplementary cementitious materials (SCMs). One noteworthy project is the Confederation Bridge, which crosses the North Atlantic Ocean in Canada, connecting Prince Edward Island with New Brunswick. It stretches eight miles and is exposed to some of the world’s harshest weather, including high wind, salty waves, and ice. It was built with seven different concrete mix designs incorporating SCMs. The SCMs included silica fume and fly ash. They were used to achieve low permeability, high strength, low heat rise, and resistance to freezing and thawing. SCMs can be used either as separate components or as a constituent of a blended cement. Binary blends contain portland cement and one SCM; ternary blends contain portland cement and two SCMs; and quaternary blends have three SCMs. Fly ash, slag cement, and silica fume are generally the most commonly used SCMs. The spherical shape of fly-ash particles and the glassy nature of slag-cement particles reduce the amount of water needed to make a workable concrete. Silica fume can have an adverse effect on workability. Slag cements, which are generally finer than portland cement, can reduce bleed water. Their use, along with the use of fly ash, will lower early strengths (one to 14 days) but add significantly to long-term strength (28 days and beyond). Concrete with SCMs generally resists sulfate attack more successfully and prevents excessive expansion and cracking of concrete due to alkali-silica reaction. Considering that the three SCMs are industrial byproducts that are difficult to dispose of, their use in creating new pavement is a welcome step toward increased sustainability. Three other examples of projects using optimized SCM mixes are also briefly described.

Bleszynski, R., R. D. Hooton, et al. (2002). "Durability of ternary blend concrete with silica fume and blast-furnace slag: Laboratory and outdoor exposure site studies." ACI Materials Journal **99**(Compendex): 499-508.

In September 1998, an outdoor exposure site was constructed in Picton, Ontario, Canada, to investigate the durability of ternary cementitious systems. Seven concrete mixtures, including three ternary concrete mixtures consisting of various combinations of silica fume, blast-furnace slag, and portland cement were studied. Large slabs-on-ground were cast in the field, and corresponding specimens were simultaneously cast for laboratory testing to assess durability performance of alkali-silica reaction, deicer salt scaling, and ingress of chlorides. This paper describes this project in detail and presents field observations and laboratory findings up to 2 years. Significant expansion due to alkali-silica reaction has occurred in the concrete made with high-alkali portland cement used as a control but has not been observed in any of the ternary blend mixtures. A salt scaling test performed on the formed surfaces of laboratory specimens revealed mass losses slightly greater than the control but less than the specified threshold. Inspection of the field slabs showed no signs of salt scaling damage with the exception of the 50% slag mixture, which is experiencing light scaling after 2 years. Rapid chloride penetration tests, chloride bulk diffusion tests, and chloride profiles of cores taken from the field indicate that ternary blends have a greater resistance to chloride ingress than the control mixture and mixtures with a single supplementary cementing material. A comparative summary revealed that the ternary blend concretes tested have a greater durability performance than the other mixtures tested.

Bonavetti, V. L., G. Menéndez, et al. (2006). "Composite cements containing natural pozzolan and granulated blast furnace slag
" Materiales de Construcción **56**(283): 25-36.

The manufacture of cements with two or more separately ground additions to produce customized cements is becoming common practice. When the pozzolan or slag content in this type of cement is high, however, the initial strength of the resulting product may be adversely impacted. This problem can be minimized by activating one or both of the replacement materials. The present study analyzes the effect of portland cement additions such as physically activated natural pozzolan (up to 20%) and/or granulated blast furnace slag (up to 35%) on mortar flexural and compressive strength. The results show that higher strength is attained in ternary than binary cements. Initially (2 and 7 days), the highest compressive strengths are reached by mortars with up to 13% natural pozzolan and 5% slag, whereas at later ages mortars with larger proportions of additions are found to perform best.

Boukendakdji, O., S. Kenai, et al. (2009). "Effect of slag on the rheology of fresh self-compacted concrete." Construction and Building Materials **23**(Compendex): 2593-2598.

The building industry is turning increasingly to the use of self-compacting concrete (SCC) in order to improve many aspects of building construction as SCC offers several advantages in technical, economic, and environmental terms. Fresh self-compacting concrete (SCC) flows into place and around obstructions under its own weight to fill the formwork completely and self-compact without any segregation and blocking. SCC mixes generally have a much higher content of fine fillers. The use of supplementary cementitious materials is well accepted because of the improvement in concrete properties and also for environmental and economical reasons. The present paper is an effort to quantify the influence of Algerian slag on the properties of fresh and hardened self-compacting concrete. The workability-related fresh properties of SCC were observed through slump flow time and diameter, V-Funnel flow time, J-Ring test, U-Box filling height and GTM sieve stability test. The only hardened property that was included in this study was the compressive strength. An optimum slag content of 15% seems to give a good SCC mixture with workability retention of about 60 min. A decrease in compressive strength with increase of slag content was obtained, but this decrease in compressive strength is less important at late ages (56 and 90 days after mixing). 2009 Elsevier Ltd. All rights reserved.

Bouzoubaa, N., A. Bilodeau, et al. (2008). "Deicing salt scaling resistance of concrete incorporating supplementary cementing materials: Laboratory and field test data." Canadian Journal of Civil Engineering **35**(Compendex): 1261-1275.

In this study, sidewalk sections were made in the field using seven concrete mixtures, applying a finishing and curing practice that is commonly used in Montreal, Canada. For each of the sidewalk sections, large slabs (1.2m 1.2 m) were cast from which specimens were cored and tested in the laboratory for determining their basic mechanical properties and deicing salt scaling resistance following ASTM C672 test procedures. Also, during the casting of the side-walk, companion specimens were cast on site, using concrete from the same batch, and were subjected to the same tests as the "cored" specimens. The resistance to deicing salt scaling of these "laboratory specimens" was evaluated according to ASTM C672 and to BNQ NQ 2621-900 (2002 standard of the province of Quebec, Canada) test procedures. The results were compared with the performance of the sidewalk sections after four winters of outdoor exposure. The visual evaluation of the sidewalks after four winters has confirmed the severity of the ASTM C672 procedure and the adequateness of the BNQ procedure to better evaluate the deicing salt scaling resistance of concrete made with supplementary cementing materials (SCMs). The field evaluation should, however, continue for a longer period of time to increase the confidence in the BNQ test or to allow for changes as needed. 2008 NRC Canada.

Bouzoubaa, N., A. Bilodeau, et al. (2011). "Deicing salt scaling resistance of concrete incorporating fly ash and (or) silica fume: Laboratory and field sidewalk test data." Canadian Journal of Civil Engineering **38**(Compendex): 373-382.

Sidewalk sections were cast in fall 2002 with three concrete mixtures that

consisted of a control concrete, a concrete mixture incorporating 25% fly ash, and a concrete mixture made with a ternary blended cement (fly ash and silica fume). The curing practices consisted of using curing compound and wet burlap. For each of the sidewalk sections, laboratory specimens were cast on site using the concrete from the same batch. Large slabs (1.2 m 0.9 m) were also cast from which specimens could be cored and tested in the laboratory for compressive strength and deicing salt scaling resistance following the ASTM and the BNQ test procedures. The results were compared to the performance of the sidewalk sections after six winters of outdoor exposure. A similar study was completed on sidewalk sections cast in spring 2002; the objective of the present study being to confirm the results of the previous investigation, and to determine the effect of the time of casting on the scaling resistance of the concrete i.e., performance of sidewalks cast in spring versus that of sidewalks cast in fall. The field evaluation showed that all the concretes cast in fall scaled relatively more than those placed in spring. Both laboratory results and field evaluations have shown that the use of a curing compound increases the scaling resistance of all the concretes investigated. The results also confirmed the adequateness of the BNQ procedure to better evaluate the deicing salt scaling resistance of concrete made with supplementary cementing materials; however, monitoring the sidewalk sections for a longer period of time is still required to confirm the above observations.

Bouzoubaa, N., A. Bilodeau, et al. (2007). Mechanical Properties and Durability Characteristics of High-Volume Fly Ash Concrete Made with Ordinary Portland Cement and Blended Portland Fly Ash Cement.

The high-volume fly ash concrete (HVFAC) was developed by Malhotra and his associates in the mid 1980s. Typically, this concrete is made with low water-to-cementitious materials ratio, low cement content, and high fly ash content. This type of concrete has all the attributes of high-performance concrete, in addition to being environmentally friendly. In 2002, mainly because of its environmental friendly aspects, CANMET was awarded a project by the Canadian International Development Agency (CIDA), to implement the HVFAC technology in India in order to reduce the CO2 emissions related to cement production in that country. This project was funded by the Canadian Climate Change Development Fund, and was administered by CIDA. In one of the project activities, undertaken to adapt the HVFAC to Indian materials and conditions, studies were carried out in a number of Indian laboratories. This paper presents the results on one such investigation that was performed at the Bengal Engineering and Science University, Shibpur, near Kolkata, India.

Bouzoubaa, N., A. Bilodeau, et al. (2004). "Development of ternary blends for high-performance concrete." ACI Materials Journal **101**(Compendex): 19-29.

The purpose of this study is to develop ternary blends with optimum amounts of fly ash and silica fume to be used in high-performance concrete. Two series of air-entrained concrete mixtures were investigated in this study: Series 1 included concretes with a total cementitious materials content (CM) of 350 kg/m3 and a water-cementitious material ratio (w/cm) of 0.40, and Series 2 included concretes

with a total CM of 450 kg/m3 and a w/cm of 0.34. In each series, one silica fume and three fly ashes were used; these consisted of two ASTM Class F and one ASTM Class C fly ashes. Properties of the fresh and hardened concrete such as slump, air content, bleeding, setting time, autogenous temperature rise, plastic shrinkage, compressive strength, and the resistance to chloride-ion penetration were determined. The results have shown that the combined use of fly ash and silica fume in concrete are more advantageous in terms of the following parameters: the dosage of high-range water-reducing admixture (HRWRA), plastic shrinkage, and chloride-ion penetrability.

Bouzoubaa, N. and B. Fournier (2005). "Current situation with the production and use of supplementary cementitious materials (SCMs) in concrete construction in Canada." Canadian Journal of Civil Engineering **32**(Compendex): 129-143.

The data gathered on the current situation of supplementary cementing materials (SCMs) in Canada have shown that around 524 000, 347 000, and 37 000 t of fly ash, ground granulated blast furnace slag (GGBFS), and silica fume were used in cement and concrete applications in 2001, respectively, which represents 11%, 90%, and 185% of the quantity produced. The remaining 10% of GGBFS produced was used in the US, and 17 000 t of silica fume were imported from the US and Norway to meet market demand. Fly ash appears to be the only material that is underused and that represents a potential for increased use of SCMs in Canada. For the GGBFS, the quantity produced can be increased if the demand increases. This investigation has shown, however, that there are policy, technical, and economic barriers to the increased use of SCMs in Canada. Some solutions were proposed to overcome these barriers and are summarized in the conclusions of the paper. 2005 NRC Canada.

Bouzoubaa, N., B. Fournier, et al. (2002). "Mechanical properties and durability of concrete made with high-volume fly ash blended cement produced in cement plant." ACI Materials Journal **99**(Compendex): 560-567.

This paper presents the results of a study on the mechanical properties and durability of concrete made with high-volume fly ash (HVFA) blended cement produced in a cement plant. The test results obtained were compared with those of a control concrete made with a commercially available ASTM Type I cement; the control concrete had 28-day compressive strength comparable to that of the concrete made with the HVFA blended cement. The results showed that to obtain similar slump and air content to those of the control concrete, the use of HVFA blended cement required increased dosages of the high-range water-reducing admixture and the air-entraining admixture (AEA). This resulted in some delay in the initial and final setting times of concrete. The use of HVFA blended cement resulted in lower compressive and flexural strengths at early ages (before 28 days) and higher mechanical properties after 28 days as compared with those of the control concrete made with ASTM Type I cement. The concrete made the HVFA blended cement develop a 1-day compressive strength of 13 MPa (compared with 19 MPa for the control concrete) that is considered more than satisfactory for formwork removal. The use of the HVFA blended cement significantly improved the durability characteristics of the concrete; the only exception was the resistance to the deicing salt scaling as determined in the ASTM C 672 test.

Bouzoubaa, N., M. H. Zhang, et al. (2001). "Mechanical properties and durability of concrete made with high-volume fly ash blended cements using a coarse fly ash." Cement and Concrete Research **31**(Compendex): 1393-1402.

This paper presents a study on the mechanical properties and durability of concrete made with a high-volume fly ash (HVFA) blended cement using a coarse fly ash that does not meet the fineness requirement of ASTM C 618. The results were compared with those of the HVFA concrete in which unground fly ash had been added at the concrete mixer. The properties of the fresh concrete determined included the slump, air content, slump loss, stability of air content, bleeding, and setting time; those of the hardened concrete investigated included the compressive strength, flexural- and splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing cycling, and to deicing salt scaling. The results show that except for the resistance of the concrete to the deicing salt scaling, the mechanical properties and the durability of concrete made with this blended cement were superior to the concrete in which the unground fly ash and the cement had been added separately at the mixer. The production of HVFA blended cements, therefore, offers an effective way for the utilization of coarse fly ashes that do not otherwise meet the fineness requirements of ASTM C 618. 2001 Elsevier Science Ltd. All rights reserved.

Boyd, A. J. and D. R. Hooton (2007). "Long-term scaling performance of concretes containing supplementary cementing materials." Journal of Materials in Civil Engineering **19**(Compendex): 820-825.

As part of a research program investigating the effects of supplementary cementing materials (SCMs) on the performance of concretes subjected to deicer salt scaling, a field trial was initiated in 1994. A series of six in-ground pavement slabs were cast with concretes containing various proportions of SCMs and exposed to a cyclic freeze/thaw environment, deicer salt application, and regular heavy truck loads for a period of 12 years. The concretes consisted of a control mix with 100% portland cement, slag mixes containing 25, 35, and 50% blast furnace slag, a fly ash mix containing 15% Class C fly ash, and a ternary blend mix with 25% slag and 10% fly ash. Two sets of laboratory deicer salt scaling specimens were prepared concurrently with the in-ground slabs; one was immediately cured and tested in accordance with the applicable standard, whereas the second set was left on site and subjected to the same exposure conditions as the in-ground slabs for 4 months (prior to freezing) before testing. Damage exhibited by the in-ground slabs and the 4 month exposed scaling slabs was far less significant than that produced by the specimens subjected to standardized testing. 2007 ASCE.

Bradley, B. and M. L. Wilson (2005). "Using supplementary cementitious materials."

Construction Specifier **58**(Compendex): 34-41.

Supplementary cementitious materials (SCMs) can have a significant effect on concrete durability, workability, economy, and sustainability. This article looks at some of the most common materials - fly ash, slag, silica fume, and natural pozzolans - and how they affect fresh and hardened concrete. It also examines industry by-product creation and the advantages of combining multiple SCMs.

Branch, J., D. J. Hannant, et al. (2002). "Factors affecting the plastic shrinkage cracking of high-strength concrete." Magazine of Concrete Research **54**(Compendex): 347-354.

Tests were developed to quantify parameters affecting the plastic shrinkage cracking of high-strength concrete of 28-day cube strength in excess of 70 MPa. The parameters measured were tensile stress-strain performance during the first 5 h after mixing and negative pore pressure development and free shrinkage during the first 24 h. Eight high-strength mixes were used containing a variety of supplementary cementing materials such as microsilica, pulverised fuel ash, granulated slag and metakaolin. Two types of superplasticers were included. Plastic shrinkage cracking was assessed using restrained ring tests in which measurements were taken using sealed samples and samples exposed to wind. The research has shown that there is no simple relationship between early age stress-strain curves, negative pore pressure, early age shrinkage and macrocracking in adverse conditions but two factors were always present when plastic cracking was observed, these being microsilica and wind.

Braselton, J. and B. Blair (2004). "Performance-based specifications for concrete." Construction Specifier **57**(Compendex): 20-22.

Different properties and performance based specifications for concrete are discussed. The specifications focuses on the properties which includes consistency, strength, durability and aesthetics, innovation and technical knowledge. Slump and specific strength are found to be the simplest types of performance-based specification. It also delivers benefits for owners, contractors and producers and create incentives for quality and innovation, and encourage the use of higher-performing portland, blended and slag cement.

Brooks, J. J. (2002). "Prediction of setting time of fly ash concrete." ACI Materials Journal **99**(Compendex): 591-597.

A model for predicting the initial setting time of concrete with and without fly ash is presented. Based on a theoretical initial spacing between the particles of unhydrated cementitious material and the rate of growth of hydration products, the model is developed in terms of parameters that are usually known. The rate coefficient is shown to be very sensitive to temperature and also dependent on chemical composition. Generally, initial setting times of all previous investigators' data, as determined by the ASTM C 403 method, are estimated to within 16%. The input data required for the model are water-cementitious material ratio, fineness, specific gravity, temperature, and the blended oxide ratio: $CaO/(SiO_2 + Al_2O_3 + Fe_2O_3)$. Final setting time can be estimated to within 13% by simply increasing the initial setting time by a factor of 1.35.

Brooks, J. J. and A. F. Al-Kaisi (1990). "Early strength development of portland and slag cement concretes cured at elevated temperatures." ACI Materials Journal **87**(Compendex): 503-507.

Based on the compressive strength of isothermally cured concrete with and without slag, a model is proposed for estimating the strength of concrete in a massive concrete structure when the temperature of the concrete is known. Preliminary verification is demonstrated for ordinary portland cement concrete and concretes containing 50 and 70 percent of slag cured under simulated mass concrete conditions for a period of 28 days.

Brooks, J. J., M. A. Megat Johari, et al. (2000). "Effect of admixtures on the setting times of high-strength concrete." Cement and Concrete Composites **22**(Compendex): 293-301.

The effect of silica fume (SF), metakaolin (MK), fly ash (FA) and ground granulated blast-furnace slag (GGBS) on the setting times of high-strength concrete has been investigated using the penetration resistance method (ASTM C 403). In addition, the effect of a shrinkage-reducing admixture (SRA) on the setting times of normal and high-strength concrete was also studied. The setting times of the high-strength concrete were generally retarded when the mineral admixtures replaced part of the cement. While the SRA was found to have negligible effect on the setting times of normal strength concrete, it exhibited a rather significant retarding effect when used in combination with superplasticizer in high-strength concrete. The inclusion of GGBS at replacement levels of 40% and greater resulted in significant retardation in setting times. In general, as replacement levels of the mineral admixtures were increased, there was greater retardation in setting times. However, for the concrete containing MK, this was only observed up to a replacement level of 10%.

Burg, R. G. (1996). THE INFLUENCE OF CASTING AND CURING TEMPERATURE ON THE PROPERTIES OF FRESH AND HARDENED CONCRETE**:** 14 p.

Concretes, made with two different cements, were cast in the laboratory at temperatures of 10, 23 and 32 degrees C (50, 73, and 90 degrees F). The concrete mix design was held constant for each cement used in the study. Fresh properties, including slump, air content, and time of initial and final set, were measured. These concretes were moist cured at their casting temperature. In the case of the concrete cast at 23 degrees C (73 degrees F), an additional set of specimens was cured at a temperature of 10 degrees C (50 degrees F). Compressive strength was determined at ages between three and 56 days. Test results show workability, as measured by slump, is greatly affected by casting temperature. Slump at 10 degrees C was as much as 214% of the slump at 23 degrees C, while slump at 32 degrees C (90 degrees F) was as little as 80% of the slump at 23 degrees C. Time of set was similarly affected. Low temperature setting time was as much as 195% of setting time at 23 degrees C. High temperature setting time was as short as 68% of setting time at 23 degrees C. As expected, early age compressive strength of concrete cast and cured at high temperature was greater than concrete cast and cured at 23 degrees C. However, after seven days, compressive strength of concrete cast and cured at high temperature was lower than concrete cast and cured at 23 degrees C. Concrete cast and cured at low temperature had initial strength lower than concrete cast and cured at 23 degrees C. However, later age strength either equaled or exceeded that of concrete cast at 23 degrees C.

Burridge, J. (2010). "Embodied CO2 in construction." Structural Engineer **88**(Compendex): 10-12.

A new study by Arup has shown that the embodied CO2 (eCO 2) in construction can be affected by the design decisions of the structural engineer. Structural engineers can have influence over two areas, the impacts of the operation of buildings by facilitating the use of fabric energy storage and the eCO2 by specification of the material within the structural frame. The study found that the eCO2 in the structure of the buildings was in the order of 200kg/m2. This represented 50-60% of the total eCO2, significantly more than the percentage found in other studies. The study also showed that optimizing the eCO2 of the structure can be done without compromising the efforts of other design team members to reduce impact. The use of blended cements containing other cementitious materials such as fly ash or ggbs reduces the eCO2 of the concrete, but delays the setting time, which might impact the construction program.

Buttler, W. B. (1997). Durable concrete containing three or four cementitious materials. Fourth CANMET/ACI International Conference on Durability of Concrete Sydney, Australia,, American Concrete Institute.

In most concrete markets these days, there are several varieties of pozzolans and ground slag available for use in regular and high-performance concretes. Each one has its strong points when blended with portland cement in concrete and, properly used, will provide concrete of enhanced durability. Recently, concrete containing more than one such material has become common, even to the point of being available as ternary or quaternary blend. This paper reviews the data available on durability of concrete produced from multiple blends and discusses some of the potential benefits to specifiers and users.

Byard, B. E., A. K. Schindler, et al. (2010). "Cracking tendency of bridge deck concrete." Transportation Research Record(Compendex): 122-131.

Early-age cracking can adversely affect the behavior and durability of bridge deck concrete. Cracking of hardening concrete occurs when the induced tensile stress exceeds the tensile strength of the concrete. The development of in-place stresses is affected by the shrinkage, modulus of elasticity, coefficient of thermal expansion, setting characteristics, restraint conditions, stress relaxation, and temperature history of the hardening concrete. Tensile strength increases as the hydration of the cementitious system progresses. Rigid cracking frame (RCF) testing techniques capture the combined effects of modulus of elasticity, creep and relaxation, coefficient of thermal expansion, thermal conductivity, autogenous shrinkage, and tensile strength on the cracking potential of a mixture in a specific application. This paper describes an experimental evaluation of the effect of supplementary cementing materials, water-to-cement ratio (w/c), and placement temperature conditions on the early-age cracking tendency of bridge deck concrete through the use of RCF testing techniques. Specimens were tested under temperature conditions that match those in an 8-in.-thick bridge deck to explore early-age cracking mechanisms. The laboratory testing program revealed that the placement temperature and curing temperature significantly affected the time to cracking of all the mixtures. Use of either fly ash or ground-granulated blast-furnace slag was effective in reducing the heat generation and rate of stiffness development in bridge deck concretes and thus in significantly reducing restraint stresses and delayed the occurrence of cracking at early ages. A decrease in w/c resulted in increased stresses, and it accelerated the occurrence of cracking at early ages.

Byles, R. (2004). "Green dream." Highways **74**(Compendex): 41-42.

FM Conway's efforts in producing aggregates through recycling are discussed. The company is investing over 3.75 million in a 14 strong fleet of mobile concrete mixer lorries and a hydroclean high pressure water washing plant, for cleaning and screening up to 80t/hour of dirty feed material into reusable sand and aggregate. This 500,000 worth of specialized equipment will be joined later by a 600,000 plant, which will recycle up to 95% of drainage waste from its cleansing division activities and transfer the recovered grit and sand to the HaverBoecker washing plant. The company feels that recycling will reduce the amount and cost of primary aggregates that it needs to purchase, and will protect the environment.

Cabrera, J. G. and A. S. Al-Hasan (1997). "Performance properties of concrete repair materials." Construction and Building Materials **11**(Compendex): 283-290.

Maintenance, repair and strengthening of concrete structures has become a verb' important part of the activities of the concrete industry. This is reflected in the innumerable proprietary repair materials available in the market and the substantial increase in the number of firms offering specialist maintenance and repair services. Because proprietary compounds are relatively expensive and because the life cost of a repaired structure is also potentially very high, there is much need to provide engineers and specifiers with independent data with which to make appropriate decisions in this field. This paper presents information which arises from a large project on the evaluation of the performance and durability of repair materials being carried out at the Civil Engineering Materials Unit, University of Leeds. The paper includes data on the performance related properties of the following materials: 1. a commercial pre-packed cementitious material; 2. a commercial pre-packed cementitious material modified with polymer; 3. a pozzolanic cement containing 70% ordinary Portland cement and 30% pulverized fuel ash: 4. an ordinary Portland cement containing a commercial organic corrosion inhibitor. The test carried out for evaluation of the repair materials were: compressive strength, bond strength, porosity and permeability. The laboratory results are discussed and the implication of potential performance of the repair materials evaluated.

Cahyadi, J. H. and T. Uomoto (1994). "Effect of carbonation on compressive strength of mortar." Transactions of the Japan Concrete Institute **16**(Compendex): 185-190.

Accelerated, normal and cyclic carbonation tests were performed to investigate change in compressive strength of mortar made of ordinary portland cement or blended cement. Carbonation depth and microstructure of mortar were also measured. Relationship between compressive strength and microstructure of carbonated mortar was obtained. It was also found that carbonation affects characteristic strength of mortar.

Cakir, O. and F. Akoz (2008). "Effect of curing conditions on the mortars with and without GGBFS." Construction and Building Materials **22**(Compendex): 308-314.

The effect of curing conditions on properties of mortars with and without ground granulated blast furnace slag (GGBFS) was studied. In the present work, cement was replaced by ground granulated blast furnace slag 0% (control), 30%, and 60% by weight, and mortars were produced. One of the two groups of mortars was kept in water at 20 C standard conditions, and the other was kept in moisture cabinet at 40 C temperature and approximately at 100% relative humidity (RH). Flexural strength, compressive strength, ultrasonic pulse velocity, capillarity coefficient, and volumetric water absorption were investigated at the ages of 7, 28, 56, 90, and 180 days. The results obtained indicate that elevated temperature increases performance of mortar at early ages but decreases at later-age, and this affect is more significant at slag replaced mortars. 2006 Elsevier Ltd. All rights reserved.

Camarini, G., P. S. Bardella, et al. (2008). Silica fume for cement replacement and its influence on strength and permeability of steam-cured high-strength concrete. 5th ACI/CANMET/IBRACON International Conference on High-Performance Concrete Structures and Materials 2008, June 18, 2008 - June 20, 2008, Manaus, Brazil, American Concrete Institute.

Steam curing at atmospheric pressure is an important technique for obtaining high early strength values in precast concrete production. The aim of this work was to explore the potential benefits of steam curing in concrete products made with different cements types and with supplementary cementitious materials. All concretes mixtures had the same workability and were produced with two cements both with and without silica fume replacement (10% by mass): highearly-strength portland cement and blast-furnace slag portland cement. For.each mixture, specimens were subjected to three curing conditions. Immersion curing until the age of 7 days, curing in air and steam curing at temperatures of 60C and 80C maximum temperature over 4 h. Concretes were prepared and tested for initial surface absorption and air permeability. Compressive strength was also determined. The concretes were tested at different ages: 1, 3, 7, 28, 90, and 180 days. The results showed that the concretes with silica fume presented a lower air permeability and capillary absorption, mainly in later ages, when compared with concretes without silica fume for all curing procedures and both portland cements used. The inclusion of silica fume improved performance of concrete produced with blast-furnace slag portland cement at temperature of 80C. High-early-strength portland cement had a good performance with silica fume replacement. The curing method adopted had significant effects on the near-surface properties of concrete incorporating silica fume.

Cao, C., W. Sun, et al. (2000). "Analysis on strength and fly ash effect of roller-compacted concrete with high volume fly ash." Cement and Concrete Research **30**(Compendex): 71-75.

In this paper, the strength of roller-compacted concrete with high volume fly ash (HFRCC) is examined. By using the notion of `specific strength,' the qualified contribution of fly ash effect to construction formation and strength development of HFRCC is also analyzed. The research results show that: (1) The strength at early ages of HFRCC is poor, while the fly ash effect is low or negative. (2) The strength of HFRCC increases rapidly following its curing age; meanwhile, the fly ash effect gradually improves and is more beneficial to raising flexural strength. (3) With increasing proportion of fly ash, its effect on HFRCC at long curing age becomes more remarkable.

Cao, J. (2010). Influence of the micro-gradation of fly ash and slag on the properties of cement mortar. 2010 GeoShanghai International Conference - Paving Materials and Pavement Analysis, June 3, 2010 - June 5, 2010, Shanghai, China, American Society of Civil Engineers.

The particle size distributions of the mixture of fly ash, slag and cement were studied. The micro gradation of the mixture of fly ash and slag, also named as Ultra Fly ash and Slag (UFS), was analyzed and optimized. The properties of cement mortar containing fly ash, slag and UFS were studied through laboratory tests. The hydration of UFS when adding the activator was also analyzed. Test results indicated that best ratio of fly ash to slag was 4:1, which would achieve the best filling effect, much better micro gradation and the highest density for UFS, and thus improve the early strength. Both the early and late stage strength of cement mortar containing fly ash was lower than those of the cement mortar containing slag or UFS. At the environment provided by the activator, the strength performance of cement mortar would be highly improved because of the secondary hydration of the cementitious material due to the water reducing and densifying effect of the UFS. 2010 ASCE.

Carrasco, M. F., V. L. Bonavetti, et al. (2003). "Drying shrinkage of mortars with limestone filler and blast-furnace slag." Materiales de Construcción **53**(272): 5-16.

During the 1990's the use of cements made with portland clinker and two mineral admixtures, called ternary or blended cements, has grown considerably. Nowadays, cements containing several combinations of fly ash and silica fume, blast-furnace slag and silica fume or blast-furnace slag and limestone filler are commonly used. There are numerous works on the influence of blended cements on the fresh state and mechanical properties of mortar and concrete, but

deformations due to drying shrinkage are not so well described. Analysis of drying shrinkage is relevant because this property influences the possibility of cracking occurrence and, hence, the deterioration of mechanical and durable properties of concrete structures.
This paper evaluates the influence on the drying shrinkage of mortars of variable contents of limestone filler and/or blast-furnace slag in portland cement. Additionally, flexion strength and non evaporable water content were evaluated. Test results show that the inclusion of these mineral admixtures, jointly or separately, increases drying shrinkage of mortars at early ages. Despite this fact, mortars made with limestone filler cement are less susceptible to cracking than mortars made with cements incorporating blast-furnace slag or both admixtures.

Carrasco, M. F., G. Menendez, et al. (2005). "Strength optimization of "tailor-made cement" with limestone filler and blast furnace slag." Cement and Concrete Research **35**(Compendex): 1324-1331.
The use of cements made with portland clinker and two or three additions has grown because they present several advantages over binary cements. Production of composite cements has produced a necessary shift in the manufacture process used in the cement industry. Now, it is known that the separate grinding and mixing technology is more convenient in order to produce these cements, called market-oriented or tailor-made cements. However, their optimum formulations require the help of methods of experimental design to obtain an appropriate performance for a given property with the least experimental effort. In this study, the interaction between limestone filler (LF) and blast-furnace slag (BFS) is analyzed in mortars in which portland cement (PC) was replaced by up to 22% LF and BFS. For this proposition, a two-level factorial design was used permitting to draw the isoresponse curves. Results show that compressive and flexural strength evaluated at 2, 7, 14, 28, 90 and 360 days are affected in different ways by the presence of mineral additions. 2004 Elsevier Ltd. All rights reserved.

Cassagnabere, F., M. Mouret, et al. (2010). "Metakaolin, a solution for the precast industry to limit the clinker content in concrete: Mechanical aspects." Construction and Building Materials **24**(Compendex): 1109-1118.
The current trend to decrease the clinker content in cements through the use of mineral additions in order to limit CO2 emissions into the atmosphere is of major concern for the precast industry as the resulting binders are generally not very reactive at early ages. Here, composed cements (clinker + slag) or combinations between clinker and mineral admixtures are studied with a view to investigating the compressive strength of cement-based materials at both early (1 day) and later (28 days) ages under steam curing conditions. Limestone and siliceous fillers, silica fume and four metakaolins differing in their production process and impurity content were investigated. Considering performance, economic and environmental criteria, results in the laboratory showed that metakaolin (MK) is a very promising solution at a clinker replacement rate of 12.5-25% by mass. Compressive strength was significantly increased (1-day age) or practically the

same as for reference mortars incorporating cement only (28-day age). Thus, in comparison with a reference concrete containing no MK and for an identical granular skeleton, the combination clinker/MK was validated in the precast factory in full-scale trials for slip-forming (25% replacement) and self-compacting (17.5% replacement) concrete applications: compressive strength and porosity were not affected. 2010.

Chang, P. K. (2004). "AN APPROACH TO OPTIMIZING MIX DESIGN FOR PROPERTIES OF HIGH-PERFORMANCE CONCRETE." Cement and Concrete Research **34**(4): p. 623-629.

This paper describes how laboratory and in situ test results revealed that the densified mixture design algorithm (DMDA) can be used to produce high-performance concrete (HPC) of good durability and high workability. The water-to-solid (W/S) weight ratio is known to have significant influence on the volume stability of concrete. This paper discusses strength of f?c>56 MPa, slumps of 230-270 mm, effect of the W/S ratio on the development of strength and durability of HPC at both fresh and hardened states. In addition to the water-to-cement (W/C) ratio and water-to-binder (W/B) ratio, the W/S ratio also has a significant effect on the performance of concrete. The utilization of fly ash and slag has been proven beneficial to the rheology of HPC in enhancing its strength development and durability.

Chang, Z. T., M. Marosszeky, et al. (2001). SETTING TIME AND BLEEDING OF CONCRETE WITH BINARY AND TERNARY CEMENTS CONTAINING SILICA FUME, FLY ASH AND SLAG.

This paper presents and discusses the results of an investigation into setting time and bleeding of concrete with binary and ternary cements containing three supplementary cementitious materials (SCM), silica fume, fly ash and GGBF slag. While the major parameters influencing the setting and bleeding of Type GP cement concrete have been well identified, the use of SCM in the cement introduces new influences on these properties. A total of thirteen concrete mixes were investigated in this work, which was part of a larger project using binary and ternary cements containing SCM from local sources. The comparisons between SCM mixes and Type GP control mixes were based on the same cement content and water to cement ratio. It was found that setting was retarded in all the binary and ternary SCM mixes compared to the control mixes. The bleeding of SCM concrete was found not only to be affected by the fineness of the cement but also by the type, or the chemical and physical properties, of the SCM in the cement. The results of this investigation indicate that properties of concretes containing a large proportion of fly ash and/or slag need careful assessment with respect to particular construction applications given the significant changes to bleeding and setting time associated with cement type. (a) For the covering entry of this conference, please see ITRD abstract no. E206071.

Chang-wen, M., T. Qian, et al. (2007). "Water consumption of the early-age paste and the determination of "time-zero" of self-desiccation shrinkage." Cement and Concrete

Research **37**(Compendex): 1496-1501.

Self-desiccation shrinkage (SDS) is closely related to the interior water consumption and the relative humidity (IRH) drop in the cement paste. Substantial self-desiccation shrinkage has been observed at very early-age for high performance concrete. However, it is difficult to investigate the IRH by conventional method of hygrometer at this time because the materials are still in the superhygroscopic range. In this paper, an automatically measuring system of meniscus depression is developed on the base of the mechanism of tensiometer and Laplace formula. The interior water consumption and the IRH changing within the paste could be automatically monitored at the very early-age (here specially refers to the stage from the beginning of casting till several hours after final setting). By using this system, the effects of water to binder ratio and replacement of cement by fly ash and ground granulated blast furnace slag on the self-desiccation were investigated for the very early-age cement paste. Experimental results could potentially explain the mechanism of the SDS at very early-age as well as determine the "time-zero" of SDS corresponding to its definition. 2007 Elsevier Ltd. All rights reserved.

Chen, B. and J. Liu (2008). "Experimental application of mineral admixtures in lightweight concrete with high strength and workability." Construction and Building Materials **22**(Compendex): 655-659.

The effects of mineral admixtures including fly ash (FA), blast furnace slag (BS) and silica fume (SF) on workable high strength lightweight concrete were investigated. The results showed that both BS and SF can effectively improve the bonding of the mixtures, and then improve the concrete strength at both early and late age; however, there is a tradeoff of workability of the mixtures. FA can greatly improve the workability of the mixture; however, associated bleeding deteriorates the homogeneity of the mixture. Combining FA and BS provides the optimum HSLC with good workability and strength. 2006 Elsevier Ltd. All rights reserved.

Chen, H. S., P. Stroeven, et al. (2003). "Prediction of compressive strength and optimization of mixture proportioning in ternary cementitious systems." Materials and Structures/Materiaux et Constructions **36**(260): 396-401.

This paper discussed the application of the method of the simplex-lattice design for predicting the properties of cement-based composites. On the basis of the compressive strength, its use was demonstrated on ternary paste systems composed of cement, silica fume and fly ash with constant water to binder ratio and a mass fraction of mineral admixtures not exceeding 30%. The regression model between compressive strength of paste and binder proportion was built up. The F-test method was utilized for validation of the regression model. The nonlinear programming system with upper and lower bound was solved. This allowed assessment of optimum mixture proportions and corresponding maximum compressive strength. It was shown that: (1) the 3rd-order regression model constructed by using the simplex-lattice design method could accurately predict the compressive strength in ternary paste system made of cement, silica fume and fly ash (the total mass fraction of all mineral admixtures was up to 30%); (2) to solve the nonlinear programming with the constraints of upper and lower bound played an important role in getting the optimum compressive strength and its corresponding mixture proportion at different ages; (3) the combination of the simplex-lattice design method and the optimization theory could be valuable tool for optimization of cement-based composites' properties. 10 Refs.

Chen, W. and H. J. H. Brouwers (2011). "A method for predicting the alkali concentrations in pore solution of hydrated slag cement paste." Journal of Materials Science **46**(Compendex): 3622-3631.

The alkalinity of the pore liquid in hardened cement paste or concrete is important for the long-term evaluation of alkali-silica reaction (ASR) expansion and corrosion prevention of steel bar in steel reinforced structures among others. It influences the reactivity of supplementary cementitious materials as well. This paper focuses on the alkali binding in hydrated slag cement paste and a method for predicting the alkali concentrations in the pore solution is developed. The hydration of slag cement is simulated with a computer-based model CEMHYD3D. The amount of alkalis released by the cement hydration, quantities of hydration products, and volume of the pore solution are calculated from the model outputs. A large set of experimental results reported in different literatures are used to derive the alkali-binding capacities of the hydration products and practical models are proposed based on the computation results. It was found that the hydrotalcite-like phase is a major binder of alkalis in hydrated slag cement paste, and the C-S-H has weaker alkali-binding capacity than the C-S-H in hydrated Portland cement paste. The method for predicting the alkali concentrations in the pore solution of hydrated slag cement paste is used to investigate the effects of different factors on the alkalinity of pore solution in hydrated slag cement paste. 2011 The Author(s).

Chidiac, S. E. and D. K. Panesar (2008). "Evolution of mechanical properties of concrete containing ground granulated blast furnace slag and effects on the scaling resistance test at 28 days." Cement and Concrete Composites **30**(Compendex): 63-71.

Compressive strength, ultrasonic pulse velocity (UPV), non-evaporable water content and the interplay between them were investigated at 1, 3, 7 and 28 days to determine the effects of using ground granulated blast furnace slag (GGBFS) as cement replacement. The variables considered include percentage of GGBFS as cement replacement (0-60%), total binder content (270-450 kg/m3), water-to-binder ratio (0.31, 0.38) and curing period. The dilution effect was observed at day 3, at which point, increasing the amount of GGBFS as cement replacement yielded lower compressive strengths. The results show that the evolution of mechanical properties is affected by the amount of water, percent of GGBFS added and curing regime. By 28 days, the benefit of using GGBFS as cement replacement owing to its effect on the concrete's packing density and hydration processes was reflected in the compressive strength and UPV measurements when used up to 50% cement replacement. Compressive strength of concrete containing GGBFS is found to increase on average by 10% from 28 days to 120 days. Measurements of non-evaporable water content and mass loss due to scaling revealed that the scaling resistance test for concrete at 28 days is more favorable towards OPC concrete and discriminates against concrete containing high percentages of GGBFS as cement replacement. 2007 Elsevier Ltd. All rights reserved.

Chinnaraju, K., K. Subramanian, et al. (2010). "Strength properties of HPC using binary, ternary and quaternary cementitious blends." Structural Concrete **11**(Compendex): 191-198.

Use of high-performance concrete for structural applications has grown substantially in recent years. This paper focuses on studying the effect of different supplementary cementitious materials (silica fume, fly ash, ground granulated blast furnace slag, and their combinations) on strength characteristics of high-performance concrete. An experimental test programme was conducted to study the effect of such admixtures on compressive strength at 7 days and 28 days, splitting tensile and flexural tensile strengths at 28 days for high-performance concrete. A set of 60 different concrete mixtures were cast and tested with different cement replacement levels (0, 10, 20 and 30% by weight of cement) by various combinations of fly ash and ground granulated blast furnace slag with silica fume as addition (0, 2-5, 5, 7-5, 10 and 12-5% by weight of cement) for each combination. Super plasticiser was added at different dosages to achieve a constant range of slump for desired workability with a constant water-binder (w/b) ratio. Based on the test results the influence of such admixtures on strength aspects were critically analysed and discussed. A regression analysis has been carried out to relate compressive strength to flexural and splitting tensile strengths, 2010 Thomas Telford and fib.

Chou, J.-S., C.-K. Chiu, et al. (2011). "Optimizing the prediction accuracy of concrete compressive strength based on a comparison of data-mining techniques." Journal of Computing in Civil Engineering **25**(Compendex): 242-253.

This study attempts to optimize the prediction accuracy of the compressive strength of high-performance concrete (HPC) by comparing data-mining methods. Modeling the dynamics of HPC, which is a highly complex composite material, is extremely challenging. Concrete compressive strength is also a highly nonlinear function of ingredients. Several studies have independently shown that concrete strength is determined not only by the water-to-cement ratio but also by additive materials. The compressive strength of HPC is a function of all concrete content, including cement, fly ash, blast-furnace slag, water, superplasticizer, age, and coarse and fine aggregate. The quantitative analyses in this study were performed by using five different data-mining methods: two machine learning models (artificial neural networks and support vector machines), one statistical model (multiple regression), and two metaclassifier models (multiple additive regression trees and bagging regression trees). The methods were developed and tested against a data set derived from 17 concrete strength test laboratories. The cross-validation of unbiased estimates of the prediction models for performance comparison purposes indicated that multiple additive regression tree (MART) was superior in prediction accuracy, training time, and aversion to overfitting. Analytical results suggested that MART-based modeling is effective for predicting the compressive strength of varying HPC age. 2011 American Society of Civil Engineers.

Chowdhury, S., S. Kadam, et al. (2009). "Impact of aggregate sizes on fresh hardened states of concrete." Indian Concrete Journal **83**(Compendex): 25-30.

There is a general view that the size of coarse aggregate affects only the properties of fresh concrete and its impact on hardened properties is insignificant. This paper presents the results of a series of tests on concrete mixtures to examine the impact of different sizes ofcoarse aggregate on fresh and hardened properties of concrete. While slump cone test evaluated the fresh concrete properties, compressive strength test and rapid chloride penetration test (RCPT) determined the hardened state properties. Concrete mixtures were proportioned with three types of cements; Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). Graded coarse aggregates with maximum aggregate size (MSA) as 12.5, 16 and 20 mm; and water-binder ratios of 0.3 and 0.4 were selected for this experimental programme for each cement. The results show that while the coarse aggregate size influences the slump, it is not relevant to compressive strength and RCPT. The latter properties are governed by (w/b) ratio, cement type and cement content.

Chung, Y., H.-C. Shin, et al. (2011). Stress of Sustainable PCC Pavements Under Nonlinear Temperature and Moisture Profiles.

Pavement deformation caused by the temperature and moisture variation within the slab thickness is known as curling and warping. The curling and warping stresses without traffic loading can be critical on the performance of portland cement concrete (PCC) pavements at early ages. Supplementary cementitious materials (SCMs) are used often in concrete mixtures to improve the mixture properties in both fresh and hardened concrete with the current demand for PCC sustainability. Fly ash and slag are one hundred percent recycled materials. They mitigate CO2 emissions in order to produce Portland cement concrete, and reduce landfill disposal of industrial byproducts. In this research, nine concrete mixtures including one control mixture, two binary mixtures, and six ternary mixtures, with various combinations of fly ash (class C), slag (grade 100 ground granulated blast furnace slag), and Portland cement (Type I), were fabricated. The thermal and mechanical properties of selected ternary mixtures were measured to characterize each mixture and critical temperature gradient through the slab thickness were generated using the enhanced integrated climatic model (EICM). Using the measured mechanical properties, nonlinear temperature, and coefficient of thermal expansion (CTE) gradients throughout the slab thickness, the stress analysis of ternary mixtures were performed to calculate the critical tensile stress on the PCC pavements. The calculated tensile stresses of ternary mixture were compared to the tensile strengths of each ternary mixture, and it was found that several ternary mixtures are vulnerable to curling tensile cracking at the bottom of the pavement at an early age.

Collins, F. and J. G. Sanjayan (1998). "Early age strength and workability of slag pastes activated by NaOH and Na2CO3." Cement and Concrete Research **28**(Compendex): 655-664.

This paper reports the results of an investigation on activation of blast furnace slag with the emphasis on achievement of equivalent one-day strength to Portland cement at normal curing temperatures and reasonable workability. The effects of varying dosages of activators NaOH and Na2CO3 are discussed in terms of strength of mini cylinders and also workability by the mini slump method. The results are mainly based on pastes, but comparisons are also made with mortar and concrete results. The effects of preblended gypsum dosage within the slag as well as the effect of ultrafine slag on workability are reported. The results of trials with various water-reducing admixtures and superplasticizers and their effects on strength and workability are reported.

Collins, F. and J. G. Sanjayan (2000). "Cracking tendency of alkali-activated slag concrete subjected to restrained shrinkage." Cement and Concrete Research **30**(Compendex): 791-798.

Alkali-activated slag concrete (AASC) has higher drying shrinkage than ordinary Portland cement concrete (OPCC). However, the cracking tendency of AASC under drying conditions, when restrained, is unreported. AASC has lower elastic modulus, higher creep, and higher tensile strength than OPCC, and the combined effects of these can affect the cracking tendency of AASC. This article reports the results of cracking tendency utilizing restrained ring tests and discusses the development of a restrained beam test. The effects of curing, aggregate type, and incorporation of shrinkage reducing chemical admixture on the cracking tendency of AASC are reported.

Collins, F. and J. G. Sanjayan (2001). "Early age strength and workability of slag pastes activated by sodium silicates." Magazine of Concrete Research **53**(Compendex): 321-326.

This article reports the results of an investigation on the activation of blast furnace slag with emphasis on the achievement of equivalent one-day strength to Portland cement at normal curing temperatures and reasonable workability. The effects of varying dosages of sodium silicate activators are discussed in terms of strength of mini cylinders and also workability by the mini slump method. The results are mainly based on pastes but comparisons are also made with mortar and concrete results. The effects of preblended gypsum dosage within the slag, as well as the effect of ultra fine slag on workability are reported. The results of trials with various water reducing admixtures and superplastisers and their effects on strength and workability are reported.

Corinaldesi, V. and G. Moriconi (2009). "Influence of mineral additions on the performance of 100% recycled aggregate concrete." Construction and Building

Materials **23**(Compendex): 2869-2876.

A judicious use of resources, by using by-products and waste materials, and a lower environmental impact, by reducing carbon dioxide emission and virgin aggregate extraction, allow to approach sustainable building development. Recycled aggregate concrete (RAC) containing supplementary cementitious materials (SCM), if satisfactory concrete properties are achieved, can be an example of such sustainable construction materials. In this work concrete specimens were manufactured by completely replacing fine and coarse aggregates with recycled aggregates from a rubble recycling plant. Also RAC with fly ash (RA + FA) or silica fume (RA + SF) were studied. Concrete properties were evaluated by means of compressive strength and modulus of elasticity in the first experimental part. In the second experimental part, compressive and tensile splitting strength, dynamic modulus of elasticity, drying shrinkage, reinforcing bond strength, carbonation, chloride penetration were studied. Satisfactory concrete properties can be developed with recycled fine and coarse aggregates with proper selection and proportioning of the concrete materials. 2009 Elsevier Ltd. All rights reserved.

Corradi, M., R. Khurana, et al. (2005). New superplasticizers for the total control of performances of fresh and hardened concrete. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

Admixtures for concrete and mortars are considered as additions that modify their properties in the fresh and the hardened state. Often, modifying one property may alter another equally important one, in an adverse manner. This behaviour is highlighted by the reduction of the water cement ratio with the help of the superplasticizers to improve the compressive strengths. Reduction of the water content may lead to a rapid slump loss. The ready mixed concrete industry is asked to provide concrete as per EN 206-1. It has to meet the requirements for the class of consistence, strength and exposure conditions. This is a concrete with long workability retention at a low water cement ratio; two properties in conflict with each other. New admixtures, using nanotechnology, address these demands of extreme performances through the understanding of admixture-cement interaction. Tailor made superplasticizers, meeting the market requirements, where different types of cements (Portland, slag, fly ash, limestone blends) are utilised, are now available. The characteristics and mechanism of action of these new superplasticizers and significant International field applications are presented.

Crouch, L. K. (2009). Rapid Green Base Repair Controlled Low-Strength Material.

High-early strength controlled low-strength material mixture designs containing no portland cement were developed using three different fine aggregates (natural sand, manufactured sand, and limestone screenings) for “green” rapid subgrade repair applications under the direction of the Federal Highway Administration (FHWA). An attempt was made to determine if fifty percent by volume replacement of the fine aggregate with ASTM No.67 stone would allow the modified mixtures to function as emergency “green” base repair materials. The substitution of coarse aggregate increased the static modulus of elasticity by an average of 69 and 78 percent at 24 hours and 28 days, respectively. The mixtures achieved a high level of stiffness, with a minimum of 7.9-GPa (1150-ksi) at one day. Further, the mixtures with coarse aggregate substitution had average California Bearing Ratios (CBR) of 83 and 605 percent at 6.5 and 24 hours, respectively. No mixture with coarse aggregate substitution had a CBR less than 55 at 6.5 hours and the mixture with limestone screenings as fine aggregate had a base quality CBR of 129 percent. At 24 hours, the CBRs of the mixtures with coarse aggregate substitution were above 300, far above the typically specified 100 for a good base. Coarse aggregate substitution increased CBR by 324 and 244 percent on average at 6.5 and 24 hours. Finally, average compressive strengths of the mixtures with coarse aggregate substitution were 0.3 and 3.5-MPa (43 and 507-psi) at 4 and 24 hours, respectively.

Crouch, L. K. and J. Phillips (2009). Lean, green and mean (LGM) concrete. 3rd World of Coal Ash, WOCA Conference, May 4, 2009 - May 7, 2009, Lexington, KY, United states, Unavailable.

Sustainability is currently a factor of extreme importance for the concrete industry. Presently, standard practice limits the replacement of cement with fly ash to only about 25 percent. High Volume Fly Ash (HVFA) concrete has recently gained popularity for a resource-efficient concrete application. However, HVFA concrete contains at least 50 percent by mass of the cementitious material content is fly ash. Therefore, many producers have a desire to be more "green" but are constrained from using HVFA due to its tendencies for slower setting times. In this study two types of LGM mixtures, one containing Class F fly ash and one tertiary mix containing Class F fly ash and slag cement, were compared with an East Tennessee commercial mixture. To ensure statewide applicability each mixture was produced with both river sand and manufactured limestone sand as the fine aggregate. The LGM mixtures reached higher long-term compressive strengths, due to the pozzolanic properties of the fly ash and the lower w/cm ratios. In addition, all four LGM mixes produced one-day compressive strengths exceeding 750 psi (5.17 MPa), which is considered the minimum strength for wrecking concrete forms. The compressive strength of the LGM mixtures all exceed 5000 psi (34.47 MPa) at 28-days. Also, the water permeable void contents and absorptions were lower for the LGM mixtures at all ages, indicating that the durability of the LGM is superior to that of the East Tennessee mixtures. Overall, the LGM mixtures exhibit comparable costs, increased compressive strengths, and enhanced durability properties.

Cusson, D. (2008). Effect of blended cements on effectiveness of internal curing of HPC. Internal Curing of High-Performance Concretes: Laboratory and Field Experiences - ACI Fall Convention 2007, October 14, 2007 - October 18, 2007, Fajardo, Puerto rico, American Concrete Institute.

The effects of internal curing, type of blended cement and coarse aggregate size on early-age expansion, autogenous shrinkage, and strength of high-performance concrete were investigated. To do so, 12 high-performance concrete mixtures were developed and tested under sealed and room temperature conditions. The results were statistically analyzed using the paired comparison design method. It was shown that internal curing of HPC with presaturated porous lightweight aggregate allowed significant autogenous expansion and resulted in considerable reduction in net autogenous shrinkage. The type of cement used in concrete, which was either ordinary portland cement, silica fume blended cement, or slag/silica fume blended cement, had a strong effect on early-age expansion, autogenous shrinkage, and the effectiveness of internal curing. For instance, the concrete specimens made with silica fume blended cement, which yielded the largest autogenous shrinkage strains under sealed conditions, obtained the best reductions in autogenous shrinkage when tested under an internal curing condition.

Cusson, D., Z. Lounis, et al. (2010). "Benefits of internal curing on service life and life-cycle cost of high-performance concrete bridge decks - A case study." Cement and Concrete Composites **32**(Compendex): 339-350.

This paper investigates the impact of internal curing on the service life of high-performance concrete (HPC) bridge decks by using analytical models to predict the times to onset of corrosion, onset of corrosion-induced damage, and failure of decks. Three bridge deck design options were compared: (i) normal concrete deck; (ii) HPC deck with supplementary cementing materials (SCM); and (iii) HPC deck with SCM and internal curing. It was found that the use of internal curing can extend the service life of high-performance concrete bridge decks by more than 20 years, which is mainly due to a significant reduction in the rate of penetration of chlorides in concrete as a result of reduced early-age shrinkage cracking and reduced chloride diffusion. Compared to normal concrete, HPC with SCM and internal curing was predicted to add more than 40 years to the service life of bridge decks in severe environmental conditions. Life-cycle cost reductions of 40% and 63% were estimated when conventional HPC and internally-cured HPC were used in bridge decks instead of normal concrete, respectively, despite the fact that the in-place unit cost of internally-cured HPC can be 4% higher than that of conventionally-cured HPC, which in turn can be up to 33% higher than that of normal concrete. This is due to a longer service life and less frequent maintenance activities offered by low-permeability HPC bridge decks. Crown Copyright 2010.

Cyr, M., P. Lawrence, et al. (2005). "Mineral admixtures in mortars: Quantification of the physical effects of inert materials on short-term hydration." Cement and Concrete Research **35**(Compendex): 719-730.

This work is the second part of an overall project, the aim of which is the development of general mix design rules for concrete containing different kinds of mineral admixtures. The first part presented the separation of the different physical effects responsible for changes in cement hydration when chemically inert quartz powders are used in mortars. This second part describes the development of an empirical model, based on semiadiabatic calorimetry measurements, which leads to the quantification of the enhancement of cement hydration due to the heterogeneous nucleation effect at short hydration times. Experimental results show that not all the admixture particles participate in the heterogeneous nucleation process. Consequently, the concept of efficient surface Seff is introduced in the model. Seff is the total admixture surface S (m2 of mineral admixture/kg of cement) weighted by a function (p). The efficiency function (p) depends only on the replacement rate p and is independent of time, fineness and type of mineral admixture used. It decreases from 1 to 0: Low replacement rates give an efficiency value near 1, which means that all admixture particles enhance the hydration process. An efficiency value near 0 is obtained for high replacement rates, which indicates that, from the hydration point of view, an excess of inert powder does not lead to an increase in the amount of hydrates compared with the reference mortar without mineral admixture. The empirical model, which is mainly related to the specific surface area of the admixtures, quantifies the variation of the degree of hydration induced by the use of inert mineral admixtures. One application of the model, coupled with Powers' law, is the prediction of the short-term compressive strength of mortars. 2004 Elsevier Ltd. All rights reserved.

Cyr, M., P. Rivard, et al. (2009). "Reduction of ASR-expansion using powders ground from various sources of reactive aggregates." Cement and Concrete Composites **31**(Compendex): 438-446.

This study assesses the potential of ground reactive aggregates to reduce or suppress expansion associated with ASR. Particular attention is paid to fine admixtures (80 m) added to mortars, which contain the reactive aggregates from which the fines were ground. Many varieties of aggregate (quarried and natural, igneous, metamorphic and sedimentary rocks) from different geological settings were subjected to an autoclave test. The replacement of 10-20% of the sand by reactive aggregate powder (RAP) of different surface areas from 11 different reactive aggregates led to the reduction of ASR-expansion by up to 78% compared with control mortars. Increasing the amount of fines led to better performance. No clear relationship was observed between the reactivity degree of the aggregates and the efficiency of their ground powder to reduce expansion. A general trend was found regarding the fineness of ground aggregates: finer particles were more effective in reducing expansion. The reduction of the expansion due to RAP is discussed in terms of parameters affecting its efficiency and of the mechanisms responsible for the reduction. 2009 Elsevier Ltd. All rights reserved.

Damtoft, J. S., J. Lukasik, et al. (2008). "Sustainable development and climate change initiatives." Cement and Concrete Research **38**(Compendex): 115-127.

In the present paper we argue that the cement and concrete industry is contributing positively to the Climate Change Initiative by:* Continuously reducing the CO2 emission from cement production by increased use of bio-fuels and alternative raw materials as well as introducing modified low-energy clinker types and cements with reduced clinker content.* Developing concrete compositions with the lowest possible environmental impact by selecting the cement type, the type and dosage of supplementary cementitious materials and the concrete quality to best suit the use in question.* Exploiting the potential of concrete recycling to increase the rate of CO2 uptake.* Exploiting the thermal mass of concrete to create energy-optimized solutions for heating and cooling residential and office buildings. 2007 Elsevier Ltd. All rights reserved.

Darquennes, A., M. I. A. Khokhar, et al. (2011). "Early age deformations of concrete with high content of mineral additions." Construction and Building Materials **25**(Compendex): 1836-1847.

Under the project "EcoBeton" (Green concrete) funded by the French National Agency (ANR), concrete mixtures with a high quantity of mineral additions, such as blast-furnace slag and fly ash were studied. A first approach to quantify their cracking risk was to measure their plastic shrinkage evolution. In parallel, the evolution of other parameters such as setting, capillary depression and porosity were also monitored to relate this deformation to the evolution of the microstructure of the studied mixtures. Setting monitoring by means of ultrasonic measurements allows obtaining significant macroscopic information such as hardening process and rigidity evolution. The correlation between these different parameters shows that the plastic shrinkage evolution can be divided into three phases driven by different mechanisms. Moreover, it appears that the use of mineral additions has an effect on the plastic shrinkage behaviour, but this impact is not proportional to the percentage of additions. It depends on the hydration process and the microstructure of the cementitious materials. So, it seems that an optimum content of cement replacement by mineral additions must be sought to limit the development of plastic shrinkage of concretes with mineral additions at early age. However, a high rate of substitution of cement may affect the early age compressive strength of the concrete. So these mixtures were also optimised to obtain a significant compressive strength at an early age, but this optimisation leads to a higher risk of cracking for some of them. 2010 Elsevier Ltd. All rights reserved.

Darquennes, A., M. I. A. Khokhar, et al. (2011). "Early age deformations of concrete with high content of mineral additions." Construction & Building Materials **25**(4): 1836-1847.

Abstract: Under the project “EcoBéton” (Green concrete) funded by the French National Agency (ANR), concrete mixtures with a high quantity of mineral additions, such as blast-furnace slag and fly ash were studied. A first approach to quantify their cracking risk was to measure their plastic shrinkage evolution. In parallel, the evolution of other parameters such as setting, capillary depression and porosity were also monitored to relate this deformation to the evolution of the microstructure of the studied mixtures. Setting monitoring by means of ultrasonic measurements allows obtaining significant macroscopic information such as hardening process and rigidity evolution. The correlation between these different parameters shows that the plastic shrinkage evolution can be divided into three phases driven by different mechanisms. Moreover, it appears that the use of

mineral additions has an effect on the plastic shrinkage behaviour, but this impact is not proportional to the percentage of additions. It depends on the hydration process and the microstructure of the cementitious materials. So, it seems that an optimum content of cement replacement by mineral additions must be sought to limit the development of plastic shrinkage of concretes with mineral additions at early age. However, a high rate of substitution of cement may affect the early age compressive strength of the concrete.So these mixtures were also optimised to obtain a significant compressive strength at an early age, but this optimisation leads to a higher risk of cracking for some of them. [ABSTRACT FROM AUTHOR]

Darquennes, A., S. Staquet, et al. (2011). "Effect of autogenous deformation on the cracking risk of slag cement concretes." Cement and Concrete Composites **33**(Compendex): 368-379.

Autogenous deformation under restrained conditions often leads to cracking and durability problems in concrete structures. It is therefore important to monitor accurately the early age development of autogenous deformation. However, its expression depends strongly on the measuring methods and on the choice of the time-zero. In order to determine the effect of slag on the evolution of autogenous deformation, a test rig was designed to monitor this deformation for three concretes with different slag content. The choice of different time-zero was also discussed based on different methods: setting evolution, time of peak expansion and evolution of deformation rate. Moreover, their restrained shrinkage was studied by means of a Temperature Stress Testing Machine (TSTM). Following these experiments, the slag cement concretes crack later than the Portland cement concrete despite the fact that they are characterized by a larger autogenous shrinkage. This behavior is mainly due to the expansion of their cement matrix at early age and their largest capacity to relax internal stresses. 2011 Published by Elsevier Ltd.

Darquennes, A., S. Staquet, et al. (2009). Autogenous shrinkage development and setting monitoring of slag cement concrete. 8th International Conference on Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures, September 30, 2008 - October 2, 2008, Ise-Shima, Japan, CRC Press.

Slag cement concrete presents many advantages leading to its intensive use in the construction industry in Belgium. However, it may exhibit a high sensitivity to cracking at early ages. The understanding of this behaviour involves a detailed study of its deformations at early ages. Therefore, our analysis begins with the autogenous deformations examination and the development of an experimental

device enabling to measure this deformation in isothermal conditions. For processing of these measurements, two essential parameters are needed: the apparent activation energy and the zero time obtained by means of mechanical and ultrasonic tests respectively. 2009 Taylor Francis Group.

Darquennes, A., S. Staquet, et al. (2009). Early age properties development of concrete with different slag contents. Transition from Fluid to Solid: Re-examining the Behavior of Concrete at Early Ages - Technical Session at the 2009 ACI Spring Conference, March 15, 2009 - March 19, 2009, San Antonio, TX, United states, American Concrete Institute.

Slag cement concrete is characterized by many advantages, which leads to its intensive use in the construction industry in Belgium. However, it may exhibit a high sensitivity to cracking at early age in case of restrained shrinkage. The understanding of this behavior involves an in-depth analysis of the early age deformations. Firstly, an experimental investigation of the mechanical properties (compression strength, elastic modulus) and the microstructure evolution (hydration kinetic and hydrates development) was performed on three concretes containing different slag proportions (o%, 42% and 71% of the mass of binder), but with identical total binder content, in order to understand the effect of slag on these parameters. Secondly, the autogenous deformations were measured from casting time on concrete cylinders under isothermal conditions. The apparent activation energy and the time of initial set were also evaluated in order to analyse these deformations. The apparent activation energy is used to convert the actual age into equivalent age to express the concrete properties independently of the temperature variations. The time of initial set from which the strains are expressed is determined by ultrasonic detection and by the Kelly-Bryant method.

Darwin, D., J. Browning, et al. (2004). "Control of cracking in bridge decks: Observations from the field." Cement, Concrete and Aggregates **26**(Compendex): 148-154.

Crack surveys of bridge decks, performed over a 10-year period in northeast Kansas as part of three studies, provide strong guidance in identifying the parameters that control cracking in these structures. The surveys involve steel girder bridges - bridges that are generally agreed to exhibit the greatest amount of cracking in the concrete decks. The surveys include monolithic decks and decks with silica fume and conventional concrete overlays. The study demonstrates that crack density increases as a function of cement and water content, and concrete strength. In addition, crack density is higher in the end spans of decks that are integral with the abutments than decks with pin-ended supports. Most cracking occurs early in the life of a bridge deck, but continues to increase over time. This is true for bridges cast in both the 1980s and the 1990s. A key observation, however, is that bridge decks cast in the 1980s exhibit less cracking than those in the 1990s, even with the increase in crack density over time. Changes in materials, primarily cement fineness, and construction procedures over the past 20 years, are discussed in light of these observations.

A major bright spot has been the positive effect of efforts to limit early evaporation, suggesting that the early initiation of curing procedures will help reduce cracking in bridge decks.

Day, R. L. (1990). Strength, durability and creep of fly-ash concrete. Part II. Serviceability and Durability of Construction Materials - Proceedings of the First Materials Engineering Congress Part 1 (of 2), August 13, 1990 - August 15, 1990, Denver, CO, USA, Publ by ASCE.

Tests on sulphate durability of various plain and fly ash mortars soaked in pH-controlled sulphate solutions were performed. The performance of several types of ash have been examined, including those described in a previous paper. The sulphate-expansion results indicate that care must be taken when choosing the type of fly ash for applications where sulphate durability is critical. The shrinkage and creep behaviour of plain and fly-ash concretes (30% and 50% replacement levels by volume) under saturated and drying conditions is also reported. Two design grades of concrete were manufactured and tested: (a) a 'high' strength, 45 MPa, non air-entrained mix, and (b) a 'low' strength 25 MPa air-entrained mix. All specimens were loaded when they achieved the same nominal strengths (rather than loading at a given age) - 40 MPa for the high-strength mixes and 20 MPa for the low-strength mixes. In these tests the time-dependent behaviour of concretes made with three different fly ashes, as well as appropriate plain control mixes, was examined. In general fly ash concretes showed reduced shrinkage and creep when compared to control concretes although the degree of improvement depended upon the type of fly ash used.

De Gutierrez, R. M. (2003). "Effect of supplementary cementing materials on the concrete corrosion control." Revista de Metalurgia (Madrid)(Compendex): 250-255.

Failure of concrete after a period of years, less than the life expected for which it was designed, may be caused by the environment to which it has been exposed or by a variety of internal causes. The incorporation of supplementary materials has at the Portland cement the purpose of improving the concrete microstructure and also of influence the resistance of concrete to environmental attacks. Different mineral by-products as ground granulated blast furnace slag (GOBS), silica fume (SF), metakaolin (MK), fly ash (FA) and other products have been used as supplementary cementing materials. This paper is about the behavior of concrete in the presence of mineral additions. Compared to Portland cements, blended cements show lower heat of hydration, lower permeability, greater resistance to sulphates and sea water. These blended cements find the best application when requirements of durability are regarded as a priority specially on high performance concrete.

De Schutter, G. and L. Taerwe (2000). "Fictitious degree of hydration method for the basic creep of early age concrete." Materials and Structures/Materiaux et Constructions **33**(Compendex): 370-380.

At the Magnel Laboratory for Concrete Research, University of Ghent, Belgium, an extensive experimental programme was set up in order to study the basic creep behaviour of early age concrete. Tests were carried out for a loading age ranging from 12 hours to 14 days, with two different stress levels: 20% and 40% of the compressive strength at the age of loading. Three different cement types were considered: one Portland cement and two blast furnace slag cements. Based on the experimental results a new fundamental model is proposed. The basic creep evolution is completely related to the evolution of the degree of hydration. Time is no longer an explicit parameter. The stress-strain non-linearity of the basic creep is correlated with the stress-strain non-linearity of the instantaneous deformation at loading. Furthermore, based on the fundamental basic creep model and following the principles of the equivalent time method a new degree of hydration based formulation for the early age basic creep under varying stresses is developed: the fictitious degree of hydration method. Simulations of experimental results show that this new method provides a good alternative for the traditional superposition method.

De Souza Rodrigues, C., K. Ghavami, et al. (2010). "Rice husk ash as a supplementary raw material for the production of cellulose-cement composites with improved performance." Waste and Biomass Valorization **1**(Compendex): 241-249.

Rice husk is an agricultural by-product worldwide in large quantities available. This is a suitable biomass source for energy production. Compared to other agricultural by-products, the burned rice husk presents a high yield of ash (about 20%) mainly composed of silica that will be mostly amorphous when properly incinerated. Extensive research in the past three decades has allowed the introduction of rice husk ash (RHA) as a supplementary raw material in cement-based products, whereby significant improvements in strength and durability can be achieved, also contributing to ecological demands. This paper investigates the influences of two RHA admixtures on the physical and mechanical properties of bamboo-pulp-reinforced cement composites. These fibers suffer early degradation in the alkaline environment. RHA blending will reduce the ordinary Portland cement (OPC) content and can improve strength and density due to more effective particle packing, and significantly diminish alkalinity. The composites were produced in the laboratory by a method resembling the Hatschek process used by the fibrocement industry, with fixed reinforcement content and varying amounts of RHA. The results revealed that partial replacement of ordinary Portland cement by up to 30% of RHA had not impaired the mechanical behavior of the composites. Further, use of low-carbon-content RHA decreased porosity in the matrix and enhanced interfacial bonding of the composites. Since the deterioration of cellulose- cement composites is closely related to moisture movement and alkalinity, it is concluded that introduction of low-carbon content RHA can lead to improved durability performance of these composites. Springer Science+Business Media B.V. 2010.

Deb, S. K. and A. C. Borsaikia (2006). "Mixture proportioning of mass concrete for gravity dam based on fineness modulus and geometrical gradation." Indian Concrete Journal **80**(Compendex): 52-56.

Mixture proportioning procedure for mass concrete using a maximum size of aggregate (MSA) upto 150 mm based on fineness modulus and geometrical gradation is presented in this paper. In this approach, reduction in heat of hydration is achieved by lowering cement content in the concrete mix. Specially blended low-heat portland pozzolana cement (PPC) was used in this study. Fly ash or other supplementary cementitious material was not available in the vicinity and hence not used in the study. The ideal fineness moduli were experimentally determined for 40 mm MSA by making concrete mixtures with aggregates of different fineness modulus and determining which of them give the highest compressive strength for a given cement-to-aggregate ratio. For each cement-to-aggregate ratio, three different mixture proportions with different water-to-cement ratios were considered. Examples on mixture proportioning of mass concrete with 80 mm and 150 mm MSA, based on the previously established mixture proportion for 40 mm MSA, are presented in this paper.

Debaiky, A. S., M. F. Green, et al. (2006). "Long-Term Monitoring of Carbon Fiber-Reinforced Polymer-Wrapped Reinforced Concrete Columns Under Severe Environment." ACI Structural Journal **103**(6): pp 865-873.

Although fiber-reinforced polymer (FRP) wraps show promise in restoring the integrity of corroded reinforced concrete structures, their effectiveness and impact on corrosion activity is still in question. This study investigates these issues by inducing corrosion in columns using an aggressive environment that simulates natural corrosion and using carbon FRP (CFRP) wraps for repair of corrosion-damaged reinforced concrete columns. The experiment included 12 large-scale circular columns. Ten columns were cast with 3% sodium chloride (by weight of cement) premixed with the mixing water in the outer 75 mm (3 in.) thick ring. The two remaining columns were uncontaminated and used as control specimens (one wrapped and one unwrapped). The ten chloride-laden columns were corroded using an aggressive environment. The experiment incorporated electrochemical chloride extraction (ECE) treatment on four of the columns followed by CFRP wrapping on eight columns. The results indicate that the CFRP wraps applied over corrosion-damaged reinforced concrete columns significantly decreased the corrosion rate of the reinforcement and restored the structural integrity of the column. The ECE and wrapping combination provided the best protection against future corrosion. The strength of the wrapped columns was very close to that of the wrapped control column. The application of the wraps would be most effective when applied at early signs of corrosion.

Demerchant, D. P., B. Fournier, et al. (2000). "Alkali-aggregate research in New Brunswick." Canadian Journal of Civil Engineering **27**(Compendex): 212-225.

New Brunswick is located within the northeast-southwest trending Appalachian Region. The basement rocks consist largely of metamorphosed sedimentary types with some granitic intrusions and the composition of the natural gravels reflects the bedrock types. Research into alkali-aggregate reaction (AAR) problems in the province was sponsored initially solely by CANMET and more recently in association with the Department of Transportation. The research consisted of (i) petrographic studies of aggregates, (ii) petrographic studies and case histories of existing concrete structures, and (iii) laboratory expansion testing of concrete and mortar bar specimens. Alkali-aggregate reaction has been found to be one of the factors responsible for premature concrete deterioration in New Brunswick. Visual signs of Alkali-aggregate reaction require up to 10 years to appear and the reaction takes up to 30 years to fully develop. Principal reactive rock types are greywacke, argillites, and fine-grained volcanic rocks. The reactive component is thought to be fine-grained quartz less than 100 m in size. Laboratory expansion test results on concrete specimens are sensitive to alkali levels. Concrete prism tests (CSA A23.2-14A) with 5.5-5.4 kg/m3 Na2O equivalent have been used to predict aggregate performance. By comparison the water soluble alkali contents of field concretes constructed since about 1970 have been found to range from 3.5 to 5 kg/m3 Na2O equivalent. Accelerated mortar bar expansion test results (CSA A23.2-25A) do not correlate well with concrete prism expansion tests and indicate a much higher percentage of deleterious aggregates. Use of supplementary cementing materials such as fly ash and silica fume have been found to be effective in long duration laboratory tests to control aggregate reactions.

Demirboga, R. (2003). "Influence of mineral admixtures on thermal conductivity and compressive strength of mortar." Energy and Buildings **35**(Compendex): 189-192.

Cement paste with natural sand content and the effect of silica fume (SF), class C fly ash (FA) and blast furnace slag (BFS) on the thermal conductivity and compressive strength of mortar was investigated. SF, FA and BFS were added as replacement for cement by decreasing the cement in the ratios of 10, 20 and 30% by weight. The maximum thermal conductivity of 1.186W/mK was observed with the samples containing plain cement. It decreased with the increase of SF, FA and BFS as replacement for cement. The reductions due to SF were 17, 31 and 40% for 10, 20 and 30% SF (replacement for cement), respectively. FA induced reductions of 14, 26 and 33% for 10, 20 and 30% FA, respectively. Both SF and FA had a decreasing effect on thermal conductivity. BFS effect on the thermal conductivity, was approximately the same at all percent (BFS replacement for Portland cement, PC) and the reduction values were between 12 and 14%. Ten percent SF and 10 and 20% FA and all level BFS increased compressive strength a little at 120 days. However, except 10% SF the other admixters at all level replacement decreased compressive strength at early ages, especially FA decreased compressive strength as function of replacement percent. 2002 Elsevier Science B.V. All rights reserved.

Demirboga, R. and R. Gul (2006). "Production of high strength concrete by use of industrial by-products." Building and Environment **41**(Compendex): 1124-1127.

Blast furnace slag aggregates (BFSA) were used to produce high-strength concretes (HSC). These concretes were made with total cementitious material content of 460-610 kg/m3. Different water/cement ratios (0.30, 0.35, 0.40, 0.45 and 0.50) were used to carry out 7- and 28-day compressive strength and other properties. Silica fume and a superplasticizer were used to improve BFSA concretes. Slump was kept constant throughout this study. Ten percent silica fume was added as a replacement for ordinary portland cement (OPC) in order to obtain HSC. The silica fume was used as highly effective micro-filler and pozzolanic admixture. Superplasticizer at dosages of 2%, 1.5%, 1%, 0.5% and 0% by OPC weight for 0.30, 0.35, 0.40, 0.45 and 0.50 w/c ratios, respectively, were adopted. Results showed that compressive strength of BFSA concretes were approximately 60-80% higher than traditional (control) concretes for different w/c ratios. These concretes also had low absorption and high splitting tensile strength values. It is concluded that BFSA, in combination with other supplementary cementitious materials, can be utilized in making high strength concretes. 2005 Elsevier Ltd. All rights reserved.

Demirboga, R., I. Turkman, et al. (2004). "RELATIONSHIP BETWEEN ULTRASONIC VELOCITY AND COMPRESSIVE STRENGTH FOR HIGH-VOLUME MINERAL-ADMIXTURED CONCRETE." Cement and Concrete Research **34**(12): p. 2329-2336.

This study focused on the relationship between compressive strength of mineral admixtured concrete and ultrasonic pulse velocity (UPV). Both compressive strength and UPV were very low for all levels of mineral admixtures at an early age of curing, especially for samples containing fly ash. With the increase of curing period, both compressive strength and UPV of all the samples increased.

Demirboga, R., I. Turkmen, et al. (2004). "Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete." Cement and Concrete Research **34**(Compendex): 2329-2336.

Ultrasound is used to evaluate the compressive strength of concrete with mineral admixtures. In addition, the relationship between ultrasound velocity and compressive strength of concrete are evaluated. High-volume fly ash (FA), blast furnace slag (BFS) and FA + BFS are used as the mineral admixtures in replacement of Portland cement (PC). Compressive strength and ultrasonic pulse velocity (UPV) were determined at the 3-, 7-, 28- and 120-day curing period. Both compressive strength and UPV were very low for all the levels of mineral admixtures at an early age of curing, especially for samples containing FA. However, with the increase of curing period, both compressive strength and UPV of all the samples increased. The relationship between UPV and compressive strength was exponential for FA, BFS and FA+BFS. However, constants were different for each mineral admixture and each level replacement of PC. 2004 Elsevier Ltd. All rights reserved.

Detwiler, R. J., J. I. Bhatty, et al. (2001). "DURABILITY OF CONCRETE CONTAINING CALCINED CLAY." Concrete International **23**(4): p. 43-47.

This article reports a laboratory study of the behavior of concretes containing calcined clay, either as an admixture or as a component of blended cement. The blended cement was originally formulated with a lower content of supplementary cementing material than optimum in order to be used with a Class C fly ash. The tests conducted in Phase I of this study relate primarily to the durability of concrete containing alkali-reactive aggregates and exposed to deicing salts. Phase II pertains to concretes using in the construction of a parking garage at

Kansas City International Airport. Both Phase I and Phase II show the benefits of using calcined clay in concrete, either in binary mixtures or in combination with fly ash or silica fume. These stem from improvements to the pore structure of the concrete that enhance the concrete's resistance to the ingress of chloride ions and other harmful materials.

Detwiler, R. J., C. A. Fapohunda, et al. (1994). "Use of supplementary cementing materials to increase the resistance to chloride ion penetration of concretes cured at elevated temperatures." ACI Materials Journal **91**(Compendex): 63-66.

It has long been known that elevated curing temperatures, while accelerating the early strength gain of concrete, reduce the ultimate strength. Recent research has shown that elevated curing temperatures can also reduce the resistance to chloride diffusion of plain portland cement concretes. This paper describes an investigation of the chloride penetration of 0.40 and 0.50 water-cement ratio (w/c) concretes containing either 5 percent silica fume or 30 percent blast furnace slag (substitution by mass) cured at elevated temperatures. Plain portland cement concretes were used as controls. The concretes were cured at constant temperatures of 23, 50, or 70 C (73, 122, or 158 F) to a degree of hydration of approximately 70 percent. Supplemental tests were performed on concretes cured overnight using a steam-curing regime. Both the silica fume and slag concretes performed better than the controls in these tests.

Devillers, P., J. P. Bournazel, et al. (2006). Durability Indicators of High Performance Concrete Including a Ternary Blend. Seventh CANMET/ACI 2006: Durability of Concrete (SP-234), Farmington Hills, MI, ACI.

In the framework of radioactive waste storage, the French atomic energy agency needs to design a concrete container with a service life of 300 years. Regarding durability and mechanical problems, we propose a mixture of proportions of high performance and self compacting concrete including a ternary blend. In order to evaluate the durability of such a formulation a large set of experiments was carried out. Gas and water permeability, diffusivity of chlorides, carbonation, freezing and thawing resistance were studied in laboratory. All results obtained during this study show that the concrete mixture proportions chosen are in accordance with the durability criteria imposed for security reasons. Nevertheless several complementary tests were performed to investigate the microstructure of the material, such as x ray diffraction, thermo-gravimetric analysis or microscope analysis, in order to confirm the results obtained for the durability indicators. In this paper we present all the results obtained during this experimental study, which has been carried out over two years. All values of durability indicators obtained will be introduced in mathematical models in order to verify the service life of 300 years.

Diaz, E. I., E. N. Allouche, et al. (2010). "Factors affecting the suitability of fly ash as source material for geopolymers." Fuel **89**(Compendex): 992-996.

The suitability of fly ash stock piles for geopolymer manufacturing was studied. The results of chemical analyses, X-ray diffraction (XRD) and particle size distribution (PSD) of five sources of fly ash obtained from coal-fired power generating plants in the US are presented. Geopolymer paste and concrete specimens were prepared from each stock pile. The specimens were subjected to an array of chemical and mechanical tests including XRD, RAMAN spectroscopy, setting time and compressive strength. A correlation study was undertaken comparing the fly ash precursor chemical and crystallographic compositions as well as particle size distribution, with the mechanical and chemical characteristics of the resulting geopolymer. Factors inherent to the fly ash stockpile such as particle size distribution, degree of vitrification and location of the glass diffraction maximum were found to play an important role in the fresh and hardened properties of the resulting geopolymer. 2009 Elsevier Ltd. All rights reserved.

Dinakar, P., K. G. Babut, et al. (2009). "Corrosion resistance performance of high-volume fly-ash self-compacting concretes." Magazine of Concrete Research **61**(Compendex): 77-85.

The corrosion performance of self-compacting concretes with high-volume replacements of fly ash was evaluated by some electrochemical techniques. In this study, eight self-compacting fly-ash concretes of various strength grades were designed at desired fly ash percentages of 0, 10, 30, 50, 70 and 85%, and were compared with five different mixtures of normal vibrated concretes at equivalent strength grades. The corrosion characteristics of the developed concretes were studied through the measurement of resistivity, pH, carbonation depth, half-cell potential and corrosion rate. Results demonstrate that self-compacting concretes at all levels of fly ash replacement performed significantly better than the corresponding normal vibrated concretes. This can be mainly attributed to the pozzolanic activity of fly ash. The carbonation was, however, higher in low- and medium-strength self-compacting concretes compared to the normal concretes.

Dockter, B. C. (2009). Using class C fly ash to mitigate alkali-silica reactions in concrete. 3rd World of Coal Ash, WOCA Conference, May 4, 2009 - May 7, 2009, Lexington, KY, United states, Unavailable.

High-calcium fly ashes, classified as Class C by ASTM International (ASTM) C618 definition, are often excluded as a means to mitigate alkali-silica reactions (ASR) in concrete. This is because a relationship between high-calcium content and expansion was often documented when Class C fly ash was used at a 10% to 15% replacement level in concrete. It is generally true that low replacement levels (15%) of Class C fly ash may not offer ASR mitigation; however, it has been demonstrated that Class C fly ashes can mitigate the effects of ASR at higher replacement levels than specified. For highly reactive aggregates, the required dosage of Class C fly ash may be quite high, resulting in reduced early strengths. In some cases, the amount of Class C fly ash needed to control ASR may exceed specification limits set by state Department of Transportations. In these instances, combining Class C fly ash with silica fume, for example, can help to mitigate ASR and improve early strength gain. The University of North

Dakota Energy Environmental Research Center has completed the second year of a 3-year series of investigations to evaluate the performance of several Class C fly ashes (10% CaO) using existing predictive ASR test methods. ASTM standard methods were applied to fly ash samples and cast specimens produced using varying levels of Class C fly ashes. The results have confirmed limited and unpublished work that indicates the effectiveness of using higher percentages of Class C fly ash to mitigate ASR when using moderately reactive aggregates. Results indicate that all the Class C fly ashes submitted for this study helped reduce the expansion of the mortar mixtures, even at the lowest replacement level of 15%. This reduction in expansion continued as the fly ash content increased.

Domone, P. L. and M. N. Soutsos (1995). "Properties of high-strength concrete mixes containing PFA and ggbs." Magazine of Concrete Research **47**(Compendex): 355-367.

The effects of incorporating pulverized fuel ash (PFA) and ground granulated blastfurnace slag (ggbs) on the workability (stump), adiabatic temperature rise during hydration and long-term (up to 570 days) strength of high-strength concretes have been measured. Binary (PFA/ggbs and Portland cement) and ternary (PFA/ggbs plus microsilica and Portland cement) blends at water-binder ratios from 0.38 to 0.20 have been tested. The results show broadly similar effects to those in lower strength concrete, although of differing magnitude in some cases. Some potential advantages of ternary blends for optimization of properties have been demonstrated.

Douglas, E., A. Bilodeau, et al. (1992). "Properties and durability of alkali-activated slag concrete." ACI Materials Journal **89**(Compendex): 509-516.

The purpose of this study was to formulate the proportioning of concrete mixes made with ground granulated blast furnace slag activated with sodium silicate, and to determine their properties and durability. Six mixes were made with a solution having silicate modulus Ms = 1.47 and one mix with sodium silicate of Ms = 1.22. All the mixes were air-entrained. Compressive and flexural strengths, Young's modulus of elasticity, shrinkage, and chloride ion penetration were determined. Measurements of length and mass changes, as well as resonant frequency and pulse velocity, were performed to evaluate the resistance of the concretes to repeated cycles of freezing and thawing. Sulfate resistance was evaluated by the same technique. The study shows that air content, volume of air-entraining admixture, slump, and early-age compressive strength are affected by the sodium silicate-slag ratio. Compressive and flexural strengths of the concretes at 7 days and beyond are comparable to or better than those of a portland cement concrete with equivalent water-cement ratio and workability. Drying shrinkage and expansion shrinkage strains were higher than those of a comparable portland cement concrete. Low sodium silicate-slag ratios adversely affected the resistance to repeated freezing and thawing cycles but improved the resistance to chloride ion penetration. Longer term test measurements are necessary to evaluate the resistance of the concretes to sulfate attack.

Douglas, E. and G. Pouskouleli (1991). "Prediction of compressive strength of mortars made with portland cement - blast-furnace slag - fly ash blends." Cement and Concrete Research **21**(Compendex): 523-534.

A statistical design for three component mixtures was used to select the mixture proportions of the experimental points required to describe the strength development of portland cement - blast-furnace slag - fly ash mortars at various ages. A minimum of seven design points was required to fit the equations for a three-component mixture. With the experimental compressive strength values of the seven design points, a computerized statistical approach was used to find the equations governing strength development of the ternary systems at different ages. Once the equations were obtained, experimental checkpoints were run to verify the predicted compressive strength values of several mixtures at 1, 7, 28 and 91 days. With few exceptions, the accuracy of the predicted values was 95% or better. Compressive strengths of mortars of ternary blends at the ages mentioned above can also be predicted from the ternary diagrams with the iso-strength contour plots corresponding to the models chosen.

Duchesne, J. and M.-A. Berube (2001). "Long-term effectiveness of supplementary cementing materials against alkali-silica reaction." Cement and Concrete Research **31**(Compendex): 1057-1063.

The long-term effectiveness of six supplementary cementing materials (SCM) were tested according to the CSA-A23.2-14A Concrete Prism Method in the presence of two very alkali-silica reactive aggregates from Canada. Three fly ashes, two silica fumes, and one ground granulated blast furnace slag (GGBFS) were selected based on their elemental composition in order to represent a wide range of composition. The performance of SCMs in suppressing expansion due to alkali-silica reaction was compared with that obtained by a low-alkali cement. Pore solution composition of the mixtures was also determined. Results show that expansion curves flatten out after 2 years of curing. This phenomenon was due to alkali leaching from the concrete prisms and alkali binding by the alkali aggregate reaction products in the presence of the very reactive aggregates used, which was supported by very low alkali ion concentrations measured on concrete samples at the end of the experiment. A 2-year expansion limit is then suggested when using the CAN/CSA-A23.2-14A method to evaluate mixtures containing SCM. The proportion of SCM and total alkali content of the concrete are very significant factors controlling concrete expansion. 2001 Elsevier Science Ltd. All rights reserved.

Duran-Herrera, A., C. A. Juarez, et al. (2011). "Evaluation of sustainable high-volume fly ash concretes." Cement and Concrete Composites **33**(Compendex): 39-45.

This article presents experimental research work oriented toward developing practical design tools for industrial application, and illustrates the potential benefits of the synergistic effect of an ASTM C 618 Class F fly ash (FA) and a high-range polycarboxylate superplasticizer (SP) in the production of conventional concrete. The different concretes considered in this study were produced with mass substitutions of cement by FA between 15% and 75%, and a target slump of 200 mm 20 mm. The total water content was minimized through the use of an optimum SP dosage that resulted in water reductions of 18%, 15% and 11% respectively for the reference mixtures of w/b = 0.5, w/b = 0.55, and w/b = 0.6, which leads to the same percentage reductions of cement. Heat release and heat flow were analyzed through isothermal and semi-adiabatic calorimetry, illustrating that heat release per unit mass of cement is independent of w/b, contrasting with the time of setting results that vary by several hours between the three different w/b ratios. The paper highlights the beneficial effect of the SP in terms of cement reduction and slump retention. Correlations between the FA substitution and slump loss, setting times, compressive strength and static modulus of elasticity (E) were established and they represent very useful tools for the practical applications of the results. Compressive strength developments up to an age of 56 d are also reported, as well as correlations between the modulus of rupture and compressive strength or splitting tensile strength at an age of 28 d. 2010 Elsevier Ltd.

Earney, T. P., V. S. Gopalaratnam, et al. (2006). Understanding Early-Age Shrinkage of High-Performance Concrete for Bridge Deck Applications.

The paper discusses results and analyses from a series of early-age autogenous shrinkage measurements for several high performance concrete mixtures developed for bridge deck applications using fly ash and silica fume tests. These tests were performed under temperature-controlled conditions to investigate the influence of mixture proportions and binder composition on early-age shrinkage measurements. For bridge decks, it is desirable to minimize autogenous shrinkage. Because autogenous shrinkage is due to self-dessication, it cannot be mitigated with curing techniques. Rather it must be addressed during mix design. Excessively high autogenous shrinkage can lead to cracking that reduces the life span of bridge decks and negates the benefit of reduced permeability by providing a direct path for chlorides to reach reinforcing steel. Corrections for measured strains resulting from temperature effects are also discussed. The problem of autogenous shrinkage measurement at early ages is complicated by the nebulous definition of strains during the transition from a semi-liquid to a solid. It is hence necessary to complement autogenous shrinkage measurements with measurements of concrete setting times. The presence of free water within the concrete matrix (as indicated by setting times) greatly influences the thermal expansion of concrete. In order to accurately represent very early-age measurement of autogenous shrinkage, the thermal expansion of the concrete due to heat of hydration must be corrected for. A tri-linear model was used where the coefficient of thermal expansion varies from initial to final set. Results show that silica fume significantly increases autogenous shrinkage, and the fly ash reduces autogenous shrinkage slightly. Additionally, companion tests on chloride permeability show that silica fume causes the permeability to increase significantly. Ternary blends of cement, fly ash, and silica fume are shown to take advantage of the best features of both silica fume and fly ash, offering the durability improvement typical of silica fume, along with the early-age shrinkage-reducing effects of fly ash.

Edwardson, C. F. (2001). Green blending to improve panel durability. 35th International Particleboard/Composite Materials Symposium Proceedings, April 3, 2001 - April 5, 2001, Pullman, WA, United states, Forest Products Society.

Throughout the rapid growth of the commodity-based oriented strandboard (OSB) industry, much attention has focused on developing value added panels. Certain specialty products, such as OSB siding, have achieved commercial success; while others, such as concrete form panels, have experienced more challenges. Both products use resin-impregnated paper overlays to protect against water exposure and other agents of degradation. A chemically enhanced OSB panel is a niche product with a potential for greater financial returns, thus providing some protection from price downturns prevalent with commodities. In OSB manufacture, numerous opportunities exist to introduce chemicals such as preservatives and fire retardants, which would add value to the finished product. If a diffusible chemical is used, applying it to freshly cut (green) wood strands is sensible. This paper will discuss the concept of "green blending," as it might be used in the OSB industry. Generic product concepts will be reviewed. Some of the challenges of incorporating this method in the OSB production process will be discussed based on past laboratory and pilot plant experience. Green blending can be used to produce fire retardant, decay resistant, or dimensionally stable OSB panels. However, green blending will only become a feature of OSB manufacturing when potential returns outweigh the risk of the investment required to establish and maintain the technology.

Elahi, A., P. A. M. Basheer, et al. (2010). "Mechanical and durability properties of high performance concretes containing supplementary cementitious materials." Construction and Building Materials **24**(Compendex): 292-299.

An experimental investigation was carried out to evaluate the mechanical and durability properties of high performance concretes containing supplementary cementitious materials in both binary and ternary systems. The mechanical properties were assessed from the compressive strength, whilst the durability characteristics were investigated in terms of chloride diffusion, electrical resistivity, air permeability and water absorption. The test variables included the type and the amount of supplementary cementitious materials (silica fume, fly ash and ground granulated blast-furnace slag). Portland cement was replaced with fly ash up to 40%, silica fume up to 15% and GGBS up to a level of 70%. The results confirmed that silica fume performs better than other supplementary cementitious materials for the strength development and bulk resistivity. The ternary mixes containing ground granulated blast-furnace slag/fly ash and silica fume performed the best amongst all the mixes to resist the chloride diffusion. The mix containing fly ash showed favourable permeation results. All the ternary combinations can be considered to have resulted in high performance concretes with excellent durability properties. 2009 Elsevier Ltd. All rights reserved.

Eren, O. (2002). "Strength development of concretes with ordinary Portland cement, slag or fly ash cured at different temperatures." Materials and Structures/Materiaux et Constructions **35**(Compendex): 536-540.

This paper presents the results of an investigation on the effect of Portland cement replaced by fly ash or granulated blast-furnace slag on the concrete strength at different curing temperatures. Compressive strength results are analysed according to the hyperbolic strength-age function by introducing a power index n. The regression analysis is done considering different n values and t0 (final setting times) values.

Esmaily, H. and H. Nuranian (2012). "Non-autoclaved high strength cellular concrete from alkali activated slag." Construction and Building Materials **26**(Compendex): 200-206.

In this study, the use of alkali activated slag (AAS) in place of usual cementitious materials in the production of autoclave aerated concrete (AAC) was studied. This substitution altered autoclave curing stage by steam curing in AAC production process. In this way, after mixing of AAS paste with aluminum powder, enough time was given to the mixture. The resultant green body was then cured at 70, 78 and 87 C. To achieve the best results, microscopic pore structure, compressive strength of the body and mini-slump of initial paste were studied. The results approved that AAC can be produced without autoclave by using AAS. 2011 Elsevier Ltd. All rights reserved.

Ezziane, K., E.-H. Kadri, et al. (2010). "Analysis of Mortar Long-Term Strength with Supplementary Cementitious Materials Cured at Different Temperatures." ACI Materials Journal **107**(4): pp 323-331.

This article will discuss an experimental study that was done to quantify the evolution of the mechanical strength modifications resulting from the presence of several supplementary cementitious materials (SCMs) in the mixture design of a mortar hardening under various curing temperatures. Mortars were made with various replacement levels of the cement by mass: 30 and 50% for slag; 10, 20, 30, and 40% for natural pozzolan; and 5, 15, and 25% for limestone powder. Samples were stored in a saturated-humidity moist room under various temperatures, namely 68, 104, and 140°F (20, 40, and 60°C). The results enable the verification of some hardening properties, such as half-strength age and long-term strength. The experimental results of half-strength age perfectly match with the previous studies that show a slower hydration of the cement with an increase in SCM. This effect decreases with the curing temperature. The long-term strength—depending on the curing temperature—is expressed by a parabolic expression contrary to the classical linear form in the case of ordinary portland cement (OPC). This new expression is more accurate in predicting the concrete longterm strength versus curing temperature with a part of cement replaced by SCM. Many experimental results obtained by other researchers have supported the proposed expression with a satisfactory accuracy, encouraging its generalization.

Fajardo, G., P. Valdez, et al. (2009). "Corrosion of steel rebar embedded in natural pozzolan based mortars exposed to chlorides." Construction and Building Materials **23**(Compendex): 768-774.

Corrosion of steel is considered the most important durability problem of reinforced concrete. The application of supplementary cementitious materials has been proposed in order to mitigate this durability problem, reduce the production costs and control the emission of greenhouse gases. Mexico is rich in volcanic areas from which natural pozzolanic materials can be obtained. This paper examines the use of such natural pozzolans as a partial substitute of normal portland cement in reinforced mortar specimens. Compositions with substitution levels of 0%, 10% and 20% by mass of normal Portland cement of natural pozzolanas were investigated. The specimens were exposed to penetration of chlorides. Compressive strength, corrosion potential, polarization resistance, electrical resistivity, and chloride content of the mortars were determined in order to characterize the physical, mechanical, electrical, and electrochemical behavior of the mortar as well as the embedded steel. It was found that the use of pozzolan has resulted in a significant increase in mortar resistivity and corrosion initiation time for the same cover depth, and as a result, decreases the rate of corrosion of rebars once corrosion was initiated. 2008 Elsevier Ltd. All rights reserved.

Farny, J. A. (2004). "Green Building Promotes Healing." Masonry Today, **14**(1): 2.

Felekoglu, B., K. Tosun, et al. (2009). "Effects of fibre type and matrix structure on the mechanical performance of self-compacting micro-concrete composites." Cement and Concrete Research **39**(Compendex): 1023-1032.

The compatibility of matrix and fibre properties is one of the key parameters in the successful design of fibre reinforced cementitious composites. In order to achieve the desired performance, the properties of each constituent of composite should be properly configured. The aim of this study was to investigate the performance of two polymer based micro-fibres (polypropylene and polyvinyl alcohol) in different matrices (high strength and comparatively low strength with fly ash incorporation) which were designed to contain considerably high amounts of fibres (1% by volume) while maintaining their self-compactability. The fresh state thixotropic behaviour of fibre reinforced matrices was minimised by proper adjustment of water/cementitious material ratio and admixture dosage. The mechanical properties (first crack strength and displacement, flexural strength and relative toughness) of prismatic composite samples were compared by three point flexural loading test. The typical behaviours of selected composites and collapse mechanisms of PP and PVA fibres in these matrices were characterised by microstructural studies. It was concluded that, a high strength matrix with a high strength fibre give the best performance from the view point of flexural strength and toughness performance. However, incorporation of fly ash did not cause a significant reduction in composite performance possibly due to its enhancing effect on matrix-fibre interface adhesion. The possibilities and suggestions to further improve the performance of the composites were also discussed. 2009 Elsevier Ltd. All rights reserved.

Fernandez-Jimenez, A., A. Palomo, et al. (2005). "Microstructure development of alkali-activated fly ash cement: A descriptive model." Cement and Concrete Research **35**(Compendex): 1204-1209.

The microscopic study of a set of alkali-activated and thermally cured fly ash samples enabled the authors to establish a descriptive model for the microstructural development of fly ash-based cementitious geopolymers. The morphology of most fly ash particles (perfect spheres) not only makes microscopic research highly productive but facilitates the formulation of hypothesis explaining the fly ash activation over time through a series of consecutive steps that can be successfully fitted to real situations. 2004 Elsevier Ltd. All rights reserved.

Fernandez-Jimenez, A. and F. Puertas (2003). "Effect of activator mix on the hydration and strength behaviour of alkali-activated slag cements." Advances in Cement Research **15**(Compendex): 129-136.

This paper examines on the setting time and mechanical strength behaviour of slag cement pastes activated with different alkaline activators. For this purpose three alkaline solutions were used: waterglass solution (27% SiO2, 18% Na2O and 55% H2O), NaOH and Na2CO3, maintaining always a constant concentration of Na2O (4% by mass of slag). The solutions were prepared with mixes of 0%, 80%/20% and 20%/80%. The activation process was studied at early ages by conduction calorimetric and fourier transform infrared spectroscopy (FTIR). Results show that the initial pH of the alkaline solution plays an important role in the initial slag dissolution. However the factor playing a decisive role in the acceleration or delay of setting times and in the development of mechanical strengths is the nature of the anion present in the solution. SiO42- ions act as an accelerator of the setting time, but CO32- ions delay the setting time.

Fidjestol, P. (2005). Marine concrete infrastructure: More than ready for 100 years service life. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

While structures in the marine environment built 30 years ago have caused a lot of concern over durability and service life, the development in concrete and construction technology have given confidence in the ability to build infrastructure objects that will have the desired 80, 100 or even 120 years anticipated service life. This paper will consider some of the experiences and possibilities that are based on the use of high performance concrete with silica fume.

Fournier, B., P. C. Nkinamubanzi, et al. (2004). Feasibility of Ternary Blends with Class C Fly Ash for High Performance Concrete, International Centre for the Sustainable Development of Cement and Concrete (ICON), Materials Technology Laboratory (MTL)/CANMET Department of Natural Resources Canada**:** 52.

The alkali-silica reaction (ASR) is one of the various deterioration processes that

can affect the serviceability and the service life of concrete structures. Past field experience and extensive laboratory investigations have shown that an adequate amount of an effective fly ash can significantly reduce and even control deleterious expansion due to ASR in concrete. In 2002, CANMET initiated a research project dealing with the evaluation of the effectiveness of binary and ternary systems incorporating a variety of fly ashes (i.e. with calcium oxide contents ranging from 1 to 28%) in controlling alkali-silica reaction (ASR) in concrete.

The main objective of this project, which is a comparative field and laboratory study, is to develop an engineering data base on the long-term effectiveness of ternary systems of fly ash and silica fume in controlling and/or reducing expansion and cracking in concrete due to ASR.

Freyne, S. F., B. W. Russell, et al. (2003). "Heat Curing of High-Performance Concrete Containing Type III Cement." ACI Materials Journal **100**(Compendex): 449-454.

A variety of high-performance concrete (HPC) mixtures were examined under a number of heat curing schemes in parallel with ASTM C 192 standard curing to investigate the effect of curing on compressive strength development. The heat curing schemes were classified as either moderate or intense based on peak temperature of the curing environment. These were intended to simulate the heat curing processes regularly employed in the manufacture of precast/prestressed concrete bridge beams. The study involved 31 different HPC mixtures, each containing Type III cement and many having partial replacement of cement with fly ash, silica fume, and/or slag. Under standard curing, compressive strength results were near 60 MPa (8700 psi) at 1 day and 100 MPa (14,500 psi) at 28 and 56 days. Different mixtures responded differently to heat curing, but, in general, heat curing was found damaging to ultimate strength potential and sometimes even failed to accelerate early strength development.

Frias, M., R. Garcia, et al. (2008). "Calcination of art paper sludge waste for the use as a supplementary cementing material." Applied Clay Science **42**(Compendex): 189-193.

This study shows the effect of calcination clay wastes from an art paper sludge for the use as supplementary cementing materials in blended cements. The starting clay sludge rich in kaolinite and talc was calcined at 600, 650 and 700C between 2 and 5h, kaolinite was transformed into amorphous metakaolinite. This study reveals that calcination at 650C for 2h is recommended to obtain a good supplementary cementing material for manufacture of blended cements. 2008 Elsevier B.V. All rights reserved.

Frias, M., O. Rodriguez, et al. (2008). "Properties of calcined clay waste and its influence on blended cement behavior." Journal of the American Ceramic Society **91**(Compendex): 1226-1230.

This paper describes research on clay wastes (CWs) produced in the paper manufacture process. Once activated under controlled thermal conditions, CW is transformed into calcined clay products providing added value as supplementary cementing materials. The obtention of a pozzolanic material (metakaolin (MK))

from valorized CW constitutes an alternative source of pozzolans for the elaboration of blended Portland cements, as well as a priority research line from the environmental point of view. This research work presents the properties of calcined CW (chemical, mineralogical, and pozzolanic) and its influence on Portland cements containing 10% calcined clay product. The results obtained with different characterization techniques (XRF, DTA, XRD, SEM-EDX) showed that the thermally activated CW exhibits acceptable properties to be used as supplementary cementing materials in the manufacture of commercial Portland cements. The derived MK can react with calcium hydroxide, from cement hydration, producing hydrated phases with hydraulic properties (calcium silicate hydrate gels, tobermorite, C4AH13, zeolite). These novel blended cements comply with the chemical, physical, and mechanical specifications established in the existing standards. 2008 The American Ceramic Society.

Fridrichova, M. (2007). "Hydration of belite cement prepared from recycled concrete residues." Ceramics - Silikaty **51**(Compendex): 45-51.

Undersize fractions occurring during the recycling of concrete waste were used for the preparation of belite clinker. The ratio of the undersizes to limestone containing a high percentage of CaO was 1 to 2.25. The mix was converted into the belite cement and its hydration properties along with those of two types of alite cements prepared from the same recycled undersizes were investigated. The hydration character of Portland cements corresponds to the kinetics of the reaction of the 1st order and its progress may be assessed from the reduction in the content of unhydrated CaO in the cement body. Quantified data characterizing the hydration products were obtained by means of the thermal analysis after standard reaction soaks of 1, 3, 7 and 28 days. The original CaO content (55 %) in the belite cement dropped to 51 % after 7 days; there was only 44 % of unhydrated CaO after a month. The original CaO content (56 %) in the ternary alite cement dropped consistently to 21 % after the hydration lasting a month; the decrease in the original CaO content (54 %) in the binary alite cement follows a similar pattern in the first 7 days, with an inflection occurring within a month and a decrease to the final value of 12 % of unhydrated CaO. The values of the velocity constants in the kinetic reaction of the 1st order were expressed statistically from the values of the residual CaO remaining after the hydration. Belite cement is characterized by the value k = 0.0071 whereas the alite cements show the value k = 0.225 (ternary system), respectively k= 0.326 (binary system). This means that the belite cement prepared from recycled concrete would require an unacceptably long hydration time.

Frigione, G. and R. Sersale (1985). "INFLUENCE OF THE CHEMICAL COMPOSITION OF THE CLINKER ON THE STRENGTH PROPERTIES OF BLAST FURNACE SLAG CEMENTS." Cement and Concrete Research **15**(Compendex): 159-166.

The authors describe an attempt to correlate, using linear regression analysis, the chemical composition of the portland clinker to the compressive strength of blast furnace slag cements. The investigation shows that the main constituents of the clinker do not influence compressive strength of the slag fraction, which, in turn, is influenced by the alkali content of the clinker. Although it has not been possible to distinguish the role of soluble alkalis from the total content, nevertheless, compressive strength of blast furnace slag cements appears to depend upon two different and opposite contributions from the clinker fraction, negatively affected by its alkali content, and the other factor from the slag fraction, positively influenced by the same alkali content.

Fu, Y., J. Ding, et al. (1997). "Temperature dependence of compressive strength of conversion-inhibited high alumina cement concrete." ACI Materials Journal **94**(Compendex): 540-545.

The strength reduction of high alumina cement (HAC) concrete due to conversion is one of the major reasons given for limiting the use of HAC in structural members. A conversion-inhibited concrete is introduced in this paper. The effect of curing and exposure conditions (e.g., temperature) on the compressive strength of HAC or modified HAC concretes was studied. Ground granulated blastfurnace slag (ggbs) and a conversion-preventing additive (CPA) containing natural zeolite or silica fume in combination with sodium sulfate were used to inhibit the strength reduction of the HAC concretes. The results indicated that conversion-inhibited HAC concrete containing a CPA has a one-day compressive strength greater than 55 MPa when cured at 4-5 deg C. The strength of the HAC/CPA concrete is much less affected by the concrete temperature than plain HAC or HAC/ggbs concrete.

Fujikura, Y. and H. Oshita (2011). "Pore structure model of hydrates comprising various cements and SCMs based on changes in particle size of constituent phases." Journal of Advanced Concrete Technology **9**(Compendex): 133-147.

A simulation model to estimate the pore structure of cement hydrates is presented. This paper describes procedures for predicting phase compositions based on the classical hydration model of portland cement, calculating the particle size distribution of constituent phases and evaluating the pore size distribution by stereological and statistical considerations. To evaluate the effectiveness of this model, simulation results were compared with experimental results of the pore size distribution measured by mercury porosimetry. As a result, it was found that the experimental and simulated results were in close agreement, and the simulated results indicated characterization of the pore structure of cement hydrates. Copyright 2011 Japan Concrete Institute.

Ganjian, E., P. Claisse, et al. (2006). "Factors affecting measurement of hydraulic conductivity in low-strength cementitious materials." Cement and Concrete Research **36**(Compendex): 2109-2114.

The hydraulic conductivity (water permeability) is one of the most significant transport properties of concrete and measuring it is a key step in predicting the performance of concrete as a barrier to the movement of fluids and ions. The transport properties are critical for the performance of the cover layer in protecting embedded reinforcement as waste containments barriers (which are considered in this paper) and other applications such as dams. The measurements are difficult to interpret due to experimental effects of sample size and changes of flow with time and the chemistry of the fluid used. The intrinsic permeability to water and synthetic leachate was determined and the relationship between the eluted volume passing and permeability was established for mortar mixtures having compressive strengths ranging from 5 to 20MPa. Two mortar mixtures containing portland cement and one without portland cement and incorporating cement kiln dust, lagoon ash, and Ferrosilicate slag were tested. The effects of the sample size were also investigated. The results indicate a decrease in hydraulic conductivity for lower strength mixtures and a slight increase in permeability coefficient for the higher strength mixtures with increasing permeating volumes. Increasing the testing specimen size also slightly increased the coefficient of permeability in lower strength mixtures and decreased the coefficient in higher strength mixtures. The permeability coefficient did not change significantly with pore solution pressure. 2006 Elsevier Ltd. All rights reserved.

Garas, V. Y. and K. E. Kurtis (2008). "Assessment of methods for optimising ternary blended concrete containing metakaolin." Magazine of Concrete Research **60**(Compendex): 499-510.

The relative effectiveness of three approaches - isothermal calorimetry, trial batching and particle packing models-for optimising mix proportions in Portland cement/metakaolin (MK)/jly ash (FA) ternary blended concretes was compared through measurements of workability and compressive strength, in consideration of economy. Mixtures were prepared using single cement and class C FA and two MKs of varying fineness. The finer MK showed a higher rate of reaction, but the isothermal calorimetry also suggested that MK replacements of 5% or higher are needed to overcome the hydration delay resulting from the use of 25% by mass FA. Trial batches at three water-to-cementitious materials ratios (w/cm) - 0-30, 0-40 and 0-50-were designed based on the calorimetry results. While workability decreased with increasing MK content, similar or better workability than the control mixes was achieved in the ternary blends. The compressive strength significantly increased with increasing MK content, as compared to the ordinary concrete and the FA binary blends, and especially at low w/cm (i.e. w/cm = 0-30). The trial batch strength results confirmed that the hydration rates (measured by isothermal calorimetry) could be used to optimise binder composition for early concrete strength. However, in the third approach, the particle packing model was found to be insufficiently related to measured 1-day strength or to strength in higher w/cm concrete; the closest relationship between the primary model parameter (q) and strength was found at lower w/cm and at later ages (i.e. 28 days). It is proposed that the lack of consideration of the constituent's chemical reactivity of highly reactive materials, such as MK, makes this approach unreliable at early ages and at higher w/cm. Finally, despite the lack of correlation between q and strength, results show q values of 0-26-0-29 are optimal for workability. 2008 Thomas Telford Ltd.

Gardner, N. J., P. L. Sau, et al. (1986). "STRENGTH DEVELOPMENT AND

DURABILITY OF CSA TYPE 30 CEMENT/SLAG/FLY-ASH CONCRETES FOR ARCTIC MARINE APPLICATIONS." Durability of building materials **4**(Compendex): 179-200.

This report describes an experimental investigation into the strength development and durability of CSA Type 30 cement concretes, 50% CSA Type 30 cement/50% slag concretes, and 75% Type 30 cement/ 25% fly-ash concretes cast at 0 degree C and cured at 0 degree C in sea water relative to conventionally cast and cured concretes. All concretes incorporated air-entraining admixtures and had air contents of between 4 and 6%. Strength development of all concretes with temperature is dependent upon the water-to-cementitious -ratio. The strength development of concretes with low water-to-cementitious ratios is less affected by 0 degree C casting and curing than those with high water-to-cementitious ratios. The early-age strength development of CSA Type 30 cement/slag concretes and Type 30 cement/fly-ash concretes is significantly slower for concretes cast and cured at 0 degree C in sea water compared to standard cast and cured concretes. The resistance to freezing and thawing of Type 30 cement concretes is better than Type 30 cement/slag concretes.

Gartner, E. (2003). Scientific and societal issues involved in developing sustainable cements. Role of Concrete in Sustainable Development - International Symposium Celebrating Concrete: People and Practice, September 3, 2003 - September 4, 2003, Dundee, United kingdom, Thomas Telford Services Ltd.

This paper discusses the practicality of replacing Portland cements with alternative hydraulic cements that could result in lower total CO2 emissions per unit volume of concrete of equivalent performance. Currently, the cement industry is responding rapidly to the perceived societal need for reduced CO2 emissions by increasing the production of blended Portland cements, using supplementary cementitious materials that are principally derived from industrial by-products such as blast-furnace slags and coal-combustion fly ashes. However, the supplies of such by-products of suitable quality are limited, so more radical solutions to the CO2 emissions problem may ultimately be needed. In this paper, we show that the most promising alternative systems currently appear to be those based at least in part on calcium sulfates, the availability of which is increasing due to the widespread implementation of sulfur dioxide emission controls. These include calcium sulfoaluminate-based cements, especially those that can be made from relatively common raw materials. They also include cementing systems that make better use of the potential synergies between calcium sulfate, calcium silicate and calcium aluminate hydrates. However, a great deal more RD, mainly oriented towards establishing the usage properties and durability of concretes made from such cements, will be needed to provide the data necessary to modernise our construction codes and standards if we are to effectively use these potentially more "CO2 efficient" technologies on a large enough scale to have a significant global impact.

Gartner, E. (2004). "Industrially interesting approaches to "low-CO2" cements." Cement and Concrete Research **34**(Compendex): 1489-1498.

This article discusses the practicality of replacing portland cements with alternative hydraulic cements that could result in lower total CO2 emissions per unit volume of concrete of equivalent performance. Currently, the cement industry is responding rapidly to the perceived societal need for reduced CO2 emissions by increasing the production of blended portland cements using supplementary cementitious materials that are principally derived from industrial by-products, such as blast-furnace slags and coal combustion fly ashes. However, the supplies of such by-products of suitable quality are limited. An alternative solution is to use natural pozzolans, although they must still be activated either by portland cement or lime or by alkali silicates or hydroxides, the production of all of which still involves significant CO 2 emissions. Moreover, concretes based on activated pozzolans often require curing at elevated temperatures, which significantly limits their field of application. The most promising alternative cementing systems for general concrete applications at ambient temperatures currently appear to be those based at least in part on calcium sulfates, the availability of which is increasing due to the widespread implementation of sulfur dioxide emission controls. These include calcium sulfoaluminate-belite-ferrite cements of the type developed in China under the generic name "Third Cement Series" (TCS) and other similar systems that make good use of the potential synergies among calcium sulfate, calcium silicate and calcium aluminate hydrates. However, a great deal more research is required to solve significant unresolved processing and reactivity questions and to establish the durability of concretes made from such cements. If we are to use these potentially more CO2-efficient technologies on a large enough scale to have a significant global impact, we will also have to develop the performance data needed to justify changes to construction codes and standards. 2004 Elsevier Ltd. All rights reserved.

Ge, Z. and K. Wang (2009). "Modified heat of hydration and strength models for concrete containing fly ash and slag." Computers and Concrete **6**(Compendex): 19-40.

This paper describes the development of modified heat of hydration and maturity-strength models for concrete containing fly ash and slag. The modified models are developed based on laboratory and literature test results, which include different types of cement, fly ash, and slag. The new models consider cement type, water-to-cementitious material ratio (w/cm), mineral admixture, air content, and curing conditions. The results show that the modified models well predict heat evolution and compressive strength development of concrete made with different cementitious materials. Using the newly developed models, the sensitivity analysis was also performed to study the effect of each parameter on the hydration and strength development. The results illustrate that comparing with other parameters studied, w/cm, air content, fly ash, and slag replacement level have more significantly influence on concrete strength at both early and later age.

Ge, Z., K. Wang, et al. (2009). Properties and early-age cracking potential of blended

cement concrete. 2009 GeoHunan International Conference - Material, Design, Construction, Maintenance, and Testing of Pavement, August 3, 2009 - August 6, 2009, Changsha, Hunan, China, American Society of Civil Engineers.

Stress due to the temperature and moisture gradients in concrete slab often causes pavement curling and warping that may further cause concrete crack if the slab is under restraint conditions. The adding of supplementary cementitious materials (SCMs) can reduce the risk of cracking by reducing the temperature stress. However, under cold weather condition, the slower strength development due to SCMs could increase the risk. This paper reported a study result of using blended cement to reduce such as risk. In this study, the properties of ternary cement concrete, such as setting time, heat of hydration, and datum temperature, were investigated. The risk of early-age cracking for different concrete mixes under different weather conditions was evaluated by the HIPERPAV. The test results indicated that fly ash replacement generally increase the setting time; while the slag replacement reduced the setting time. Both fly ash and slag replacement reduced the generated heat. When the amount of slag increased, the datum temperature and activation energy increased. HIPERPAV analysis indicated that there was little risk of early-age cracking for binary or ternary cement concrete under average summer weather conditions due to proper strength development of the concrete. However, the risk of early-age cracking for the concrete pavement increased under spring or fall weather conditions. 2009 ASCE.

Gesoglu, M., E. Guneyisi, et al. (2009). "Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume." Construction and Building Materials **23**(Compendex): 1847-1854.

Self-compacting concretes (SCCs) have brought a promising insight into the concrete industry to provide environmental impact and cost reduction. However, the use of ternary and especially quaternary cementitious blends of mineral admixtures have not found sufficient applications in the production of SCCs. For this purpose, an experimental study was conducted to investigate properties of SCCs with mineral admixtures. Moreover, durability based multi-objective optimization of the mixtures were performed to achieve an optimal concrete mixture proportioning. A total of 22 concrete mixtures were designed having a constant water/binder ratio of 0.44 and a total binder content of 450 kg/m3. The control mixture included only a Portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, fly ash (FA), ground granulated blast furnace slag (S), and silica fume (SF). Fresh properties of the SCCs were tested for slump flow diameter, slump flow time, L-box height ratio, and V-funnel flow time. Furthermore, the hardened properties of the concretes were tested for sorptivity, water permeability, chloride permeability, electrical resistivity, drying shrinkage, compressive strength, and ultrasonic pulse velocity. The results indicated that when the durability properties of the concretes were taken into account, the ternary use of S and SF provided the best performance. 2008 Elsevier Ltd. All rights reserved.

Gesoglu, M. and E. Ozbay (2007). "Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: Binary, ternary and quaternary systems." Materials and Structures/Materiaux et Constructions **40**(Compendex): 923-937.

The paper presented herein investigates the effects of using supplementary cementitious materials in binary, ternary, and quaternary blends on the fresh and hardened properties of self-compacting concretes (SCCs). A total of 22 concrete mixtures were designed having a constant water/binder ratio of 0.32 and total binder content of 550 kg/m3. The control mixture contained only portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, fly ash (FA), ground granulated blast furnace slag (GGBFS), and silica fume (SF). After mixing, the fresh properties of the concretes were tested for slump flow time, L-box height ratio, V-funnel flow time, setting time, and viscosity. Moreover, compressive strength, ultrasonic pulse velocity, and electrical resistivity of the hardened concretes were measured. Test results have revealed that incorporating the mineral admixtures improved the fresh properties and rheology of the concrete mixtures. The compressive strength and electrical resistivity of the concretes with SF and GGBFS were much higher than those of the control concrete. 2007 RILEM has copyright.

Ghafoori, N. and H. Diawara (2008). Sulfate resistance of fly ash concrete in wet-dry conditions. 4th International Structural Engineering and Construction Conference, ISEC-4 - Innovations in Structural Engineering and Construction, September 26, 2007 - September 28, 2007, Melbourne, VIC, Australia, Taylor and Francis/Balkema.

This investigation evaluates the sodium sulfate resistance of Portland cement concrete proportioned to have four levels of cement replacement (15, 20, 25, and 30%) with class F fly ash. Control mixtures containing no fly ash are also used for comparison purposes. The sulfate medium consisted of 5% sodium sulfate solution and wet-dry exposure condition was utilized. The demolded unit weight and fresh characteristics; such as, slump, bleeding, and setting times, were obtained to characterize the trial matrices. Length change, mass loss, and compressive strength were monitored for a period of 360 days to evaluate the performance of the test specimens exposed to "very severe" sulfate attack. 2008 Taylor Francis Group.

Ghanem, H., S. Phelan, et al. (2008). "Chloride ion transport in bridge deck concrete under different curing durations." Journal of Bridge Engineering **13**(Compendex): 218-225.

During freezing temperatures, ice accumulates on exposed concrete slabs such as bridge decks. Deicing salts such as calcium chloride are applied to control this ice formation. These salts migrate down to the reinforcing steel, and they can break down the passivation layer on steel, causing it to corrode. This paper is part of a broader research study to explore the possibility of opening the bridge decks earlier than the 10-12 days as practiced now, by decreasing the number of wet-mat curing days. Seven concrete mixtures typically used in Texas bridge decks were evaluated for chloride permeability using the ponding test (AASHTO T259). The primary experimental variables were the curing duration, type and percentage of supplemental cementitious materials, type of coarse aggregate, duration of ponding, and the surface preparation of ponded concrete specimens. Results of the investigation indicated that curing duration may be decreased for some concrete mixtures as no apparent improvement was shown after a specific curing duration, which ranged from 2 to 8 days depending on the mix. 2008 ASCE.

Ghorab, H. Y., M. S. Hilal, et al. (1990). "Effect of mixing and curing waters on the behaviour of cement pastes and concrete. Part 2. Properties of cement paste and concrete." Cement and Concrete Research **20**(Compendex): 69-72.

The effect of natural waters on the setting time of some hydraulic cements and on the compressive strength of the corresponding concrete is investigated. The setting time of ordinary portland cement is most affected by the water type followed by the sulfate resisting cement; the mixed cement (El-Karnak) and the portland blastfurnace slag cement are quite insensitive. The compressive strength of plain concrete cubes aged up to 17 months is unaffected by the type of mixing and curing water.

Ghrici, M., S. Kenai, et al. (2007). "Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements." Cement and Concrete Composites **29**(Compendex): 542-549.

The benefits of limestone filler (LF) and natural pozzolana (NP) as partial replacement of Portland cement are well established. Economic and environmental advantages by reducing CO2 emission are well known. However, both supplementary materials have certain shortfalls. LF addition to Portland cement causes an increase of hydration at early ages inducing a high early strength, but it can reduce the later strength due to the dilution effect. On the other hand, NP contributes to hydration after 28 days improving the strength at medium and later ages. Hence, ternary blended cement (OPC-LF-NP) with better performance could be produced. In this paper, mortar prisms in which Portland cement was replaced by up to 20%LF and 30%NP were tested in flexure and compressive strength at 2, 7, 28 and 90 days. Some samples were tested under sulfate and acid solutions and for chloride ions permeability. Results show that the use of ternary blended cement improves the early age and the long-term compressive and flexural strengths. Durability was also enhanced as better sulfate, acid and chloride ions penetration resistances were proved. 2007 Elsevier Ltd. All rights reserved.

Gifford, P. M. and J. E. Gillott (1997). "Behaviour of mortar and concrete made with activated blast furnace slag cement." Canadian Journal of Civil Engineering **24**(Compendex): 237-249.

Activated blast furnace slag cement (ABFSC) was used as binder in mortar and concrete. A commercial pelletized slag, produced for use in the construction industry, was activated with sodium sulphate, sodium carbonate, or sodium silicate; and both normal curing and heat curing were used. Laboratory results of the effect on strength development of activator dosage, water-binder ratio, curing temperature, duration of heat curing, chemical admixtures, and the use of fly ash or silica fume in a slag replacement role are presented. It was found that there was an optimum dosage of sodium carbonate and sodium sulphate for maximum strength utilizing either curing regime, and this dosage was found to correspond approximately to the fully saturated activator solution concentration. However, for sodium silicate ABFSC, strength continued to increase well beyond this point and this activator proved to be the most effective. Although the strength of the ABFSC mixtures benefited from heat curing, the response depended mainly on the type of activator and the duration of curing; increased curing temperature had only a modest effect. With only one exception, chemical admixtures were found to be ineffective when used in ABFSC mixtures. Both fly ash and silica fume increased workability, and silica fume also increased medium term strength of the sodium sulphate activated mixtures. The results show that ABFSC mortar and concrete provide strengths comparable to, or better than, similar ordinary portland cement mixtures, given similar paste content, water content, and curing conditions. Compared with ordinary portland cement mixtures, the early volume stability of ABFSC mixtures was found to be lower, and both drying shrinkage and cracking due to hardening were found to be greater.

Gleize, P. J. P., A. Muller, et al. (2003). "Microstructural investigation of a silica fume-cement-lime mortar." Cement and Concrete Composites **25**(Compendex): 171-175.

Several additions, minerals and organic, are used in mortars, such as pozzolanic materials, cementicious materials and polymers. Literature about the use of additions in masonry mortars (cement/lime/sand mixes) is scarce; usually, studies are about concrete mortars. The purpose of this work is to study the microstructural effects of the substitution of 10% of Portland cement by silica fume in a 1:1:6 (cement/lime/sand mix proportion by volume) masonry mortar. Scanning electron microscopy with energy dispersive X-rays analysis (SEM/EDX) shows that, with silica fume, the C-S-H formed is type III at early ages and that type III and type I coexist at later ages. Silica fume lowers the total porosity and increases compressive strength only at later age and, as expected, the pore structure of mortar with silica fume is found to be finer than of non-silica fume mortar. 2003 Elsevier Science Ltd.

Golaszewski, J., J. Szwabowski, et al. (2005). Interaction between cement and superplasticizer in presence of metakaolin. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

Usage of metakaolin (MK) significantly improves properties of concrete, especially those related with durability. The addition of MK to concrete influences also rheological properties (and therefore workability) of fresh mix. It is due to high specific surface and chemical activity of MK itself and due to its influence on interaction of cement superplasticizer (SP) system. The results of an investigation into the influence of MK on interaction of cement - SP system are presented and discussed in the paper. The interaction of cement - SP system in presence of MK was studied using Two Point Workability Test (TPWT) made on modified mortars according to EN 196-1:1996 which can be considered as a model of concrete. Additionally, influence of MK on setting times and compressive strength of concrete were determined. The results establish that the addition of MK significantly influences Theological properties of concrete mix. The character and range of this influence depends on the properties of the cement, properties of SP and MK content. Discussion of results covers the mechanism of MK influence on Theological properties of fresh concrete and comparison of effects of MK with effects of condensed silica fume and fly ash. On the ground of obtained results basic relationships of MK influence were elaborated. It is concluded that compatibility of cement - SP system must be tested taking into account the presence of mineral additives. TPWT made on modified standard mortars enables selecting optimal SP - mineral additive system and collecting data for adjusting concrete workability.

Gonchar, J. (2007). "Building even better concrete." ENR (Engineering News-Record) **259**(Compendex): 45-49.

Manufacturers, scientists and designers are making effort to reduce the carbon dioxide emission and energy use while producing cement, which is the fundamental ingredient in concrete. Manufacturers in US have adopted voluntary performance improvement targets for concrete production. The cement producers have already made significant progress by reducing energy use by 12%. Calcination and the burning of fossil fuel required to maintain the kiln at high temperatures are responsible for about 95% of the greenhouse gas emissions generated by cement manufacturing. The embedded energy in concrete can also be reduced by replacing some of the cement with supplementary cementitious materials (SCM). Replacement of cement with SCMs can also impart physical benefits to concrete.

Gopalakrishnan, S., N. P. Rajamane, et al. (2001). "Effect of partial replacement of cement with flyash on the strength and durability of HPC." Indian Concrete Journal **75**(Compendex): 335-341.

The performance of high performance concrete (HPC) mixes having different replacement levels of cement with low calcium flyash is reported. The mechanical and durability characteristics of the HPC mixes with fly ash are compared with the reference mix without flyash. A 25% replacement of cement with flyash achieved a compressive strength of 80 MPa in 28 days.

Goyal, S., M. Kumar, et al. (2009). "Resistance of mineral admixture concrete to acid attack." Journal of Advanced Concrete Technology **7**(Compendex): 273-283.

The effect of an aggressive chemical environment on concrete prepared with ordinary Portland cement and silica fume, either as a binary combination or a ternary combination with fly ash, is investigated in the present study. The adverse environmental conditions are simulated by using either 1% sulfuric acid, 1% hydrochloric acid or 1% nitric acid. The corrosion process was monitored by measuring the mass loss and compressive strength for a period of one year. It was found that the course of action of acid attack is dependent on the type of acid and solubility of the calcium salt formed. The presence of mineral admixtures was found to lower the detrimental effect of all types of acids on concrete. Ternary mixes with OPC, silica fume and fly ash performed better than binary mixes containing only silica fume as supplementary cementitious material. 2009 Japan Concrete Institute.

Grabowski, E. and J. E. Gillott (1989). "Modification of engineering behaviour of thermal cement blends containing silica fume and silica flour by replacing flour with silica sand." Cement and Concrete Research **19**(Compendex): 449-508.

Replacement of silica flour with coarser particles of sand in cement blends containing silica fume affected the compressive strength and permeability of hardened mixes at ambient and hydrothermal conditions. At ambient conditions the major effect was a marked increase in water permeability due to larger and/or better interconnected pores. Early compressive strength also increased. After 7 days of hydrothermal treatment at 230C and 2.75 MPa, strength increased markedly. Values were practically independent of period of precuring for two proportions of fume to sand used in this work. Higher strength values resulted for mixes with higher fume:sand ratio. Water permeability was not significantly affected.

Grattan-Bellew, P. E., G. Cybanski, et al. (2003). "Proposed Universal Accelerated Test for Alkali-Aggregate Reaction the Concrete Microbar Test." Cement, Concrete and Aggregates **25**(Compendex): 29-34.

The Concrete Microbar Test is modified after a Chinese test, for alkali-carbonate reactive aggregates. The protocol for the test is essentially the same as for ASTM C 1260, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method), except for the size of the bars, the grading of the aggregate, the water to cement ratio and the length of the test. The concrete microbars are 40 by 40 by 160 mm. The aggregate is graded to pass a 12.5 mm sieve and be retained on a 4.75 mm sieve. The water to cement ratio is 0.33. The length of the test is 30 days in 1 M sodium hydroxide (NaOH) at 80. The test results show that the method is applicable to both alkali-carbonate and alkali-silica reactive aggregates. Moderate correlation was found between the expansions measured in this test at 30 days, and in the concrete prism test (CSA A23.2-14A) at 1 year. Alkali-carbonate reactive aggregates may be distinguished from alkali-silica reactive aggregates in this test by replacing a portion of the portland cement by a supplementary cementing material. The expansions of alkali-silica reactive aggregates, in this test, are significantly reduced by the presence of the supplementary cementing material but expansion of alkali-carbonate reactive aggregates is largely unaffected. It is tentatively suggested that the expansion limit to separate deleteriously alkali silica reactive siliceous limestones from innocuous limestones is 0.140 % at 30 days; the proposed limit for all other aggregates is 0.04 %.

Grove, J., S. Vanikar, et al. (2011). "Sustainability opportunities for concrete pavements." Indian Concrete Journal **85**(Compendex): 7-15.

There is an increasing awareness about sustainability in our societies. Even in the highway construction sector, there is an understanding that construction activities should focus on ways to preserve or enhance economic, environmental and social well being. Sustainability approaches can be incorporated during the design, construction, and maintenance phases of highway projects. Concrete paving traditionally incorporates many environmentally responsible practices into routine practice and has done so for decades. Building on these current practices will aid in advancing sustainable technology to further raise the bar. This paper outlines the opportunities that are available before construction, during construction, and after construction of concrete pavements. A look into the future is also included, providing a glimpse of new materials and paving innovations. Opportunities before construction must focus on longevity. They include optimizing the pavement design, the selection of by-product materials for the concrete mixture, and minimizing the amount of cement in the mixture. The use of supplementary cementitious material both utilizes by-product material at the same time enhancing the performance of concrete. Other responsible uses of by-products are discussed. Opportunities during construction focus on the use of locally available materials, and means to complete projects sooner. Through the use of two lift paving, local materials may be used that normally do not meet durability requirements. In-place recycling can save time, money, and reduce the environmental impact. Methods to complete projects sooner positively impact sustainability by minimizing work zone durations and minimizing the impact to the travelling public. Opportunities after construction focus on maintenance practices which extend the pavement life thereby increasing safety and delaying the need for future construction. Concrete pavement restoration and concrete overlays provide a long term solution to many pavement rehabilitation needs. By taking advantage of all these sustainable strategies before, during, and after construction, highway administrators and engineers can ensure that highway infrastructure is part of the solution to sustainability challenges, enhancing their overall societal footprint in the process.

Grutzeck, M., S. Kwan, et al. (2004). "Zeolite formation in alkali-activated cementitious systems." Cement and Concrete Research **34**(Compendex): 949-955.

Autoclaved aerated concrete (AAC) is a unique building material. Because of its cellular nature, it is lightweight, self-insulating, sound- and fireproof, as well as insect and mold resistant. Furthermore, AAC is free of VOCs and various fibers associated with wood and glass wool construction. In an attempt to toughen AAC and make it less prone to on-site damage, a conventional fly-ash-based AAC formulation is being supplemented with sodium hydroxide (NaOH). The introduction of sufficient alkali promotes the growth of crystalline zeolites in the tobermorite matrix during autoclave curing. It is postulated that in situ grown zeolites will serve the same purpose as added fibers. Inasmuch as fly-ash-based

AAC reactions often do not go to completion, a phase study of the development of tobermorite and zeolites from a gel-like slurry made from reagent grade chemicals was undertaken. Mixtures were studied as a function of time and temperature. Phase development depends on bulk composition and curing conditions. Longer curing at higher temperatures causes the Na-P1 that forms initially to change to analcime. Whereas Na-P1 is bladelike in habit and is seen to intermingle with the slightly larger blades of tobermorite, the Na-P1 gradually undergoes a phase change to analcime that forms very large cubes. This change has the potential to disrupt the AAC matrix. 2003 Elsevier Ltd. All rights reserved.

Gueneyisi, E., M. Gesoglu, et al. (2010). "Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures." Construction and Building Materials **24**(10): 1878-1887.

Drying shrinkage can be a major reason for the deterioration of concrete structures. The contraction of the material is normally hindered by either internal or external restraints so that tensile stresses are induced. These stresses may exceed the tensile strength and cause concrete to crack. The present study investigated compressive strength and particularly drying shrinkage properties of self-compacting concretes containing binary, ternary, and quaternary blends of Portland cement, fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), and metakaolin (MK). For this purpose, a total of 65 self-compacting concrete (SCC) mixtures were prepared at two different water to binder ratios. It was observed that drying shrinkage lessened with the use of FA, GGBFS, and MK while incorporation of SF increased the drying shrinkage. (A) Reprinted with permission from Elsevier.

Guneyisi, E. (2010). "Fresh properties of self-compacting rubberized concrete incorporated with fly ash." Materials and Structures/Materiaux et Constructions **43**(Compendex): 1037-1048.

Solid waste management is one of the major environmental concerns in all over the world. High amounts of waste tires are generated each year and utilization of this waste is a big problem from the aspects of disposal, environmental pollution, and health hazards. In the production of self-compacting concrete, the incorporation of waste tires as partial replacement of aggregates is very limited. However, the use of waste tires might join the characteristics of self-compacting concrete (high flowability, high mechanical strength, low porosity, etc.) with the tough behavior of the rubber phase, thus leading to be a building material with more versatile performances. Thus, in this study, the usability of untreated crumb rubber as a partial substitute of fine aggregates with and without fly ash in the application of selfcompacting concretes was investigated experimentally. For this purpose, a water-cementitious material ratio (0.35), four designated crumb rubber contents (0, 5, 15, and 25% by fine aggregate volume), and four fly ash content (0, 20, 40, and 60%) were considered as experimental parameters. Test results indicated that use of crumb rubber (CR) without fly ash (FA) aggravated the fresh properties of self-compacting rubberized concretes (SCRC) (slump flow diameter, T50 slump flow time, V-funnel flow time, L-box height ratio, initial and final setting times, and viscosity). However, the use of CR with FA amended the fresh properties of SCRC. RILEM 2009.

Guneyisi, E. and M. Gesoglu (2008). "Properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and metakaolin." Materials and Structures/Materiaux et Constructions **41**(Compendex): 1519-1531.

The link between flow properties and the formulation is actually one of the key-issues for the design of self-compacting concretes (SCC). As an integral part of a SCC, self-compacting mortars (SCMs) may serve as a basis for the design of concrete since the measurement of the rheological properties of SCCs is often impractical due to the need for complex equipment. This paper discusses the properties of SCMs with mineral admixtures. Portland cement (PC), metakaolin (MK), and fly ash (FA) were used in binary (two-component) and ternary (three-component) cementititios blends. Within the frame work of this experimental study, a total of 16 SCMs were prepared having a constant water-binder (w/b) ratio of 0.40 and total cementitious materials content of 550 kg/m3. Then, the fresh properties of the mortars were tested for mini-slump flow diameter, mini-V-funnel flow time, setting time, and viscosity. Moreover, development in the compressive strength and ultrasonic pulse velocity (UPV) of the hardened mortars were determined at 1, 3, 7, 14, and 28 days. Test results have shown that using of FA and MK in the ternary blends improved the fresh properties and rheology of the mixtures when compared to those containing binary blends of FA or MK. 2007 RILEM.

Guneyisi, E. and M. Gesoglu (2008). "A study on durability properties of high-performance concretes incorporating high replacement levels of slag." Materials and Structures/Materiaux et Constructions **41**(Compendex): 479-493.

This paper presents an experimental study of combined effects of curing method and high replacement levels of blast furnace slag on the mechanical and durability properties of high performance concrete. Two different curing methods were simulated as follows: wet cured (in water) and air cured (at 20C and 65% RH). The concretes with slag were produced by partial substitution of cement with slag at varying amounts of 50-80%. The water to cementitious material ratio was maintained at 0.40 for all mixes. Properties that include compressive and splitting tensile strengths, water absorption by total immersion and by capillary rise, chloride penetration, and resistance of concrete against damage due to corrosion of the embedded reinforcement were measured at different ages up to 90 days. It was found that the incorporation of slag at 50% and above-replacement levels caused a reduction in strength, especially for the early age of air cured specimens. However, the strength increases with the presence of slag up to 60% replacement for the 90 day wet cured specimens. Test results also indicated that curing condition and replacement level had significant effects on the durability characteristics; in particular the most prominent effects were observed on slag blended cement concrete, which performed extremely well when the amount of slag used in the mixture increased up to 80%. 2007 RILEM has copyright.

Guneyisi, E. and M. Gesoglu (2011). "Properties of self-compacting portland pozzolana and limestone blended cement concretes containing different replacement levels of slag." (Compendex): 1-12.

In order to reduce energy consumption and CO2 emission, and increase production, cement manufacturers are blending or inter-grinding mineral additives such as slag, natural pozzolana, and limestone. This paper reports on the results of an experimental study on the production of self-compacting concrete (SCC) produced with portland cement (PC), portland pozzolana (PPC) and portland limestone (PLC) blended cements. Moreover, the effect of different replacement levels (0-45%) of ground granulated blast furnace slag (GGBFS) with the PPC, PLC, and PC cements on fresh properties (such as slump flow diameter, T500 slump flow time, V-funnel flow time, L-box height ratio, setting time, and viscosity) and hardened properties (such as compressive strength and ultrasonic pulse velocity) of self-compacting concretes are investigated. From the test results, it was found that it was possible to manufacture self-compacting concretes with PPC or PLC cements with comparable or superior performance to that of PC cement. Furthermore, the use of GGBFS in plain and especially blended cement self-compacting concrete production considerably enhanced the fresh characteristics of SCCs. 2011 RILEM.

Guneyisi, E., M. Gesoglu, et al. (2009). "Effects of marble powder and slag on the properties of self compacting mortars." Materials and Structures/Materiaux et Constructions **42**(Compendex): 813-826.

In this study, binary and ternary use of marble powder (MP) and ground granulated blast furnace slag (GGBFS) have been investigated in the production of self compacting mortars (SCMs). The marble powder was obtained as an industrial by-product during sawing, shaping, and polishing of marble. A total of 19 SCM mixtures were proportioned having a constant water-binder ratio of 0.40 and the total binder content of 550 kg/m3. The control mixture contained only portland cement (PC) as the binder while the remaining mixtures incorporated binary and ternary blends of PC, MP, and GGBFS. After mixing, the fresh properties of the SCM were tested for mini-slump flow diameter, mini-V funnel flow time, initial and final setting times, and viscosity. Moreover, compressive strength and ultrasonic pulse velocity of the hardened SCMs were measured. Test results indicated that the inclusion of MP increased the V-funnel flow time, setting times, and viscosity of SCMs whereas decreased the hardened properties. Using GGBFS, on the other hand, decreased the V-funnel flow time and viscosity while increased the setting times of SCMs. 2008 RILEM.

Guneyisi, E., M. Gesoglu, et al. (2011). "Permeation properties of self-consolidating concretes with mineral admixtures." ACI Materials Journal **108**(Compendex): 150-158.

This paper addresses the permeation properties of self-consolidating concretes (SCCs) with different types and amounts of mineral admixtures. Portland cement (PC), metakaolin (MK), fly ash (FA), and ground-granulated blast-furnace slag (GGBFS) were used in binary, ternary, and quaternary cementitious blends to improve the durability characteristics of SCCs. For this, a total of 22 SCCs were designed that have a constant water-binder ratio (w/b) of 0.32 and a cementitious materials content of 926.75 lb/yd3 (550 kg/m3). In addition to compressive strength and ultrasonic pulse velocity, the permeation resistance of SCCs was determined by means of chloride ion permeability, water permeability, and sorptivity tests. The test results indicated that the permeation properties of SCCs appeared to be very dependent on the type and amount of the mineral admixture used; the SCC mixtures containing MK were found to have considerably higher permeability resistance than the control mixture. Copyright 2011, American Concrete Institute. All rights reserved.

Guneyisi, E., M. Gesolu, et al. (2010). "Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures." Construction and Building Materials **24**(Compendex): 1878-1887.

Drying shrinkage can be a major reason for the deterioration of concrete structures. The contraction of the material is normally hindered by either internal or external restraints so that tensile stresses are induced. These stresses may exceed the tensile strength and cause concrete to crack. The present study investigated compressive strength and particularly drying shrinkage properties of self-compacting concretes containing binary, ternary, and quaternary blends of Portland cement, fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), and metakaolin (MK). For this purpose, a total of 65 self-compacting concrete (SCC) mixtures were prepared at two different water to binder ratios. It was observed that drying shrinkage lessened with the use of FA, GGBFS, and MK while incorporation of SF increased the drying shrinkage. 2010 Elsevier Ltd. All rights reserved.

Guo, J. (1999). "Study on high content of blends in cement." Journal Wuhan University of Technology, Materials Science Edition **14**(Compendex): 25-29.

The technology of activation by adding few activators (1%) to increase the amount of blends in cement was investigated. The results show that outer activation has a remarkable effect on improving the physical properties of slag cement, flyash cement and volcanic cement. For example, the compressive strength was increased by 5-10 MPa. Morever, the application of activation is beneficial to grind-aiding, early strength and water-reducing etc.

Hale, W. M., T. D. Bush Jr, et al. (2005). "Effect of curing temperature on hardened concrete properties : Mixtures of ground granulated blast furnace slag, fly ash, or a combination of both." Transportation Research Record(Compendex): 97-104.

Often, concrete is not mixed or placed under ideal conditions. Particularly in the winter or the summer months, the temperature of fresh concrete is quite different from that of concrete mixed under laboratory conditions. This paper examines the influence of supplementary cementitious materials on the strength development (and other hardened properties) of concrete subjected to different curing regimens. The supplementary cementitious materials used in the research program were ground granulated blast furnace slag (GGBFS), fly ash, and a combination of both materials. The three curing regimens used were hot weather curing, standard curing, and cold weather curing. Under the conditions tested, the results show that the addition of GGBFS at a relatively low replacement rate can improve the hardened properties for each curing regimen. This improvement was noticeable not only at later ages but also at early ages. Mixtures that contained both materials (GGBFS and fly ash) performed as well as and, in most cases, better than mixtures that contained only portland cement in all curing regimens.

Hale, W. M., S. F. Freyne, et al. (2008). "Properties of concrete mixtures containing slag cement and fly ash for use in transportation structures." Construction and Building Materials **22**(Compendex): 1990-2000.

The research program was designed to supply initial data on the influence of slag cement on the fresh and hardened properties of concrete to be used in pavements and bridge structures. There were three goals in the study. The first goal was to determine if slag cement performed better or worse with different Type I cements available in Oklahoma. Three different Type I cements were examined along with four different concrete mixtures. The four mixtures contained varying amounts of slag cement, fly ash, or a combination of both materials. The second goal of the research program was providing the Oklahoma Department of Transportation with information on ternary concrete mixtures. The final goal was to determine if the proposed replacement limits for slag cement and fly ash were adequate for concrete pavements and bridge structures. The results of the research showed that the addition of slag cement was largely positive for all cements, whereas the addition of fly ash produced mixed effects. 2007 Elsevier Ltd. All rights reserved.

Hanna, K. E., G. Morcous, et al. (2010). Class C Fly Ash in Pavements**:** 172p.

Portland cement is the most dominant material used in concrete pavements in the state of Nebraska. In order to improve performance, reduce cost, and advance sustainability, a percentage of the Portland cement is replaced with a recycled material known as fly ash. In recent years, Nebraska Department of Roads (NDOR) began noticing premature deterioration in many Portland cement concrete pavements (PCCP). A preliminary investigation into these pavements led NDOR to identify Class C fly ash used as a supplementary cementious material (SCM) in PCCP as one of the possible causes of the distress. As a result, NDOR changed their specifications banning the use of Class C fly ash in PCCP. This research project was conducted to investigate the cause of the PCCP deterioration and propose methods of mitigation while allowing the use of Class C fly ash. A thorough review of all relevant literature was conducted and potential mixes using Class C fly ash were identified. A testing program was established to determine which potential mixes meet the expected performance criteria. The first phase of testing was to assess the potential for Alkali Silica Reactivity (ASR) using ASTM C 1567. The testing was carried out on 14 potential mixes as well as the mix used in deteriorated PCCP and the reference mix currently used by NDOR in PCCP. Based on ASR testing results, four mixes were chosen to undergo overall performance testing, which includes strength and durability properties as well as fresh concrete properties. The testing comprised ASTM C666, C1202, C157, C403, C39, C78, and NDOR's wet-dry test. Testing results have indicated that three mixes have superior performance over the reference mix with 25% Class F fly ash as the only SCM. The three mixes were used in two field applications and specimens were taken for further laboratory testing to ensure their overall performance. The three proposed mixes have the same aggregate composition of the reference mix (70% 47B sand and gravel + 30% limestone), while containing different percentages of Class C fly ash and other SCM: 16% Class C fly ash + 20% Class F fly ash; 20% Class C fly ash + 20% Class F fly ash; and 15% Class C fly ash + 18% Class F fly ash + 15% Slag.

Hanson, E. M., N. J. Connolly, et al. (2010). Evaluating and Optimizing Recycled Concrete Fines in PCC Mixtures Containing Supplementary Cementitious Materials**:** 66p.

Portland cement concrete (PCC) is used throughout transportation infrastructure, for roads as well as bridges and other structures. One of the most effective ways of making PCC more "green" is to replace a portion of the portland cement (the portion of a PCC mixture with the greatest carbon footprint) with a supplementary cementitious material such as flyash or ground granulated blast furnace slag (GGBFS). Since these supplementary cementitious materials are waste byproducts, they can significantly reduce the carbon footprint of PCC. A consequence of using these materials, however, is that they can reduce the rate of early PCC strength gain. This reduced rate of strength gain can cause problems, especially in urban areas where user costs from delayed construction must be considered when evaluating a project's overall cost. Previous work (Janssen, et al., 2006) demonstrated that the use of recycled concrete fines could offset some or all of the delayed strength-gain effects from cement-GGBFS blends. Current work appears to indicate that the use of such fines could allow for increased cement replacement with no additional reduction in early strength gain. Unfortunately, recycled concrete fines can be quite variable from batch to batch. To effectively utilize recycled concrete fines to offset delayed strength gains associated with the use of supplementary cementitious materials, a procedure must be developed that: 1) evaluates the effectiveness of a specific recycled concrete fines source, and 2) determines PCC mixture proportions that utilize the recycled concrete fines to offset reduced strength-gain effects associated with the use of supplementary cementitious materials as cement replacement. This procedure must be rapid and inexpensive so that ready-mix concrete producers could easily perform the procedure whenever a new recycled concrete fines source is obtained.

Haque, M. N. and T. Chulilung (1990). "Strength development of slag and ternary blend concrete." Cement and Concrete Research **20**(Compendex): 120-130.

Ground granulated blast furnace (GGBF) slag is increasingly used in concrete construction due to its technical and economic benefits. This paper describes the strength development of 3 grades of plain cement concretes, portland blast furnace slag (slagment) concretes and concretes in which 15 and 35% of slagment was replaced by flyash (ternary blends). These concretes were cured in standard and nonstandard curing conditions using standard and nonstandard cylindrical specimens. The straight replacement of portland cement by slagment (65% cement and 35% slag) gave higher strength for low to medium strength concretes (20 and 35 MPa). The results also suggest that the strength of the concretes made with slagment was less affected under inadequate curing conditions as compared to the strength of the plain cement concretes. It was also found that the indicated strength of the smaller cylinders (75150 mm) was adversely affected in the drying curing regimes whereas it was only marginally different from the strength of 150300 mm cylinders under continuous fog curing. For all the concretes tested, initial curing for 7 days seems to be the most appropriate as it is both practicable and gives adequate strength.

Hardjito, D., S. E. Wallah, et al. (2004). "On the development of fly ash-based geopolymer concrete." ACI Materials Journal **101**(Compendex): 467-472.

To reduce greenhouse gas emissions, efforts are needed to develop environmentally friendly construction materials. This paper presents the development of fly ash-based geopolymer concrete. In geopolymer concrete, a by-product material rich in silicon and aluminum, such as low-calcium (ASTM C 618 Class F)fly ash, is chemically activated by a high-alkaline solution to form a paste that binds the loose coarse and fine aggregates, and other unreacted materials in the mixture. The test results presented in this paper show the effects of various parameters on the properties of geopolymer concrete. The application of geopolymer concrete and future research needs are also identified.

Hassan, K. E., J. J. Brooks, et al. (2001). "Compatibility of repair mortars with concrete in a hot-dry environment." Cement and Concrete Composites **23**(Compendex): 93-101.

Strengthening, maintenance and repair of concrete structures are becoming more recognized in the field of civil engineering. There is a wide range of repair mortars with varying properties, available in the market and promoted by the suppliers, which makes the selection of the most suitable one often difficult. A research programme was conducted at Leeds University to investigate the properties of cementitious, polymer and polymer modified (PMC) repair mortars. Following an earlier publication on the intrinsic properties of the materials, this paper presents results on the compatibility of these materials with concrete. The dimensional stability is used in this study to investigate the compatibility of the repair mortars and the parent concrete. Composite cylindrical specimens (half repair mortar/half concrete) were prepared and used for the measurements of modulus of elasticity and shrinkage. The results of the different combined systems were obtained and compared to those calculated using a composite model. The variations between the measured and calculated values were less than 10%. The paper attempts to quantify the effect of indirect differential shrinkage on the permeability and diffusion characteristics of the different combined systems.

Hauggaard, A. B., L. Damkilde, et al. (1999). "TRANSITIONAL THERMAL CREEP OF EARLY AGE CONCRETE." Journal of Engineering Mechanics **125**(4): p. 458-465.

Couplings between creep of hardened concrete and temperature/water effects are well-known. Both the level and the gradients in time of temperature or water content influence the creep properties. In early age concrete, the internal drying and the heat development caused by hydration increase the effect of these couplings. The purpose of this work is to set up a mathematical model for creep of concrete that includes the transitional thermal effect. The model governs both early age concrete and hardened concrete. The development of the material properties in the model is assumed to depend on the hydration process and the thermal activation of water in the microstructure. The thermal activation is assumed to be governed by the Arrhenius principle, and the activation energy of the viscosity of water is found applicable in the analysis of the experimental data. Changes in temperature create an imbalance in the microstructure termed the microprestresses, which reduce the stiffness of the concrete and increase the creep rate. The aging material is modeled in an incremental way, reflecting the hydration process in which new layers of cement gel solidify in a stress free state and add stiffness to the material. Analysis of experimental results for creep of early age and hardened concrete, either at different constant temperature levels or for varying temperature histories, illustrate the model.

Hazaree, C. and H. Ceylan (2006). High volume fly ash concrete for pavement applications with gap graded aggregates: Marginal and fine sands. 2006 Airfield and Highway Pavement Specialty Conference, April 30, 2006 - May 3, 2006, Atlanta, GA, United states, American Society of Civil Engineers.

Depleting aggregate resources and the inherent variability and inconsistencies in the aggregates' geometric properties are becoming topics of greater concern in the delivery of concrete. Gap-graded concrete can be used in lower workability ranges and it has been proved that superior quality and greater economic benefits can be achieved by its usage. This study was undertaken to understand the qualitative and economic alterations when high volume fly ash concrete and gap-graded aggregates were used simultaneously. Marginal and fine sands were defined on the basis of the grading limits of the Indian standard. A set of 41 concrete mixture proportions incorporating various fine and marginal sands and high volumes of fly ash (HVFA) were used in this investigation. Fresh properties of like Vee-Bee time, density, air content, compaction factor and hardened properties in the form of uniaxial unconfined compressive strength and flexural strengths were measured up to 181 days. Results show that with proper mix proportioning and optimization, marginal materials in combination with HVFA could be utilized in concrete for pavement applications. The results also demonstrate a possibility of effortless cement replacement by fly ash in the range of 40-50%, with resultant economic benefits.

He, Z. and W. Q. Liang (2001). "The properties and applications of high-effective mineral admixture CRM for concrete." Journal Wuhan University of Technology, Materials Science Edition **16**(Compendex): 41-45.

To utilize industrial residue as building materials is not only the demand for modern concrete technology but also the requirements for maintaining ecological balance and sustainable development. CRM, a new high-effective mineral admixture for concrete, is developed recently from industrial residue, and the systematical studies on CRM's various properties have been performed. The laboratory tests, industrial tests and field applications have shown that CRM can be used as inorganic cementitious material to replace cement, and is also an excellent supplementary cementitious material for high performance concrete (HPC).

He, Z., J. Liu, et al. (2011). Mechanical properties of steam-cured concrete with combined mineral admixtures. 2011 International Conference on Structures and Building Materials, ICSBM 2011, January 7, 2011 - January 9, 2011, Guangzhou, China, Trans Tech Publications.

In precast concrete elements manufacturing, steam-cured concrete incorprating 30% mineral admixtures encountered the problem of too low demoulding compressive strength. To resolve it, this paper mainly studied the influence of mineral admixtures on the compressive strength, the tensile-splitting strength and the flexural strength of the steam-cured concrete. The experimental results indicated that, compared with steam-cured concrete incorprating mineral admixtures, the later strength of steam-cured concrete incorprating 0% mineral admixtures has lower increment degree and its increment of tensile-splitting strength and flexural strength inverted to some extent. The demoulding compressive strength is too low for the high volume fly ash concrete mixtures. The problem of too low demoulding compressive strength is solved by incorprating composites of ground blast furnace slag(GBFS) and fly ash. Different varieties of mineral admixture used in the concretes can produce a certain degree of potentiation.

Heffron, R. (2010). Numerical modeling to achieve concrete durability for new waterfront structures of 100 years or more, but at what price? 12th Triannual International Conference - Ports 2010: Building on the Past, Respecting the Future, April 25, 2010 - April 28, 2010, Jacksonville, FL, United states, American Society of Civil Engineers.

Concrete durability design need not be black magic. Technologies and products exist in the market today to achieve durability goals of 100 or even 200 years. But the key questions that must be asked are: 1.What is the cost? 2. How can we convince ourselves that we can achieve these goals? 3. What quality control measures are needed to achieve these goals? The U.S. Navy has been making pioneering advances in concrete durability modeling techniques to ensure their extensive investments in new waterfront assets are sound investments. This technology is available to all and is being used on commercial waterfront projects as well. With the advances made in numerical modeling techniques, it is now possible to quantitatively predict durability with decent accuracy. The STADIUM&reg model, developed by Materials Service Life of Quebec, Canada, has been adopted by the U.S. Navy as their service life model of choice for predicting marine concrete durability. The numerical model relies on the use of

four "transport properties" that are tested from actual concrete samples to determine how aggressive agents such as chloride ions move through the concrete over time. The advent of this new technology now allows engineers to place more emphasis on performance specifications rather than relying only on prescriptive methods. Engineers can specify strength and durability (in terms of required design life) requirements and allow contractors to innovate to achieve the desired results. There are numerous methods of achieving enhanced durability, including adding concrete cover distance of reinforcing steel, choosing a less corrosive or non-corrosive reinforcing steel, using fusion-bonded epoxy-coated rebars, using corrosion inhibitor admixtures, applying external barrier coatings, using supplementary cementitious materials such as fly ash and silica fume, and varying the concrete mix design parameters such as water cement ratio and cement content, for example. Numerical modeling allows the engineer to evaluate the myriad options on an even playing field to determine the optimal solution. The use of a standardized service-life model also allows suppliers to innovate and develop new products to improve durability performance, knowing that they will be subject to fair and unbiased evaluation. Such innovation is sorely lacking in the U.S. construction industry at present since it can often take 10 to 15 years to bring a new product to market. Durable concrete also requires effective quality control measures in the field to ensure the final product matches or exceeds performance in the laboratory. This paper will describe the beta-testing experience and lessons learned by the U.S. Navy on a major new wharf project in a corrosive tropical environment. 2010 ASCE.

Hicks, J. (2010). Durable "green" concrete from activated pozzolan cement. Green Streets and Highways 2010: An Interactive Conference on the State of the Art and How to Achieve Sustainable Outcomes, November 14, 2010 - November 17, 2010, Denver, CO, United states, American Society of Civil Engineers.

Concrete is the most widely used man-made material, and the manufacture of Portland cement - the active ingredient of concrete - accounts for 6 to 8 percent worldwide of all anthropogenic emissions of carbon dioxide, a leading greenhouse gas involved in global warming. Globally, nearly 2.77 billion metric tons (t) (3.05 billion st) of portland and hydraulic cement was produced in 2007. The concrete construction sector has a responsibility to take immediate action to reduce its environmental impacts, including the generation reduction of CO2. This responsibility also brings the opportunity to develop innovative technologies, including use of materials from Coal Combustion Products (CCP's). These newly developed activated fly ash based products leave virtually no carbon footprint. Updated cementitious binder technology eliminates approximately 0.9 t (1 st) of CO2 emitted into the atmosphere per ton of portland cement produced. These cements have been engineered for use in fast track concrete repairs and construction, conventional paving, walls and concrete block masonry, new construction and repair projects. Activated pozzolanic material cements and resulting products are comprised of up to 95 percent green sustainable industrial waste stream materials, primarily fly ash. They are manufactured via a low energy, powder blending process. Key to green cement development was

creating a material matrix that has a very dense crystal structure. This green cement technology possesses excellent performance and durability characteristics, including high early strengths and 28-day strengths over 70 MPa (10,000 psi). Moreover, they can be placed effectively with ambient temperatures ranging from -1C to 49C (30F to 120F). 2010 ASCE.

Hicks, J. K., M. Riley, et al. (2009). Utilization of recovered materials for high quality cements and products. 3rd World of Coal Ash, WOCA Conference, May 4, 2009 - May 7, 2009, Lexington, KY, United states, Unavailable.

CeraTech, Inc. has advanced the state of the art in reactive pozzolanic cements for use in most cement and concrete markets. The result is an enabling technology that utilizes a very large percentage of coal fly ash to produce a high performance family of cements. This cement technology can be used as a direct replacement for portland cement in most concrete, mortar or grout applications, thereby reducing the consumption of portland cement and the associated greenhouse gases generated from that manufacturing process. The production of activated fly ash cements generates virtually no "carbon footprint". In contrast, portland cement production generates approximately 1 ton of CO2 for each ton of clinker produced. These green cements and resulting products are comprised of more than 90% sustainable industrial waste stream materials. They are manufactured via a simple low energy, powder blending process. This revolutionary green cement technology possesses exceptional mechanical performance characteristics highlighted by rapid strength development properties. The highly reactive nature of the cement matrix allows for a broad range of mix designs as low as 3,000 psi (21 MPa) to over 12,000 psi (69 MPa) compressive strength at 28 days with nominal cementitious content per cubic yard of concrete. Moreover, this activated fly ash cement is mixed, placed and finished like standard cement concrete. Resulting products can be effectively placed in ambient temperatures ranging from 30F (-1.1 C) to 120F (48.9C). Post placement temperature rise is minimal and less than most other hydraulic cements and their products.

Higgins, D. D. and N. J. Crammond (2003). Resistance of concrete containing ggbs to the thaumasite form of sulfate attack, Elsevier Ltd.

A long-term laboratory study has investigated how cement-type, aggregate-type and curing, affect the susceptibility of concrete to the thaumasite form of sulfate attack (TSA). The cements were Portland cement (PC), sulfate-resisting Portland cement (SRPC) and a combination of 70% ground granulated blastfurnace slag (ggbs) with 30% PC. These were combined with various carbonate aggregates or a non-carbonate control. Initial curing was either in water or in air. Concrete cubes were immersed in four strengths of sulfate solution at 5 and 20 C. This paper reports the results after up to six years of immersion in sulfate solution. Deterioration, consistent with TSA, was observed on many of the PC and SRPC concretes that had been made with carbonate aggregate and stored in sulfate solutions at 5 C, with SRPC providing no better resistance to TSA than PC. Good quality concretes made with 70%ggbs/30%PC showed high resistance to TSA and the presence of carbonate in the mix substantially improved their general sulfate resistance. An initial air-cure, proved beneficial against both the conventional and thaumasite form of sulfate attack. 2003 Elsevier Ltd. All rights reserved.

Hime, W. and B. Erlin (2004). "The versatility of, and tidbits about, concrete." Concrete Construction - World of Concrete **49**(Compendex): 24.

Various use of concrete in industrial and domestic purpose is discussed. The June 2004 issue of Concrete International is dedicated to decorative concrete and contains a number of articles that demonstrate the splendid use of concrete as an artistic material. The final product of cement, concrete uses reinforcing and prestressing steels, aggregates, admixtures, supplementary cementing materials like fly ash, slag, pozolans and silica fume. Smokestack dust from portland cement manufacturing plants provided a source of free fertilizer.

Hime, W. and B. Erlin (2005). "Some things about the strength of concrete." Concrete Construction - World of Concrete **50**(Compendex): 24.

The various aspects of strength of concrete in the construction industry are discussed. Concrete made today without supplementary cementitious materials gains strength more quickly. Type F fly ashes slow strength development, and they also lower costs, increasing resistance to water penetration, increasing resistance to aggressive chemicals and slowing and reducing heat development in mass concrete. Fly ash is a patriotic material because it extends the use of portland cement, which consumes a lot of energy in the making.

Hoffman, G. (2009). Factors influencing use of mineral admixtures for the past decade in the western US. SME Annual Meeting and Exhibit and CMA's 111th National Western Mining Conference 2009, February 22, 2009 - February 25, 2009, Denver, CO, United states, Society for Mining, Metallurgy and Exploration.

Sustainable development has brought social, environmental and energy efficiency concerns together with management and governance of natural resources. Cement manufacturing, an energy- and natural resource-intensive industry, is adapting to meet sustainable development goals. Emission standards for cement plants and increasing energy costs have lead to changes in the use of natural resources and recycled materials. Utilizing pozzolans or supplementary cementitious materials (SCMs) as mineral admixtures in blended cement or as a substitute for cement in concrete lowers energy costs and CO2 emissions. Although the western U.S. is rich in natural pozzolans, artificial products, particularly fly ash, have greater use as mineral admixtures. Pozzolans and SCMs have many beneficial properties, such as preventing alkali-silica reactivity, a common problem in the western U.S. Barriers exist for mineral admixtures in the cement and concrete industries because of past inconsistencies in quality or availability. New environmental regulations on the primary industries producing artificial mineral admixtures could adversely affect the quality and quantity of these materials in the future.

Hong, S.-Y. and F. P. Glasser (2002). "Alkali sorption by C-S-H and C-A-S-H gels: Part II. Role of alumina." Cement and Concrete Research **32**(Compendex): 1101-1111.

In Part I, it was shown that alkali partition between C-S-H gel and an aqueous phase can be represented by a partition function, Rd, the numerical value of which, at constant temperature, is defined by the Ca/Si ratio. This Rd value is constant or nearly so over wide ranges of NaOH and KOH concentrations up to 0.3 M. In the present paper, Al has been introduced to form C-A-S-H gels, and the influence of Al on alkali sorption properties was determined: Approximately 6-7% replacement of Si by Al was used. Microprobe evidence is presented to show that the Al is actually in solid solution. Introduction of Al into C-S-H markedly increases Rd, indicating enhancement of alkali binding. The results underpin and quantify the beneficial effects of alkali binding arising from the introduction of aluminous supplementary cementing materials, such as fly ash, into cement pastes. 2002 Elsevier Science Ltd. All rights reserved.

Hooton, R. D. (1986). PERMEABILITY AND PORE STRUCTURE OF CEMENT PASTES CONTAINING FLY ASH, SLAG, AND SILICA FUME. Blended Cements., Denver, CO, USA, ASTM.

As part of research to develop a highly durable concrete container for radioactive waste disposal in chloride and sulfate bearing granite groundwaters, a variety of cement pastes were studied. A sulfate resisting portland cement was used with various replacement levels of Class F fly ash and pelletized blast furnace slag at a water to solids ratio (W/S) equals 0. 36. Blends with fly ash, slag, and silica fume were also combined with a super water reducer at W/S equals 0. 25. Results are presented for strength development, permeability to water, and pore size distribution after 7, 28, 91, and 182 days moist curing. As a direct measure of durability, after 91 days moist curing, paste prisms were immersed in both de-ionized water and a synthetic chloride and sulfate bearing groundwater at 70 degree C. While all three supplementary cementing materials (mineral admixtures) reduced ultimate permeabilities, silica fume was more effective in reducing permeability at early ages. Silica fume was also the most effective in reducing calcium hydroxide contents of the pastes.

Hooton, R. D. (2000). "Canadian use of ground granulated blast-furnace slag as a supplementary cementing material for enhanced performance of concrete." Canadian Journal of Civil Engineering **27**(Compendex): 754-760.

The performance of concrete, in terms of its placeability, physical properties, and its durability, can be enhanced by the use of slag-blended cements or separately added ground granulated blast-furnace slag. It also has advantages for architectural purposes due to the whiteness it imparts to concrete. Properly proportioned and cured slag concretes will control deleterious alkali-silica reactions, impart sulphate resistance, greatly reduce chloride ingress, and reduce heat of hydration. Setting times and early age strengths can be controlled through appropriate proportioning, while later age properties are typically enhanced. CSA and ASTM standards cover both slag-blended cements (CSA A362; ASTM C595; ASTM C1157) and slag as a supplementary cementing material (CSA A23.5; ASTM C989). Since Lafarge introduced the first large-scale slag grinding plant near Hamilton in 1976, slag has become the predominant supplementary cementing material in Ontario. Recently, its availability in the U.S. has expanded dramatically.

Hooton, R. D., K. Hover, et al. (2005). "Performance standards and specifications for concrete: Recent Canadian developments." Indian Concrete Journal **79**(Compendex): 31-37.

Traditional standards and specifications for concrete have largely been prescriptive, (or prescription-based), and can sometimes hinder innovation and in particular the use of more environmentally friendly concretes by requiring minimum cement contents and replacement levels of supplementary cementing materials (SCM). The Canadian CSA A23.1-04 standard has made provisions for high-volume SCM concretes and has clearly outlined the requirements and responsibilities for use in performance-based concrete specifications. A review was made of international standards, especially ones that include performance-based provisions, and it was found that the CSA standard is amongst the most progressive national performance standards in the world at the present time. One of the main concerns with performance specifications has been the lack of, or lack of confidence in, test methods for judging all relevant performance concerns. A review was made of currently used or available test methods for both fresh, hardened physical, and durability properties, and it was found that although there may be no ideal testing solutions, there are a number of practical and useful tests available. New performance tests will be added in future revisions. Another concern is different perspectives on the point of testing for performance. Some suppliers may prefer processes for prequalifying the plant, and for prequalifying specific mixtures, followed only with testing only end-of-chute fresh properties on-site. However, owners want to know the in-place performance of the concrete, especially with high-volume SCM concretes where placing and curing are important. Also, the contractor must be aware of, and share the responsibility for handling, constructability, curing, and scheduling issues that influence the in-place concrete properties.

Hooton, R. D. and M. P. Titherington (2004). "Chloride resistance of high-performance concretes subjected to accelerated curing." Cement and Concrete Research **34**(Compendex): 1561-1567.

The strengths and chloride penetration resistance of a series of high-performance concretes were measured after curing either at 23 C or accelerated by heating to 65 C. The results confirm that concretes containing silica fume (SF) or ternary blends of SF and ground granulated blast-furnace slag (GGBFS) exhibit improved chloride penetration resistance compared to those of plain Portland cement concretes. In addition, chloride penetration resistance of Portland cement concrete is adversely affected by accelerated curing. With the use of the ternary ordinary Portland cement (OPC)-SF-GGBFS binders, accelerated curing did not have detrimental effects on chloride penetration resistance and provided 18-h strengths in excess of 40 MPa. 2004 Elsevier Ltd.

All rights reserved.

Hossain, A. B., S. Shrestha, et al. (2009). "Properties of concrete incorporating ultrafine fly ash and silica fume." Transportation Research Record(Compendex): 41-46.

A laboratory study on the influence of the combination of ultrafine fly ash (UFFA) and silica fume (SF) on the properties of fresh and hardened concrete is described. Also compared are the performance of concrete incorporating UFFA and SF (ternary blend of cement), concrete incorporating UFFA or SF (binary blend of cement), and control portland cement concrete. The test results show that the incorporation of SF or UFFA in concrete resulted in higher strength and improved durability (resistance to chloride penetration). These benefits were found to be more pronounced in the SF concrete. However, the SF concrete demonstrated several limitations such as low slump and high early-age shrinkage. These limitations were not observed in the UFFA concrete; addition of UFFA increased the slump and decreased the early-age shrinkage. To minimize the shortcomings of SF without losing its strength and durability benefits, a concrete mixture incorporating both SF and UFFA was prepared. The test results show that the incorporation of both SF and UFFA produces a concrete mixture that demonstrates high early-age strength and improved durability similar to those properties in SF concrete. In addition, unlike SF concrete, the new concrete mixture demonstrates a higher level of slump and a lower level of free shrinkage.

Hossain, K. M. A. and M. Lachemi (2008). "Bond behavior of self-consolidating concrete with mineral and chemical admixtures." Journal of Materials in Civil Engineering **20**(Compendex): 608-616.

Self-consolidating concrete (SCC) is known for its excellent deformability, high resistance to segregation, and use in congested reinforced concrete structures characterized by difficult casting conditions without applying vibration. Research has been conducted on the development of SCC using high volumes of supplementary cementing materials (SCM) (such as fly ash and slag) and viscosity modifying admixtures (VMA). The bond characteristics of such SCCs are very important for their application in practical construction. An extensive investigation was conducted to determine the bond strength between deformed reinforcing steel bar and SCM and VMA based SCC as well as normal concrete (NC). Bond tests were conducted using a specially developed pullout test. The SCC pullout specimens were cast without applying any consolidation, whereas the NC specimens were cast by conventional practice with consolidation and vibration. It was found that the reduction in bond strength due to bleeding and inhomogeneous nature was less in SCC compared to NC. Although the variation in bond strengths at different casting elevations was observed in SCC, the extent was less significant than that of NC. SCC also exhibited a less significant top-bar effect compared to NC. This can be attributed to the more consistent nature of SCC and its superior filling capability. Performance of various code based and other existing bond equations are validated through experimental results illustrating the influence of concrete types (either SCC of different types or NC).

2008 ASCE.

Huang, Y. and Z. Lin (2010). "Effect of sodium hydroxide on the properties of phosphogypsum based cement." Journal Wuhan University of Technology, Materials Science Edition **25**(Compendex): 342-345.

The effect of sodium hydroxide (NaOH) amount on phosphogypsum based cement was investigated. The mechanical performances and hydration mechanism of the phosphogypsum- based cement with different proportions of NaOH and steel slag were analyzed based on setting time, volume stability, strength test, XRD and SEM analyses. The experimental results show that, NaOH as an alkali activator significantly reduces the cement setting time and improves the cement early strength. But the acceleration of hydration proces produces coarse crystalline hydration products and the osteoporosis structure of hardened paste, which has a negative effect on later age strength. The combination of 1% NaOH and 5% steel slag as alkali activating agents is optimal with respect to early and later age strengths. Overdose of NaOH not only decreases the cement strength at later age, but also may cause problem of volume stability. Wuhan University of Technology and Springer-Verlag Berlin Heidelberg 2010.

Huang, Y. and X. Yu (2007). No-fines concrete as ecologic stream bank erosion control. Geo-Denver 2007: New Peaks in Geotechnics, Febrary 18, 2007 - Febrary 21, 2007, Denver, CO, United states, American Society of Civil Engineers.

No-fines concrete is a pervious concrete obtained by eliminating the sand from normal concrete mix. Compared with conventional concrete, no-fines concrete has unique properties desirable for various applications. Because of the presence of large voids, no-fines concrete has lower density, cost and thermal conductivity, smaller dying shrinkage, no segregation, larger contaminant retaining capability, and reduced capillary movement of water. No-fines concrete is used for construction of pavement, storm water control utilities and green houses. This paper discusses the application of no-fines concrete as an ecology preservative method for stream bank erosion control. Soil erosion is an important factor that can trigger the instability of an embankment. A sustainable revetment should provide soil erosion protection without significantly changing the existing ecologic environment. The strength of no-fines concrete provides sufficient protection against scour of embankments. Although grasses are found to be hard to survive with ordinary types of bank revetment, especially when subjected to periodic inundation from river water level fluctuations, the large pore spaces of no-fines concrete protect grass seeds and provide an environment for grasses to grow. By installing artificial access holes in the no-fines concrete revetment, the ecologic conditions can be preserved to the maximal extent. The design criteria and durability of no-fines concrete revetments are discussed in this paper. This paper also provides an example application of a no-fines concrete revetment that achieved the desirable ecologic effects. Copyright ASCE 2007.

Hubler, M. H., J. J. Thomas, et al. (2011). "Influence of nucleation seeding on the hydration kinetics and compressive strength of alkali activated slag paste." Cement and Concrete Research **41**(Compendex): 842-846.

Addition of pure calcium silicate hydrate (C-S-H) to alkali-activated slag (AAS) paste resulted in an earlier and larger hydration rate peak measured with isothermal calorimetry and a much higher compressive strength after 1 d of curing. This is attributed to a nucleation seeding effect, as was previously established for Portland cement and tricalcium silicate pastes. The acceleration of AAS hydration by seeding indicates that the early hydration rate is controlled by nucleation and growth. For the experiments reported here, the effect of C-S-H seed on the strength development of AAS paste between 1 d and 14 d of curing depended strongly on the curing method. With sealed curing the strength continued to increase, but with underwater curing the strength decreased due to cracking. This cracking is attributed to differential stresses arising from chemical and autogenous shrinkage. Similar experiments were also performed on Portland cement paste. 2011 Elsevier Ltd. All rights reserved.

Huizhen, L. and Y. Peiyu (2004). FOR SUSTAINABLE DEVELOPMENT: TO PRODUCE CEMENT BY ANOTHER CONCEPT, Iowa State University, Ames.

The study considers production of cement by a new method beneficial for imp[roving properties of the cement and concrete while increasing sustainable development. The following three issues must be considered for the production principle: hydration characteristics of the new cement; particle size distribution; and compatibility of chemical admixtures and hydraulic constituents. Some new property proofing methods and standards must also be developed to enhance the utilization of this new cement.

Husain, A., S. Al-Bahar, et al. (2004). "Accelerated AC impedance testing for prequalification of marine construction materials." Desalination **165**(Compendex): 377-384.

The AC impedance technique was used in this study for the evaluation and prequalification of concrete materials prepared with chemical corrosion inhibitors and pozolanic admixtures of GGBS slag. In the Arabian Gulf region, marine seawater corrosion has caused severe concrete deterioration over the past decades. Major industrial buildings such as power generation plants, desalination plants and off-shore structures, and oil or water piers deteriorate severely in the marine industrial seawater environment due to the deleterious effect of chloride ions and CO2 gas. It has only recently been appreciated in this difficult region that concrete with supplementary cementing materials exhibit a very significant reduction in permeability and corrosion effects. Assessment of the corrosion condition of steel rebar in concrete for newly proposed projects can be carried out with different techniques. Most of the testing methods suggested are based on the ASTM standards G-109, ASTM C876, and ASTM C 1202. The duration for ASTM testing requires at least a minimum of 1 to 3 years of exposure in simulated weathering conditions before any reliable conclusion can be drawn. In the present study, accelerated AC impedance measurements were carried out over a wide frequency range on reinforced Lollipop specimens of GGBS slag with different degrees of compaction of the concrete mix. The AC impedance technique allows detection of the breakdown of passivity and performance of the steel reinforcement in concrete within a much shorter time than with other tests. The correlation between the AC impedance technique and traditional ASTM standards indicated concurring results of the benefit of the application of multicomponent corrosion protection systems under the prevailing conditions of the marine environment in the Arabian Gulf region. 2004 Elsevier B.V. All rights reserved.

Hwang, C.-L. and C.-C. Chiang (2006). "The study on partial replacement of Portland cement with EAF slag in concrete." SEAISI Quarterly (South East Asia Iron and Steel Institute) **35**(Compendex): 39-43.

The slag from the waste of stainless steel or carbon steel by electric arc furnace (EAF) is investigated to know the feasibility of partial replacement of cement for making high performance concrete (HPC). The properties of HPC with different water-to-binder ratio (w/b) and different quantity of reduction slag are studied. The fresh and harden concrete properties are emphasized. Results show that the major chemical compositions of the reduction slag are CaO, Al 2O3 and SiO2 that are similar to those of blast furnace slag. The concrete slump can be designed to over 230 mm, an excellent working condition of self-consolidating concrete (SCC). The setting time ofHPC is similar to that of ordinary Portland concrete (OPC). The compressive strength and pulse velocity of HPC with stainless steel slag (SSC) and carbon steel slag (CSS) may exceed 100 percent and 95 percent of that of OPC, respectively. The reduction slag (RS) can be concluded as a cementitious material for production HPC or SCC, however long-term durability is still needed further examination.

Hwang, C.-L. and C.-Y. Lin (1986). "STRENGTH DEVELOPMENT OF BLENDED BLAST-FURNACE SLAG-CEMENT MORTARS." Chung-kuo Kung Ch'eng Hsueh K'an/Journal of the Chinese Institute of Engineers **9**(Compendex): 233-239.

Blast-furnace slags cooled at different rates were used to study the effect of fineness, mixing method and content of slag on the strength development of blended-slag mortar. Activator and curing temperature were used to activate the early strength. The microstructure of blended-slag paste was also investigated in this study to explain the strengthening effect.

Hwang, C.-L. and D.-H. Shen (1991). "Effects of blast-furnace slag and fly ash on the hydration of portland cement." Cement and Concrete Research **21**(Compendex): 410-425.

In this study, a calorimeter, an ultrasonic tester, an optical microscope, and other pieces of conventional laboratory equipment, such as a Vicat needle, were employed in the investigation of the effect of blast-furnace slag and fly ash on the hydration of fresh cement paste. Test results indicate that a strong relationship exists among the calorimetric curve, the ultrasonic pulse velocity curve, and the penetrative resistance strength curve. A transition zone appearing in the ultrasonic pulse velocity curve corresponds to the period between the end of the dormant period and the deceleration period in the calorimetric curve. In the calorimetric curve during the end of the dormant period, the ultrasonic pulse velocity curve rises rapidly and the penetrative resistance strength curve begins to develop simultaneously. From optical microscopy observations, it is found that CH crystals develop rapidly and contribute to the early strength development of cement paste in the plastic state. The end of the dormant period and the second peak in the calorimetric curve are similar to both the initial and final setting times as measured by the Vicat needle. Although the transition zone of hydration introduced by the blast-furnace slag and fly ash differ slightly, they both appear somewhat later in comparison to that of ordinary portland cement.

Idorn, G. M. (1983). CONCLUDING ASSESSMENT OF FUTURE DEVELOPMENT. Technology in the 1990s: Developments in Hydraulic Cements, Proceedings of a Royal Society Discussion Meeting., London, Engl, Royal Soc.

The contributions to the conference are reviewed with the aim of identifying their potential influence on the development of hydraulic cement science and technology in the 1990s. The high-technology-low-volume innovations presented are emphasized because they point towards future efforts in this direction. Most of the contributions commented upon are related to the basic materials, the processing characteristics and the performance behaviour of concrete and cement paste. The availability of fly ash and slag is referred to because it is encouraging more determined research. The need for more concern about research and development systems as means to transform research into reliable technology, accessible to the practising engineer and labour forces, is stressed.

Igarashi, S., A. Bentur, et al. (1999). "Stresses and creep relaxation induced in restrained autogenous shrinkage of high-strength pastes and concretes." Advances in Cement Research **11**(Compendex): 169-177.

The development of internal stresses induced by restrained autogenous shrinkage in cement pastes and concretes with low water/binder ratios was investigated. The restrained autogenous stress developed was smaller than that expected on the basis of consideration of the autogenous shrinkage strain only. This was accounted for by relaxation due to early age creep. Reduction of w/b and the addition of silica fume led to stresses that could approach 50% of the strength. At such high stresses, the risk of cracking was significant. Development of the stress in high-strength concrete could not be directly related to the properties of its cement paste matrix. The presence of aggregates reduced proportionally the autogenous shrinkage. However, this was not accompanied by a similar proportional reduction in the induced stress, since the aggregate also caused a reduction in the creep relaxation effect. The reduced creep in the concrete, compared with the paste, was not always proportional to the aggregate content.

Igarashi, S. and M. Kawamura (2002). "Effects of microstructure on restrained autogenous shrinkage behavior in high strength concretes at early ages." Materials and Structures/Materiaux et Constructions **34**(Compendex): 80-84.

Fluorescence microscopic examinations were conducted to identify damages induced by restraining autogenous shrinkage. Characteristics of fluorescent areas and their correspondence to autogenous shrinkage behavior of high strength concretes were discussed. Silica fume concrete exhibited a greater creep potential when loaded at very early ages. The microstructure in sealed concretes with an extremely low water/binder ratio was porous. The vicinity of aggregate grains was more porous and weaker than the bulk matrix in sealed concretes. In addition, sealed silica fume concretes contained many unhydrated cement particles which were profiled by thin gaps between the core cement particles and the surrounding cement paste matrix. These features of microstructure were not observed in water ponded concretes. The detected fluorescent areas may be defects caused by self-desiccation and autogenous shrinkage. The flaws has little effects on the development of strength. However, the presence of thin gaps around remnant cement particles may increase creep deformation to relieve internal stresses.

Igarashi, S.-I., A. Bentur, et al. (2000). "Autogenous shrinkage and induced restraining stresses in high-strength concretes." Cement and Concrete Research **30**(Compendex): 1701-1707.

Development of internal stresses induced by restrained autogenous shrinkage in high-strength concretes at early ages was investigated. Effects of water/binder ratio and the presence of silica fume on the stress developed were evaluated and considered in conjunction with the creep behavior of the concretes. The restrained autogenous shrinkage resulted in a relatively high stress that sometimes caused premature cracking in the high-strength concrete. This occurred mainly when the ratio between the restraining stress and the tensile strength approached 50%. The stresses were not as high as expected from the autogenous shrinkage, since considerable relaxation took place due to creep. Thus, the viscoelastic nature of the concrete at early age has a considerable influence on the stresses generated.

Igarashi, S.-I., H. R. Kubo, et al. (2000). "Long-term volume changes and microcracks formation in high strength mortars." Cement and Concrete Research **30**(Compendex): 943-951.

Volume changes of high strength mortars cured in water were investigated. Effects of characteristic microstructure on the volume stability were considered in relation to the formation of microcracks. Mortars without silica fume exhibited swelling at early ages while the ones with silica fume started to swell at long ages after a certain period of initial shrinking in water. Cracking at long ages was confirmed for the both mortars with and without silica fume. However, there were distinct differences in the characteristics of crack patterns, such as the situation for cracking and their effects on the strength development between both. It was suggested that a mechanism other than autogenous shrinkage was involved in volume changes which occurred in mortars with an extremely low water/binder ratio. Generation of the internal expansive pressure due to the late cement hydration should be taken into account for a mechanism to cause microcracks in mortars at long ages.

Irassar, E. F., E. F. Bonavetti, et al. (2006). Durability of Ternary Blended Cements Containing Limestone Filler and GBFS Seventh CANMET/ACI International Conference on Durability of Concrete (SP-234), Farmington Hills, MI: ACI.

In this laboratory investigation, the effects of limestone filler and granulated blast-furnace slag (GBFS) additions on the mechanical and durable characteristics of concrete are analyzed. The evolution of compressive and flexural strength were determined and,water absorption and sorptivity were used to characterize the permeability of concrete. The chloride penetration under continuous soaking was evaluated using the pounding tests and the sulfate resistance of cement was determined using ASTM C1012 test. The results show that, the complementary behavior of limestone filler and GBFS additions permits to obtain concrete with strength development similar to portland cement with 35 % less clinker, and the incorporation of GBFS into the mixtures prevents and improves the inadequate performance of limestone filler cement in chloride and sulfate environments. Consequently,concretes made with ternary cement offer economic and ecological benefits, with similar strength evolution and similar or better durable properties compared with binary and plain concretes. However, to assure the reduction of permeability of concrete an adequate cured time should be proportionate to assure the hydration progress

Isaia, G. C. (1999). "Synergic action of fly ash in ternary mixtures of high-performance concrete." High-performance concrete: performance and quality of concrete structures(ACI SP-186): 463-501.

High-performance concrete (HPC) has been studied extensively at many research centres, because of its increasing use in reinforced concrete buildings. Since HPC is a brittle material, studies have been done to increase its ductility. Increases in longitudinal and/or transverse steel ratios can improve the ductility of HPC elements. The addition of fibres also increases the deformability and thus the ductility. Hence, the transverse steel ratio can be reduced by using fibres. This paper presents a study of axially loaded columns made with high-performance concrete containing steel fibres. The average compressive strength of the concrete was 80 MPa. The volumetric ratios of fibres were: 0.25%; 0.50% and 1.00%, and the stirrup ratios were 0.55% and 0.82%. The longitudinal steel ratio was the same for all column tests, the W/C was 0.37, 10% silica fume was added and it was also necessary to use about 3% superplasticizer to improve workability. A comparison was made between the results for columns in high-strength concrete with and without fibres. It was observed that only the cross-sectional core effectively contributed to the load capacity of the columns.

Ito, H., I. Maruyama, et al. (2004). "Early age deformation and resultant induced stress in expansive high strength concrete." Journal of Advanced Concrete Technology **2**(Compendex): 155-174.

Expansive additive is well known to be effective in compensating early-age shrinkage and the resultant induced stress in reinforced high-strength concrete

(HSC) members. On the other hand, there have been few studies on numerical analysis methods for evaluating such early-age induced stress, which are vital to verify the risk of cracking. The present study formulates a 3-dimensional finite element method as well as a practical calculation method based on the beam theory, both of which consider the principle of superposition and linear stress-strain relationship of creep, in order to evaluate the early-age shrinkage/expansion-induced stress in reinforced members. The applicability of the proposed methods is evaluated by comparing computed values with experimental values on shrinkage/expansion-induced stress in RC beam specimens composed of various HSCs, using expansive additive and/or shrinkage reducing chemical agent and/or low-heat Portland cement. The results demonstrate that the proposed finite element method can accurately simulate induced stress in the reinforced concrete beams, even when expansive additive is used, and this indicates that the linear stress-strain relationship may be valid for expansive high strength concrete. Furthermore, there is a good agreement between the finite element method and a practical calculation method based on the beam theory, even in the case of RC beams with stirrups that cause a three-dimensional restraint condition in concrete.

Janotka, I. (2007). Durability of High-Strength Concrete with Silica Fume: Temperature Attack and Freezing-and-Thawing Cycles.

This paper reports high-strength concrete behavior subjected to temperatures up to 200 degrees Celsius and 100 freezing and thawing cycles in regime of 8 hours in water at +20 degrees Celsius and 16 hours at -20 degrees Celsius (weekends in frost). The concrete is composed of 425 kg/m(3) of Portland cement of CEM I 42.5 type, 32 kg/m(3) of silica fume, 5.6 L/m(3) of superplasticizer Melment and has a W/C of 0.32. Compressive strength is 78.5 MPa at 28-day curing on cubes for temperature resistance tests and 63.1 MPa on prisms for freezing and thawing tests, both after 28-basic curing in 20 degrees Celsius/100% R.H. – air. Evident C-S-H dewaterization of the cement paste is observed between 100 degrees Celsius and 200 degrees Celsius. Initial shrinkage within 24-hour period due to rapid cooling is more detrimental on the cement past strength than shrinkage due to C-S-H dewatering at temperature elevation from 100 degrees Celsius to 200 degrees Celsius. The strength, elastic modulus and volume deformation of concrete are irreversibly influenced either by temperature elevation or rapid cooling to 20 degrees Celsius. Differences in strength, elastic modulus and shrinkage or expansion after 100 freezing and thawing cycles relative to those in water are negligible. The compressive strength of prisms subjected to 118-day freezing and thawing was 62.9 MPa, compared to 65.2 MPa for those kept in water.

Jayakumar, M. and A. M. Salman (2011). Experimental study on sustainable concrete with the mixture of low calcium fly ash and lime as a partial replacement of cement. 1st International Conference on Civil Engineering, Architecture and Building Materials, CEABM 2011, June 18, 2011 - June 20, 2011, Haikou, China, Trans Tech Publications.

Even though the use of fly ash in concrete is nowadays a common practice, its

relatively slow pozzolanic reactivity hinders its greater utilization; hence efficient methods of activation are on demand. This study was carried out to evaluate the influence of lime as a chemical activator on the mechanical and durability properties of high strength fly ash concrete. Mixtures were made with 0, 30, 40, and 50% of cement replaced by low calcium fly ash. Corresponding mixtures were also made with the same amount of fly ash and addition of 10% of lime to each mixture. For each concrete mixture, slump, compressive strength, water absorption, sorptivity, apparent volume of permeable voids, and resistance to chloride-ion penetration were measured. The results obtained showed that addition of lime improved the compressive strength significantly at all ages. The strength of all the fly ash mixtures containing lime surpassed that of the corresponding Portland cement mix at 60 days. Addition of lime also improved the sorptivity and resistance to chloride-ion penetration of the fly ash concrete. It however increases the water absorption and the volume of permeable voids of the fly ash concrete. (2011) Trans Tech Publications, Switzerland.

Jegandan, S., M. Liska, et al. (2010). "Sustainable binders for soil stabilisation." Proceedings of the Institution of Civil Engineers: Ground Improvement **163**(Compendex): 53-61.

Portland cement is the most commonly and widely used binder in ground improvement soil stabilisation applications. However, many changes are now affecting the selection and application of stabilisation additives. These include the significant environmental impacts of Portland cement, increased use of industrial by-products and their variability, increased range of application of binders and the development of alternative cements and novel additives with enhanced environmental and technical performance. This paper presents results from a number of research projects on the application of a number of Portland cement-blended binders, which offer sustainability advantages over Portland cement alone, in soil stabilisation. The blend materials included ground granulated blastfurnace slag, pulverised fuel ash, cement kiln dust, zeolite and reactive magnesia and stabilised soils, ranging from sand and gravel to clay, and were assessed based on their mechanical performance and durability. The results are presented in terms of strength and durability enhancements offered by those blended binders.

Jiang, L., B. Lin, et al. (1999). "Studies on hydration in high-volume fly ash concrete binders." ACI Materials Journal **96**(Compendex): 703-706.

Pastes made with different fly ash contents, water-cementitious ratios (w/cm), and admixtures were tested for up to 90 days. Strength development, thermal analysis, silicate polymerization analysis, pore structure analysis, x-ray diffraction analysis, and scanning electron microscopy were employed to study the hydration progress, hydration product, and microstructure of the pastes. It is determined that admixtures affect the progress of hydration, and activator admixtures can accelerate the hydration of high-volume fly ash (HVFA) concrete binders. The total porosity increases with increasing fly ash content and w/cm, and decreases with increasing age. The presence of fly ash can improve the pore size distribution. The fly ash in HVFA systems cannot be fully hydrated. The changes of (SiO4)4- polymerization degree behave irregularly during the hydration of HVFA systems. The contents of monomer and dimer in fly ash are very low, and the activity of fly ash is low. It is suggested that the fly ash content in HVFA concrete should be lower than 70%.

Jiang, L. H. and V. M. Malhotra (2000). "Reduction in water demand of non-air-entrained concrete incorporating large volumes of fly ash." Cement and Concrete Research **30**(Compendex): 1785-1789.

This paper presents the results of an investigation dealing with the reduction in water demand of the non-air-entrained concrete incorporating large volumes of ASTM Class F and C fly ashes. The eight fly ashes investigated were from Canada and the USA, and the percentage replacement of fly ash in concrete was 55% by mass of Portland cement. No superplasticizer was used in the concrete mixtures. The test results show that the reduction in water demand of the concrete incorporating the fly ashes ranged from a low of 8.8 for Lingan fly ash from Nova Scotia, Canada to a high of 19.4% for Coal Creek fly ash from the USA. The 1-day compressive strength of the concrete ranged from 6.3 MPa for fly ash from Belews Creek, USA to a high of 13.9 MPa for fly ash from Thunder Bay, Canada. The 28-day compressive strength of the concrete ranged from 30.7 to 55.8 MPa.

Jiang, X. J., Y. Yun, et al. (2011). Development of non-autoclaved aerated concrete by alkali activated phosphorus slag. 1st International Conference on Civil Engineering, Architecture and Building Materials, CEABM 2011, June 18, 2011 - June 20, 2011, Haikou, China, Trans Tech Publications.

The feasibility of manufacturing non-autoclaved aerated concrete using alkali activated phosphorus slag as a cementitious material was investigated in this paper. Liquid sodium silicate with various modules (the molar ratio between SiO2 and Na2O) was used as alkali activator and a part of phosphorus slag was replaced with fly ash which was used to control the setting time of aerated concrete. The influences of the fly ash, curing procedure, modulus of sodium silicate solution and concentration of alkalis on the compressive strength and bulk density of non-autoclaved aerated concrete have been studied. Moreover, the types of the hydration products were investigated using XRD and SEM. The results indicate that: the compressive strength of aerated concrete was influenced by concentration of alkalis obviously. The compressive strength of 11.9MPa and the bulk density of 806kg/m3 were obtained with an activator of 1.2 modulus of sodium silicate and 6% concentration of alkalis under the circumstance of 60C curing for 28 days. (2011) Trans Tech Publications, Switzerland.

*Jin, Z., X. Lu, et al. (2011). Alkali activation of granulated blast furnace slag. 2010 International Forum on Powder Technology and Application, July 22, 2010 - July 24, 2010, Qingdao, China, Trans Tech Publications.

In order to stimulate the potential cementitious property of granulated blast furnace slag (GBFS), the ground GBFS sample (Wei Fang Iron and Steel Corporation, China) was activated by lime and gypsum under different dosages. The results showed that lime is an effective activator for the slag, and the optimum dosage of lime is about 10% (w/w) of the slag. At the optimum dosage of lime, the 28 days compressive strength of the lime-slag paste is higher than that of 32.5 ordinary Portland cement (OPC). But, the early age strength (3 and 7 days compressive strength) of the lime-slag paste is lower than that of the OPC. Addition of gypsum can effectively improve the early age strength of the lime-slag paste. At the ratio of gypsum:lime:slag of 8.2:9.2:82.6 (w/w), both the early and long-term compressive strengths of the gypsum-lime-slag paste are higher than that of the OPC. According to XRD, TG-DTA and SEM detections of the hydration products of the lime-slag paste, the gypsum-lime-slag paste and the OPC paste, it reveals that the hydration process of the GBFS-based cementitious material is different from the ordinary Portland cement and the presence of ettringite (AFt) contributes to the early age strength of the pastes. The major hydration product of the OPC paste (7 days) were measured as ettringite (AFt), but the AFt phase was not detected in the hydration product of the lime-slag paste and the major hydration product of the lime-slag paste was determined as amorphous CSH gel. However, AFt was detected in the hydration products of the gypsum-lime-slag paste in the early stages of hydration, and the formation of AFt is favorable for the early strength improvement of the material.

Jolicoeur, C., N. Mikanovic, et al. (2002). "Chemical admixtures: Essential components of quality concrete." Indian Concrete Journal **76**(Compendex): 537-547.

Modern-day concrete frequently incorporates one or more chemical admixtures to achieve specified material properties. In a context where binder systems have become increasingly complex, either due to addition of pozzolans (for example, silica fume), or partial cement replacement by supplementary cementitious materials (fly ash, blast furnace, slag, etc), or addition of fillers, and where concrete performance requirements are increasingly demanding, chemical admixtures are rapidly gaining in importance and in diversity. For concrete practitioners, the variety of concrete admixture types, and the diversity of admixtures within each type, create a rather complex environment. This paper attempts to present an overview of the field of chemical admixtures and provide some perspective on the need for these admixtures, their function and benefits in application. A particular emphasis is given to those admixtures-water-reducing and colloidal - Which influence the rheological properties of fresh concrete.

Justice, J. M. and K. E. Kurtis (2007). "Influence of metakaolin surface area on properties of cement-based materials." Journal of Materials in Civil Engineering **19**(Compendex): 762-771.

Two metakaolins, with similar mineralogical composition but which vary in their surface area (11.1 versus 25.4m2m/g), were evaluated for use as supplementary cementitious materials through measurements of workability, setting time, strength, elastic modulus, heat evolution, calcium hydroxide (CH) content, and surface area. Compressive and flexural strength of concrete were greater and increased at a faster rate when the finer metakaolin was used, as expected. The addition of metakaolin increased early age (i.e., 1-3 days) flexural strength by as much as 60%. The effect of metakaolin surface area on compressive strength was particularly evident at the lower water-to-cementitious materials ratios (w/cms) examined and generally at later ages (i.e., 7 days or later). However, although greater in the metakaolin-cement concretes than the ordinary concretes (particularly at the lowest w/cm examined, 0.40) elastic modulus measured at 28 days, was not affected by the metakaolin surface area. The greater surface area metakaolin caused a greater and more rapid heat evolution, indicating a higher reactivity and a greater rate of hydration product formation. Both metakaolins decreased CH content compared to controls, with the consumption of CH extending beyond 14 days. Surface area measurements indicated a more refined pore structure relative to controls by 28 days. These analyses illustrate the effect of metakaolin fineness on pozzolanic reactivity, associated CH consumption, and pore structure refinement, and suggest links to the observed increased mechanical properties of metakaolin-concretes. 2007 ASCE.

*Kadri, E. H. and R. Duval (2002). "Effect of ultrafine particles on heat of hydration of cement mortars." ACI Materials Journal **99**(Compendex): 138-142.

This paper presents the results of the effect of fine inert and hydraulic fillers on the early hydration of mortars incorporating these powders. The activity of the mineral additives is assessed by measuring the heat of hydration of the different blended mortars that consist of 90% portland cement and 10% admixture with a 0.45 water-binder ratio (w/b). During the early stages, the fine particles accelerate the hydration rate by providing an increased number of nuclei sites for hydrates growth. These results concern the inert filler (alumina) and the hydraulic or pozzolanic microfillers (ultrafine calcite, silica fume, and quartz powder), or both. At very early stages, the finest particles increase the compressive strength of blended mortars compared with control mortar. Moreover, silica powders, especially silica fume, develop a pozzolanic activity that later increases the compressive strength.

Kanstad, T., O. Bjontegaard, et al. (2001). "EFFECTS OF SILICA FUME ON CRACK SENSITIVITY." Concrete International **23**(12): p. 53-59.

The sensitivity of concrete to cracking is a complex interaction between structural geometry and several material properties during the hardening process. This paper describes an investigation that was conducted to assess the crack sensitivity of high-performance concretes with different silica fume contents (0%, 5%, or 10%). First, the material properties, including heat development, coefficient of thermal dilation, autogenous shrinkage, mechanical properties and relaxation behavior of these concretes, were determined under isothermal and semiadiabatic conditions. This data was then used to rate crack sensitivity by calculating the ratio of self-induced stress to strength over time under a variety of external conditions. Results show that the effects of variations in silica fume content are of minor importance compared with other factors such as cement type, water-cementitious materials ratio, structural configuration, degree of insulation, and environmental conditions. No single concrete property should be used to assess cracking risk since, in practice, the interaction between several properties over time defines the risk.

Kathirvel, P., M. Galesh, et al. (2010). "Extent of fly ash blended cement concrete deterioration under sulphate attack." Nature Environment and Pollution Technology **9**(Compendex): 427-432.

Fly ash, which was once an environmental pollutant, has now found a good place in the construction industry, mainly in production of blended cement. Blended cement has replaced ordinary Portland cement (OPC) to a major extent, in lieu of its increased durability and lesser cost. In addition there is reduction in green house gases in the manufacturing of cement, thereby reducing pollution. The main aim of this work is to study the effect of sulphate attack in OPC and blended cement made by replacement of OPC with fly ash by 10%, 20% and 30%. When the analysis of concrete reveals a high sulphate content this does not necessarily indicate any deterioration although conversely, loss of strength or visible deterioration accompanied by high sulphate content would be evidence of sulphate attack. The properties were monitored periodically to examine durability. Here, an attempt is made to know the effect of sulphate attack on blended cement by monitoring the properties like density variation, compressive strength and water absorption. The test results discussed above conclude the effect of sulphate attack on OPC specimens and OPC specimens replaced with fly ash. The deterioration starts significantly after 60 days of curing in all cases. The concrete is good in sulphate resistant when fly ash is added. The fly ash added specimens performed better than OPC specimens. The result of the study indicated that the replacement of cement with 20% fly ash improved the durability of concrete to a larger extent. The final strength reduction for the specimens attacked by magnesium sulphate solution were higher than that those attacked by sodium sulphate solution.

*Khatib, J. M. (2008). "Performance of self-compacting concrete containing fly ash." Construction and Building Materials **22**(Compendex): 1963-1971.

The influence of including fly ash (FA) on the properties of self-compacting concrete (SCC) is investigated. Portland cement (PC) was partially replaced with 0-80% FA. The water to binder ratio was maintained at 0.36 for all mixes. Properties included workability, compressive strength, ultrasonic pulse velocity (V), absorption and shrinkage. The results indicate that high volume FA can be used in SCC to produce high strength and low shrinkage. Replacing 40% of PC with FA resulted in a strength of more than 65 N/mm2at 56 days. High absorption values are obtained with increasing amount of FA, however, all FA concrete exhibits absorption of less than 2%. There is a systematic reduction in shrinkage as the FA content increases and at 80% FA content, the shrinkage at 56 days reduced by two third compared with the control. A linear relationship exists between the 56 day shrinkage and FA content. Increasing the admixture content beyond a certain level leads to a reduction in strength and increase in absorption. The correlation between strength and absorption indicates that there is sharp decrease in strength as absorption increases from 1 to 2%. After 2% absorption, the strength reduces at a much slower rate. 2007 Elsevier Ltd. All rights reserved.

Khayat, K. H. (1999). "WORKABILITY, TESTING, AND PERFORMANCE OF SELF-CONSOLIDATING CONCRETE." ACI Materials Journal **96**(3): p. 346-353.

Self-consolidating concrete (SCC) is a new category of high-performance concrete that exhibits a low resistance to flow to ensure high flowability and a moderate viscosity to maintain a homogeneous deformation through restricted sections, such as closely spaced reinforcement. This paper reviews the benefits of using SCC to facilitate the casting of densely reinforced sections and improve productivity and onsite working conditions. Workability requirements necessary to secure self-consolidation and the principles involved in proportioning such highly flowable concrete are discussed. Field-oriented tests useful in evaluating the deformability, filling capacity, and stability of SCC are presented. The performance of concrete mixes proportioned according to two main approaches needed to ensure high deformability, low risk of blockage during flow, and proper stability are compared. Such approaches involved the proportioning of concrete with a moderate water-to-cementitious material ratio (w/cm) of 0.41 and using a viscosity-enhancing admixture to increase stability, as well as mixes without any viscosity-enhancing admixture, but with lower w/cm of 0.35-0.38 to reduce free water content and provide stability. Mixes with both moderate and high contents of ternary cementitious materials were evaluated. The performance of each concrete was compared to that of a flowable concrete with 250-mm slump.

Khayat, K. H. (2000). "Optimization and performance of air-entrained, self-consolidating concrete." ACI Materials Journal **97**(Compendex): 526-535.

The use of self-consolidating concrete (SCC) can enable the reduction of labor demand for vibration and surface finishing, accelerate placement rate of concrete, and secure superior surface quality. Despite the low yield value required for deformability, SCC is characterized by a moderate viscosity to enhance cohesiveness and stability of the fresh concrete. The air entrainment of SCC for frost durability can reduce viscosity leading to greater risk of segregation and blockage of concrete flow upon spreading between closely spaced obstacles. This paper investigates the mixture proportioning of air-entrained SCC suitable for filling congested sections, such as in the case of repair of the underside of bridge deck girders, and conventional non-restricted elements. The results of a laboratory study undertaken to optimize and evaluate properties of air-entrained SCC are presented in this paper. The mixtures were proportioned with 370, 450, and 550 kg/m3 of cementitious materials and water-cementitious material ratios (w/cm) of 0.45 to 0.50. Ternary binders containing 20% Class C fly ash of 40% ground blast-furnace slag with 3% silica fume were used. The mixtures were evaluated for slump flow consistency, restricted deformability and surface settlement, strength development, elastic modulus, temperature rise, shrinkage, permeability, and frost durability. Examples of the use of such concrete for repair of a densely reinforced beam in a parking structure and a moderately reinforced beam-wall element with restricted access in a powerhouse are also discussed. Test results clearly indicate the feasibility of proportioning air-entrained SCC of high stability and resistance to blockage. Optimized mixtures exhibited adequate engineering properties and durability. The field studies demonstrated the effectiveness of such high-performance concrete to repair damaged sections presenting difficulties for placement and consolidation.

Khedr, S. A. and M. N. Abou-Zeid (1994). "Characteristics of silica-fume concrete." Journal of Materials in Civil Engineering **6**(Compendex): 357-375.

Proper introduction of silica fume in concrete improves both the mechanical and durability characteristics of the concrete. This paper presents the results of research effort conducted at the American University in Cairo using Egyptian silica fume in concrete. The program investigated various characteristics of silica-fume concrete. It emphasized the effect of silica fume on workability level and its maintenance of fresh concrete; strength development, strength optimization and elastic modulus of hardened concrete; and chemical and mechanical durability of mortar. The experimental program comprised six levels of silica-fume contents (as partial replacement of cement by weight) at 0% (control mix), 5%, 10%, 15%, 20%, and 25%, with and without superplasticizer. It also included two mixes with 15% silica fume added to cement in normal concrete. Durability of silica-fume mortar was tested in chemical environments of sulfate compounds, ammonium nitrate, calcium chloride, and various kinds of acids. It was found that there was an optimal value of silica-fume content at which concrete strength improved significantly. Due to the slow development of pozzolanic effect, there was a drop in early strength up to seven days and late significant gains up to 56 days upon introducing silica fume to concrete. Elastic modulus, toughness, and steel-concrete bond increased at the optimum silica-fume content in concrete. Silica-fume mortar exhibited significant improvement in durability against chemical attacks of most salts and acids. The improvement was moderate in the case of sulfate compounds. Mechanical erosion resistance increased moderately in silica-fume concrete.

Khokhar, M. I., E. Roziere, et al. (2010). "Mix design of concrete with high content of mineral additions: Optimisation to improve early age strength." Cement & Concrete Composites **32**(5): 377-385.

The concrete industry is an important source of CO2 gas emissions. The cement used in the design of concrete is the result of a chemical process linked to the decarbonation of limestone conducted at high temperature and results in a significant release of carbon dioxide. Under the project EcoBéton (Green concrete) funded by the French National Research Agency (ANR), concrete mixtures have been designed with a low cement quantity, by replacing cement by mineral additions i.e., blast-furnace slag, fly ash or limestone fillers. Replacement of cement by other materials at high percentages generally lowers the early age strength of the resulting concrete. To cope with this problem, an optimisation method for mix design of concrete using Bolomey’s law has been used. Following the encouraging results obtained from mortar, a series of tests on concretes with various substitution percentages were carried out to validate the optimisation method. (A) Reprinted with permission from Elsevier.

Kilic, A., C. D. Atis, et al. (2003). "HIGH-STRENGTH LIGHTWEIGHT CONCRETE MADE WITH SCORIA AGGREGATE CONTAINING MINERAL ADMIXTURES." Cement and Concrete Research **33**(10): 5 p.

Lightweight concrete can greatly reduce the mass or dead weight of a structure. This paper presents some results from ongoing laboratory work to design a structural lightweight high strength concrete (SLWHSC) made with and without mineral admixtures. Basaltic-pumice (scoria) was used as lightweight aggregate in the mixtures. A control lightweight concrete mixture made with lightweight basaltic-pumice (scoria) containing normal Portland cement as the binder was prepared. The control lightweight concrete mixture was modified by replacing 20% of the cement with fly ash. The control lightweight concrete mixture was also modified by replacing 10% of the cement with silica fume. A ternary lightweight concrete mixture was prepared, modifying the control lightweight concrete by replacing 20% of cement with fly ash and 10% of cement with silica fume. Two normal weight concrete (NWC) were prepared for comparison. Cylinder specimens with 150 mm diameter and 300 mm height and prismatic specimens with dimension 100x100x500 mm were cast from the fresh mixtures to measure compressive and flexural tensile strength. The concrete samples were cured at 65% relative humidity with 20 deg C temperature. The density and slump workability of fresh concrete mixtures were also measured. These results indicate that scoria can be used in the production of structural lightweight concrete (SLWC). The use of mineral additives seems to be essential for production of SLWHSC. Findings also indicate that the ternary mixture offers satisfactory strength development while being environmentally-friendly.

Kim, H. and D. P. Bentz (2008). Internal Curing with Crushed Returned Concrete Aggregates for High Performance Concrete.

This paper will discuss how high performance concrete (HPC) requires a low water-to-cementitious materials mass ratio (w/cm), often with the inclusion of supplemental cementitious materials such as silica fume in the mixture, thus necessitating the use of a superplasticizer. Because of the low w/cm and rapid reaction at early ages, proper curing from the earliest time possible is very essential in HPC. Internal curing has been developed and demonstrated to substantially reduce autogenous shrinkage and minimize early-age cracking of HPC. In 1991, Philleo suggested this new concept of “water-entrained” concrete with the addition of saturated lightweight fine aggregates (LWAS) as a remedy to provide an internal source of water to offset the chemical shrinkage that occurs during hydration of the paste. This article explores the use of less expensive crushed returned concrete aggregate (CCA) as an internal curing material. In this investigation, CCAs in the 1000 psi (6.9 MPa), 3000 psi (20.7 MPa) and 5000 psi (34.5 MPa) strength range were prepared for evaluation as internal curing agents. The best performing CCA was then selected and further tested in combination with LWAS. Test results showed a significant reduction in net autogenous shrinkage (79 % and 70 % reduction of the control at the ages of 1 d and 56 d, respectively) found with the CCA/LWAS blended mixture, while the compressive strength reduction was negligible (6 % and 0 % reduction of the control at the ages of 28 d and 56 d, respectively).

Konsta-Gdoutos, M. S., J. K. Dattatreya, et al. (2003). INFLUENCE OF MINERAL ADMIXTURES ON THE AUTOGENOUS SHRINKAGE AND POROSITY OF HIGH-STRENGTH CONCRETE.

This paper illustrates the effect of silica fume, ultra fine ash, and ground granulated blast furnace slag on compressive strength, shrinkage, and development of pore structure of high performance concrete (HPC). Shrinkage measurements were conducted using a modified version of ASTM C-341, as proposed by Tazawa. The experimental data obtained demonstrates how the material composition, the water to binder ratio, and the distribution of pore volume influence strength, autogenous, drying, and total shrinkage. HPC mixtures containing ultra fine fly ash, silica fume, and ordinary Portland cement exhibited an increased drying shrinkage rate, as compared with the slag mixture. By using a 10% replacement of UFFA, a large improvement with respect to autogenous shrinkage, relative to a 10% silica fume replacement in HPC occurs, without any noticeable effect on compressive strength. Pore structure of the matrix paste at early stages of hydration seems to have a strong effect on autogenous shrinkage.

Konsta-Gdoutos, M. S. and S. P. Shah (2003). "Hydration and properties of novel blended cements based on cement kiln dust and blast furnace slag." Cement and Concrete Research **33**(Compendex): 1269-1276.

The aim of the present paper is to address the key technical issues pertaining to the utilization of cement kiln dust (CKD) as an activator for ground granulated blast furnace slag (GGBFS) to create nonconventional cementitious binders for concrete. The relatively high alkaline content of CKD is the predominant factor preventing its recycling in cement manufacture. However, it was observed that depending on the water-soluble alkali and sulfate compounds, CKD could provide the environment necessary to activate latent hydraulic materials such as GGBFS. Binary blends containing slag and CKDs from different sources were characterized and compared in terms of the rates of heat evolution and strength development, hydration products, and time of initial setting. A study of the effects of the influencing factors in terms of soluble alkali content, particle size, and free lime content was undertaken. The results confirm the dependence of the dissolution rate of slag on the alkalinity of the reacting system, and the importance of the optimum lime content on the rate of strength gain. 2003 Elsevier Science Ltd. All rights reserved.

Krauss, P. D., J. S. Lawler, et al. (2005). Development of High-Performance Concrete Mixtures for Durable Bridge Decks in Montana Using Locally Available Materials.

The Montana Department of Transportation (MDT) is performing research to develop a cost-effective, indigenous high-performance concrete (HGC) for use in bridge applications. The investigation was divided into two tasks: (1) identification of the optimum cementitious matrix for the HPC and (2) evaluation of the performance of this matrix in combination with aggregates readily available in Montana. The work focused on the use of binary, ternary, and quaternary blends of portland cement with fly ash (Class C and F), slag, calcined clay, metakaolin, and silica fume, in combination with Yellowstone River and Western Montana aggregate sources. Testing included plastic properties, setting characteristics, air-void system parameters, electrical conductivity, strength, chloride diffusion, freezing and thawing resistance, scaling resistance, and drying shrinkage. The paper discusses the process required to test and implement HPC specifically for bridge deck applications and presents the test results for this MDT study. The supplementary cementitious material combinations that produced the best performance were silica fume alone, silica fume and slag, Class F fly ash, silica fume and slag-blended cement, and silica fume and calcined clay-blended cement. The importance of raw material testing and the practical reproducibility of the concrete mixtures are also considered.

Kumar, P. and S. K. Kaushik (2005). Sem investigation of microstructure in high strength concrete with OPC alone, binary ternary mixes. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

High strength concrete (HSC) mixes may be made with cement alone as the binder or with binary or ternary mixes involving supplementary cementitious materials such as flyash and silica fume. Use of the 'cement alone' option results into formation of a large quantity of calcium hydroxide (CH), particularly in the interfacial transition zone (ITZ) near the aggregate surfaces. This may lead to early deterioration of such concretes. Binary mixes involving cement and silica-fume consumes CH in the ITZ. Addition of flyash together with a small quantity of silica-fume in the concrete leads to development of a different morphology in ITZ. The paper presents scanning electron micrographs for the three options and an evaluation of the ITZ in the three cases for making HSC, i.e. OPC alone, OPC and silica fume, and OPC, high volumes of low calcium flyash together with little amount of silica fume.

*Lachemi, M., K. M. A. Hossain, et al. (2003). "Development of Cost-Effective Self-Consolidating Concrete Incorporating Fly Ash, Slag Cement, or Viscosity-Modifying Admixtures." ACI Materials Journal **100**(Compendex): 419-425.

Self-consolidating concrete (SCC) in the fresh state is known for its excellent defomability, high resistance to segregation, and use, without applying vibration, in congested reinforced concrete structures characterized by difficult casting conditions. Such a concrete can be obtained by incorporating either mineral admixtures such as fly ash (FA) and slag cement or viscosity-modifying admixtures (VMAs). The use of VMAs has proved very effective in stabilizing the rheology of SCC. Commercial VMA currently available in the market is costly and increases the price of such a concrete. Research to produce an economical SCC

with desired properties was conducted over the last few years with the use of mineral admixtures or use and development of a cost-effective VMA. This paper presents the comparative performance of SCCs manufactured with FA, slag cement, and various VMAs based on fresh and mechanical properties and also on cost. Twenty-one concrete mixtures were investigated. FA SCC mixtures had cement replacement of 40, 50, and 60%, while slag cement SCC mixtures had 50, 60, and 70% replacement. The water-cementitious material ratios (w/cm) ranged from 0.35 to 0.45. Three different VMAs including Welan gum (WM), a commercial one named COM, and a new saccharide-based VMA named A were used in VMA SCC mixtures with w/cm of 0.45. Tests were carried out on all mixtures to obtain fresh properties such as viscosity and stability as well as mechanical properties such as compressive strength. The influence of percentages of FA or slag cement, w/cm, dosage of high-range water-reducing admixture, dosages of air-entraining agent, and types of VMA on the properties of SCC were critically reviewed. The results showed that an economical SCC with desired properties could be successfully developed by incorporating FA, slag cement, or VMA. Three different economical mixtures were identified from FA, slag cement, and VMA-based SCC satisfying the targeted strength of 35 MPa. These mixtures included FA with 50% replacement, slag cement with 60% replacement, and a mixture with new VMA A with a w/cm of 0.45. It was found that these SCC could replace the control concrete and could be more economical (30 to 40% in case of FA and slag cement). The new VMA A was found to develop a SCC with better fresh and hardened properties and at significantly lower cost compared with its commercial counter parts - COM and WM. Although the VMA SCC with new A-VMA was slightly costlier than those with FA and slag cement, it was more resistant to segregation and had higher early strength development.

*Laldji, S., A. Phithaksounthone, et al. (2010). "Synergistic effect between glass frit and blast-furnace slag." ACI Materials Journal **107**(Compendex): 75-79.

Partial replacement of portland cement with one or more supplementary cementitious materials has become a widely accepted practice due to its beneficial effects on concrete durability. Because it is a highly reactive material, silica fume has always been a major component of high-performance blended cements. In Eastern Canada, two major ternary blended cements containing portland cement, silica fume, and either fly ash or slag are available. The use of silica fume, however, is sometimes limited due to lack of local availability and high cost; therefore, developing ternary cementing matrix systems without silica fume could be of great interest. This investigation was carried out to study the properties of two ternary blended cement concretes incorporating glass frit and granulated blast-furnace slag. Results showed that even with 40% Portland cement replacement, and in the absence of silica fume, the ternary concrete performed remarkably well. Its performance was very similar to that of the commercially available ternary blends tested. Copyright 2010, American Concrete Institute. All rights reserved.

Laldji, S. and A. Tagnit-Hamou (2006). "Properties of Ternary and Quaternary Concrete Incorporating New Alternative Cementitious Material." ACI Materials Journal **103**(2): pp 83-89.

Mineral admixtures are known to have a beneficial influence on many properties of fresh and hardened concrete, either through purely physical effects associated with the presence of very fine particles or through physico-chemical effects associated with pozzolanic and cementitious reactions. This research was conducted to study the performances of ternary and quaternary cementitious systems incorporating glass frit. Results given herein show that the presence of glass frit enhances rheological behavior, and subsequently improves the hardened properties as well as some durability aspects such as compressive strength, permeability, resistance to freezing/thawing, and drying shrinkage. For a similar slump, the ternary and quaternary blends required nearly as much water reducer dosage as the control. Despite the lower early strength of concrete made from ternary and quaternary blends, strengths developed after 91 days of hydration varied from 1.05 to 1.25 times those of the control. Permeability was also reduced and varied from 35% to 17.7% of the control.

Laldji, S. and A. Tagnit-Hamou (2007). "Glass frit for concrete structures: A new, alternative cementitious material." Canadian Journal of Civil Engineering **34**(Compendex): 793-802.

With today's requirements for high-performance concrete, mix proportions containing cementitious materials as partial replacement of, or in addition to, Portland cement, are being used more frequently. The most commonly used cementitious materials nowadays are fly ash, silica fume, and ground, granulated blast-furnace slag. However, alternative supplementary cementitious materials can successfully be used as long as they meet the acceptance criteria stated in various specifications. This paper provides data on properties of structural concrete containing glass frit. The performance of this type of concrete is highlighted by its rheological and mechanical behaviour, as well as its durability. Later-age compressive, splitting tensile, and flexural strengths are well above estimated values, and in many cases, are higher than those obtained with the control concrete. Durability aspects and characteristics expressed by drying shrinkage, surface scaling, and chloride-ion permeability have shown that concrete incorporating glass frit has a very good potential for long-term resistance. 2007 NRC Canada.

Lane, D. S. (2010). Effect of Wet Curing Duration on Durability Parameters of Hydraulic Cement Concretes:** 46p.

Hydraulic cement concrete slabs were cast and stored outdoors in Charlottesville, Virginia, to study the impact of wet curing duration on durability parameters. Concrete mixtures were produced using portland cement, portland cement with slag cement, and portland cement with Class F fly ash concretes with water–cementitious materials ratios (w/cm) of 0.45 and 0.35. These concretes were subjected to immediate liquid membrane-forming curing (LMFC) or 1, 3, 7, or 14 days wet curing. Two slabs were cast for each of the wet curing

durations. Following the curing period, one slab was allowed to dry naturally, and LMFC compound was applied to the other. Three additional concretes containing saturated lightweight fine aggregate were produced to study the potential impact of internal curing on the durability parameters. These concretes contained portland cement with fly ash, silica fume, and both, at 0.35 w/cm. Three slabs were cast from each mixture and subjected to LMFC, 1 or 3 days wet curing. The slabs were instrumented with humidity probes at two depths below the surface. Specimens were removed from two depths and tested for tensile strength, electrical conductivity, and sorptivity at 3 and 12 months of age. The success rate of the humidity measurements within the slabs was low because of water condensation. However, water condensation qualitatively indicates that the slabs did not dry out to an extent that would adversely impact concrete property development. Neither the strength, electrical conductivity, nor sorptivity results were impacted appreciably by the duration of moist curing. At most, 1 to 3 days wet curing was sufficient. Reducing w/cm had a positive impact on reducing permeability parameters, and previous work by others has shown the duration of curing needed to achieve discontinuity in the capillary pore system decreases with decreasing w/cm. No added benefit was observed by application of LMFC following the wet curing. The prevailing weather conditions in the months during and following placement were humid, which would obviate any benefit from post wet-curing applications of LMFC compound to slow drying. Prevailing weather conditions and the w/cm of the concrete mixture are important factors in determining adequate curing procedures and duration and should be considered by the project management team at the time of construction to establish appropriate procedures. A direct cost savings could be realized by removing the requirement for wet curing and using LMFC only in situations where it is likely to benefit the curing process. Alternatively, there may be long-term benefits that could be realized by applying these cost savings to the application of penetrating sealers, particularly for concretes that will be subjected early in their life to aggressive anti-icing and deicing programs.

*Lane, D. S. and C. Ozyildirim (1999). COMBINATIONS OF POZZOLANS AND GROUND, GRANULATED BLAST-FURNACE SLAG FOR DURABLE HYDRAULIC CEMENT CONCRETE**:** 22 p.

Hydraulic cement concretes were produced using pozzolans and ground, granulated, blast-furnace slag to investigate the effect of these materials on durability. The pozzolans used were an ASTM C 618 Class F fly ash with a low lime content and a dry, densified silica fume. The slag was an ASTM C 989 Grade 120 material. Concretes with a fixed cementitious materials content of 377 kg/cu m and water-to-cementitious materials ratio (w/cm) were produced with an ASTM C 150 Type I/II cement and pozzolans or slag. The following replacement levels were used: fly ash: 0, 15, 20, 25, and 35 percent; silica fume: 2.5, 5, and 7 percent; and slag: 25, 35, 50, and 60 percent. Concretes were also produced by combining small amounts of silica fume with small amounts of fly ash or slag. The concretes were evaluated for strength, electrical resistance (ionic transport, permeability), drying shrinkage, resistance to freezing and thawing, and

resistance to alkali-silica reaction (ASR)-related expansions. Early-age strengths and resistance to freezing and thawing were compromised by high replacement levels of fly ash or slag, although the use of a constant w/cm may have exaggerated these responses. Concrete durability, as indicated by electrical resistance and resistance to ASR, was greatly improved by increasing the pozzolan or slag content. Use of ternary blends produced the desired property levels while maintaining the necessary durability characteristics.

Lane, D. S. and C. Ozyildirim (1999). "Preventive measures for alkali-silica reactions (binary and ternary systems)." Cement and Concrete Research **29**(Compendex): 1281-1288.

Efforts to prevent alkali-silica reactions (ASR) in Virginia transportation facilities have focused on the selection of ASR-resistant cementitious materials. Initial evaluations of binary systems of ordinary portland cement (OPC) with pozzolans or slag in mortars with Pyrex glass aggregate suggested that high replacement levels of OPC with fly ash or slag could be necessary for ASR resistance. Concern that such high replacement levels could negatively impact early strengths prompted evaluations of concretes with construction aggregates. Concretes were produced with binary and ternary (OPC+silica fume+fly ash or slag) systems and evaluated for strength, transport properties, and ASR resistance. The results illustrate how ternary blends can be used to reduce transport properties or increase ASR resistance of concretes with low replacement levels of fly ash or slag and thus avoid low early strength problems.

*Langley, W. S., G. G. Carette, et al. (1992). "Strength development and temperature rise in large concrete blocks containing high volumes of low-calcium (ASTM class F) fly ash." ACI Materials Journal (American Concrete Institute) **89**(Compendex): 362-368.

Three large concrete blocks, 3.053.053.05 m, were cast in Halifax in 1988 to monitor the long-term strength development of concrete. Two blocks were cast from concrete incorporating approximately 55 percent ASTM Class F fly ash and the third block was a control block using concrete incorporating portland cement only. The water-to-cementitious materials ratio of these concretes ranged from 0.27 to 0.49, and their cementitious content ranged from 400 to 225 kg/m3. A large number of 150300-mm cylinders were cast for testing up to 3 years, with half of the cylinders being cured under moist-room conditions and the other half under field conditions. A large number of 150300-mm cores were drilled from the blocks up to 24 months to monitor the in situ strength development of concrete. The ratio of the 42-day core compressive strength to the 28-day laboratory-cured cylinder compressive strength ranged from 78 percent for the control concrete to 120 percent for the high-volume fly ash concrete from the block having a total cementitious content of 400 kg/m3. At 365 days, the respective ratios were 78 and 92 percent, and at 730 days, the respective ratios were 88 and 98 percent. Blocks incorporating 400 kg/m3 of portland cement, 180 kg/m3 of portland cement and 220 kg/m3 of fly ash, and 100 kg/m3 of portland cement and 125 kg/m3 of fly ash reached peak temperatures of 83 C at 24 hr, 54 C at 96 hr, and 30 C at 168 hr, respectively.

Lawler, J. S. and P. D. Krauss (2005). Development of High-Performance Concrete Mixtures for Durable Bridge Decks in Montana Using Locally Available Materials**:** 45p.

The Montana Department of Transportation (MDT) is performing research to develop a cost-effective, indigenous high-performance concrete (HPC) for use in bridge deck applications. The investigation was divided into two tasks: 1) identification of the optimum cementitious matrix for the HPC and 2) evaluation of the performance of this matrix in combination with aggregates readily available in Montana. The work focused on the use of binary, ternary, and quaternary blends of portland cement with fly ash (Class C and F), slag, calcined clay, metakaolin, and silica fume, in combination with Yellowstone River and Western Montana aggregate sources. Testing included plastic properties, setting characteristics, air-void system parameters, electrical conductivity, strength, chloride diffusion, freezing and thawing resistance, scaling resistance, and drying shrinkage. The paper discusses the process required to test and implement HPC specifically for bridge deck applications and presents the test results for this MDT study. The supplementary cementitious material combinations that produced the best performance were silica fume alone, silica fume and slag, Class F fly ash, silica fume and slag-blended cement, and silica fume and calcined clay-blended cement. The importance of raw material testing and the practical reproducibility of the concrete mixture are also considered.

Lee, H. K., K. M. Lee, et al. (2004). "Ultrasonic in-situ monitoring of setting process of high-performance concrete." Cement and Concrete Research **34**(Compendex): 631-640.

The present standard test for the setting times of concrete is the penetration resistance test specified by ASTM C403. This test, while good for standard concrete mixtures, may not be appropriate for high-performance concrete (HPC) because of the high viscosity of the mortar. To address this issue, the ultrasonic pulse velocities (UPV) were measured using an ultrasonic monitoring system during the first 24 h of age for mortar and concrete specimens having various water-to-cementitious materials (w/cm) ratios and with and without fly ash (FA). Various characteristics observed from the measured UPV agreed with the previous theory of cement hydration, which describes the mixture as viscous suspension transforming into saturated porous solid phase. It was also found that the development of UPV in concretes, particularly without FA, was faster than that of mortars with the same w/cm. The values of concrete UPV corresponding to the initial and final setting (ASTM C403) did not show a trend consistent with those of mortar UPV. Two alternative criteria were applied to determine the setting characteristics from the UPV evolution curves. They were found to better represent the microstructural changes than the penetration method, as suggested by the consistent trend with decreasing w/cm among various mortars and concretes. Thus, the potential use of these alternative methods is suggested by specifying, at each w/cm, general target UPVs that are valid for both mortar and concrete with or without FA. It was concluded that the methods and monitoring device used in this research were useful for the in-situ monitoring of

the setting of concrete, particularly in HPC. 2004 Elsevier Ltd. All rights reserved.

*Lee, K.-H., K.-S. You, et al. (2007). A study of alternative construction materials for slag derived from steel making industry. 8th International Symposium on Eco-Materials Processing and Design, ISEPD-8, January 11, 2007 - January 13, 2007, Kitakyushu, Japan, Trans Tech Publications Ltd.

The present study examined the effect of the activation properties of granulated blast furnace slag according to the type of alkaline activator, the specific surface area of blast furnace slag, and the amount of ordinary Portland cement substituted on the compressive strength of the cement containing blast furnace slag. For activators, Na2SiO3, Na 2CO3, NaOH, and Na2SO4 were used. Na2SiO3, Na2CO3, and Na 2SO4 were converted into Na2O, to which 1 wt.%, 3 wt.%, 5 wt.%, and 7 wt.% were added, and subjected to experimentation, with the W/S (water/solid) ratio = 0.5. The principal hydration products were C-S-H, C4AH13, Aft (ettringite), and Al(OH)3. Na 2CO3 exhibited the largest slag hydration rate. Consequently, the present study used Na2CO3 as the alkaline activator. The compressive strength of blast furnace slag cement mortar was then measured according to the amount of Na2CO3 added (2.5 wt.% and 5.0 wt.%), the specific surface area of blast furnace slag (4,000 cm2/g, 6,000 cm2/g, and 8,000 cm2/g), and the substitution rate (30 wt.%, 50 wt.%, and 70 wt.%) of the blast furnace slag in terms of ordinary Portland cement. The results are as follows: at the ages of 1 day and 3 days, respectively, the early strength increased as the specific surface area of blast furnace slag and the amount of alkaline activator added increased; at the age of 7 or more days, the compressive strength increased as the amount of alkaline activator added decreased and as the specific surface area of blast furnace slag increased.

*Lee, W. K. W. and J. S. J. Van Deventer (2002). "The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements." Cement and Concrete Research **32**(Compendex): 577-584.

Alkali-activated fly ash-based cements are concrete binders that utilise fly ash as their major solid raw material. The solid particles are activated using concentrated silicate and hydroxide solution to produce high-strength products. Due to the highly alkaline nature of the solution, precipitation of the reactive species, both from the solids and from the solution, proceeds at a very fast rate. This renders short setting times, which can be advantageous or disadvantageous depending on the practical situation. The present work examines the effects of inorganic salt addition towards the setting and rheological characteristics of the early pastes. Compressive strength, Fourier transform infrared spectroscopy (FTIR) and X-ray diffractograms were collected to examine the hardened products. It was found that calcium (Ca) and magnesium (Mg) salts shortened the setting time by providing heterogeneous nucleation centers in the initial paste solution. Potassium salts retarded setting only to the cements, which used less sodium silicate in the initial solution for activation. Managed ionic contamination can be used to increase the product early strength. However, its long-term effects still need to be identified. 2002 Elsevier Science Ltd. All rights reserved.

*Liu, Z. Y., Y. S. Zhang, et al. (2011). Ultrasound in situ testing of early hydration process of supplementary cementitious pastes. International Symposium on Ecological Environment and Technology of Concrete, August 1, 2011 - August 4, 2011, Beijing, China, Trans Tech Publications Ltd.

The early hydration process was investigated using ultrasonic monitoring apparatus for pastes made with various mineral admixtures: silica fume (4%, 13%), slag (10%, 30%, 50%, 70%), and fly ash (10%, 30%, 50%). The influence of water to binder ratio (0.23, 0.35 and 0.53) was also studied. The results show that the hydration rate of cementitious material is obviously accelerated with decreasing in water to cement ratio and Silica fume addition, while the reverse phenomenon is observed when fly ash and slag are incorporated. (2011) Trans Tech Publications.

Lizarazo-Marriaga, J., P. Claisse, et al. (2011). "Effect of steel slag and portland cement in the rate of hydration and strength of blast furnace slag pastes." Journal of Materials in Civil Engineering **23**(Compendex): 153-160.

This paper presents an experimental study of the influence of steel basic oxygen slag (BOS) and ordinary portland cement (OPC) on the compressive strength and the hydration mechanisms of blended grounded granulated blast furnace slag (GGBS) pastes. The compressive strength, the mineralogical changes due to hydration, the setting times, the alkalinity of the raw materials, and the pore solution, and the volume stability were measured on binary and ternary mixes. It is concluded that the steel slag can be used as an activator of GGBS and the optimum composition of those materials was determined with a proposed parameter called "slag index." The properties measured in blended OPC-GGBS-BOS mixes showed encouraging results to be used industrially. The mechanisms of hydration of the blended slag mixes are discussed and a hydration model of the blended system GGBS-BOS is proposed. 2011 ASCE.

*Lothenbach, B., K. Scrivener, et al. (2011). "Supplementary cementitious materials." Cement and Concrete Research **41**(Compendex): 217-229.

The use of silica rich SCMs influences the amount and kind of hydrates formed and thus the volume, the porosity and finally the durability of these materials. At the levels of substitution normally used, major changes are the lower Ca/Si ratio in the C-S-H phase and consumption of portlandite. Alumina-rich SCMs increase the Al-uptake in C-S-H and the amounts of aluminate containing hydrates. In general the changes in phase assemblages are well captured by thermodynamic modelling, although better knowledge of the C-S-H is needed. At early ages, "filler" effects lead to an increased reaction of the clinker phases. Reaction of SCMs starts later and is enhanced with pH and temperature. Composition, fineness and the amount of glassy phase play also an important role. Due to the diverse range of SCM used, generic relations between composition, particle size, exposure conditions as temperature or relative humidity become increasingly crucial. 2010 Elsevier Ltd. All rights reserved.

*Magureanu, C. and C. Negrutiu (2009). Performance of concrete containing high volume coal fly ash - green concrete. 4th International Conference on Computational Methods and Experiments in Materials Characterisation, Materials Characterisation 2009, May 17, 2009 - May 19, 2009, New Forest, United kingdom, WITPress.

Concrete is usually the most common element in a building and over the years, many solutions were developed in order to improve its qualities. We conducted a comparison between ordinary Portland cement concrete and high volume coal fly ash concrete, with the fly ash used as a substitute for the cement. Generally accepted, the total binder in a green concrete is composed of 50% cement and 50% fly ash, which is less than 200 kg/m3 in our case (P. Kumar Mehta - High Performance, high-volume fly ash concrete for sustainable development. University of California, Berkeley, USA). We investigated concrete mixes containing 40% and 50% fly ash as partial replacements of the cement. A C20/25 class concrete was tested at 7, 28, 90 and 365 days of age for: compressive and tensile strength, modulus of elasticity, freeze thaw resistance, water permeability, and shrinkage and bond strength. We found that concrete made with fly ash is a good choice for a medium concrete class with increased durability properties. 2009 WIT Press.

Mak, S. L. (2000). "Thermal reactivity of slag cement binders and the response of high strength concretes to in-situ curing conditions." Materials and Structures/Materiaux et Constructions **33**(Compendex): 29-37.

Concretes placed in thick structural elements experience high hydration temperatures and restricted access to moist curing. This is particularly the case in concretes with relatively high binder contents and low water/binder ratios. Under high temperature curing, thermally reactive binders show significantly enhanced development of early age properties which may be exploited for increased construction speed. However, there is currently very little data on either the early age or medium-term properties of concrete subjected to the combined impact of high temperature and restricted moist curing. This is particularly the case for blended cements containing supplementary cementitious materials, in spite of such binders being increasingly specified in all forms of construction. In this paper, the early and medium-term performance of high strength concretes containing blast furnace slag subjected to in-situ curing is described. The thermal reactivity of slag blended cements is evaluated in relation to key early age engineering properties, which in turn were found to develop at substantially different rates. The prediction of early age properties using equivalent age principles is assessed.

*Mak, S. L. and K. Torii (1995). "Strength development of high strength concretes with and without silica fume under the influence of high hydration temperatures." Cement and Concrete Research **25**(Compendex): 1791-1802.

High performance concretes of high compressive strength are finding increasing applications in many fields of construction such as core walls and columns in tall buildings, long-span bridges and marine structures. In thick cross-sections, the high binder contents of some high strength concretes can result in the

development of high in-situ temperatures. The combined influence of limited moist curing and high hydration temperatures may significantly influence the progress of hydration. This can affect the long-term development of in-situ strength and other engineering properties. Knowledge of in-situ strength development under these conditions is needed to ensure safe utilisation of this new generation of construction materials. This paper presents results of an investigation on the strength development of high strength concretes with and without silica fume subjected to high in-situ temperature conditions. A temperature match conditioning (TMC) system was developed and used to simulate the semi-adiabatic temperature development within medium sized high strength concrete columns. The results of this investigation show that in-situ temperatures of up to 70C significantly increased the 7-day strength of a high strength silica fume concrete. Although no strength regression was observed up to 1 year, the silica fume concrete subjected to high early temperatures showed significantly lower strengths when compared to concrete cured at standard temperature. For the silica fume concrete subjected to high early temperatures, non-evaporable water contents suggest little additional hydration beyond 3 days.

Malhotra, V. M., M.-H. Zhang, et al. (2000). "Long-term mechanical properties and durability characteristics of high-strength/high-performance concrete incorporating supplementary cementing materials under outdoor exposure conditions." ACI Materials Journal **97**(Compendex): 518-525.

This paper presents the results of tests performed on the compressive strength of high-strength/high-performance concrete at ages up to 10 years, the modulus of elasticity after 2, 4, and 10 years, and the carbonation depth and the resistance of concrete to chloride-ion penetration after 10 years. The tests were performed on drilled cores taken from the structural test elements simulating concrete columns. In addition, the compressive strength of cylinders cured in a moist room and in the field, as well as the compressive strength of drilled cores taken from the structural elements (walls) at ages up to 4 years was determined. After 10 years, the compressive strength of the cores drilled from the column elements of the control portland cement concrete and concrete incorporating various supplementary cementing materials ranged from 86.4 to 110.3 MPa. The highest strength was obtained for the high-volume fly ash concrete followed by the control portland cement concrete, slag concrete, silica fume concrete, and concrete incorporating a combination of slag and silica fume, in that order. Even though the high-volume fly ash concrete at ages up to 28 days had lower strength than the other concretes, it attained the highest strength gain of more than 120% between 28 days and 10 years. On the contrary, the concrete incorporating 12% silica fume had the highest compressive strength at ages up to 28 days, but it had a strength gain of only 18% beyond that age. In general, the moduli of elasticity of the moist- and field-cured cylinders and the cores taken from the column elements were similar. For the cores drilled from the column elements, the fly ash concrete had the highest E-modulus at all three ages of 2, 4, and 10 years. The experimentally determined E-moduli ranged from 83 to 116% of the values calculated according to ACI Code 318. In tests performed in

accordance with ASTM C 1202, the charge passed through all the concretes at 10 years was less than 1000 coulombs indicating very high resistance of the concretes to the chloride-ion penetration. After 10 years of outdoor exposure, the depth of carbonation in all the concretes was negligible.

*Marchand, J., M. Jolin, et al. (2005). Deicer salt scaling resistance of supplementary cementing matemal concrete: Laboratory results against field performance. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

In North-America, the de-icer salt scaling resistance of concrete containing supplementary cementing materials (such as fly ash and granulated blast-furnace slag) has been a matter of concern over the past decade. In order to provide more information on the real durability of these mixtures, nine test sections were cast in the City of Quebec (Canada). The test site was selected for its harsh winter climate that combines low temperatures and regular exposure to de-icing salts. As part of this program, three sources of fly ash and one source of slag were tested. In addition, a reference concrete mixture made of an ordinary Portland cement was also tested. Test sections were cast as sidewalks and cured with a white membrane curing compound. After 60 days and five years of exposure to natural conditions, cores were extracted from the sections and brought back to the laboratory for testing. In addition, specimens were also cast on site in PVC moulds and moist cured in the laboratory for a minimal period of 14 days. The salt scaling resistance of all field and laboratory samples was evaluated using ASTM C672. Additional porosity measurements and chloride content determinations were performed on the five-year old samples. Cores extracted from the test sections were much more resistant to de-icer salt scaling than the specimens cured under laboratory conditions, confirming the importance of casting and finishing operations on the behavior of concrete. Furthermore, the good performance of the test sections after 10 years of exposure to natural conditions clearly emphasizes the severity of the ASTM C 672 procedure.

*McCarthy, M. J. and R. K. Dhir (2005). Development of high volume fly ash cements for use in concrete construction, Elsevier Ltd.

The paper describes a study undertaken to examine the use of high levels of low-lime fly ash (high volume FA) as a cement component in concrete, beyond the 30% level commonly adopted. The results indicate that FA levels up to 45% by mass can be combined with Portland cement (PC, C1) to produce the range of practical concrete design strengths, although early strength, which may be critical in construction, can be reduced compared to PC, and lower level FA concretes. The study progressed to consider the use of a rapid hardening Portland cement (C2) and low energy clinker (C3) combined with FA at 45%, as a means of overcoming these early strength shortfalls. Both were found to be effective in matching early strength behaviour of PC concrete. Tests covering fresh (workability loss, bleeding and moisture loss), engineering (strength development, modulus of elasticity, drying shrinkage and creep) and durability (absorption, permeability, carbonation rates and chloride diffusion) properties of

these concretes were then carried out. The results indicate that in almost all cases, either similar or enhanced performance was achieved with the high volume FA concrete, compared to that of PC and these findings offer a route to extending FA use. The practical implications of the study are also examined. 2004 Elsevier Ltd. All rights reserved.

*McPolin, D. O., P. A. M. Basheer, et al. (2007). "New test method to obtain pH profiles due to carbonation of concretes containing supplementary cementitious materials." Journal of Materials in Civil Engineering **19**(Compendex): 936-946.

The writers have carried out an investigation to develop apparent pH profiles of concretes for a variety of cement blends viz. normal portland cement containing by mass 30% pulverized fuel ash, 50% ground granulated blast-furnace slag, 10% metakaolin, and 10% microsilica, chosen to replicate common replacement levels, along with 100% normal portland cement (OPC) mix. The samples were exposed in an accelerated carbonation environment (5% CO_2) for 6weeks during which pH profiles were obtained every week as the concrete carbonated. Measurement of air permeability, carbonation depth, resistivity, and calcium hydroxide content were performed to assist in interpretation of the results. The nature of the pH profiles obtained depended on both the type of binder and the duration of exposure to the carbonation environment. Utilizing the pH profiles, a rate of carbonation was determined, which was found to depend on the type of binder. Both the rate of carbonation and the depth of carbonation after 6weeks of exposure indicated that OPC concrete performed better than concretes containing supplementary cementitious materials. It was also determined that the gas permeability alone cannot provide an accurate indication of the likely rate of carbonation. The thermogravimetric analysis suggests the existence of a relationship between calcium hydroxide content and the apparent pH of carbonated concretes. On the basis of the results in this paper, it can be concluded that the pH profiles, using the technique described in this paper, can be used for measuring the carbonation resistance of concretes containing supplementary cementitious materials. 2007 ASCE.

*McPolin, D. O., P. M. Basheer, et al. (2009). "Carbonation and pH in mortars manufactured with supplementary cementitious materials." Journal of Materials in Civil Engineering **21**(Compendex): 217-225.

An investigation of carbonation in mortars and methods of measuring the degree of carbonation and pH change is presented. The mortars were manufactured using ordinary portland cement, pulverized fuel ash, ground granulated blast-furnace slag, metakaolin, and microsilica. The mortars were exposed to a carbon dioxide-rich environment (5% CO_2) to accelerate carbonation. The resulting carbonation was measured using phenolphthalein indicator and thermogravimetric analysis. The pH of the pore fluid and a powdered sample, extracted from the mortar, was measured to give an accurate indication of the actual pH of the concrete. The pH of the extracted powder mortar sample was found to be similar to the pH of the pore fluid expressed from the mortars. The thermogravimetric analysis suggested two distinct regions of transport of CO_2

within mortar, a surface region where convection was prevalent and a deeper region where diffusion was dominant. The use of microsilica has been shown to decrease the rate of carbonation, while pulverized fuel ash and ground granulated blast-furnace slag have a detrimental effect on carbonation. Metakaolin has little effect on carbonation. 2009 ASCE.

Megat Johari, M. A., J. J. Brooks, et al. (2011). "Influence of supplementary cementitious materials on engineering properties of high strength concrete." Construction and Building Materials **25**(Compendex): 2639-2648.

The influence of supplementary cementitious materials (SCMs), namely silica fume, metakaolin, fly ash and ground granulated blast-furnace slag, on the engineering properties of high strength concrete (HSC) has been investigated in this study. Workability, compressive strength, elastic modulus, porosity and pore size distribution were assessed in order to quantify the effects of the different materials. The results show that the inclusion of the different SCMs has considerable influence on the workability of HSC. Silica fume and metakaolin significantly enhanced the strength of HSC. Fly ash reduced the early-age strength; however, it enhanced the long-term strength of the HSC. Likewise, ground granulated blast-furnace slag impaired the early-age strength, but marginally improved the long-term strength at low replacement levels. The general effect of the different SCMs on the elastic modulus of HSC is rather small compared to their effect on strength. There are good correlations between both static and dynamic moduli and compressive strength. The EC 2 and ACI 209 provide a good estimate of static modulus of elasticity from compressive strength, while the BS8110 gives a good estimate of static modulus of elasticity from dynamic modulus of HSC containing the different SCMs. Porosity and pore size were reduced with the addition of the different SCMs. The volume of mesopores in the ranges of 15 nm and 15 - 30 nm was notably increased for HSC containing SCMs, whereas the percentage of macropores was significantly reduced. 2010 Elsevier Ltd. All rights reserved.

*Mendes, A., J. G. Sanjayan, et al. (2009). "Long-term progressive deterioration following fire exposure of OPC versus slag blended cement pastes." Materials and Structures/Materiaux et Constructions **42**(Compendex): 95-101.

The normal practice of repairing fire-damaged concrete structures is to remove the visibly damaged portions and restore them with new concrete. However, little attention has been given to the long-term performance of fire exposed concrete which is not removed from the structure. This paper addresses this issue. Ordinary Portland cement (OPC) pastes, when exposed to a critical temperature of 400C, undergo complete breakdown. This behaviour was attributed to the dehydration of Ca(OH)2, followed by the expansive rehydration of CaO. In contrast, partial replacement of the OPC binder with slag, had a beneficial effect in the mechanical properties of the paste after exposure to high temperatures, as slag significantly reduces the amount of available Ca(OH)2 in the cement paste. The present work provides new data regarding the long-term (after the exposure event) effect of CaO rehydration in the OPC and OPC/slag pastes. After 1 year the ongoing effect of the CaO rehydration was severe in the OPC paste while OPC/slag blends were not affected by rehydration. Compressive strength and thermogravimetric results are presented to explain this behaviour. 2008 RILEM.

Menendez, G., V. Bonavetti, et al. (2003). "Strength development of ternary blended cement with limestone filler and blast-furnace slag." Cement and Concrete Composites **25**(Compendex): 61-67.

The benefits of limestone filler (LF) and granulated blast-furnace slag (BFS) as partial replacement of portland cement are well established. However, both supplementary materials have certain shortfalls. LF addition to portland cement causes an increase of hydration at early ages inducing a high early strength, but it can reduce the later strength due to the dilution effect. On the other hand, BFS contributes to hydration after seven days improving the strength at medium and later ages. Mortar prisms in which portland cement was replaced by up to 20% LF and 35% BFS were tested at 1, 3, 7, 28 and 90 days. Results show that the contribution of LF to hydration degree of portland cement at 1 and 3 days increases the early strength of blended cements containing about 5-15% LF and 0-20% BFS. The later hydration of BFS is very effective in producing ternary blended cements with similar or higher compressive strength than portland cement at 28 and 90 days. Additionally, a statistical analysis is presented for the optimal strength estimation considering different proportions of LF and BFS at a given age. The use of ternary blended cements (PC-LF-BFS) provides economic and environmental advantages by reducing portland cement production and CO2 emission, whilst also improving the early and the later compressive strength. 2002 Elsevier Science Ltd. All rights reserved.

Menendez, G., V. L. Bonavetti, et al. (2002). Ternary blended cements for high-performance concrete. High-Performance Concrete: Performance and Quality of Concrete Structures: Proceedings, Third International Conference, Recife, PE, Brazil.

This paper analyzes the mechanical behavior and its relation with the development of the hydration reaction in concretes with low water-to-cementitious material ratio made with binary and ternary cements containing limestone filler and blast furnace slag. It explores the maximum level of replacement of portland cement by both additions to obtain high early strength concrete. Results show that the combination of limestone filler and blast furnace slag is complementary: the filler improves the early strength while the slag improves the later strength. The concretes also showed low permeability.

Millard, M. J. and K. E. Kurtis (2008). "Effects of lithium nitrate admixture on early-age cement hydration." Cement and Concrete Research **38**(Compendex): 500-510.

Although the benefits of lithium admixtures for mitigation of alkali-silica reaction (ASR) have been well documented, the potential ancillary effects of lithium compounds on cement and concrete remain largely uncharacterized. To examine the effects of the most common lithium admixture - lithium nitrate - on early-age behavior, the admixture was introduced at dosages of 0% to 400% of the recommended dosage to six cements of varying composition and to a cement-fly ash blend. Behavior was examined by isothermal calorimetry and measurements of chemical shrinkage, autogenous shrinkage, and setting time. Results indicate that lithium nitrate accelerates the early hydration of most cements but may retard hydration after 24h. In the lowest alkali cement tested, set times were shortened in the presence of lithium nitrate by 15-22%. Higher dosages appeared to increase autogenous shrinkage after 40days. The replacement of cement by Class F fly ash at 20% by weight appeared to diminish the early acceleration effects, but later hydration retardation and autogenous shrinkage were still observed. 2007 Elsevier Ltd. All rights reserved.

Mira, P., V. G. Papadakis, et al. (2002). "Effect of lime putty addition on structural and durability properties of concrete." Cement and Concrete Research **32**(Compendex): 683-689.

The effect of lime putty addition on main structural and durability properties of concrete was studied. Different types of cement were used for concrete preparation: a Portland cement, a pozzolanic cement and a Portland cement with the addition of 20% fly ash. The measured concrete properties were compressive strength, setting times, length change, porosity, carbonation depth and degree of steel bar corrosion. It was found that the lime putty addition has a positive effect on the properties of concrete that contain pozzolans and a slightly negative effect on the properties of pure Portland cement. This behavior was correlated with the availability of active silica of cementitious materials. The active silica of pozzolans reacts with the added calcium hydroxide giving constituents, which improve the concrete stability and durability. 2002 Elsevier Science Ltd. All rights reserved.

Mishulovich, A. and E. R. Hansen (1996). "Manufacture of supplementary cementitious materials from cement kiln dust." World Cement **27**(Compendex): 116-120.

The formulation and production of supplementary cementitious materials (SCM) based on cement kiln dust (CKD) was studied with the dual objective of waste reduction and inhibition of alkali-silica reactivity (ASR) in concrete. The SCM's were produced by melting and vitrification of mixes containing CKD with additives, such as clay, shale, and some industrial wastes, including power plant and incinerator ashes. The product chemical composition was close to low-melting eutectics in the ternary system CaO-SiO2-Al2O3 and most melts were produced at temperatures below 1200C. Vitrification provided the necessary hydraulic reactivity of the product and prevented leaching of the trace elements present in source materials. Blended cements incorporating SCMs proved to be competitive with ordinary Portland cement in strength. Adding SCM to cement reduced the ASR-related expansion by 85 to 90% in the standard test with highly reactive aggregates.

*Miura, T. and I. Iwaki (2000). "Strength development of concrete incorporating high levels of ground granulated blast-furnace slag at low temperatures." ACI Materials Journal **97**(Compendex): 66-70.

This paper presents the effect of mixture proportions and curing method on the strength development of concrete incorporating high levels of ground granulated blast-furnace slag (GGBS) at low temperatures. In this study, the strength development of mortar specimens incorporating GGBS for various mixture proportions and curing methods is investigated. The test parameters include the specific surface area measured by the Blaine method (400, 600, and 800 m2/kg), the level of cement replacement by GGBS (50, 60, 70, and 80% by mass), curing method (water curing, sealed curing, and air curing), and curing temperature (20 and 5 C). The test results demonstrate that the strength development at early ages of GGBS mortar cured at 5 C is lower than that of plain mortar not containing GGBS. Thus, the effect of heat curing on the strength development of GGBS concrete is researched. First, the periods of heat curing suitable for each mixture proportion are determined, then strength development after heat curing is examined. The test results indicate that GGBS concrete with a specific surface area of 400 m2/kg has serious problems with strength development at early ages and low curing temperatures. Heat curing is one way to improve strength development at early ages at lower temperatures. On the other hand, GGBS concrete with a specific surface area of 800 m2/kg has no strength development problem at early ages, even when cured at 5 C, and heat curing seems to have a bad influence on strength development, particularly at later ages.

*?Mohammad, I. K. (2011). Measurement and prediction of absorption of cementitious systems using RILEM vacuum saturation method. 1st International Conference on Civil Engineering, Architecture and Building Materials, CEABM 2011, June 18, 2011 - June 20, 2011, Haikou, China, Trans Tech Publications.

Measurement and prediction of absorption of concrete by saturation method is presented. Measurement of absorption of concrete consisting of supplementary cementitious materials was conducted by using vacuum saturation method in accordance to RILEM. Pulverized fuel ash and silica fume were incorporated as partial cement replacements for the preparation of various combinations of cementitious composite systems. Absorption of cement matrix containing ordinary Portland cement, pulverized fuel ash and silica fume at various ages is reported. Based on the experimentally obtained results, analytical prediction models were developed. These models enabled the establishment of isoresponse contours showing the interactive influence between the various parameters investigated. (2011) Trans Tech Publications.

Mokarem, D. W., R. M. Meyerson, et al. (2003). DEVELOPMENT OF CONCRETE SHRINKAGE PERFORMANCE SPECIFICATIONS**:** 40 p.

During its service life, concrete undergoes volume changes. One of the types of deformation is shrinkage. The four main types of shrinkage associated with concrete are plastic, autogenous, carbonation, and drying shrinkage. The volume changes in concrete due to shrinkage can lead to cracking of the concrete. In the case of reinforced concrete, the cracking may produce a direct path for chloride ions to reach the reinforcing steel. Once chloride ions reach the steel surface, the steel will corrode, which itself can cause cracking, spalling, and delamination of the concrete. The unrestrained drying shrinkage and restrained cracking tendency of concrete mixtures typically used by the Virginia Department of Transportation (VDOT) were assessed to establish an appropriate limit on drying shrinkage for use in a performance specification. Five existing shrinkage prediction models were assessed to determine the accuracy and precision of each model as it pertains to the VDOT mixtures used in this study. The five models assessed were the ACI 209 Code Model, Bazant B3 Model, CEB 90 Code Model, Gardner/Lockman Model, and Sakata Model. The CEB 90 Code Model performed best for the portland cement concrete mixtures, and the Gardner/Lockman Model performed best for the supplemental cementitious material mixtures. Based on a comparison of the unrestrained drying shrinkage and restrained cracking tendency, it was determined that the potential for cracking could be minimized by limiting the unrestrained shrinkage of the concrete mixtures. Based on the results of this study, the recommended percentage length change specification limits are 0.0300 at 28 days and 0.0400 at 90 days for the portland cement concrete mixtures. For the supplemental cementitious material mixtures, the percentage length change specification limits were 0.0400 at 28 days and 0.0500 at 90 days.

* ?Mokarem, D. W., R. E. Weyers, et al. (2005). "Development of a shrinkage performance specifications and prediction model analysis for supplemental cementitious material concrete mixtures." Cement and Concrete Research **35**(Compendex): 918-925.

The unrestrained shrinkage along with restrained cracking tendency of concrete mixtures typically used by the Virginia Department of Transportation (VDOT) were assessed to establish an appropriate limit on drying shrinkage for use in a performance specification. Five existing shrinkage prediction models were assessed to determine the accuracy and precision of each model as it pertains to the VDOT mixtures used in this study. The five models assessed were the ACI 209 Code Model, Bazant B3 Model, CEB90 Code Model, Gardner/Lockman Model, and the Sakata Model. The Gardner/Lockman Model performed best for the supplemental cementitious material (SCM) mixtures. Based on a comparison of the unrestrained drying shrinkage and restrained cracking tendency, it was determined that the potential for cracking could be minimized by limiting the unrestrained shrinkage of the concrete mixtures. The recommended percentage length change specification limits for the supplemental cementitious material mixtures are 0.0400 at 28 days and 0.0500 at 90 days. 2004 Elsevier Ltd. All rights reserved.

Mou, S.-B. and Z.-J. Zheng (2002). "The early strength of slag cements with addition of hydrate microcrystals." Journal Wuhan University of Technology, Materials Science Edition **17**(Compendex): 83-85.

The effect of hydrate microcrystals such as calcium silicate hydrates (CSH) and ettringite on the early strength of slag cements was studied. The authors explored the possibility of improving the early strength of the slag cement by applying crystal seed technology. It is shown that slag crystal seeds make the early strength of the cement increased due to the action of hydrate crystal seeds, which speed up the hydration of clinker minerals in the nucleation of ettringite.

Therefore, the early strength of the slag cement is obviously improved.

*Mounanga, P., M. I. A. Khokhar, et al. (2011). "Improvement of the early-age reactivity of fly ash and blast furnace slag cementitious systems using limestone filler." Materials and Structures/Materiaux et Constructions **44**(Compendex): 437-453.

This article analyzes the effects of the addition of limestone filler on the hydration rate, setting times and early-age mechanical properties of binary and ternary-binder mortars containing Portland cement, blast furnace slag (BFS) and fly ash (FA), with various substitution rates of cement with mineral additions going up to 50%. Vicat needle penetration tests and measurements of heat flow of reaction, compressive strength and dynamic Young's modulus were carried out on 14 mortars prepared with binary and ternary binders, at 20C. The results obtained on the mortars containing binary binders, show that their loss of mechanical strength at early age is not caused by a deceleration of the reactions of cement in the presence of mineral additions, but is mainly explained by the dilution effect related to the reduction in cement content. A moderate addition of limestone filler (8-17%) makes it possible to obtain ternary binders with early-age reactivity equal or even higher than that of Portland cement, and with 28-days mechanical resistance close to those of the binary-binder mortars. This accelerating effect of limestone filler is particularly sensitive in the case of mortars containing FA. 2010 RILEM.

*Mun, K. J., S. Y. So, et al. (2007). "The effect of slaked lime, anhydrous gypsum and limestone powder on properties of blast furnace slag cement mortar and concrete." Construction and Building Materials **21**(Compendex): 1576-1582.

Basic properties of blast furnace slag cement mortar and concrete are investigated by adding inorganic activators. The result of this research concludes that slag cement mixed with suitable activator agents such as lime, gypsum and limestone powder could accelerate the compressive strength and tighten pore structure at early age. The addition of activator into mortar and concrete containing slag cement produces superior properties, reduced shrinkage and less carbonation compared to mortar and concrete containing slag cement without the addition of activator. Consequently, there are possibilities for manufacturing blast furnace slag cement, which could compensate the weak properties at early curing age. When compared with ordinary Portland cement, this cement has superior characteristics for long curing age. 2006 Elsevier Ltd. All rights reserved.

Muthupriya, P., K. Subramanian, et al. (2010). "Strength and durability characteristics of high performance concrete." International Journal of Earth Sciences and Engineering **3**(Compendex): 416-433.

High performance concrete is fast getting acceptability for a wide range of applications in the construction of concrete structures. It is a tailor made material for specific applications and having advantageous properties like high strength, high durability and high constructability as compared to the conventional type of normal strength concrete. To produce such a HPC, mineral admixtures such like

metakaolin, silica fume and fly ash on the one hand and super plasticizer on the other hand used along with normal ingredients. The use of mineral admixtures in concrete enhances its properties regarding strength, durability, workability and economy. The scope of the present study is to investigate the effect of mineral admixtures such as silicafume, metakaolin and fly ash towards the performance of HPC. An effort has been made to focus on the mineral admixture towards their pozzolanic reaction, contribution towards strength properties, and durability studies. The strength characteristics such as compressive strength, tensile strength and flexural strength were investigated to find the optimum replacement of mineral admixtures. The compressive strength of HPC with mineral admixtures at the replacement levels of 0%, 5%, 10% and 15% were studied at 3 days, 7 days, 28 days, of curing. The strengths were compared and the optimum replacement level of each mineral admixture was arrived at. The tensile and flexural strength of HPC were obtained at the replacement levels of mineral admixtures at 28 days of curing. The durability studies such as permeability, acid resistance, alkalinity measurement and water absorption were conducted. The efficiency factors for silica fume and flyash with different levels at 7 days and 28 days were obtained. From the studies conducted, it was observed that silica fume play a vital role in improving the strength of concrete particularly at early ages. From the durability point of view, all the three mineral admixtures perform well. 2010 CAFET-INNOVA TECHNICAL SOCIETY.

Nagataki, S., S. Miyazato, et al. (1998). Effects of fly ash and silica fume in high performance concrete Fly Ash, Slag, Silica Fume, and Natural Pozzolans-Proceedings, CANMET/ACI Sixth International Conference, Bangkok, Thailand, American Concrete Institute.

Nagataki, S. and C. Wu (1995). A study of Portland cement incorporating silica fume and blast furnace slag Fly Ash, Slag, Silica Fume and Other Pozzolans –Proceedings, Fifth International Conference, Milwaukee, Wis., , American Concrete Institute.

The workability, strength, and durability of concrete are affected by particle distribution and chemical composition of cement. So, a cement which has ideal particle distribution and chemical composition is needed is needed for making high performance concrete. This kind of cement can be realized by blending portland cement, silica fume, and blast furnace slag, because they have different particle distributions and chemical compositions. In this paper, the triple blended cement was composed of 10 percent silica fume, 30 percent blast furnace slag, and 60 percent portland cement as it had suitable chemical composition and the densest particle distribution in portland cement or portland cement admixed by silica fume or blast furnace slag in this research. The hydration process of the triple blended cement was similar to the portland cement, but the heat of hydration and Ca(OH)2 content in the hydrates were much lower than that for portland cement. It was found that the porosity of the hardened paste was so low that it was half of that in portland cement paste. The R2O in its pore solution was only 88 percent of that in pore solution of portland cement paste. This fact means the triple blended cement may reduce the alkali-silica reaction of concrete. The flows of the fresh mortars made by the triple blended cement were higher or lower than the flow of the control mortar depending on the specific surface area of silica fume used. The compressive strengths of the mortar were higher than that of the control mortar as its denser paste. Because of the low Ca(OH)2 content in the hydrates and R2O in the pore solution, the resistance of the mortars to sulfate attack and alkali-silica reaction was high. However, the drying shrinkage of the mortars made with the triple blended cement was higher than that of the control mortar.

Nataraja, M. C. and B. M. Ramalinga Reddy (2005). Mix proportioning and some properties of slag concrete. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

There is currently no well-tried mix proportioning methods available for slag concrete. Presently this supplementary cementitious material is being used widely in India in almost all fields of construction, as it is a cheaper material. The use of such mineral admixture is also recommended in IS: 456-2000. This paper presents a simple method to produce concrete having a 28-day compressive strength varying from 30 MPa to 60 MPa at different percentages of slag namely 30%, 60% and 90% as a replacement to cement. Though the strength of slag concrete decreases as the slag content increases, it is found that the slag concrete possessed significant compressive strength even at higher replacement levels. Concrete mixes are designed for three exposure conditions as per IS: 456-2000 satisfying the durability requirements. Their compressive strength characteristics are reported in this paper. Mix design procedure suggested in the draft IS: 10262(2003) is adopted.

Nazari, A. and S. Riahi (2011). "The effects of TiO2 nanoparticles on physical, thermal and mechanical properties of concrete using ground granulated blast furnace slag as binder." Materials Science and Engineering A **528**(Compendex): 2085-2092.

In the present study, flexural strength, pore structure, thermal behavior and microstructure characteristics of concrete containing ground granulated blast furnace slag and TiO2 nanoparticles as binder have been investigated. Portland cement was replaced by different amounts of ground granulated blast furnace slag and the properties of concrete specimens were investigated. Although it negatively impacts the properties of concrete at early ages, ground granulated blast furnace slag was found to improve the physical and mechanical properties of concrete up to 45wt% at later ages. TiO2 nanoparticles with the average particle size of 15nm were partially added to concrete with the optimum content of ground granulated blast furnace slag and physical and mechanical properties of the specimens were measured. TiO2 nanoparticle as a partial replacement of cement up to 3wt% could accelerate C-S-H gel formation as a result of increased crystalline Ca(OH)2 amount at the early age of hydration and hence increase flexural strength of concrete. The increased the TiO2 nanoparticles' content more than 3wt%, causes the reduced the flexural strength because of the decreased crystalline Ca(OH)2 content required for C-S-H gel formation and unsuitable dispersed nanoparticles in the concrete matrix. TiO2 nanoparticles could improve the pore structure of concrete and shift the distributed pores to harmless and few-harm pores. 2010 Elsevier B.V.

Nazari, A. and S. Riahi (2011). "TiO2 nanoparticles effects on physical, thermal and mechanical properties of self compacting concrete with ground granulated blast furnace slag as binder." Energy and Buildings **43**(Compendex): 995-1002.

In this work, strength assessments and percentage of water absorption of self compacting concrete containing different amounts of ground granulated blast furnace slag and TiO2 nanoparticles as binder have been investigated. Portland cement was replaced by 45 wt% of ground granulated blast furnace slag and up to 4.0 wt% TiO2 nanoparticles and the properties of concrete specimens were investigated. TiO2 nanoparticle as a partial replacement of cement up to 3.0 wt% could accelerate C-S-H gel formation as a result of increased crystalline Ca(OH)2 amount at the early age of hydration and hence increase strength and improve the resistance to water permeability of concrete specimens. Several empirical relationships have been presented to predict flexural and split tensile strength of the specimens by means of the corresponding compressive strength at a certain age of curing. 2010 Elsevier B.V. All rights reserved.

Nazari, A. and S. Riahi (2011). "TiO2 nanoparticles' effects on properties of concrete using ground granulated blast furnace slag as binder." (Compendex): 1-10.

In the present study, compressive strength, pore structure, thermal behavior and microstructure characteristics of concrete containing ground granulated blast furnace slag and TiO2 nanoparticles as binder were investigated. Portland cement was replaced by different amounts of ground granulated blast furnace slag and the properties of concrete specimens were investigated. Although it negatively impacts the properties of concrete at early ages, ground granulated blast furnace slag up to 45 wt% was found to improve the physical and mechanical properties of concrete at later ages. TiO2 nanoparticles with the average particle size of 15 nm were partially added to concrete with the optimum content of ground granulated blast furnace slag and physical and mechanical properties of the specimens were measured. TiO2 nanoparticle as a partial replacement of cement up to 3 wt% could accelerate C-S-H gel formation as a result of increased crystalline Ca(OH)2 amount at the early age of hydration and hence increase compressive strength of concrete. The increased TiO2 nanoparticles' content of more than 3 wt% may cause reduced compressive strength because of the decreased crystalline Ca(OH)2 content required for C-S-H gel formation and unsuitable dispersed nanoparticles in the concrete matrix. TiO2 nanoparticles could improve the pore structure of concrete and shift the distributed pores to harmless and less-harm pores. 2011 Science China Press and Springer-Verlag Berlin Heidelberg.

Nehdi, M., M. Pardhan, et al. (2004). "Durability of self-consolidating concrete incorporating high-volume replacement composite cements." Cement and Concrete Research **34**(Compendex): 2103-2112.

Self-consolidating concrete (SCC) decreases construction time, labor and equipment on construction sites, makes the construction of heavily congested structural elements and hard to reach areas easier, reduces noise- and vibration-related injuries, and helps in achieving higher quality finish surfaces. However, because it usually requires a larger content of binder and chemical admixtures compared to ordinary concrete, its material cost is generally 20-50% higher, which has been a major hindrance to a wider implementation of its use. There is growing evidence that incorporating high volumes of mineral admixtures and microfillers as partial replacement for portland cement in SCC can make it cost effective. However, the durability of such SCC needs to be proven. This research investigates the rapid chloride ion penetrability, sulfate expansion and deicing salt surface scaling resistance of SCC mixtures made with high-volume replacement binary, ternary, and quaternary cements. The fresh concrete properties and compressive strength at 1, 7, 28 and 91 days of such SCC mixtures were measured. Moreover, rapid chloride ion penetrability was investigated for the various SCC mixtures at 28 and 91 days, while the deicing salt surface scaling under 50 freezing-thawing cycles and sulfate expansion after up to 9 months of immersion in a 5% Na 2SO4 solution were investigated as per the ASTM C-672 and ASTM C1012 guidelines, respectively. Results indicate that SCC can be made with high-volume replacement composite cements and achieve good workability, high long-term strength, good deicing salt surface scaling resistance, low sulfate expansion and very low chloride ion penetrability.

Nehdi, M. L. and J. Sumner (2002). "Optimization of ternary cementitious mortar blends using factorial experimental plans." Materials and Structures/Materiaux et Constructions **35**(Compendex): 495-503.

Producing cements incorporating high-volume replacement of ordinary portland cement (OPC) by recycled industrial by-products is perceived as the most promising venture for the cement and concrete industry to meet its environmental obligations. However, the two-component (binary) cements thus produced are often associated with shortcomings such as the need for extended moist-curing, increased use of chemical admixtures, low early age strength, increased cracking tendency due to drying shrinkage, and de-icing salt scaling problems. There is need for research to investigate whether high-volume replacement multi-component (ternary and quaternary) cements could be optimized with synergistic effects allowing component ingredients to compensate for any mutual shortcomings. This study uses factorial experimental plans to investigate the performance of OPC-silica fume (SF)-class F fly ash (FA) and OPC-SF-ground granulated blast furnace slag (GBFS) ternary cementitious blends. Response surfaces for the superplasticizer requirement to achieve a constant flow, setting time, drying shrinkage up to 112 days, compressive strength at 1, 7, 28 and 56. days, and for the sulfate expansion up to 9-months were obtained for up to 20%, 60%, and 60% replacement levels of OPC by SF, FA and GBFS, respectively. A multiparametric optimization is used to establish response surfaces for a desirability function, which is used to rate ternary cementitious blends. Results

indicate that when rheological, mechanical, durability and cost requirements are combined; the use of costly mineral admixtures such as silica &middot fume is not economic in ternary OPC-SF-FA or OPC-SF-GBFS blends beyond levels of about 3 to 5%. Moreover, it is shown that the major hurdle for high-volume replacement of OPC with class F fly ash is compromising the early age performance. Results also indicate that a good quality high-fineness GBFS can be used at replacement levels of OPC up to 60% without major disadvantages.

Olek, J., A. Lu, et al. (2002). PERFORMANCE RELATED SPECIFICATIONS FOR CONCRETE BRIDGE SUPERSTRUCTURES - VOLUME 2 - HIGH PERFORMANCE CONCRETE**:** 192 p.

Volume 2 of the final report deals with the topic of high performance concrete (HPC). The investigation of HPC included the development of optimized concrete mixtures and identifying their performance characteristics related to durability for the purpose of using these characteristics in performance-related specifications in the state of Indiana. The research effort described in this report was divided into two phases. Phase I was focused on development of concrete mixtures optimized with respect to selected performance-related parameters. During this phase, ten optimum concrete mixes have been identified from 45 mixes in terms of compressive strength, Young's modulus of elasticity, rapid chloride penetration and chloride conductivity using a statistical design procedure. Through surface response methodology, 27 statistical models were developed for each of four parameters. Based on the models developed, 81 contour maps were generated, which indicated how performance of concrete varied in response to the change of dosages of binders at constant water-binder ratio. Based on the overlaid contour maps and the threshold values chosen for the properties of concrete, optimum concrete mixtures including portland cement and the combinations with fly ash, silica fume and slag were identified. In Phase II of this study, the ten optimum mixtures were further evaluated with respect to mechanical properties and durability characteristics. Several different tests related to the evaluation of the resistance of concrete to chloride permeability were used: rapid chloride permeability test, chloride conductivity test, test for the resistance of concrete under DC electrical field, ponding test for the determination of the resistance of concrete to chloride penetration, and rapid test for the determination of diffusion coefficient from chloride migration. Tests related to the resistance of concrete to freezing and thawing, and scaling were also investigated. Other tests, such as the determination of drying shrinkage and test for curing effects on the properties of HPC, were also evaluated in this research. Special emphasis was placed on determining and quantifying those parameters that control the ingress of the chloride ions. Based on the results generated during this research, models have been developed that allow for prediction of certain mechanical and durability-related parameters related to the mixture composition. The parameters that can be predicted include strength, rapid chloride permeability values, and chloride diffusion coefficient. Limited validation of these models was performed using field data provided by the Indiana Department of Transportation. The strength and chloride diffusion coefficient values generated by these models can serve as an input for the life-cycle costing model described in volume 1 of this report.

Oluokun, F. A. (1994). "Fly ash concrete mix design and the water-cement ratio law." ACI Materials Journal **91**(Compendex): 362-371.

When the water-cement ratio law was proposed by Abrams in 1918, the use of fly ash and silica fume as replacements or substitutes for part of the cement was virtually unknown. Consequently, the effects of fly ash and silica fume were not considered in the development of Abrams' law. Since the early 1960s, concrete mix compositions have changed, and cement is no longer the only cementitious material in concrete mixes. In a high percentage of situations, today's cementitious material content is made up of cement plus fly ash. This study investigates the applicability of Abrams' law to concrete mixes containing fly ash. As initially expected, it was found that Abrams' water-cement ratio law is not directly applicable to mixes with fly ash. An alternative augmented water-cementitious materials ratio law is proposed for designing concrete mixes containing fly ash.

O'Rourke, B., C. McNally, et al. (2009). "Development of calcium sulfate-ggbs-Portland cement binders." Construction and Building Materials **23**(Compendex): 340-346.

Binders manufactured using a blend of gypsum, ground granulated blast furnace slag and Portland cements are technically viable and possess considerable environmental and economic advantages when compared to binders manufactured using Portland cement alone. As such, the evaluation of binders made from these materials offers a promising research focus in the quest to produce technically sound, environmental and economical binders for specialist uses as an alternative to traditional concrete binders of higher carbon footprint. The aim of the test programme was to investigate the viability of a series of binders designed to fulfil particular user needs while having significantly decreased carbon footprints. Two distinct series of binders were designed; the dominant ingredient in the first was calcium sulfate while in the second it was ggbs. Potential applications for both series of binders were considered and the strength development of each binder was analysed. In addition, the effect of water on the gypsum-based binders was analysed, as was the sulfate resistance of the ggbs-based binder. The results of the laboratory tests carried out were varied. For the calcium sulfate-based binders, those manufactured using anhydrite II as the dominant ingredient were found to achieve highest strengths. However these binders were found to be particularly susceptible to moisture-induced deterioration. For the ggbs-based binders, it was found that the early strength development was improved by the addition of small quantities of anhydrite II and gypsum. The strengths and sulfate resistance at later ages remained unaffected. These binders may have significant potential in situations where early strength development is a requirement. 2007 Elsevier Ltd. All rights reserved.

Osborne, G. J. (1986). "CARBONATION OF BLASTFURNACE SLAG CEMENT CONCRETES." Durability of building materials **4**(Compendex): 81-96.

The depth of carbonation in 100-mm cubes from two series (short term and long term) of concrete mixes, with and without blastfurnace slag in the cements, has been measured. The specimens has been stored in air at 20 degree C and 65% relative humidity, since demoulding one day after casting, for periods of time ranging from one to nine years. It should be stressed that the Portland and slag cement concretes tested were designed to equal cement content and workability and not to the same 28-day strength, although the short- and long-term series had different cement contents of 380 and 335 kg/m**3 respectively. The results showed a good correlation between depth of carbonation and compressive strength of concrete, a relationship which held at all ages of test from 28 days on. The most critical factor determining the carbonation rate for slag cement concretes was the type of curing involved. Two secondary but important factors affecting both carbonation and strength development of the air-stored concrete cubes were the slag content of the slag cement and the tricalcium aluminate (C//3A) content of the Portland cement. Carbonation was greater in the higher slag content cements and in the lower C//3A Portland cements.

Osborne, G. J. (1999). "Durability of Portland blast-furnace slag cement concrete." Cement and Concrete Composites **21**(Compendex): 11-21.

This paper summarizes the results of studies carried out the Building Research Establishment in the UK, on the performance and long-term durability of concrete where ground glassy blast-furnace slag (granulated and pelletized) has been used as a cementitious material. Using data from tests on site structures and laboratory and exposure site studies, comparisons are made of the properties and performances of the slag cement concretes with normal Portland cement concretes of similar mixture proportions. A number of recommendations are given for the effective use of ground glassy blast-furnace slag in concrete. The many technical benefits available to the concrete user, such as reduced heat evolution, lower permeability and higher strength at later ages, decreased chloride ion penetration, increased resistance to sulfate attack and alkali silica reaction were affirmed. However, a cautionary warning of the importance of good early curing is made to ensure that the adverse effects of higher rates of carbonation, surface scaling and frost attack are minimized. The paper is intended to provide guidance for those concerned with the design, specification, application and performance of concrete in practice where slag can also help to reduce costs and energy demands in the production of cement compared with normal Portland cement.

Ozyildirim, C. and W. J. Halstead (1994). "Improved concrete quality with combinations of fly ash and silica fume." ACI Materials Journal **91**(Compendex): 587-594.

Portland cement concretes and concretes with various combinations of cement (Types II and III), fly ash (Class F), and silica fume were tested to establish parameters for strength and chloride permeability. The effects of different curing temperatures and different durations of moist-curing were also determined. In general, the laboratory tests showed that in the temperature range of 23 to 38 C (73 to 100 F), concretes at a water-cement ratio of 0.40 to 0.45 with satisfactory

28-day strengths and good resistance to chloride-ion penetration at 28 days can be obtained with either type of cement and various combinations of fly ash and silica fume. Similar specimens cured at 6 C (43 F) generally did not develop an adequate early strength, and the chloride permeability was high. Combinations of the pozzolans with Type III cement yielded a higher strength and lower chloride permeability than did similar combinations with Type II cement.

Ozyildirim, C. and C. Zegetosky (2010). "Exploratory investigation of nanomaterials to improve strength and permeability of concrete." Transportation Research Record(Compendex): 1-8.

Concrete containing various supplementary cementitious materials (SCMs) such as silica fume, fly ash, and slag has improved properties. Nanomaterials, new SCMs with possible applications in concrete, have the smallest particle size (less than 100 nm). Nanomaterials are reactive because of the small size and large surface area of the particles, and they have great potential in improving concrete properties such as compressive strength and permeability. This study evaluates the use of a variety of nanomaterials in concrete compared with conventional concrete and concrete containing common SCMs. The potential benefits of using nanomaterials over other SCMs are high reactivity and cost-effectiveness; in addition, smaller amounts are necessary, resulting in less cement replacement. Concretes containing nanosilica and nanoclay were prepared in the laboratory. They were compared with concretes containing silica fume, fly ash, slag, or only portland cement. Specimens were tested for compressive strength and permeability. The microstructure of selected concretes with improved compressive strength and permeability was analyzed by using an atomic force microscope and nanoindenter to explain the improvements. The results of this study indicate that some of the nanomaterials tested have potential in concrete applications. The microstructure of the nanosilica concrete was denser and more uniform than the conventional concrete microstructure. In addition, the nanosilica had the largest improvement in both compressive strength and permeability among the nanomaterials tested.

Ozyildirim, C. and C. Zegetosky (2010). Laboratory Investigation of Nanomaterials to Improve the Permeability and Strength of Concrete**:** 21p.

Concretes containing various supplementary cementitious materials (SCMs) such as silica fume, fly ash, and slag have improved properties. Nanomaterials (a nanometer, nm, is 10 to the -9 power m), new SCMs with possible applications in concrete, have the smallest particle size that is less than 100 nm. Nanomaterials are very reactive because of the particles’ small size and large surface area and have great potential in improving concrete properties such as compressive strength and permeability. This study evaluated the use of a variety of nanomaterials in concrete compared with conventional concrete and concrete containing common SCMs. The potential benefits of using nanomaterials over other SCMs are their high reactivity; the need for smaller amounts, resulting in less cement replacement; and cost-effectiveness. Concretes containing nanosilica and nanoclay were prepared in the laboratory and compared to concretes containing silica fume, fly ash, slag, or only portland cement. Specimens were tested for compressive strength and permeability. The microstructure of selected concretes with improved compressive strength and permeability were analyzed using an atomic force microscope and nanoindenter to determine the reason for the improvements. The microstructure of the nanosilica concrete was denser and more uniform than that of the conventional concrete microstructure. In addition, the nanosilica had the largest improvement in both compressive strength and permeability among the nanomaterials tested. The results of this study indicate that some of the nanomaterials tested have potential in concrete applications. However, further evaluation is required before nanomaterials can be used in concrete. Specifically, they should be evaluated for improved dispersion to achieve uniformity, optimized amounts of ingredients, and cost-effectiveness.

Papadakis, V. G. (2000). "Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress." Cement and Concrete Research **30**(Compendex): 291-299.

In this work the durability of Portland cement systems incorporating supplementary cementing materials (SCM; silica fume, low- and high-calcium fly ash) is investigated. Experimental tests simulating the main deterioration mechanisms in reinforced concrete (carbonation and chloride penetration) were carried out. It was found that for all SCM tested, the carbonation depth decreases as aggregate replacement by SCM increases, and increases as cement replacement by SCM increases. The specimens incorporating an SCM, whether it substitutes aggregate or cement, when exposed to chlorides exhibit significantly lower total chloride content for all depths from the surface, apart from a thin layer near the external surface. New parameter values were estimated and existing mathematical models were modified to describe the carbonation propagation and the chloride penetration in concrete incorporating SCM.

Papadakis, V. G., S. Antiohos, et al. (2002). "Supplementary cementing materials in concrete. Part II: A fundamental estimation of the efficiency factor." Cement and Concrete Research **32**(Compendex): 1533-1538.

For comparing the relative performance of various supplementary cementing materials (SCMs: silica fume, fly ash, slag, natural pozzolans, etc.) as regards Portland cement, the practical concept of an efficiency factor may be applied. The efficiency factor (or k value) is defined as the part of the SCM in an SCM-concrete that can be considered as equivalent to Portland cement. In the present work, an alternative procedure for experimental determination of the k value is proposed, using the concept of the pozzolanic activity index. For the first time, also, the k value for equivalent strength was correlated with the active silica content of the SCM through analytical expressions. Artificial pozzolanic materials of various compositions and some natural pozzolans were studied. It was found and verified by experimental comparison that these expressions are valid only for artificial SCMs (fly ash, slag), whereas in the case of natural SCMs the k value is overestimated. Thus, knowing primarily the active silica content of the SCM, a first approximation of the k value can be obtained and, further, the strength of a concrete incorporating artificial SCM can be predicted. 2002 Elsevier Science Ltd. All rights reserved.

Papadakis, V. G. and S. Tsimas (2002). "Supplementary cementing materials in concrete: Part I. Efficiency and design." Cement and Concrete Research **32**(Compendex): 1525-1532.

Many solid industrial by-products such as siliceous and aluminous materials (fly ash, silica fume, slags, etc.) as well as some natural pozzolanic materials (volcanic tuffs, diatomaceous earth, etc.) may be characterized as supplementary cementing materials (SCM) as they exhibit cementitious and/or pozzolanic properties. Due to plenty of these materials and their large variations on physical and chemical composition, the development of a general design for their use in concrete is required. In this work, the concept of an efficiency factor is applied as a measure of the relative performance of SCM compared with Portland cement. Artificial materials of various compositions and some natural pozzolans were studied. Compressive strength and accelerated chloride penetration tests were performed. With regard to these characteristics, efficiency factors for these materials were calculated. A mix design strategy to fulfil any requirements for concrete strength and service lifetime was developed and it enables concrete performance to be accurately predicted. 2002 Elsevier Science Ltd. All rights reserved.

Papayianni, I. and E. Anastasiou (2003). Concrete Incorporating High Volumes of Industrial By-Products.

Fly ashes and slags are by-products of the energy and steel industry, respectively. They are produced in large quantities and their disposal creates many environmental problems. In the frame of a project by the Greek Secretariat of Research and Technology, the two by-products were used for concrete production. Therefore, a concrete incorporating high volume of local calcareous fly ash and steel slags as aggregates has been manufactured and tested in the laboratory. The characteristics of the two by-products used, as well as the mechanical, elastic and physicochemical properties of this concrete are given in this paper in comparison with conventional concrete. It seems that a concrete with special characteristics, which is particularly suitable for many applications in construction, can be produced with only 5% by mass Portland cement.

Papayianni, I. and F. Karkantelidou (2009). Performance of superplasticizers in blended cement systems. 9th ACI International Conference on Superplasticizers and Other Chemical Admixtures, October 12, 2009 - October 15, 2009, Seville, Spain, American Concrete Institute.

The combination of different type of blending materials with portland cement such as natural pozzolans, fly ashes, and slags provides high flexibility in designing concrete mixtures with several technical advantages and low cost. However, their addition influences the properties of fresh concrete and causes problems of compatibility in blended cement systems containing superplasticizers that are usually used either for reduction of water demand or for increase of workability. In this study, two of the widely used type of superplasticizers, one based on sulphonated naphthalene formaldehyde condensate (SNF) and another based on polycarboxylate polymers (PC), were tested with ten blended cement mixtures containing 20, 30, 50, or 80% portland cement replacement with one or more of the above-mentioned supplementary cementitious materials. The action of superplasticizer on cement pastes was monitored by making zeta potential, pH, and temperature measurements as well as by using DTA-TG method for determining the hydration and hardening process. Porosity and strength development were also measured at different ages. The aim of the research work was to find which type of superplasticizer was more suitable for each type of binder system. The highest reduction of water demand was achieved with polycarboxylate polymer superplasticizer. Results show that compared to the plain portland cement system, the decrease of water/binder ratio with superplasticizer addition was lower in blended cements.

Parrott, L. J. (1996). "Some effects of cement and curing upon carbonation and reinforcement corrosion in concrete." Materials and Structures/Materiaux et Constructions **29**(Compendex): 164-173.

Experimental data are presented to illustrate the effects of cement type and curing upon the depth of carbonation and reinforcement corrosion in cover concrete after exposure for 18 months at 20 C and 60% relative humidity. Three curing periods (1, 3 and 28-days) and 17 cements, with various proportions of granulated blastfurnace slag or limestone, were used to make concretes, at 0.59 water/cement ratio, with 28 day strengths in the range 26 to 46 MPa. The depth of carbonation after 18 months was 64% greater than after 6 months and was affected more by cement type than by curing. The depth of carbonation increased when Portland cement clinker was replaced by 19% or more of limestone or granulated blastfurnace slag. The depth of carbonation after 18 months correlated better with the air permeability of cover concrete, initial weight loss (an indicator of moisture diffusion rate in cover concrete) or the cube strength 8 days after the end of curing than it did with 28-day cube strength. The rate of reinforcement corrosion increased steeply when the carbonation front approached the reinforcing steel, and it was still increasing after the carbonation front had completely passed the reinforcement. For a given unneutralized remainder (i.e. cover depth minus the depth of carbonation), curing had little effect upon the rate of corrosion but higher rates were observed when the cement contained granulated blastfurnace slag. The results were broadly consistent with a simple engineering strategy in which the rate of carbonation was related to the air permeability of cover concrete, and the rate of any subsequent reinforcement corrosion was largely dependent upon moisture conditions, without any obvious influence of the cover depth or the permeability of the cover concrete. The results also suggested that estimation of the rate of reinforcement corrosion could be improved by taking account of the cement type and treating the unneutralized remainder as a variable.

Persson, B. S. M. (2004). "SHRINKAGE AND CREEP OF HIGH-PERFORMANCE SELF-COMPACTING CONCRETE (HPSCC). IN: AUTOGENOUS DEFORMATION OF CONCRETE." Publication of: American Concrete Institute: p. 155-180.

This paper describes an experimental investigation of the fresh properties, strength and elastic modulus, shrinkage, and creep in high-performance self-compacting concrete (HPSCC). Optimizations were performed on a laboratory scale according to an ideal grading of the particles in the fresh concrete for SCC, with high strength, high durability in marine environment or with fire spalling safety. SCC was introduced in the full-scale production of beams and piles. The results showed high slump flow and robustness that allowed for a reasonable variation of the water-cement ratio (w/c), keeping the fresh concrete properties within the limits of the full-scale production even at elevated temperature. The early strength development was extremely high even though w/c was slightly higher in the SCC than in vibrated concrete (NC). Internal frost resistance was improved for SCC compared with NC but the chloride migration was larger in SCC with limestone powder than in NC. Spalling of the concrete during fire, especially in low w/c concrete, was avoided by use of polypropylene fibers. The elastic modulus was slightly smaller in SCC than in NC due to lower aggregate content in SCC than in NC. Creep, shrinkage, salt frost scaling and sulfate resistance did not differ much from the corresponding properties of NC.

Poon, C. S., L. Lam, et al. (2000). "Study on high strength concrete prepared with large volumes of low calcium fly ash." Cement and Concrete Research **30**(Compendex): 447-455.

This paper presents the results of a laboratory study on high strength concrete prepared with large volumes of low calcium fly ash. The parameters studied included compressive strength, heat of hydration, chloride diffusivity, degree of hydration, and pore structures of fly ash/cement concrete and corresponding pastes. The experimental results showed that concrete with a 28-day compressive strength of 80 MPa could be obtained with a water-to-binder (w/b) ratio of 0.24, with a fly ash content of 45%. Such concrete has lower heat of hydration and chloride diffusivity than the equivalent plain cement concrete or concrete prepared with lower fly ash contents. The test results showed that at lower w/b ratios, the contribution to strength by the fly ash was higher than in the mixes prepared with higher w/b ratios. The study also quantified the reaction rates of cement and fly ash in the cementitious materials. The results demonstrated the dual effects of fly ash in concrete: (i) act as a micro-aggregate and (ii) being a pozzolana. It was also noted that the strength contribution of fly ash in concrete was better than in the equivalent cement/fly ash pastes suggesting the fly ash had improved the interfacial bond between the paste and the aggregates in the concrete. Such an improvement was also reflected in the results of the mercury intrusion porosimetry (MIP) test.

Prashant, H., B. Vijay, et al. (2010). "Self compacting concrete by using ternary blends." International Journal of Earth Sciences and Engineering **3**(Compendex): 582-591.

In this paper an attempt is made to study the various properties of self compacting concrete (SCC) when cement is replaced (using ternary blends) in various proportions by waste glass powder (i.e. fly ash, blast furnace slag and silica fume) which can act as a pozzolana. To produce ternary blended self compacting concrete (SCC) the combination of supplementary cementeceious material like (cement + fly ash + blast furnace slag) and (cement + fly ash + silica fume) is used. Keeping the percentage of fly ash constant i.e. 10 % (by weight of cement), blast furnace slag and silica fume percentage is to be varied as 5% to 10%. The fresh and hardened properties of ternary blended Self compacting concrete (SCC) are studied in this particular work. The flow characteristics of self-compacting concrete (SCC) using ternary blends are measured from J-ring test apparatus, V-funnel test apparatus, U-box test apparatus, L- box test apparatus and Orimet apparatus, along with the strength properties like compressive strength, tensile strength, flexural strength and pull out strength, Also studied the effect of temperature on the properties of self compaction concrete produced with ternary blends. 2010 CAFET-INNOVA TECHNICAL SOCIETY. All rights reserved.

Quiroga, P. N., N. Ahn, et al. (2006). "Concrete Mixtures with High Microfines." ACI Materials Journal **103**(4): pp 258-264.

Manufactured fine aggregate (MFA) differs from natural sands in grading, particle shape, and texture. The use of MFA has been increasing in the U.S. because good quality natural sand is not economically available in many areas. Good quality concrete, with proper workability and finishability, can be made with MFA with high microfines, however the amount of water or chemical admixtures may need to be increased. This article reports on two studies that were performed to evaluate the effect of the amount and type of microfines (material passing the No. 200 sieve), as well as the effect of shape, texture, and grading of aggregates on concrete behavior. In the first study, several MFAs and one natural sand were used for mortar and concrete mixtures, without chemical admixtures. Results showed that generally, concrete with MFA was stiffer and less workable than concrete with natural sand, but in most cases MFA resulted in higher compressive and flexural strengths, higher resistance to chloride penetration, and higher abrasion resistance. In the second study, five aggregates with varied shape and texture were used to make concrete with microfines, chemical admixtures, and supplementary cementing materials. Results showed significant variations due to the combined effect of shape and texture of aggregate, grading, and the type and amount of microfines. The authors note that chemical admixtures and cementing materials can also be used to enhance workability of concrete with high microfines. The packing density of aggregates appears to be a useful characteristic to compare the effect of different aggregates on the performance of fresh concrete. Slump does not adequately predict the workability of stiff concrete because it cannot differentiate among low slump mixtures.

Radlinski, M., J. Olek, et al. (2008). "Influence of curing conditions on strength development and strength predictive capability of maturity method: Laboratory and field-made ternary concretes." Transportation Research Record(Compendex): 49-58.

Applicability of the maturity method to ternary systems with fly ash (FA) and silica fume (SF) has been investigated through laboratory and field studies. The laboratory study explored the impact of the combined effect of initial curing conditions and mixture composition on the compressive strength development and strength predictive capability of the maturity method. It was demonstrated that the maturity method can be used effectively to predict compressive strength of ternary concrete containing ordinary portland cement, FA, and SF. However, the accuracy of this method was strongly influenced by the amount of moisture supplied during early stages of curing and to a lesser extent by relative amounts of FA and SF in the mixture. Further (intermittent) moist curing of field trial batch (FTB) concrete (potentially simulating natural precipitation) was found to have a beneficial effect on strength development and, consequently, on the accuracy of strength prediction using the maturity method. Thus, even an occasional supply of moisture to high-performance concrete (especially at early age) may significantly minimize potential strength losses. Finally, applicability of the maturity method to ternary bridge deck concrete made and placed under field conditions and exposed to ambient temperature variations was verified. The predicted strength of bridge deck concrete was found to be approximately 10 MPa lower than the actual strength, irrespective of age. However, a correction factor was established to account for different air content in field concrete (compared with FTB concrete that was used for development of maturity function), which resulted in much more accurate strength estimates.

Rahhal, V. and R. Talero (2004). Influence of two different fly ashes on the hydration of portland cements, Kluwer Academic Publishers.

Fly ashes from the combustion of coal thermal power stations are commonly incorporated into portland cements and/or concretes and mortars. The chemical and morphological composition of fly ashes, together with their particle size, make them suitable as pozzolanic(non-calcic) or pozzolanic/hydraulic(highly calcic) additions to manufacture such building materials. This work focuses on the incorporation of two different fly ashes (non-calcic but of very different Fe2O3(%) contents, fineness and morphology) to two ordinary portland cements (of very different mineralogical composition as well), to determine the effects those have and the interactions they produce in the hydration reactions of portland cement. The main techniques employed for this study have been: conduction calorimetry and Frattini test; secondary techniques applied have also been: determination of setting times and analysis by X-ray diffraction and SEM. Analysis of the results obtained permitted to find different effects of fly ash addition on the hydration reactions of portland cements. Thus, dilution and stimulation effects augment with the increased fly ash percentage. Delay and acceleration of the reactions depend mainly on the type of portland cement and are accentuated with increased fly ash contents. Their behaviour as concerns heat dissipation mainly, depends on the type of fly ash used and is more pronounced with increased cement replacement. On the other hand, the pozzolanic activity of these fly ashes has been revealed at 7 and 28 days, but not at 2 days. Finally, pozzolanic cements can be manufactured using different portland cements and/or types of fly ashes, in the appropriate proportions and compatible qualities, depending on the effect(s) one wish to enhance at a specific age, which is according to previous general conclusions drew out of sulphate attack and chloride attack researches.

Ramezanianpour, A. A. and V. M. Malhotra (1995). "Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash or silica fume." Cement and Concrete Composites **17**(Compendex): 125-133.

This paper reports an investigation in which the performance of slag, fly ash, and silica fume concretes were studied under four different curing regimes. The water-cementitious materials ratio of all the concrete mixtures was kept constant at 0.50, except for the high-volume fly ash concrete mixture, for which the ratio was 0.35. The concrete specimens were subjected to moist curing, curing at room temperature after demoulding, curing at room temperature after two days of moist curing, and curing at 38C and 65% relative humidity. The compressive strength was determined at various ages, and the resistance to chloride-ion penetration was measured according to ASTM C 1202 at different ages up to 180 days. Mercury intrusion porosimetry tests were performed on the 28-day old mortar specimens for comparison purposes. The results indicate that the reduction in the moist-curing period results in lower strengths, higher porosity and more permeable concretes. The strength of the concretes containing fly ash or slag appears to be more sensitive to poor curing that the control concrete, with the sensitivity increasing with the increasing amounts of fly ash or slag in the mixtures. The incorporation of slag or silica fume, or high volumes of fly ash in the concrete mixtures, increased the resistance to chloride ions and produced concretes with very low permeability.

Ray, I., J. F. Davalos, et al. (2005). Mechanical Properties of High-Performance Concrete Made for Bridge Decks using West Virginia Aggregates.

As a part of a research program on development and evaluations of high-performance concrete (HPC) for the state of West Virginia, in this study sixteen HPC mixtures were produced using two types of locally available 25 mm graded limestones, gravels, and one type of river sand. For each type of aggregate, four kinds of HPC were developed by using the following admixtures: (1) 10% metakaolin; (2) 20% fly ash and 5% silica fume; (3) 30% slag and 5% silica fume; and (4) 15% fly ash, 25% slag and 5% silica fume. A constant water-cementitious material ratio of 0.4 and aggregate-paste volume ratio were maintained for all mixtures. In addition to basic fresh properties, compressive strengths at 1, 3, 7, 14, 28 and 90 days, 28-day modulus of elasticity (secant and dynamic) were measured. Preliminary data show that metakaolin HPC achieved the highest strengths, particularly at ages up to 28 days, followed by slag-silica fume HPC, fly ash- silica fume HPC and fly ash-slag-silica fume HPC. At 90 dyas both metakaolin HPC and slag-silica fume HPC achieved almost the same range of strengths. Overall, limestones performed better than gravels in terms of both strength and moduli of elasticity. Modified empirical relations between

compressive strength and static modulus, and dynamic modulus and static modulus are proposed. Since the expressions are based on a large number of specimens for both limestone and gravel mixtures, including different types and dosage of mineral admixture, the results can be used for prediction of HPC of similar strength and materials.

Riding, K. A., J. L. Poole, et al. (2008). "Quantification of effects of fly ash type on concrete early-age cracking." ACI Materials Journal **105**(Compendex): 149-155.

The mechanisms that contribute to early-age cracking are complex. Determining the relative importance of each mechanism as well as the combined cracking potential for a given concrete material is essential for the concrete industry to construct structures with a long service life. A method for quantifying the cracking risk of a concrete mixture is presented. The method involves testing for the concrete heat of hydration, setting time, free thermal and autogenous movement, restrained stress, and mechanical property development. The concrete uniaxial stress under restrained conditions is measured using a rigid cracking frame. This test setup was used to quantify the effects of using fly ash on the concrete cracking risk using four different fly ashes with varying calcium oxide contents. All fly ashes reduced the cracking risk because of the decrease in the heat of hydration of the cementitious materials and, to a lesser extent, the increased early-age creep. Copyright 2008, American Concrete Institute. All rights reserved.

Rivera-Villarreal, R. (2001). EFFECT OF HIGH-TEMPERATURE CURING ON THE COMPRESSIVE STRENGTH OF CONCRETE INCORPORATING LARGE VOLUMES OF FLY ASH.

This paper provides results about the effect of using different types of curing on the compressive strength of concrete both with and without large volume fly ash (FA). In all the concrete mixtures, the portland cement content was 200 kg/m3. The FA amount was varied from zero to 33, 43, 50 and 56 percent by mass of the total binder, and a superplasticizer was used to obtain 200-220 mm slump. The compressive strength was tested at the age of 3, 7, 14, 28, 56 days and 6 months. The compressive strength of the portland cement concrete made at 35 degrees C was reduced by about 11% at 28 days when compared to that of concrete made at 23 degrees C with ASTM standard curing. With continuous moist-curing of fresh concrete, there was no strength loss of concrete made at 35 degrees C. FA concrete specimens that were under intermittent spray-water curing at 35 degrees C in the laboratory (every four hours) for 7 days and then under ambient conditions gave increased compressive strength up to the time of testing, i.e., 6 months. Reduced strength was obtained for 3 days intermittent curing. Higher strength was obtained as the amount of FA was increased for a given amount of the portland cement. The FA concrete mixtures cast at 35 degrees C were cured by covering the specimens with membrane curing compound and placed under ambient conditions until age of testing. The strengths were lower than reference concrete by about 20% to 30% at 28 days, and 30% to 50% at 56 days. It is necessary that enough curing water to promote

the pozzolanic reaction is used. The membrane curing did not allow the ingress of water to the concrete mass.

Roberts, L. R. and P. C. Taylor (2007). "Understanding Cement-SCMAdmixture Interaction Issues." Concrete International: 33-41.

Sahmaran, M. (2007). "Sodium sulphate attack on blended cements under different exposure conditions
" Advances in Cement Research **19**(2): 47–56.

The sulphate resistance of ordinary Portland cement, sulphate-resistant Portland cement, and blended cements with different proportions of natural pozzolan and low-lime fly ash were compared. Plain and blended cement mortar specimens were prepared and stored under three different conditions: (a) continuous curing in limesaturated water, (b) continuous exposure to 5% Na2SO4 solution at room temperature, and (c) cyclic exposure to 5% Na2SO4 solution at room temperature in which the cycle consisted of immersion and drying exposures (each cycle was composed of immersion in 5% Na2SO4 solution for 24 h at 23 _ 28C, oven drying at 508C for 23 h, and cooling in air at 23 _ 28C for 1 h). The sulphate resistance of the cements was evaluated from compressive strength and length change of mortar specimens after up to 1 year of exposure. Microstructural investigations such as X-ray diffraction, scanning electron microscopy and energy-dispersive X-ray analysis were also used to support the explanation of deterioration. This study revealed that under continuous sodium sulphate exposure the length changes of blended cements were less than those of sulphate-resistant Portland cement with 3.6% C3A content. However, for the mortars exposed to sulphate attack and cycles of immersion and drying exposures, sulphate-resistant Portland cement was found to perform better than blended cements when compressive strengths were considered.

Sahmaran, M., I. O. Yaman, et al. (2009). "Transport and mechanical properties of self consolidating concrete with high volume fly ash." Cement and Concrete Composites **31**(Compendex): 99-106.

This paper presents the transport and mechanical properties of self consolidating concrete that contain high percentages of low-lime and high-lime fly ash (FA). Self consolidating concretes (SCC) containing five different contents of high-lime FA and low-lime FA as a replacement of cement (30, 40, 50, 60 and 70 by weight of total cementitious material) are examined. For comparison, a control SCC mixture without any FA was also produced. The fresh properties of the SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, and segregation ratio. The hardened properties included the compressive strength, split tensile strength, drying shrinkage and transport properties (absorption, sorptivity and rapid chloride permeability tests) up to 365 days. Test results confirm that it is possible to produce SCC with a 70% of cement replacement by both types of FA. The use of high volumes of FA in SCC not only improved the workability and transport properties but also made it possible to produce concretes between 33 and 40 MPa compressive strength at

28 days, which exceeds the nominal compressive strength for normal concrete (30 MPa). 2008 Elsevier Ltd. All rights reserved.

Sahmaran, M., O. Yaman, et al. (2007). "Development of high-volume low-lime and high-lime fly-ash-incorporated self-consolidating concrete." Magazine of Concrete Research **59**(Compendex): 97-106.

The current article presents an experimental study on the use of two types of fly ash (low lime and high lime) as mineral admixtures in producing self-consolidating concrete (SCC) with the objective of assessing the effects of both types of fly ash on the fresh and hardened properties of SCCs. Within the scope of an experimental programme, SCCs were prepared by keeping the total mass of cementitious materials constant at 500 kg/m3, in which 30, 40, 50, 60 or 70% of cement, by mass, was replaced by high-lime and low-lime fly ash. The workability-related fresh properties of SCCs were observed through slump flow time and diameter, V-funnel flow time, L-box height ratio, GTM sieve stability test and the rheological parameters (relative yield stress and relative plastic viscosity). Setting times and temperature rise of SCCs were also determined as part of fresh properties. The hardened properties that were monitored for a year included the compressive strength, ultrasonic pulse velocity, drying shrinkage and chloride permeability. It was observed that the geometry and surface characteristics of fly ash affected the workability properties of SCC mixtures. Nonetheless, the compressive strength of SCC mixtures with 30-40% low-lime fly ash replacement was slightly greater than the control SCC mixture at the end of the year, as the amount of fly ash replacement increased losses in compressive strength. As a result of this experimental study, it could be concluded that SCCs incorporating a fly ash replacement of 70% could be produced with improved fresh and permeation properties and sufficient compressive strength.

Sajedi, F. and H. A. Razak (2010). "The effect of chemical activators on early strength of ordinary Portland cement-slag mortars." Construction and Building Materials **24**(Compendex): 1944-1951.

Although the use of slag has many benefits, its low hydration at early stages causes the strength to be low. Hence, the uses of slag are restricted, even before it needs to be activated. In this investigation, a chemical method was used to activate the ordinary Portland cement-slag mortars (OSM). 37 OSM were used, 4 of them as control. All mix designs were made by W/B = 0.33, S/B = 2.25, and with 0%, 30%, 40%, 50%, and 60% levels of slag. The activators; sodium hydroxide, potassium hydroxide, and sodium silicate have been used. Whenever the activators were used alone, the highest effect was obtained by sodium silicate and the lowest for sodium hydroxide. It was determined that the effects of the combined activators are better than that of an individual one. It was observed that strength loss for some mixes, at long ages, is determined by some factors, such as level of slag used, type and dosage of alkali activators, and curing regimes. 2010 Elsevier Ltd. All rights reserved.

Saraswathy, V. and H.-W. Song (2006). "Corrosion performance of fly ash blended

cement concrete: A state-of-art review." Corrosion Reviews **24**(Compendex): 87-122.
Continuous generation of waste by-products possessing hydraulic and pozzolanic properties creates not only acute environmental problems, but additionally outlines a need for their greater utilization in different market sectors. The construction sector is clearly the one that, at the moment, absorbs the majority of such materials, by incorporating them in hydraulic binders as supplementary cementing materials (SCMs). Appropriate usage of these materials not only brings economical and ecological benefits, but also imparts technological improvements to the final product. The effect of fly ash in concrete is reviewed from the point of view of durability aspects such as chloride permeability and sulphate resistance, as they are the main parameters influencing the corrosion phenomenon in reinforced concrete structures. The special importance given to the corrosion performance of fly ash blended cement concrete and an experience on this topic is also discussed.

Saric-Coric, M. and P.-C. Aitcin (2003). "High-performance concrete containing cement made from blast-furnace slag
Betons a haute performance a base de ciments composes contenant du laitier et de la fumee de silice." Canadian Journal of Civil Engineering **30**(Compendex): 414-428.
For each tonne of cement used, the cement industry emits an average of 0.9 t of CO2, which contributes to the greenhouse effect. To satisfy the demands of the concrete industry for cementing materials, new environmental requirements, and the implementation of a sustainable development policy, the use of supplementary cementitious material as a replacement of part of the Portland cement has proven to be an interesting avenue that has not yet been fully explored. Granulated blast-furnace slag has been and is being used as a supplementary cementitious material in replacement of cement in many countries. In Canada, its proportion is usually limited to 20-25% of cement replacement owing to a significant decrease in early age compressive strength as well as a lower scaling resistance. In this study, we have tried to show that by reducing the water:cement ratio we can increase cement replacement by slag up to 50% without harming its short-term compressive strength and scaling resistance. The concretes that were prepared had a workability comparable to that of the reference concrete without slag, sufficient compressive strength to allow demoulding after 24 h, very low chloride ion permeability even at 28 d, as well as very good freeze-thaw and scaling resistance, as long as it is water-cured for a slightly longer period.

Sato, T. and J. J. Beaudoin (2011). "Effect of nano-CaCO3 on hydration of cement containing supplementary cementitious materials." Advances in Cement Research **23**(Compendex): 33-43.
The efficacy of the addition of nano-CaCO3 in accelerating the hydration of ordinary Portland cement (OPC) delayed by the presence of high volumes of supplementary cementitious materials including fly ash and slag was investigated. The conduction calorimetry indicated that the early hydration of

OPC was significantly accelerated by the addition of the nano-CaCO3 and the higher the amount of CaCO3 addition, the greater was the accelerating effect. The thermogravimetric analysis results showed that the amounts of added CaCO3 became slightly lower as the hydration took place; however, any new reaction products were not detected by the X-ray diffractometry analysis. The engineering properties, including microhardness and modulus of elasticity, in the early stage of the hydration were remarkably improved by the addition of nano-CaCO3. It was suggested that the seeding effect of the nano-CaCO3 particles and the nucleation of C-S-H caused the enhanced strength development.

Sato, T. and F. Diallo (2010). "Seeding effect of nano-CaCO3 on the hydration of tricalcium silicate." Transportation Research Record(Compendex): 61-67.

A previous study indicated that the early hydration and strength development of ordinary portland cement (OPC) delayed by the presence of high volumes of supplementary cementitious materials were compensated for by the accelerating effect of nano-CaCO3. The mechanism responsible for the accelerating effect on the early hydration and strength development was, however, not fully understood. A study aimed at understanding the accelerating mechanism of the addition of nano-CaCO3 on the hydration of tricalcium silicate (C3S) is presented in this paper. A comparison with the addition of micro-CaCO3 was made. The hydration mechanism of C3S with the addition of micro- or nano-CaCO3 was studied by conduction calorimetry, thermogravimetric analysis, and scanning electron microscopy. The conduction calorimetry results indicated that the addition of nano-CaCO3 had an accelerating effect on the hydration of C 3S as well as on the hydration of OPC. Furthermore, the induction period of C3S hydration was significantly shortened by the addition of nano-CaCO3. The results of the thermogravimetric analysis indicated that the amount of nano-CaCO3 decreased as the hydration of C3S took place; the decrease was greater with the hydration of OPC. The scanning electron microscopy revealed that the accelerating mechanism in the presence of micro-CaCO3 was considerably different from that of nano-CaCO3. Calcium silicate hydrate growth was observed around the nano-CaCO3 particles. The observation suggested that the seeding effect due to the addition of nano- CaCO3 was responsible for the accelerating effect on the hydration of C3S.

Schrofl, C., M. Gruber, et al. (2010). "Interactions between polycarboxylate superplasticizers and components present in ultra-high strength concrete." Kuei Suan Jen Hsueh Pao/Journal of the Chinese Ceramic Society **38**(Compendex): 1605-1612.

The ultra-high strength concrete (UHSC) is characterized by a water cement ratio of below 0.25 and a high content of fines such as silica fume for optimized packing density. In the UHSC, due to its surface chemistry and large surface area, silica fume is the most difficult component to be dispersed. Polycarboxylates (PCEs) made of methacrylic acid, MPEG methacrylate ester and methallylsulfonic acid effectively liquefies cement, whereas allyl ether-maleic anhydride based PCEs disperse silica fume well. Thus, a combination of these PCE types which possess different molecular architectures provides superior flowability to UHSC. A low dos-age of 0.5% by mass of cement of this combination is sufficient, whereas about 1% (by mass of cement) is required when the indi-vidual PCEs are utilised. The reason for this synergistic effect of these of PCEs is their selective adsorption: the methacrylate-based PCE preferentially adsorbs on cement while the allyl ether-type PCE is strongly attracted by the silica surface. Additional experiments were conducted to probe a potential synergism between organic anions (citrate, gluconate, tartrate, with small molecular mass) and PCE. It was found that addition of only 0.1% by mass of cement of these anions further enhances the effectiveness of the allyl ether-based PCE, resulting in an even lower PCE dosage. It was mechanistically identified that these anions act as supplemental effect which adsorb simultaneously on both cement and silica fume. This way, the surface of cement is primarily occupied by the anion, whereas on the surface of silica, concomitant adsorption of the allyl ether-based PCE, and the anion occurs. The anion exercises a strong electrostatic dispersion effect which compliments the steric effect of the allyl ether-based PCE. This admixture combination was found to provide a high early strength, in spite of the known retarding effect of the carboxylate anions.

Scott, A. and M. G. Alexander (2007). "The influence of binder type, cracking and cover on corrosion rates of steel in chloride-contaminated concrete." Magazine of Concrete Research **59**(Compendex): 495-505.

Cracking of reinforced concrete can result in substantial reduction in service life owing to rapid initiation of steel corrosion. Supplementary cementitious materials (SCMs) can alter not only the pore solution chemistry but also the environment surrounding the steel and lead to significant reductions in corrosion rate. The impact of binder type on corrosion rate was assessed using seven concrete mixtures comprising ordinary Portland cement (PC) and blends of PC with ground granulated blast-furnace slag, fly ash, condensed silica fume and a ternary blend. Corrosion rates were measured in prismatic specimens with crack widths of 0-2 mm or 0-7mm. For 20mm cover, all the SCMs resulted in at least a 50% reduction in corrosion rate compared with the PC control. Increase in crack width from 0-2 mm to 0-7mm increased corrosion rate in all cases, but had far less impact than that of the SCMs. Increase in cover depth from 20 mm to 40 mm had substantial benefits for PC specimens, reducing corrosion rates by more than half; the same benefits were not observed in specimens using SCMs. This was ascribed to corrosion rates of SCM concretes being controlled primarily by resistivity of the system, while rates in PC specimens were controlled mainly by oxygen availability and thus cover depth. 2007 Thomas Telford Ltd.

Sengul, O., C. Tasdemir, et al. (2005). "Mechanical properties and rapid chloride permeability of concretes with ground fly ash." ACI Materials Journal **102**(Compendex): 414-421.

Eight concrete mixtures were prepared using the same batch of ordinary portland cement (OPC) and ground low-lime fly ash. The aggregate grading used in the mixtures of concrete, water-binder ratio, and the maximum particle size of aggregate were kept constant in all concretes, but the partial replacement of

cement by fly ash was varied from 0% (OPC concrete) to 70% in steps of 10%. The replacement was on a one-to-one weight basis. At 28 days, there was little reduction in compressive strength up to 40% cement replacement by ground fly ash; then a significant decrease was recorded for the further fly ash dosages. At 56 and 120 days, however, the compressive strength up to 40% cement replacement by fly ash is almost identical to that of the no fly ash concrete and for one year it was even higher. Beyond 40% replacement, the compressive strength decreased significantly. It was shown that the brittleness index increases substantially with increasing compressive strength of concrete. The results of the rapid chloride penetration tests indicated that high volume ground fly ash concrete had better resistance to the penetration of chloride ions. The mortar phases of these concretes were also prepared. As the dosage of fly ash increased, 2-, 7-, and 28-day compressive strengths of the mortars decreased. However, at later ages (that is, at 56, 120, and 365 days), up to 40% cement replacement by ground fly ash, the compressive strength of mortar with fly ash was nearly equal to that of mortar without fly ash. The pozzolanic effectiveness ratio, as a measure of pozzolanic reactivity and the contribution of fly ash to the strength development, increased with increasing curing time and fly ash content.

Shah, S. P. and K. Wang (2004). DEVELOPMENT OF "GREEN" CEMENT FOR SUSTAINABLE CONCRETE USING CEMENT KILN DUST AND FLY ASH, Iowa State University, Ames.

The paper describes the development of "green" cement for sustainable concrete using cement kiln dust (CKD) and Class F fly ash (FA). The effects of mechanical, chemical, and thermal activations on strength and other properties of CKD-FA binders were investigated. The study considered different CKD-FA combinations, grinding equipment and methods, chemical additions, and elevated curing temperatures, and evaluated the set time, heat of hydration, and strength of CKD-FA pastes. Based on the attained results, the binder made with CKD and FA will have the satisfactory strength and performance when blend proportions and activation are properly applied.

Shehata, M. H., G. Adhikari, et al. (2008). "Long-term durability of blended cement against sulfate attack." ACI Materials Journal **105**(Compendex): 594-602.

Five different supplementary cementing materials (SCM) were investigated for their resistance to sodium sulfate attack using ASTM C1012. The results showed high-calcium fly ash (HCFA) to have the lowest resistance, which was attributable to its calcium-aluminate glass. The performance of HCFA was improved when the ash was blended with an optimum amount of gypsum or 5% silica fume (SF), however, blending with SF produced better results. The X-ray diffraction patterns confirmed that blending HCFA with gypsum sustained early formation of stable ettringite rather than monosulfate. Low ion migration and reduced calcium hydroxide (CH) were behind the enhanced performance of the sample with HCFA and 5% SF. The observed differences in the sulfate resistance of the three tested fly ashes could not be attributed, even partly, to

their differences in CH consumption, which were insignificant. Compared with samples with only portland cement, however, all samples with SCM showed a significant reduction in CH. Copyright 2008, American Concrete Institute. All rights reserved.

Shekarchi, M., A. Rafiee, et al. (2009). "Long-term chloride diffusion in silica fume concrete in harsh marine climates." Cement and Concrete Composites **31**(Compendex): 769-775.

Supplementary cementitious materials such as silica fume are typically necessary for producing high performance concrete for marine environments in hot regions, such as the Persian Gulf. Silica fume use generally improves the strength and/or durability properties of the concrete. This paper investigates the effects of silica fume on various properties of concrete specimens that were exposed to Persian Gulf conditions. Samples were taken at the ages of 3, 9 and 36 months and analyzed to determine the chloride diffusion coefficient. The results show that partial cement replacement with up to 7.5% silica fume reduces the diffusion coefficient, whereas for higher replacement rates the diffusion coefficient does not decrease significantly. Also time-dependent chloride diffusion and compressive strength of concrete containing silica fume are investigated. 2009 Elsevier Ltd. All rights reserved.

Shi, C. and R. L. Day (1999). "Early strength development and hydration of alkali-activated blast furnace slag/fly ash blends." Advances in Cement Research **11**(Compendex): 189-196.

This study concerns the effect of two types of fly ash and the addition of lime on the strength development and hydration of sodium hydroxide- and sodium silicate-activated slag/fly ash blends which consisted of 50% fly ash and 50% slag by mass. Performance was compared to that of 100% slag cements. When NaOH was used as an activator, the slag replacement with ASTM Type F fly ash did not show a significant effect on either the strength development or hydration; Type C fly ash did not affect the strength development, but affected the hydration process due to the presence of C3A in the fly ash. Both fly ashes had a significant effect on the hydration and strength development when Na2SiO3 was used as an activator. The addition of a small amount of hydrated lime significantly increased the early-age strength but slightly decreased the later-age strength of the activated slag/fly ash blends. Measurement of the heat evolution during hydration indicated that the addition of the hydrated lime had a slight effect on the hydration during the pre-induction period, but accelerated the hydration thereafter.

Shi, C. and J. Qian (2000). "High performance cementing materials from industrial slags - A review." Resources, Conservation and Recycling **29**(Compendex): 195-207.

At the present, most industrial slags are being used without taking full advantage of their properties or disposed rather than used. The industrial slags, which have cementitious or pozzolanic properties, should be used as partial or full replacement for Portland cement rather than as bulk aggregates or ballasts because of the high cost of Portland cement, which is attributable to the high energy consumption for the production of Portland cement. The traditional way to utilize metallurgical slags in cementing materials is to partially replace Portland cement, which usually results in a lower early strength and longer setting times. Presence of activator(s) can accelerate the break-up of structure and hydration of slags. Many research results have indicated that clinkerless alkali-activated slags even exhibit higher strengths, denser structure and better durability compared with Portland cement. In this paper, the recent achievements in the development of high performance cementing materials based on activated slags such as blast furnace slag, steel slag, copper slag and phosphorus slag are reviewed.

Shi, C. and J. Qian (2003). "Increasing coal fly ash use in cement and concrete through chemical activation of reactivity of fly ash." Energy Sources **25**(Compendex): 617-628.

Nearly 60% of the electricity in the USA is produced by coal-fired plants, which results in the production of a large quantity of coal combustion residues, among which coal fly ash is the major component. Many applications have been developed for coal fly ash. The use of coal fly ash as a cement replacement in concrete is the most attractive one because of its high volume utilization and widespread construction. However, the replacement of cement with coal fly ash in Portland cement concrete usually increases the setting time and decreases the early strength of concrete. The addition of chemical activators such as Na2SO4 or CaCl2 accelerates pozzolanic reactions and changes pozzlanic reaction mechanisms between fly ash and lime, which results in decreased setting time, accelerated strength development, and increased strength of materials containing fly ash, especially with a high percentage of fly ash. The other promising cements include alkali-activated fly ash and alkali-activated fly ash-ground blast furnace slag cements, which can exhibit very high strength in the presence of proper alkaline activators. Thus chemical activation of reactivity of fly ash is an effective method to increase the use of fly ash in concrete.

Shi, C. and Y. Shao (2002). What is the most efficient way to activate the reactivity of fly ashes? Canadian Society for Civil Engineering - 30th Annual Conference: 2002 Chellenges Ahead, June 5, 2002 - June 8, 2002, Montreal, QB, Canada, Canadian Society for Civil Engineering.

Nearly 60% of the electricity in the USA is produced by coal-fired plants, resulting in the production of a large quantity of coal combustion residues, among which coal fly ash is the major component. Many applications have been developed for coal fly ash. The use of coal fly ash as a cement replacement in concrete is the most attractive because of its high volume utilization and widespread construction. The replacement of cement with coal fly ash in concrete can have many advantages including better workability, higher long-term strength and improved durability of the concrete. However, the use of fly ash is also accompanied by increased setting time and decreased early strength. Different techniques, such as grinding, elevated temperature curing and use of chemical activators, are developed to overcome those disadvantages. A comparison indicates that the use of chemical activator is the most effective and efficient technique to activate the potential pozzolanic reactivity of coal fly ashes and to improve the properties of the fly ash concrete.

Shi, H.-s., B.-w. Xu, et al. (2009). "Influence of mineral admixtures on compressive strength, gas permeability and carbonation of high performance concrete." Construction and Building Materials **23**(Compendex): 1980-1985.

Compressive strength, gas permeability and carbonation of high performance concrete (HPC) with fly ash (FA) or ground granulated blast furnace slag (GGBFS) were experimentally investigated and the relationships among them were analyzed. Test results showed that influences of FA with replacement up to 60% on these properties investigated are significantly affected by water-binder (w/b) ratios. However, unlike FA, influences of GGBFS on HPC are little affected by w/b ratios, similar changing trends could be observed for both w/b ratios selected. Moreover, HPC with GGBFS shows much better performance than that with FA at the same w/b ratio. In general, replacing FA/GGBFS with cement could not benefit the properties investigated, especially at the higher w/b ratio selected and relationship between compressive strength and gas permeability of HPC greatly depends on w/b ratios and mineral admixture types. Carbonation is obviously related to gas permeability for both HPC with FA/GGBFS. 2008 Elsevier Ltd. All rights reserved.

Sisomphon, K. and L. Franke (2007). "Carbonation Rates of Concretes Containing High Volume of Pozzolanic Materials." Cement and Concrete Research **37**(12): pp 1647-1653.

This work studied the influence of fly ash and slag replacement on the carbonation rate of concrete. The experimental work includes samples of pure Portland cement concrete (CEM I 42,5 R), blast-furnace slag concrete (CEM III-B), and fly ash blended concrete. To reveal effects of curing on carbonation rate, concretes were exposed to various submerged curing periods during their early ages. After that, the samples were subsequently exposed in the climate room controlling 20°C and 50% RH until the testing date when the samples had an age of 5 mos. Next, the accelerated carbonation test controlling the CO2 concentration of 3% by volume, with 65% RH were performed. The depth of carbonation can be observed by spraying a phenolphthalein solution on the fresh broken concrete surface. Lastly, according to Fick's law of diffusion, theoretical equations are proposed as a guide for estimating carbonation rate of fly ash and blast-furnace slag concretes exposed under natural conditions from results from accelerated carbonation tests.

Sivasundaram, V., G. G. Carette, et al. (1990). "Long-term strength development of high-volume fly ash concrete." Cement and Concrete Composites **12**(Compendex): 263-270.

This paper presents long-term data on the initial work carried out on high-volume fly ash concrete at CANMET laboratories. In the laboratory investigations, a concrete block measuring 1.5 m 1.5 m 1.5 m was cast indoors under controlled temperature conditions. The concrete contained 147 kg/m3 of ASTM Type II cement and 187 kg/m3 of ASTM Class F fly ash. The density of the concrete was high, of the order of 2500 kg/m3. The strength development of the concrete has been monitored over a period of 3 1/2 years, and it reached a maximum compressive strength of 70 MPa at 1 1/2 years. The modulus of elasticity of this concrete at 2 years was 47 GPa. The penetration of chloride ions in this concrete, when measured according to AASHTO T277-831, was 53 coulombs at 3 1/2 years. Following its excellent performance in the laboratory investigations, this concrete was utilized in a field application, a brief description of which is also presented.

Sivasundaram, V., G. G. Carette, et al. (1990). "Selected properties of high-volume fly ash concretes." Concrete International **12**(Compendex): 47-50.

The Canada Centre for Mineral and Energy Technology (CANMET) has been involved in pioneering research on high-volume fly ash concrete since 1985. The investigation reported in this article was initiated to examine the properties of high-volume fly ash concretes incorporating six low-calcium Canadian fly ashes, including the previous two. Some preliminary work was also done on a Class F fly ash from the eastern United States. Concretes with fly ash content at 58 percent of the total cementitious materials were made with each of the fly ashes. The concretes were tested for compressive strength, creep strain, and resistance to chloride ion penetration at various ages up to one year. Study results are discussed.

Sivasundaram, V., G. G. Carette, et al. (1991). "Mechanical properties, creep, and resistance to diffusion of chloride ions of concretes incorporating high volumes of ASTM Class F fly ashes from seven different sources." ACI Materials Journal **88**(Compendex): 407-416.

Reports an investigation into the performance of seven low-calcium (ASTM Class F) fly ashes in the high-volume fly ash concrete system. The cement content and water-cementitious materials ratio (w/c + f) of the concretes were kept at two levels: (a) 155 kg/m3 (261 lb/yd3) of portland cement and a w/c + f of 0.31; and (b) 225 kg/m3 (379 lb/yd3) of portland cement and a w/c + f 0.22. The concretes were made incorporating fly ash at 58 percent of the total cementitious material content. Large dosages of a superplasticizer were used to obtain the required workability. Concrete specimens were tested for compressive strength, Young's modulus of elasticity, creep strain, and resistance to chloride ion diffusion at various ages up to 1 year. The fly ash concretes did not perform alike either in the plastic or hardened condition. In the instances in which an excessive dosage of superplasticizer had to be used to obtain the workability, delay in setting was observed; however, the setting delays did not affect the strength development of the concretes. With some exceptions, the concretes incorporating fly ashes with higher fineness and higher pozzolanic index achieved higher compressive strengths and moduli of elasticity. Further, most of the fly ashes performed relatively better in concretes with 155 kg/m3 (261 lb/yd3) of cement than in concretes with 225 kg/m3 (379 lb/yd3) of cement.

Sivasundaram, V. and V. M. Malhotra (2004). "High-performance high-volume fly ash concrete." Indian Concrete Journal **78**(Compendex): 13-21.

This paper* deals with the development of engineering database on the mechanical properties and durability aspects of high-volume fly ash concretes incorporating Canadian fly ashes and cements. Six fly ashes and five ASTM Type I portland cements were selected from sources across various regions of Canada. High-volume fly ash concretes using the above materials were made at CANMET laboratories, and a large number of concrete specimens were made and tested for fresh concrete properties including slump, air content, unit mass, time of setting, and autogenous temperature rise. Mechanical properties such as compressive, flexural, and splitting-tensile strengths. Young's modulus of elasticity and creep were determined. Durability aspects concerning chloride-ion penetration were also investigated. The results show that high performance concretes incorporating about 56 percent ASTM Class F fly ash by mass of total cementitious materials can be produced using Canadian fly ashes. The high-performance concretes so produced have excellent mechanical properties and durability characteristics.

Smith, K. M., A. J. Schokker, et al. (2004). "Performance of Supplementary Cementitious Materials in Concrete Resistivity and Corrosion Monitoring Evaluations." ACI Materials Journal **101**(Compendex): 385-390.

A testing regime was established to optimize the strengths and durability characteristics of a wide range of high-performance concrete mixtures. The intent of the selected designs was to present multiple solutions for creating a highly durable and effective structural material that would be implemented on Pennsylvania bridge decks, with a life expectancy of 75 to 100 years. One of the prime methods for optimizing the mixtures was to implement supplemental cementitious materials, at their most advantageous levels. Fly ash, slag cement, and microsilica all proved to be highly effective in creating more durable concrete design mixtures. These materials have also shown success in substantially lowering chloride ingress, thus extending the initiation phase of corrosion. An additional benefit studied in this program is the ability of these materials to extend the propagation phase of corrosion due to the high resistivity they impart to the concrete. Ternary mixtures from these materials were particularly effective, showing much higher resistivity values than the materials used separately.

Sonebi, M., S. Stewart, et al. (2009). Investigation of the type of supplementary cementing materials on the durability of self-consolidating concrete. 10th ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issues, October 14, 2009 - October 16, 2009, Seville, Spain, American Concrete Institute.

Self-consolidating concrete (SCC) is designed to exhibit high deformability and moderate viscosity to maintain homogeneity and adequate stability to fill the formwork, and encapsulate the reinforcement without any mechanical vibration. Any concrete should have high impermeability and low chloride diffusion to reduce the risk of corrosion and enhance service life. In this study, the effect of the replacement content of cement by supplementary cementing materials (SCM) and fillers. Limestone powder (LSP) replacement of 15% to 30%, ground granulated blastfurnace slag (GGBS) of 40% to 60%, and pulverized fly ash (PFA) of 20% to 35% are evaluated on the durability of SCC of grade C40/50. Fresh concrete properties and development of compressive strength were also evaluated. For the durability performance, all mixtures were tested at 28 days for the air permeability, water permeability, sorptivity, and chloride diffusion which were assessed by Autoclam, and Permit tests. The chloride migration coefficient was dependent on the type SCM and filler in use. The most durable SCC mixture, taking into consideration overall properties, was found to be the one containing 20% PFA, which showed low capillary water absorption, water and air permeation, and lower ionic diffusivity in comparison to the other mixtures. In general, SCC mixtures containing GGBS exhibited inferior performance regarding air and water permeability and sorptivity, but had satisfactory chloride resistance. SCC with 50% of GGBS demonstrates the lowest chloride diffusivity.

Soutsos, M. N., S. J. Barnett, et al. (2008). The effect of temperature on the rate of strength development of slag cement. ACI Fall 2008 Convention, November 2, 2008 - November 6, 2008, St. Louis, MO, United states, American Concrete Institute.

Synopsis: The early age strength development of concretes containing slag cement (ggbs) at levels of up to 70% of the total binder have been investigated to give guidance for their use in fast track construction. 28-day target mean strength for all concrete specimens was 70 MPa (10,150 psi). Although supplementary cementitious materials such as slag cement (ggbs) are economical, their use has not gained popularity in fast track construction because of their slower strength development at early ages and at standard cube curing temperatures. There are however indications that supplementary cementitious materials are heavily penalised by the standard cube curing regimes. Measurements of temperature rise under adiabatic conditions have shown that high levels of cement replacement by ggbs, e.g. 70% are required to obtain a significant reduction in the peak temperature rise. Even though the temperature rise using slag cement is lower than from using portland cement, it is still sufficient to provide the activation energy needed for a significant reaction acceleration. Maturity measurements are needed to take advantage of the enhanced in-situ early age strength development of ggbs concrete. The contractor should confirm that the actual compressive strength of the concrete in the structure at the time of formwork removal exceeds the required strength. Maturity functions like the one proposed by Freiesleben Hansen and Pedersen (FHP), which is based on the Arrhenius equation, have been examined for their applicability to ggbs concrete. Activation energies, required as input for the FHP equation, have been determined according to ASTM C1074-98.

Subramaniam, K. V., R. Gromotka, et al. (2005). "INFLUENCE OF ULTRAFINE FLY ASH ON THE EARLY AGE RESPONSE AND THE SHRINKAGE CRACKING POTENTIAL OF CONCRETE." Journal of Materials in Civil Engineering **17**(1): p. 45-53.

In this paper, the influenc of ultrafine fly ash on the early age property development, shrinkage , and shrinkage cracking potential of concrete is investigated. In addition, the performance of ultrafine fly ash as cement replacement is compared with that of silica fume. The mechanisms responsible for an increase of the early age stress due to restrained shrinkage were assessed: free shrinkage and elastic modulus were measured from an early age. In addition, the materials resistance to tensile fracture and increase in strength were also determined as a function of age. Results of the experimental study indicate that the increase in elastic modulus and fracture resistance with age are comparable for the control, ultrafine fly ash, and silica fume concentrates. Autogeneous shrinkage is shown to play a significant role in determining the age of cracking in restrained shrinkage tests. A significant reduction in the autogenous shrinkage and an increase in the age restrained shrinkage cracking were observed in the ultrafine fly ash concrete when compared with the control and the silica fume concrete. Increasing the volume of ultrafine fly ash and decreasing the ratio of water to cementitious material resulted in further increase in the age of restrained shrinkage and significant increase in the compressive strength.

Swamy, R. N. and A. Bouikni (1990). "Some engineering properties of slag concrete as influenced by mix proportioning and curing." ACI Materials Journal **87**(Compendex): 210-220.

This paper presents a simple method to obtain a 50 MPa 28-day strength concrete having 50 and 65 percent by weight cement replacements with slag having a relatively low specific surface. The method produces slag concrete with strengths comparable to ordinary portland cement concrete from 3 days onward. The compressive and flexural strengths and the elastic modulus of these two concretes as affected by curing conditions are then presented. Prolonged dry curing is shown to adversely affect tensile strength and elastic modulus, and to create internal microcracking, as identified by pulse velocity measurements. High swelling strains at high slag replacement levels show the need for longer wet curing for such concretes.

Swamy, R. N. and A. A. Darwish (1998). Engineering properties of concretes with combinations of cementitious materials. Fly Ash, Slag, Silica Fume and Other Pozzolans –Proceedings, CANMET/ACI Sixth International Conference, Bangkok, Thailand, American Concrete Institute

The development of a high performance, high volume fly ash (HVFA) concrete incorporating a small amount of silica fume, and part replacement of both cement and sand with fly ash (FA) is reported. This paper presents the results on the engineering properties such as strength, dynamic modulus and swelling/shrinkage of such high volume fly ash concrete. The mixtures were proportioned to give 30 to 40 MPa cube strength at 28 days. Two basic mixtures with total binder contents of 350 kg/m3 and 450 kg/m3, and, with a minimum portland cement content of 150 and 200 kg/m3 respectively, were investigated. In each mixture, about 60 per cent of the cement was replaced by fly ash. In addition, in some mixtures, a nominal amount of silica fume was incorporated, and in some others, additional FA was incorporated as replacement for sand. The results show that the total binder content had little effect on strength, swelling strain and drying shrinkage, but had a significant effect on the dynamic modulus of elasticity implying a clear densification of the microstructure by fly ash and silica fume. On the whole, HVFA concrete with a nominal amount of SF, and FA as part replacement of both cement and sand showed better overall performance. The engineering properties of the HVFA concretes investigated show good potential for use in structural and mass concrete applications.

Szecsy, R. (2005). The Myth, Reality, and Construction Practically of High Volume Fly Ash Replacement.

The use of high volume fly ash (HVFA) concrete and its relationship to green building and sustainable design has been steadily increasing over the last decade. Most of the information and case examples showcase construction projects that have the luxury of time, i.e. the project is willing to wait 3 days for initial set, or 10 days for stripping strength. In most cases, specifications call for 56-day strength instead of the standard 28pday strength. These results are largely based on what designers are willing to accept as performance limits on HVFA. Recent large-scale projects have proven that it is possible to generate high strength concrete results, 5 hour initial set times and 2-day stripping strengths, utilizing HVFA. The increasing demand for green construction and sustainable design projects, compounded by LEED™ programs will only drive the demand for this type of material higher. An actual case example HVFA is included that showcases high performance results from the lab to the field and the more challenges faced in combating myth, misconception, and resistance to HVFA as high performance concrete.

Szecsy, R. (2006). "Using high-volume fly ash concrete." Concrete Construction - World of Concrete **51**(Compendex): 73-82.

The high-volume fly ash (HVFA) mix design, used by a green building or sustainable design project, is discussed. The most important implicit performance requirement is the finishing quality whereas set time and strength gain are specified as explicit performance requirements. Another concern about finishing HVFA is the ability of the finisher to know when to begin hard trowelling. An aggressive curing program is essential for success which may include a saturated curing environment or a curing compound.

Tan, K. and O. E. Gjorv (1996). "Performance of concrete under different curing conditions." Cement and Concrete Research **26**(Compendex): 355-361.

The effect of curing conditions on strength and permeability of concrete was studied. Test results showed that after 3 and 7 days moist curing only the concretes with w/c ratios equal to or less than 0.4 were accepted, while after 28 days of moist curing however, even the concrete with w/c of 0.6 could be accepted. Silica fume has a significant effect on the resistance to water penetration. For the concretes both with and without silica fume and with w/c + s of 0.5, the 28-day compressive strengths of 3 and 7 days moist curing were higher than those of 28 days moist curing, and the silica fume concrete seemed to be less sensitive to early drying. The curing temperatures did not affect the water penetration of concrete, but affected the chloride penetration and compressive strength of concrete significantly.

Tande, S. N. and K. T. Krishnaswamy (2009). "Greening of concrete industry for environmentally compatible and sustainable structures." Indian Concrete Journal **83**(Compendex): 39-44.

The portland-cement concrete industry needs to implement environmentally-friendly measures for building environmentally compatible and sustainable structures. The production and use of blended portland cements containing large proportion of cementing materials, such as coal fly ash and granulated blast-furnace slag provide a better strategy for immediate and significant reduction of direct CO2 emissions. The use of composite cements and concrete mixtures containing large proportion of complementary cementing materials will create crack-resisting structural elements with enhanced durability. Significant reduction of clinker content of cement can reduce the direct CO2 emissions from cement kilns. Reduction of cementing materials in concrete mixtures can also play a key role in reducing direct CO2 emissions from cement kilns and help in building environmentally compatible and sustainable structures.

Tang, C.-W. (2010). "Hydration properties of cement pastes containing high-volume mineral admixtures." Computers and Concrete **7**(Compendex): 17-38.

This research aimed to investigate the influence of high-volume mineral admixtures (MAs), i.e., fly ash and slag, on the hydration characteristics and microstrucrures of cement pastes. Degree of cement hydration was quantified by the loss-on-ignition technique and degree of pozzolanic reaction was determined by a selective dissolution method. The influence of MAs on the pore structure of paste was measured by mercury intrusion porosimetry. The results showed that the hydration properties of the blended pastes were a function of water to binder ratio, cement replacement level by MAs, and curing age. Pastes containing fly ash exhibited strongly reduced early strength, especially for mix with 45% fly ash. Moreover, at a similar cement replacement level, slag incorporated cement paste showed higher degrees of cement hydration and pozzolanic reaction than that of fly ash incorporated cement paste. Thus, the present study demonstrates that high substitution rates of slag for cement result in better effects on the short-and long-term hydration properties of cement pastes.

Taylor, P., P. Tikalsky, et al. (2011). Development of Performance Properties of Ternary Mixtures: Laboratory Study on Concrete**:** 228p.

This research project is a comprehensive study of how supplementary cementitious materials (SCMs) can be used to improve the performance of concrete mixtures. This report summarizes the findings of the Laboratory Study on Concrete phase of this work. The earlier “paste and mortar phase” of this work considered several sources of each type of SCM (fly ash, slag, and silica fume) so that the material variability issues could be addressed. Several different sources of portland cement and blended cement were also used in the experimental program. This phase of the research used an experimental matrix of 48 different mortar and concrete mixtures, which were identified in the earlier work as potential ternary mixtures that could benefit department of transportation (DOT) goals for long-lasting transportation bridges and pavements. This report contains test results from durability testing on mortar and concrete containing ternary cementitious materials and standard coarse and fine aggregates. Limited testing was also conducted on select mixtures for performance in hot and cold climates, to determine the potential to design ternary mixtures in adverse conditions.

Taylor, P. C., W. Morrison, et al. (2004). "Effect of finishing practices on performance of concrete containing slag and fly ash as measured by ASTM C 672 resistance to deicer scaling tests." Cement, Concrete and Aggregates **26**(Compendex): 155-159.

The test method was developed to evaluate portland cement systems with different air contents, and for the purpose of determining whether the apparent poor performance of concretes containing supplementary cementing materials in the ASTM C 672 deicer scaling test can be attributed to differences in finishing effort or timing of finishing, or both.

Thomas, M. D. A. (2003). Use of high-volume fly ash concrete in green buildings. Canadian Society for Civil Engineering - 31st Annual Conference: 2003 Building our Civilization, June 4, 2003 - June 7, 2003, Moncton, NB, Canada, Canadian Society for Civil Engineering.

Fly ash, a by-product from coal-burning electricity generation stations, has been used in concrete for more than 50 years. However, in recent years economic and environmental considerations have increased the incentive to use fly ash at higher replacement levels than those traditionally used. In some cases, fly ash has replaced more than 50% of the Portland cement in concrete mixtures. This paper discusses the technical issues surrounding the use of high fly ash contents in concrete and presents data from both laboratory and field studies conducted by the author. The appropriate use of fly ash can lead to significant improvements in the properties of both fresh and hardened concrete and some of these benefits are more pronounced at higher replacement levels. However, in order to achieve the full benefits particular attention has to be paid to certain design and placement issues when using high levels of fly ash. The water-to-cementitious-material ratio must be maintained at a sufficiently low value to ensure adequate durability regardless of the requirements for strength. Furthermore, an extended period of moist curing may be required compared with regular concrete. Provided these and other conditions are met, high-volume fly ash concrete should be highly durable. The environmental advantages of using high levels of fly ash extend beyond the use of a recycled material as the fly ash displaces a large proportion of Portland cement, the production of which consumes large quantities of energy and releases substantial quantities of carbon dioxide (a greenhouse gas). This makes high-volume fly ash concrete ideal for the construction of "green buildings".

Thomas, M. D. A., R. D. Hooton, et al. (2011). "The effect of supplementary cementitious materials on chloride binding in hardened cement paste." (Compendex).

This paper reports the results of a study to determine the effects of supplementary cementitious materials (SCMs) on the chloride binding of portland cement pastes. The results show that SCMs with significant quantities of alumina increase the binding capacity of cement paste. Pastes with metakaolin (45% Al2O3) showed the greatest chloride binding capacity and pastes with silica fume (0.5% Al2O3) showed the least binding. The chemical binding in solutions of high chloride concentration is mainly attributed to the formation of Friedel's salt, C3ACaCl210H2O. When pastes originally exposed to high chloride concentrations are subsequently exposed to chloride-free solution, a portion of the bound chloride is released, but a significant portion remains irreversibly bound. There is some evidence that Friedel's salt may partially convert to Kuzel's salt, C3A(0.5CaCl2)(0.5CaSO4)12H2O, under these conditions. The binding relationships were best described by the Freundlich isotherm and binding coefficients are given for all the binders tested. 2011 Elsevier Ltd. All rights reserved.

Thomas, M. D. A., D. S. Hopkins, et al. (2007). "Ternary Cement in Canada: Factory Blends Allow Widespread Application." Concrete International **29**(7): pp 59-64.

Ternary cement is a blend of two supplementary cementitious materials (SCMs) and portland cement. The third component is often a blend of either fly ash or slag cement with a cement and silica fume blend. The authors discuss the use of factory-blended ternary cement made with slag cement, silica fume, and portland cement, and tested in Canada between 1998 and 2000. Another type of ternary cement available in Canada, which contains Class F fly ash, silica fume, and portland cement, is not discussed. Concrete performance, including fresh concrete properties, autogenous temperature rise, compressive strength development, permeability, alkali-silica reaction, freezing and thawing, deicing salt scaling resistance, drying shrinkage, and sulfate resistance, are all discussed. The authors conclude that ternary cement is suitable for a wide concrete project range due to its versatility and, compared to portland cement, has many advantages.

Thomas, M. D. A., M. H. Shehata, et al. (1999). "Use of ternary cementitious systems containing silica fume and fly ash in concrete." Cement and Concrete Research **29**(Compendex): 1207-1214.

This paper reports the results from laboratory studies on the durability of concrete that contains ternary blends of portland cement, silica fume, and a wide range of fly ashes. Previous work has shown that high CaO fly ashes are generally less effective in controlling alkali silica reactivity (ASR) and sulfate attack compared with Class F or low lime fly ashes. Indeed, in this study it was shown that replacement levels of up to 60% were required to control expansion due to ASR with some fly ashes. However, combinations of relatively small levels of silica fume (e.g., 3 to 6%) and moderate levels of high CaO fly ash (20 to 30%) were very effective in reducing expansion due to ASR and also produced a high level of sulphate resistance. Concretes made with these proportions generally show excellent fresh and hardened properties since the combination of silica fume and fly ash is somewhat synergistic. For instance, fly ash appears to compensate for some of the workability problems often associated with the use of higher levels of silica fume, whereas the silica fume appears to compensate for the relatively low early strength of fly ash concrete. Diffusion testing indicates that concrete produced with ternary cementitious blends has a very high resistance to the penetration of chloride ions. Furthermore, these data indicate that the diffusivity of the concrete that contains ternary blends continues to decrease with age. The reductions are very significant and have a considerable effect on the predicted service life of reinforced concrete elements exposed to chloride environments.

Tikalsky, P. J., V. R. Schaefer, et al. (2007). Development of Performance Properties of Ternary Mixtures: Phase I Final Report**:** 144p.

This report summarizes the findings of Phase I of the research project. The project is a comprehensive study of how supplementary cementitious materials (SCMs), can be used to improve the performance of concrete mixtures. The initial stages of this project consider several sources of each type of supplementary cementitious material (fly ash, slag, and silica fume) so that the material variability issues can also be addressed. Several different sources of portland cement (PC) and blended cement are also used in the experimental program. The experimental matrix includes 110–115 different mixtures; hence, the project is being conducted in three different phases. This report contains a brief literature study to summarize the state of the practice in ternary mixtures. The literature study includes the efforts by state departments of transportation (DOTs) that have utilized ternary mixtures in field work (for example, Ohio DOT, New York State DOT, Pennsylvania DOT, Iowa DOT) to discuss practical concerns about field applications. The initial phase covered in this report is a study with a large scope to identify materials combinations that will likely perform adequately in Phases II and III. Phase I of the study consisted of a 24-month laboratory program that studied the influence of multiple combination and proportions of cement, slag, silica fume, and fly ash on specific performance properties of mortar specimens. Test results are presented in this report. Chemical admixtures (water reducers, air-entraining agents, and accelerators) were included in this phase of the study to compare the effects of ternary mixtures on setting time, water demand, and air content. Phase I results have created the architecture for predicting the performance of ternary systems based on the material properties of the total cementitious system.

Toutanji, H., N. Delatte, et al. (2004). "Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete." Cement and Concrete Research **34**(Compendex): 311-319.

This research focuses on studying the effect different supplementary cementitious materials (silica fume, fly ash, slag, and their combinations) on strength and durability of concrete cured for a short period of time - 14 days. This work primarily deals with the characteristics of these materials, including strength, durability, and resistance to wet and dry and freeze and thaw environments. Over 16 mixes were made and compared to the control mix. Each of these mixes was either differing in the percentages of the additives or was combinations of two or more additives. All specimens were moist cured for 14 days before testing or subjected to environmental exposure. The freeze-thaw and wet-dry specimens were also compared to the control mix. Results show that at 14 days of curing, the use of supplementary cementitious materials reduced both strength and freeze-thaw durability of concrete. The combination of 10% silica fume, 25% slag, and 15% fly ash produced high strength and high resistance to freeze-thaw and wet-dry exposures as compared to other mixes. This study showed that it is imperative to cure the concrete for an extended period of time, especially those with fly ash and slag, to obtain good strength and durability. Literature review on the use of different supplementary cementitious materials in concrete to enhance strength and durability was also reported. 2003 Elsevier Ltd. All rights reserved.

Wade, S. A., J. M. Nixon, et al. (2010). "Effect of temperature on the setting behavior of concrete." Journal of Materials in Civil Engineering **22**(Compendex): 214-222.

The effects of fluctuating temperatures on the setting times of concrete mixtures made with different water-to-cement ratios, supplementary cementing materials (SCMs), and SCM dosages are evaluated in this paper. Initial and final set times of the concrete were determined with penetration resistance testing. Wet-sieved mortar samples were placed in hot and cold water baths that cycled over 24 h between temperature ranges of 32-41C and 4-13C, respectively. The control samples were cured at temperatures between 20 and 24C. Results show that Class F fly ash will slightly retard setting, ground granulated blast furnace slag will slightly accelerate setting, and Class C fly ash will significantly increase setting times. It is shown that the equivalent age maturity method may be used to estimate setting times of concrete samples cured under fluctuating temperatures. Activation energy values are recommended for use with the equivalent age maturity method to predict setting. 2010 ASCE.

Wang, J. and P. Yan (2005). Performance of concrete containing fly ash at early ages. 2005 International Congress - Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Dundee, Scotland, United kingdom, Thomas Telford Services Ltd.

The adiabatic temperature increase of concrete containing various percentage of fly ash was measured to understand heat emission during hydration. A temperature-matching curing (TMC) schedule in accordance with adiabatic temperature increase is adopted to simulate the situation in real massive concrete. The performance of concrete cured both in TMC and standard conditions were investigated. The possibility of prediction of strength in real structures using an equivalent age approach is discussed. The hydration of high volume fly ash concrete is delayed slightly. Its final degree of hydration is high enough under the condition of low water-binder (W/B) ratio to make the adiabatic temperature increase higher than the concrete containing a lower percentage percent of fly ash. Elevated temperatures enhance the hydration of binder to benefit the gain of compressive and flexural strength of the concrete containing complex binder.

Wang, S.-D., K. L. Scrivener, et al. (1994). "Factors affecting the strength of alkali-activated slag." Cement and Concrete Research **24**(Compendex): 1033-1043.

The effect of several factors on the strength of alkali activated slags has been investigated. The most important factors were found to be the type of alkaline activator, the means of adding activator, the dosage of alkali, the type and fineness of slag, SiO2/Na2O ratio (modules, Ms) when using waterglass solution, curing temperature, liquid/slag or water/slag ratio and additive. Some of these factors are interdependent and the effect of changing more than one is usually not additive. The optimum range for each factor is suggested through reviewing previous work and our recent results of a full factorial range strength study. The interaction of factors is considered and discussed throughout the paper, hoping to gain a better understanding of the processing of alkali-activated slag (AAS) cement and concrete.

Wu, X., W. Jiang, et al. (1990). "Early activation and properties of slag cement." Cement and Concrete Research **20**(Compendex): 961-974.

Early age activation of granulated blast-furnace slag (BFS) and blends of slag and portland cement (OPC) has been studied. Activators include sodium-hydroxide, sodium sulfate, alum (potassium aluminum sulfate), superplasticizer, and calcium aluminate cement. Heat of hydration, x-ray phase characterization, compressive strength, viscometry, pore size distribution and related characterization studies have been made. Activated BFS-cement mortars having equivalent strengths at 1 day to OPC have been prepared, which also have 28- and 90-day strengths exceeding those of the OPC. Mechanisms of activation are discussed.

Yao, W. and K. Wu (2001). "Mechanical properties and flowability of high strength concrete incorporating ground granulated blast-furnace slag." Journal Wuhan University of Technology, Materials Science Edition **16**(Compendex): 42-45.

The high strength concrete (HSC) was produced by partially replacing the normal portland cement with special ground granulated blast-furnace slag (GGBS) ranging up to 60%. The effects of the GGBS on the flowability and mechanical properties of HSC were studied. The hydration process and microstructure characteristics were investigated by X-ray diffraction (XRD) and scanning electron microscopy (SEM), respectively. The test results indicate that the GGBS has especially supplementary effect on water reducing and excellent property of better control of lump loss. The concrete flowability increases remarkably with the increase of GGBS fineness and the replacement level in the range of 20% to 50%. The compressive and splitting tensile strengths of HSC containing GGBS are higher than the corresponding strength of the control concrete at all ages.

Zhang, L. and R. Wang (2011). Experimental study on alkali-activated slag-lithium slag-fly ash environmental concrete. 2011 International Conference on Advanced Engineering Materials and Technology, AEMT 2011, July 29, 2011 - July 31, 2011, Sanya, China, Trans Tech Publications.

The aim of this paper is to study the influence of lithium-slag and fly ash on the workability, setting time and compressive strength of alkali-activated slag concrete. The results indicate that lithium-slag and fly-ash can ameliorate the workability, setting time and improve the compressive strength of alkali-activated slag concrete,and when 40% or 60% slag was replaced by lithium-slag or fly-ash, above 10 percent increase in 28-day compressive strength of concrete were obtained. (2011) Trans Tech Publications.

Zhang, M.-H., A. Bilodeau, et al. (1999). "Concrete incorporating supplementary cementing materials: Effect on compressive strength and resistance to chloride-ion penetration." ACI Materials Journal **96**(Compendex): 181-189.

This paper presents the results of an investigation dealing with the effects of curing method on the compressive strength and the resistance to chloride-ion penetration of concrete incorporating supplementary cementing materials. The concrete was cured under wet burlap for 7 days, followed by exposure to the laboratory air or cured using three different curing compounds. The effect of the water-cement ratio (w/c) and the type of supplementary cementing materials, including fly ash, silica fume, and ground granulated blastfurnace slag, were evaluated. The compressive strength of the concrete was determined at 7, 28, and 91 days, and the resistance of the concrete to the chloride-ion penetration was determined at 28 and 91 days. For the portland cement concrete with a w/c of 0.32, the compressive strength and the resistance of the concrete to the penetration of chloride ions were not affected significantly by the curing conditions. The portland cement concrete with w/c of 0.55 and 0.76 and cured under wet burlap had significantly higher resistance to the penetration of chloride ions and higher compressive strength than that cured using Curing Compound I. For the portland cement concrete with a water-to-cementitious materials ratio (w/cm) of 0.32 and incorporating silica fume and slag, the compressive strength of the cores taken at 7 and 28 days and the resistance of the concrete to the penetration of chloride ions were not affected significantly by the curing conditions. However, at 91 days, the cores taken from the concrete cured under wet burlap had higher compressive strengths than those cured using Curing Compound I. For the concrete with a w/cm of 0.32 and incorporating ASTM Class F or Class Cfty ash, the compressive strength of the cores taken at 7 days was not affected by the curing conditions. However, at 28 and 91 days, the concrete cured under wet burlap showed higher compressive strengths than that cured using Curing Compound I. For the concrete incorporating ASTM Class F fly ash, the resistance to the penetration of chloride ions was affected by the method of curing, with the concrete cured under wet burlap showing superior resistance to that cured using Curing Compound I. For the concrete incorporating ASTM Class

C fly ash, the resistance to the penetration ofchlori.de ions was not affected significantly by the method nj curing. In general, the type of curing compounds used did not affect either the compressive strength or the resistance of the concrete to chloride ion penetration significantly.

Zibara, H., R. D. Hooton, et al. (2008). "Influence of the C/S and C/A ratios of hydration products on the chloride ion binding capacity of lime-SF and lime-MK mixtures." Cement and Concrete Research **38**(Compendex): 422-426.

The mechanisms of chloride ion binding in cementitious systems when supplementary cementing materials are present are not completely understood, although it is believed to relate to the alumina content of the mixture. This relationship is investigated through the use of lime-silica fume and lime-metakaolin mixtures. It was found that while the alumina content does have an important influence, the chloride binding capacity was also controlled by the calcium-to-alumina and calcium-to-silica ratios. At a high C/A ratio, the formation of monocarboaluminate is favoured, which has a high ability to form Friedel's salt, and does so at low chloride concentrations (less than 0.1M). With a low C/A ratio, the formation of stratlingite is favoured, with little formation of monocarboaluminate. If alumina is not present, chloride is bound by the C-S-H phase. The binding capacity of the C-S-H was found to depend on its calcium-to-silica ratio, C-S-H with a higher C/S having a greater binding capacity. 2007 Elsevier Ltd. All rights reserved.

Zong, X. and X. Wang (2011). Research on thermodynamical performance of concrete with excessive fly ash added in the pile cap of well tower. 1st International Conference on Civil Engineering, Architecture and Building Materials, CEABM 2011, June 18, 2011 - June 20, 2011, Haikou, China, Trans Tech Publications.

To meet the demand of high performance of mass concrete in a pile cap of well tower, excessive replacement of fly ash was applied to the mass concrete. Based on the theory of hydration heat of cement, several thermal parameters of mix proportion were analyzed and simulated test analyses and setting time test analyses were conducted in the laboratory. The results and data collected in the project locale both show that applying excessive replacement of fly ash reduces hydration heat of mass concrete in the pile cap of well tower, which extends setting time in mass concrete and avoids the cracks caused by temperature stress. The results achieve favorable effect and provide reference for design and construction of mix proportion in the project of mass concrete. (2011) Trans Tech Publications.