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LITERATURE REVIEW OF CONCRETE DURABILITY & SERVICE LIFE REQUIREMENTS IN GLOBAL CODES AND STANDARDS

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ENGINEERS

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Executive Summary

Durability design, as a framework for the design and construction of structures to achieve an intentionally specified service life, is not well understood or comprehensively documented within the guides, standards and Codes developed by ACI. Globally, ACI 318 is the most commonly used Code for design of new concrete structures. Use of ACI 318 for design of new concrete structures will result in concrete structural designs that can be economically constructed and have adequate strength to resist design loads. However, concerns exist about the effectiveness of the durability provisions in ACI 318 to produce structures that will perform successfully in aggressive environments and achieve longer term design service lives (i.e., the period of time before major repair or rehabilitation is necessary). These concerns were voiced by US practitioners that regularly use ACI 318, and people familiar with both ACI 318 and global design Codes. To examine how ACI documents compare to globally developed Codes, standards and guides, a literature review was completed that examined the durability provisions contained in over 50 documents.

Compared with global Codes and standards as a whole, durability provisions in ACI 318 do not approach durability in a direct, integrated, or systematic manner for the lifetime of the structure. Specifically:

- ACI 318 durability requirements for a given concrete cover are not harmonized with the corrosion resistance of the reinforcement. Requirements for these materials are addressed in separate chapters of the document, and not cross-referenced for a licensed design professional to consider as a system.
- ACI 318 does not include considerations for crack control/ design detailing as part of durability.
- ACI 318 addresses design and construction, but not the operational life of a structure. Concepts of design service life, maintenance, and planning for repairs to structures are not addressed. This material is covered in ACI 562, but ACI 318 does not reference this Code document as a member of its technical family.

Overall, the ACI 318 approach to durability is generally limited to prescriptive requirements for concrete materials and concrete cover based upon environmental exposure conditions. Reinforcement characteristics are addressed separately, and not in combination with the concrete cover. No specific requirements to directly measure or model system resistance to chloride-exposure and/or sulfate-resistance, etc., over time are included. Moreover, guidance for complicated or specialty structures or service environments with combinations of chemical and mechanical loads is not included. These design scenarios usually merit insight from materials producers and constructors to succeed. Other ACI documents, and ACI documents the authors understand to be in development, describe durability and design service life in a more integrated and comprehensive manner, and striving for a direct, performance-oriented approach to durability for a specific design service life. These documents are not integrated into ACI 318, and therefore the information contained in the documents is

Cover: Underside of Gardiner Expressway, Toronto, Canada. Repairs to critical infrastructure disrupt the flow of commuters and goods. Durability planning to target maintenance, repairs, and rehabilitation cycles is essential.

unlikely to reach most US design professionals.

Globally, other nations, regions and institutions have produced both consensus standards and best practice guides for both new and existing structures with both prescriptive and performance-oriented durability and service life requirements. No one region has compiled this information into an approach that can be readily applied in the US, however. Common features contained in the global Codes, standards and guidelines include consideration of the design service life as a part of the design process, service life modeling, consideration of concrete cracking (spacing and width) in design, and more comprehensive concrete material performance requirements for concrete exposed to aggressive environments or structures with an extended design service life. Many of the global documents also include requirements for future repair and maintenance into design Codes, recognizing that they were designing *structures* that need to perform for decades, and more is needed than just structural engineering for safety and serviceability.

To maintain the long-standing prominence of ACI as the global leader in the development of concrete-based knowledge, development of consensus guides and standards for durability design is essential. These documents can be developed within the framework of current ACI committees or by dedicated task groups. Critical documents include development of a planning guide for durability design and standards for durability design and service life prediction.

The investigators acknowledge the generous financial support of the American Concrete Institute Foundation (ACIF) and technical guidance received via the Advisory Panel.

Concrete guardrail, Austin, Texas, USA. Durability of life-safety elements is correlated to their ability to meet structural demands, long-term.

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1 Introduction

1.1 Background

Durability design, a systematic process for design, construction, repair and maintenance of concrete structures, is currently not well captured in documents developed by ACI. Numerous ACI technical documents include specific requirements for durability, in both new and existing construction. However, there is not a harmonized approach within ACI documents for design and construction methods to be durable for a specific service life in new or existing construction.

Outside the US, International Codes and standards are perceived to have achieved consensus in basic durability design concepts for simple structures and options for more sophisticated structures, from initial design to monitoring durability over the course of construction to verify requirements have been met, conceptually referenced in Figures 1.1 and 1.2. This report examines global concepts, standards, and practice in durability design and provides recommendations for further development of ACI Codes and standards.

1.2 Investigative Program

1.2.1 Approach

Key documents from multiple global sources were initially identified for this project, and pertinent details are listed in Table 4.1. These include the most recent versions of:

- ACI documents:
  - ACI 201 – Guide to Durable Concrete
  - ACI 222 – Protection of Metals in Concrete Against Corrosion
  - ACI 301 – Specifications for Structural Concrete
  - ACI 318 – Building Code Requirements for Structural

Figure 1.1: Plain steel reinforcement prior to concrete placement. If reinforcement is required, corrosion resistance and structural requirements contribute to the long-term durability of concrete construction.

Figure 1.2 Sequence of concrete batching (top), testing (middle), and placement (bottom). Verification that durability design requirements are met through construction is essential.

    - Concrete and Commentary
    - ACI 350.4R – Design Considerations for Environmental Engineering Concrete Structures
    - ACI 350.5 – Specifications for Environmental Concrete Structures
    - ACI 350.6 – Code Requirements for Environmental Engineering Concrete Structures
    - ACI 357 – Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures
    - ACI 362.1R – Guide for the Design and Construction of Durable Concrete Parking Structures
    - ACI 365.1R – Report on Service-Life Prediction
    - ACI 562-19 – Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary
- Australian Standards (Standards Australia) + Relevant guides (Concrete Institute of Australia):
    - AS-3600 – Concrete structures
    - CIA Z7/01-2014 –Durability Planning
    - CIA Z7/04-2014—Good Practice through Design, Concrete Supply, and Construction
    - CIA Z7/06-2017 –Durability, Concrete Cracking and Crack Control
    - CIA Z7/07—2015—Performance Tests to Assess Concrete Durability
- Canadian standards:
    - CSA A23.1-14/A23.2-14 – Concrete materials and methods of concrete construction/Test methods and standard practices for concrete
    - National Building Code of Canada
        - Note: this document does not contain materials-specific durability provisions for concrete and was not considered further.
- Chinese standards
    - GB/T 50476 – Code for Durability Design of Concrete Structures
- European standards and documents:
    - EN 206:2013+A1 -- Concrete - Specification, performance, production and conformity-2000
    - EN 1990:2002 + A1 – Eurocode-Basis of Structural Design
    - EN 1992-1-2004 – Design of concrete structures – Part 1-1: General rules and rules for buildings
- *fib* (International Federation for Structural Concrete)
    - *fib* Model Code for Concrete Structures 2010
    - *fib* Bulletin No. 34 – Model Code for Service Life Design
    - Available documents describing Model Code for Concrete Structures 2020 (under development)
        - Note: None were encountered over the course of this investigation, and therefore, none were considered.
- ISO
    - ISO 13823 – General principles on the design of structures for durability

- ISO 15686, Parts 1 through 11– Buildings and Constructed Assets, Service Life Planning
  - ISO 16204—Durability—Service Life Design of Concrete Structures
  - ISO 16311, Parts 1 through 4 – Maintenance and repair of concrete structures
  - ISO 19338 – Performance and assessment requirements for design standards on structural concrete
- Japanese standards and documents:
  - JSCE guidelines no. 15 (07) – Standard Specifications for Concrete Structures "Design"
  - JSCE guidelines no. 16 (07) – Standard Specifications for Concrete Structures "Materials and Construction"
- Other documents:
  - US Bureau of Reclamation Concrete Manual (81)
  - Unified Facilities Guide Specifications

Figure 1.3: Kouga dam, South Africa, in service. Monumental structures such as these are critical to managing water and given the investment, must be designed to resist structural and environmental loads for many decades.

- PIANC (The World Association for Waterborne Transport Infrastructure) guidelines
- PIANC MarCom report 162 - Recommendations for Increased Durability and Service Life of New Marine Concrete Infrastructure.

After a review of these documents, additional documents were considered valuable to the process and added to the research:

- American Association of State Highway and Transportation Officials (AASHTO)
    - AASHTO LFRD Bridge Design specifications, 8th edition
- Canadian Standards:
    - CSA S413 Parking Structures
    - CSA S448.1 Repair of Reinforced Concrete in Buildings and Parking Structures
    - CSA A23.3 Design of Concrete Structures
    - CSA A23.4 Precast Concrete
- Vietnamese construction standard:
    - TCVDVN 318:2004 Concrete and Reinforced Concrete Structures, Guide to Maintenance

Our general process for every document was to review and document the following:

- Type of structures covered;
- Summary of the approach used;
- Type of approach (prescriptive vs. performance specifications);
- Definition of exposure classes;
- Definition of exposure zones;
- Durability criteria;
- Service-life expectations or requirements;

Our intent is to document aspects of the reviewed documents that should be considered as a valuable basis for a future ACI durability Code, or Code provisions in the existing Codes. This research intentionally excluded research and documentation as to how global entities address robustness or resilience, response to extreme events, or non-linear analysis/global resistance approaches for safety assessment.

To supplement the review of global Codes and standards, common durability and service life terminology from reviewed documents was collected and summarized in Appendix A, brief summaries of some non-US reviewed documents were placed in Appendix B, and interviews were conducted with both Code developers and end users of some of the Codes (academics, design professionals, concrete producers). Given the candor of some of the commentary and the limited number of respondents, anonymity was granted by the investigators when requested. A summary of the feedback to date is included in Appendix C.

1.2.2 Project Goal

As ACI moves forward conceptualizing the next generation of design Codes, a review of international design Codes and standards that address durability design is warranted to help ACI develop the best possible documents. The review of international Codes was intended to develop an understanding of how durability design is approached internationally and, based upon discussions with the developers and users of international Codes, develop an understanding of the ways these Codes are implemented in practice. The review will allow for recommendations to enhance ACI Codes to be developed from successful international practice.

1.2.3 Project Team

This investigative team includes experienced and qualified experts in concrete durability, service life prediction, building Codes, structural engineering, professional standards of care, design, and international standardization. All team members are experts in ACI Codes development and the Code adoption process for buildings.

- Project Team:
    - Keith Kesner, PhD, PE, SE, FACI of CVM
    - Joseph Klein, PE of PIVOT
    - Tracy Marcotte, PhD, PE, FACI of CVM
    - Randall Poston, Ph.D., P.E., S.E., NAE of PIVOT

1.2.4 Advisory Panel

ACIF assembled the following subject matter experts for review and guidance of this report. Their insightful feedback is gratefully acknowledged:

- ACIF representatives from Strategic Development Council (SDC)
    - Joseph Sanders, Chair
    - Peter Emmons
    - Mark Perniconi
    - James Toscas
- ACI Committee 201 (Durability) representatives
    - R. Doug Hooton, Chair
    - Larry Sutter, Secretary
    - Oscar Antommattei
    - Thomas Van Dam
    - Michelle Wilson
- ACIF Staff
    - Ann Masek, Executive Director

1.2.5 Attribution and Disclaimer Statements

The investigators are grateful for the financial support of the American Concrete Institute Foundation (ACIF) and technical guidance via the Advisory Panel. This report and publications discussed are intended solely for information purposes and are not to be construed, under any circumstances, by implication or otherwise, as an endorsement or criticism of a given Code, standard, report, guide, or other document discussed herein.

2 General Concepts for Codes, Standards, Reports, and Guidelines

2.1 General

A building Code is a set of rules that specify the minimum requirements for construction and operation of buildings and nonbuilding structures. Codes are designed to provide minimum requirements for structures to ensure public safety, health, and general welfare, and are usually drafted with the expectation of being adopted by a regulatory agency. Code language is mandatory, and represents industry standard practice and standard of care, and, if adopted and enforced by an appropriate government or private authority, becomes law. Codes are drafted primarily for use by design professionals, contractors, and regulators (Code officials).

In the United States, the most widely adopted general building Codes are the International Code Council (ICC) Codes. Distinct general building Codes are developed for different areas of practice, for example International Building Code (IBC), International Existing Building Code (IEBC), International Fire Code (IFC), and International Mechanical Code (IMC), addressing various aspects associated with distinct areas of practice and whether the structure is new or existing. However, these Codes typically summarize generic requirements, and for structural construction materials like steel or concrete, these Codes rely upon allied technical standards institutes to provide detailed material-specific design requirements. For example, the American Institute of Steel Construction (AISC) provides steel requirements, while the American Concrete Institute (ACI) provides concrete requirements.

Specific to concrete, a model building Code is developed and maintained by a standards organization independent of the jurisdiction responsible for enacting the building Code. A general building Code or enforcing agency can choose to adopt a model building Code as their own. By adopting a model Code, it becomes an operational Code and enforcement agencies can enforce a technically sound Code without the associated expense and expertise required to develop their own Code. Examples of model Codes for concrete include ACI 318, ACI 562, EUROCODE 2, and the 2010 Code developed by the International Federation for Structural Concrete (*fib*), however, *fib*'s Code remains as model Code, while the former have been adopted in multiple jurisdictions.

A technical standard is an established norm or requirement for technical systems, usually written by a standards body using a consensus process. It is a formal document that establishes uniform engineering or technical criteria, methods, processes, and practices and is directed toward a technical reader. Technical standards are drafted to limit the scope of interpretation, often written in mandatory language with references only to mandatory-language documents.

The standardization process can result in several different types of standards, for example, standard specifications, test methods or operating procedures. The standardization process can be by edict or can involve the formal consensus of technical experts and is usually approved by a standards institute. Standards institutes develop the consensus process by which standards are developed. In the United States, many technical standards are developed in accordance with the requirements of the American National Standards Institute (ANSI). Other countries have their own similar standards bodies governing their standardization process, but not necessarily producing standards for their internal use. Instead, they might adopt or modify other national standards for use in their country.

A technical guide summarizes and provides recommendations for varied aspects of a project, such as analysis, design, evaluation, or testing. Technical guides often present pertinent examples or case studies and are commonly drafted in nonmandatory language. A technical report provides targeted, technical information on a specific area of practice. Reports can include research results or a review of best-practice methods to represent the current knowledge on a particular topic. Reports are drafted in nonmandatory language and may include recommended action but are not typically enforceable.

Within any Code, standard, report or guide, terminology with precise, concise definitions allows a technical reader to understand how to interpret requirements or guidance unambiguously. If terminology is harmonized and standardized across a family of documents, the resulting network of documents can be considered a knowledge base, and facilitates refinement of existing documents, development of new work, and communication amongst technical readers.

2.2 International Codes

2.2.1 General

International Codes, by definition, are those that are intentionally developed and adopted in more than one nation or region, globally. The framework of such Codes can be complex, and for concrete structures, can require other technical standards to be developed in mandatory language and be referenced to provide more detail for applicable regional loads and load combinations, materials, production requirements, and conformance.

2.2.2 ACI 318 & ACI 562

ACI 318 and ACI 562 were designed to function as stand-alone model Codes or be adopted into a general building Code. ACI 318 and ACI 562 were intended to have transparent, easily interpreted provisions for design professionals and building Code officials. ACI 318 and ACI 562 are legally enforceable (when adopted) and represent a standard of care for design or repair of concrete structures, respectively. Formal translations into languages other than English has extended the use of these documents globally. Treatment of durability within these two documents varies. ACI 318 primarily provides prescriptive means by which a design professional can address the effects of defined "exposure classes", which are defined by the expected degree of intensity of environmental actions. Most of the durability requirements within ACI 562 are performance-oriented considerations without specific solutions, due to the varied and broad range conditions encountered with existing structures. When used outside the United States, referenced standards are either maintained (e.g., ASTM) or other local standards can be substituted.

2.2.3 Eurocodes

The Eurocodes represent a common family of Codes (i.e., umbrella Codes), developed and adopted by members of the European Union (EU) and other non-EU members as their individual national Codes. This harmonized approach is intended to stimulate trade and free markets within the European Union and abroad, and facilitate common engineering and design practices. Nations tailor these general EU Codes by adding annexes indicating special requirements for their particular region or nation. The primary audience is the practicing engineer and this framework values ease of use. Both prescriptive ("deemed-to-satisfy") and performance-oriented approaches are permitted. Environmental actions are defined into classes and degrees of intensity according to anticipated deterioration mechanisms. Eurocodes require that durability provisions be incorporated into structural design, and working life, or "design service life", is encoded. EN or ISO standards are referenced to provide necessary technical detail.

2.2.4 *fib* Model Code 2010

fib Model Code for Concrete Structures 2010 is envisioned to represent the state-of-the-art in theory and practice. It was developed to provide nations with the existing knowledge base for designing concrete structures, but also to share ideas for new design requirements and achieving optimal behavior for both the structure and materials. It is an international model Code updated every 10 years with increasing focus on the "significance of design criteria for durability and sustainability." This Code is intended to provide the background information for operational Codes for regions and nations in the form of best practices and recommendations and is not presented in a manner that could be legally applied by building Code officials or design professionals (i.e., not written in mandatory language with interpretation guidance).

2.3 International Standards

2.3.1 ASTM

ASTM International (formerly, American Society for Testing and Materials) provides consensus technical standards, including standards for cementitious material testing and specifications.

2.3.2 EN

EN standards provide standardized guidance for material testing and specifications and are maintained by the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI).

2.3.3 ISO

International Standards Organization (ISO) provides extensive technical standards on testing and specifications, including standards for cementitious material testing and specifications, service life prediction, new concrete design, and repair and maintenance of concrete structures.

2.4 National or Regional Codes & Standards

2.4.1 Australia (Standards Australia)

Australian Standard AS 3600 provides standardized prescriptive guidance on design of plain, reinforced, and prestressed concrete structures along with performance criteria of the designed structures. Testing standards supporting AS 3600 are also developed by Standards Australia and ISO.

2.4.2 Canada (CSA Group)

The CSA A23 series by the CSA Group (formerly Canadian Standards Association) provides requirements for design and strength evaluation of plain, reinforced, and prestressed concrete elements primarily within building structures and special structures, including blast-resistant structures. Requirements for materials and construction methods (A23.1), standardized testing methods (A23.2), and design provisions (A23.3 and A23.4) are collectively covered within the scope of the standard A23. Requirements specific to parking structures are addressed in CSA S413. Repair of buildings and parking structures is covered in CSA S448.1, and CSA S478 addresses durability of buildings from a structures (design) viewpoint.

2.4.3 China

Initiated in 2000 and completed in 2008, GB/T 50476 Code for Durability Design of Concrete Structures addresses specific requirements for durability design of Chinese structures and commentary regarding the genesis of this Code and its provisions is included in Li's book [1]. Public structures (e.g., tunnels, bridges, typical buildings) constructed with normalweight concrete are within its scope, while special structures and concretes are excluded.

2.4.4 Japan

A suite of standard specifications developed by the Japan Society of Civil Engineers (English translation) to address the material and construction (JSCE 16), design (JSCE 15) and maintenance (JSCE 17) aspects of civil concrete structures. Design with plain concrete is not considered in these standards.

2.5 National or Regional Guidelines, Reports, and Specifications

2.5.1 General ACI, AS, CIA, ISO, etc. companion documents

Additional, more detailed guidance documents are prepared to inform the design engineer, producer, or user in a range of topics, including specification of concrete. These can be stand-alone or directly related to a given Code or standard.

2.5.2 PIANC

The Recommendations for Increased Durability and Service Life of New Marine Concrete Infrastructure by a Maritime Navigation Commission working group provides recommendations on good practices aimed at Owners and design professionals of marine concrete infrastructure. Guidance on condition assessment, preventive maintenance and repairs of marine concrete structures is included within the scope of this document.

2.5.3 United Facilities Guide

UFGS-03 31 29 prepared by the United States Navy's Naval Facilities Engineering Command (NAVFAC) provides requirements for reinforced concrete structures exposed to marine, chloride environments with a defined service life.

2.5.4 US Bureau of Reclamation

US Bureau of Reclamation has a manual compiling concrete basics and advancements in concrete technology and construction to facilitate construction administration and successful concrete work.

3 General Concepts & Terminology for Durability Design and Service Life

3.1 General

Concrete is the most used construction material, worldwide. Well-made concrete has been the subject of innumerable technical documents, and provides long-lasting, useful and aesthetically pleasing structures, for good economic value. Figure 3.1 illustrates some of the conventional thinking regarding “good, uniform” concrete, and note the equivalency within Figure 3.1 balancing strength with durability and economy. Ultimately, this figure, published in 1988, distills concrete performance in harmony with economics. If revised today, this figure would likely include “sustainability” in lieu of or in addition to “economics,” where sustainability reflects the “triple bottom line” of balancing social, environmental, and economic costs.

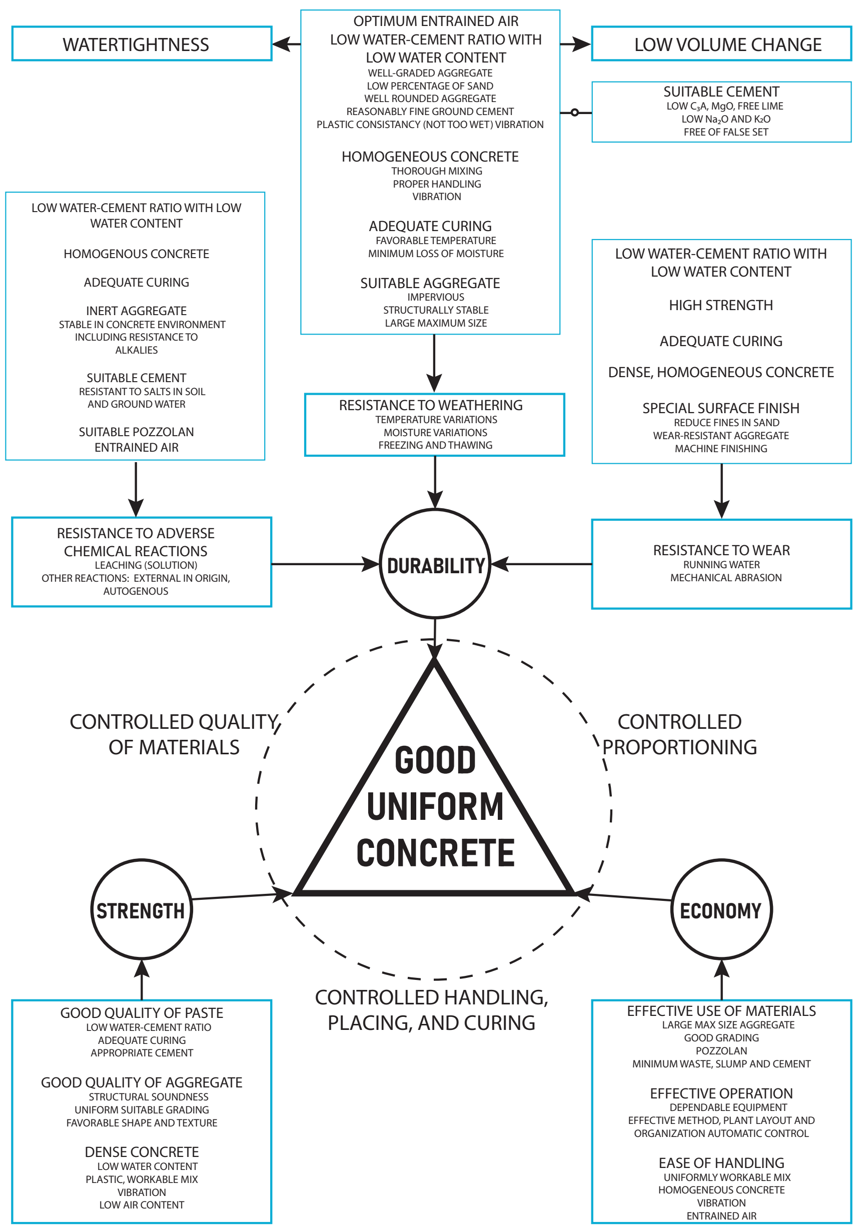


Figure 3.1: Overview of “principal properties of good concrete” from US Dept of Interior, Bureau of Reclamation, Concrete Manual, Figure 1 (Redrafted for clarity).

3.2 Defining Long-Term Performance

Most structures are not built to be temporary and are expected to provide decades of service for their Owners. Individual definitions of "long-term" can vary, but usually indicates decades of service, in the 40-60 years range for buildings, and a minimum of 75 years for infrastructure, with 100+ years becoming more routine. Design loads for building structures, in US practice, are commonly based upon a return period of 50 years for gravity and wind loads, while current US bridge design practice is based upon a 75-year return period for vehicular loads. *fib* Model Code defines service life timeframes for temporary structures (1 to 5 years) and permanent structures for 25, 50, and 100 years or more.

However, loading is just one action that must be resisted by a structure; the ability of a structure to resist loads does not constitute long-term performance. Long-term performance begins in the design and construction phase of the project, and implicit in defining the service life of a structure is that some level of maintenance and repair will be required at some frequency or planned timeframe. Figure 3.2 illustrates the key characteristics that are understood to lead to long-term performance: strength (3.2.1), serviceability (3.2.2), and durability (3.2.3). While the primary focus of this document is durability, a durable structure should also meet strength and serviceability requirements.

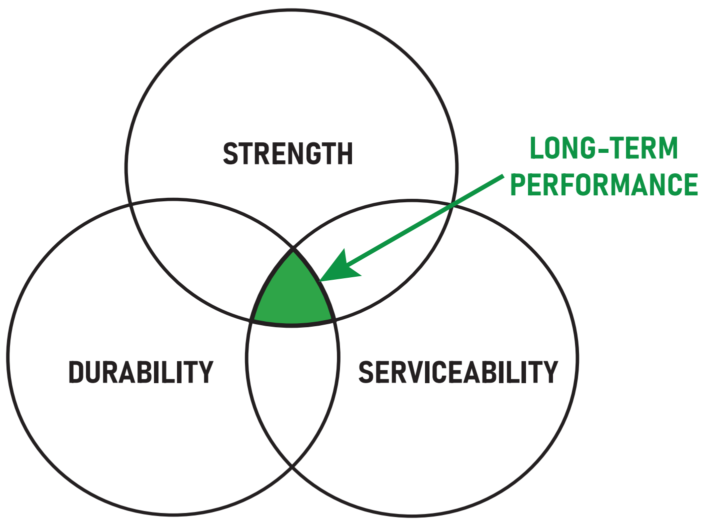


Figure 3.2: Successful harmonization of strength, durability, and serviceability permits long-term performance.

3.2.1 Strength

Structures must be designed and constructed to support themselves and any imposed loads. Without sufficient strength, a structure will never see service, much less long-term performance. Strength is the primary consideration in most structural designs, and most of the content of Codes such as ACI 318 and ACI 562 is devoted to strength. However, strength alone cannot achieve long-term performance. Strength, serviceability and durability are interrelated. A structure designed to have adequate strength might not have sufficient durability or serviceability to achieve its design service life.

Numerous considerations in structural design and detailing impact durability and serviceability. These include member continuity, joint location, joint spacing, expected cracking as a function of reinforcement details, potential crack control as a result of prestressing, and other factors. These details can easily be overlooked, yet they are often the first locations in which deterioration is observed. The reviewed technical documents provide guidance on structural design and detailing. For example, Australian CIA Z7/04 provides an entire document that outlines best practices, including trickier structural details that affect durability. Durability considerations also impact strength: deterioration such as corrosion, sulfate attack, and ASR can affect the structural integrity of concrete structures.

3.2.2 Serviceability

Serviceability of a structure can be defined in many ways, using many different metrics. Serviceability can be loosely defined as the assessment of performance from a user point of view, affecting efficient use of a structure. Serviceability includes aesthetics, deflections, vibrations, and watertightness, and serviceability considerations can be temporary, intermittent, and lead to failure. Numerous types of serviceability issues, such as significant cracking (excessive deflections or lower than expected stiffness), can contribute to a lack of durability. In addition, similar to strength, durability considerations affect serviceability as well. Spalling due to corrosion (e.g., spalled areas of concrete roads negatively impact driving conditions), or excessive cracking due to ASR can lead to a structure that is no longer functional or leaks (e.g., water retention basins, sluice gates, spillways). Issues such as improper drainage can affect both durability and serviceability.

3.2.3 Durability

Constructed circa 72 AD, the Roman Colosseum, shown in Fig. 3.2.3 is about two millennia old, and its durability can be attributed to its structural design and making the best use of local Roman cement without extensive ferrous reinforcement (i.e., ferrous cramps used to secure dry-laid stone as a facade, but these have corroded away, releasing the stone). It is unlikely that the designers and builders intended to construct this iconic global treasure to last this long, but modern design professionals and builders can learn from older structures what can work and what will not.

In current times, durability is the ability of a material or structure to survive in a service environment for a defined period of time without major repairs or rehabilitation. Defining the period of time is critical to Owners' successfully managing their structures to minimize impact on people, their budgets, or the environment. In addition, related definitions of durability often make some mention of both strength and serviceability, reflecting the aforementioned relationship between the three. Often, a deficiency in one can lead to a deficiency in the other two. For example, consider a parking structure with improper drainage:

- Initially, the ponding is primarily a serviceability concern.
- However, over time, this ponding can lead to corrosion, accelerate deterioration of joint sealants, or cause debris to accumulate in expansion joints, all durability concerns.
- Accelerated corrosion can lead to increased cracking, both a durability and a serviceability concern, as well as, ultimately, a loss in strength.

There are myriad ways in which strength, serviceability, and durability may affect long-term performance.

Figure 3.2.3: Roman Colosseum, Italy is an example of serendipitous long-term durability.

Without durability, a structure will never meet strength and serviceability requirements for the expected service life.

Because of these interrelationships, durability, at the foundation of durability design, is sometimes considered an elusive concept, but is defined internationally by consensus as, "ability of a structure and its component members to perform the functions for which they have been designed, over a specified period of time, when exposed to their environment" (AS 3600), which is roughly similar to ACI 562's, "ability of a material or structure to resist weathering action, chemical attack, abrasion, and other conditions of service and maintain serviceability over a specified time or service life." The definitions require a minimum performance for a period of time, and this is equivalent to the "design service life", described in Section 3.2.6.

3.2.4 Measuring and Verifying Performance & Reliability

Measurement and verification of performance and reliability is a well-established concept for strength and serviceability. Compressive strength testing is the most common way in which strength of concrete structures is measured and verified. Similarly, various testing methods exist for measuring and verifying different aspects of serviceability, including deflection measurements and floor flatness testing. Reliability concepts are often applied to these testing methods. For example, ACI provides guidance on target compressive strength such that design compressive strength can reliably be met. Similarly, load factors and resistance factors (phi factors) are a codified manifestation of reliability in strength.

Measurement and verification of durability performance and reliability, on the other hand, is less established in concrete Codes and standards. While numerous methods for establishing durability performance exist, including measurement of chloride and carbonation fronts and joint sealant testing, these methods are often not codified to the extent of strength and serviceability performance. The same is true of durability reliability. Many of these durability performance metrics have been in use for decades, and it is important to note that if deterioration can be modeled, then reliability concepts can be applied. Industry is beginning to do just that, with methods such as probabilistic service life modeling seeing more and more use. However, the application of these reliability concepts to durability is typically left to the discretion of the design professional. Journal articles and technical reports (ACI 365.1, CIA Z7/01 Appendix C) provide guidance on application of reliability concepts to durability and service life prediction, but concrete Codes and standards generally do not yet provide the same rigorous treatment of reliability to durability as they do to strength and serviceability.

3.2.5 End of service life

End of service life, in the context of the aforementioned framework for long-term performance, may be considered as the moment in time when some aspect of performance (e.g., structural, durability, aesthetics) falls below an acceptable threshold due to the deterioration at which time remedial costs or efforts are considered too high. Simply put, end of service life is the time at which a structure can no longer fulfill its desired function, and intervention measures will no longer be cost effective. While the considered definition seems simple on the surface, its implementation is challenging.

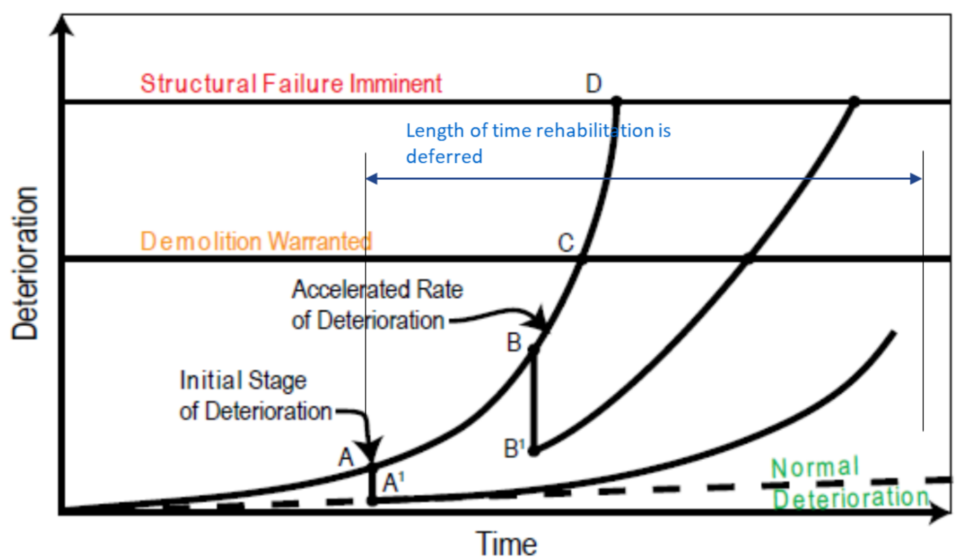
In the context of defining service life for durability, challenges arise from the difference in the treatment of new versus existing structures, as well as the difference between conceptual design of a new structure versus existing structure repair design, post-assessment. A common industry practice is to adopt a conservative approach in design, whether new or existing, and defining service life as a time period prior to the manifestation of damage or unacceptable state. When performing condition assessment and determining whether to intervene, however, it is often the consequences of durability performance on strength and serviceability, rather than the durability performance itself, by which service life is defined. Determining the end of service life in those situations relies on user-defined limit states, rather than design limit states.

Perhaps the best example of the challenge to define end of service life is treatment of corrosion due to chlorides. In design, the end of service life is considered by design professionals and Owners without durability expertise as the point at which the chloride concentration surpasses the initiation threshold and corrosion initiates. However, it could take years for this corrosion initiation to manifest itself as physical damage. Furthermore, it could take years for the corrosion to propagate to the point where the structure no longer has sufficient strength or serviceability is impacted. Realistically, no design professional or Owner would consider a structure at the end of its service life when a critical level of chlorides has reached the steel interface, especially when repair measures are feasible, yet this is often the approach taken during initial design for new structures.

Another set of challenges in directly addressing the end of service life arises from the subjective nature of the threshold acceptable performance. Returning to the example of the reinforced concrete member susceptible to chloride-induced corrosion, if corrosion initiation is not an appropriate end of service life, then multiple choices for unacceptable performance should exist. Corrosion-induced cracking is one of the potential threshold limit states while manifestation of spalling could be an alternative limit state as spalling creates a potentially unsafe condition. Defining the governing limit state is challenging because of the innumerable choices and their associated impact on different structures. Furthermore, many designs are expected to last 50 or more years with the possibility of multiple Owners / users over time, adding further difficulty for a design professional attempting to assess the future needs of an Owner over the life of the structure. Thus, durability design planning ideally would consider multiple time frameworks with individual requirements, described in fuller detail in Section 3.3, with short term as well as longer term requirements.

The impact of maintenance and repair on length of service life is also significant. Regular maintenance decreases the rate of deterioration due to loss of durability and mitigates the risk of premature failure or accelerated deterioration. Repair at early stages of deterioration can be significantly more effective than repair at later stages, as shown in Figure 3.2.5. However, a design professional might not be aware of future plans for maintenance and repair. Furthermore, maintenance and repair plans at a particular intervention cycle can be subject to change in the future.

In the light of the challenges associated with a standard definition for end of service life, the importance of a clear expectation of the end of service life between Owners and design professionals is readily apparent, and without a definition, legal consequences can emerge. Furthermore, a clear expectation of level of maintenance and repair post-construction or repair work has a significant impact on the end of service life. Without clear expectations, “end of service life” has little value, and “design service life” is more readily implemented, described in Section 3.2.6.



Source: Extending the Service Life of Parking Structures, Shiu, K, and Stanish, K. Concrete International V. 30 No. 4

Figure 3.2.5: Schematic representation of relationship between deterioration and time for typical structure [2].

3.2.6 Design (or Working) Service Life

End of service life concepts are focused upon the time after which a structure is no longer useful or the time until the structure hits a critical threshold. However, these concepts can be impractical for managing structures in service, as well-timed concrete maintenance and repairs can extend service life indefinitely. Moreover, helping Owners understand and compare strategies for managing a structure requires another concept of "design service life", "target design service life", or "working service life" and this has emerged as the preferred terminology in global standards (e.g., AASHTO, ISO, EN, *fib*, ACI 365.1, ACI 562, etc.).

Concisely, "design service life" is "period of time specified in design of structure for which a structure or its members is to be used for its intended purpose without major repair being necessary" per ISO 16311-1, and this is the general definition across numerous standards per Appendix A. Other definitions also mention that it is assumed maintenance will be performed (e.g., EN 206) as well. How this term interrelates with other service life concepts is shown in Figure 3.2.6, but in general, for any structure or member that is to be built or repaired, an Owner and design professional would ideally agree upon the time period during which no major repairs would be necessary, and only routine maintenance performed (e.g., washing down parking decks exposed to deicing salts, replacing expansion joints and joint sealants, etc.).

Figure 3.2.6 illustrates the impact of two scenarios, where Repair A might be a smaller effort or lower cost and restores a certain level of performance (with maintenance), while Repair B might restore greater performance but for a higher cost (or more maintenance). In this example, Repair B provides a longer extension in service life than Repair A. In lieu of these repair scenarios, new construction choices could be substituted: there could be different materials choices at initial construction, or implementation of supplementary protection measures. The more important nuance is for the design professional and Owner to have a framework for describing the durability of the structure, when the first repairs should be expected, and what maintenance will be needed to achieve the design service life. The design service life concept also allows a design professional to potentially limit their liability once the design service life has been met, or other pre-defined criteria have been satisfied (e.g., max. chloride penetration in 5 years). Current practice in the US is governed by state

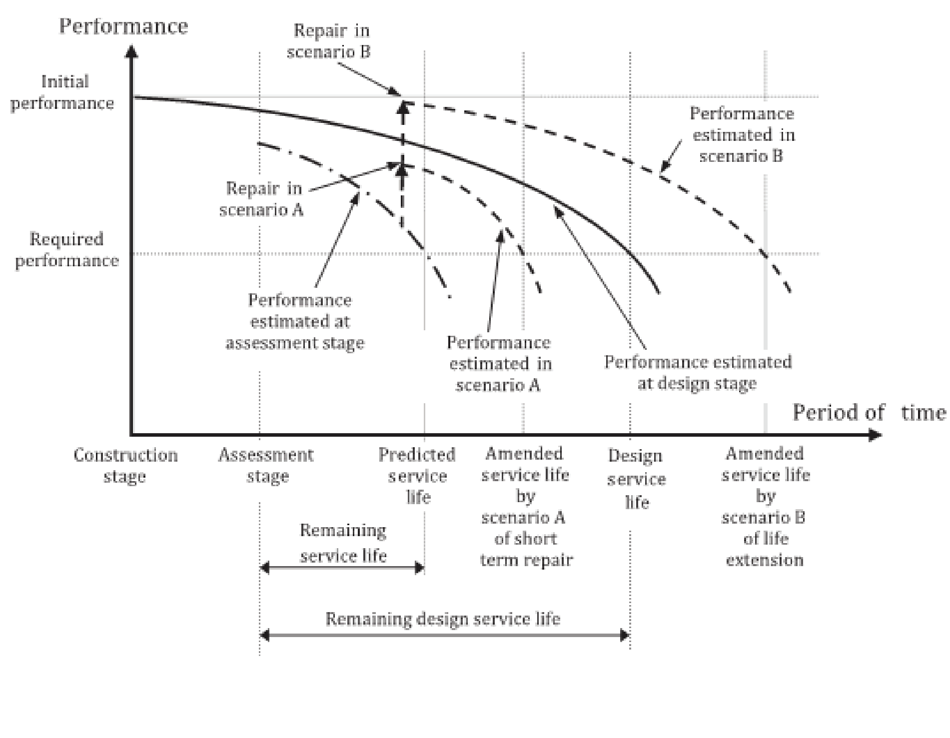


Figure 3.2.6: Schematic illustration of Design Service Life and other service life periods (ISO 16311-1, Fig, 2).

laws and contractual terms, and ideally, the framework for design acceptance would be formally delineated in advance of design and construction of repairs and maintenance.

3.3 Durability Planning & Design

Durability planning is a process by which design professionals, contractors, and Owners incorporate durability into design, construction, and maintenance. As such, durability planning is a task that should be considered for every stage in the life of a structure:

- Prior to construction, Owners and design professionals work together on durability design. Decisions are made regarding the overall plan for durability and design service life, and the consequences of design decisions on durability (e.g., resisting environmental loads and minimizing cracking) are assessed. For components and assemblies that are easier to maintain and repair, perhaps less protection might be provided, but for inaccessible or difficult areas to repair, enhanced protection might be considered (e.g., below grade foundations, or areas requiring special access). Figure 3.3 illustrates how different concrete structures require different considerations as to their design for durability. An enclosed (protected) concrete structure might need few to any considerations to provide decades or centuries of service, while exposed monumental concrete structures like government buildings or those exposed to marine environments require care and expertise to last as long.
- During construction, Owners, design professionals, and contractors work together to ensure achievement of the designed durability through proper construction, curing, and quality control. In addition, these parties work together to correct any deviations from the original durability plan that may occur during construction.
- Finally, after construction is complete, Owners and for some projects, builders, are responsible for

Figure 3.3: Comparison of concrete structures requiring reconciliation of durability design requirements with structural requirements. Concrete primary structure that will be protected with a glass facade and protected from the exterior environment (upper left). Boston City Hall constructed with an exposed concrete facade to exterior environment (upper right). Concrete piers exposed to marine environment must be designed to resist these aggressive durability conditions (right).

monitoring and maintenance planning and execution. For builders, this responsibility would be for a set timeframe prior to handing over responsibility to Owners. Design professionals (not necessarily the design professional responsible for the initial design) may also be involved to advise Owners and perform assessment and repair. The remainder of this section discusses durability design in more detail. Durability design forms the framework for the durability planning conducted throughout the life of the structure.

Durability design is a design process undertaken prior to construction or implementation of repairs. It considers the overall goals and limitations of the intended project to achieve a durable concrete structure. Durability goals should be reflected in all project design stages, beginning with the design of the global structure. For a given design service life, environment, and budget, the design professional must ensure achievement of the targeted performance levels for the global structure. Once the global structure requirements are set, structural members must also meet design service life goals with specific capacity and durability requirements for individual members. For example, repair and maintenance of a subgrade pile or foundation is more difficult than an exposed retaining wall; a design professional might then make sure that the pile is more durable or protected (e.g., 100+ year design service life) than the retaining wall (e.g., 50 year design service life). Ultimately, these choices would be ideally made in consultation with the Owner while considering maintenance cycle timing and costs. Finally, as the design progresses, structural requirements are translated into materials properties and must consider good workmanship and constructability. Proper quality assurance and control requirements are critical.

After determination of overall project durability goals, much of durability design is focused on translating these goals into material requirements, construction specifications with acceptance criteria, and quality assurance/control requirements. Without durable concrete materials and sound construction practices, a concrete structure will never achieve the desired service life goals. As discussed in the following sections, it is important for the design professional to select a concrete material design methodology and specification format to best meet the intended goals of the project.

3.3.1 Design Codes & Specifications – Prescriptive vs. Performance-Based Design

Design methodologies are separated into two distinct approaches: 1) prescriptive and 2) performance-based design. Historically, the construction industry relied on prescriptive (deemed-to-satisfy) design and specifications to deliver a concrete structure would meet or exceed project requirements for strength and be durable. Prescriptive Codes define environmental conditions affecting durability like chloride exposure, sulphate exposure, freezing and thawing conditions, etc. and indicate corresponding requirements for water/cementitious materials ratios, air-entrainment, cement replacement with supplementary cementitious materials, and chloride limits, and a design professional or Owner selects the environmental conditions that align with their project, and requirements are set. Prescriptive design Codes are valued for their ease of understanding by design professionals, and simplified interpretation by Code officials and inspectors [3]. These design requirements are then easily translated into prescriptive concrete mixture design specifications to be implemented by a contractor with a concrete producer. Conceptually, the resulting concrete mixture designs are expected to have sufficient durability for the expected exposure but this is rarely directly measured and verified during the construction process or during operations: compliance with specified water/cementitious materials ratios, compressive strength, and occasionally minimum cement contents act as indirect evaluations of durability [4], even though none of these mixture design characteristics have a direct or linear relationship with resistance to chloride penetration, cracking, freeze/thaw damage, or other durability requirements.

Countering this limitation, performance-based design directly targets these requirements with the idea that a project team would design a structure, beginning with the end in mind considering the Owner's preferred design service life, maintenance plan, and cost. The US-based ICC Performance Code defines performance-based design as, "An engineering approach to design elements of a building based on agreed upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria" [5], and a comparison to prescriptive-based design is shown in Figure 3.3.1. Specific to concrete, performance-based

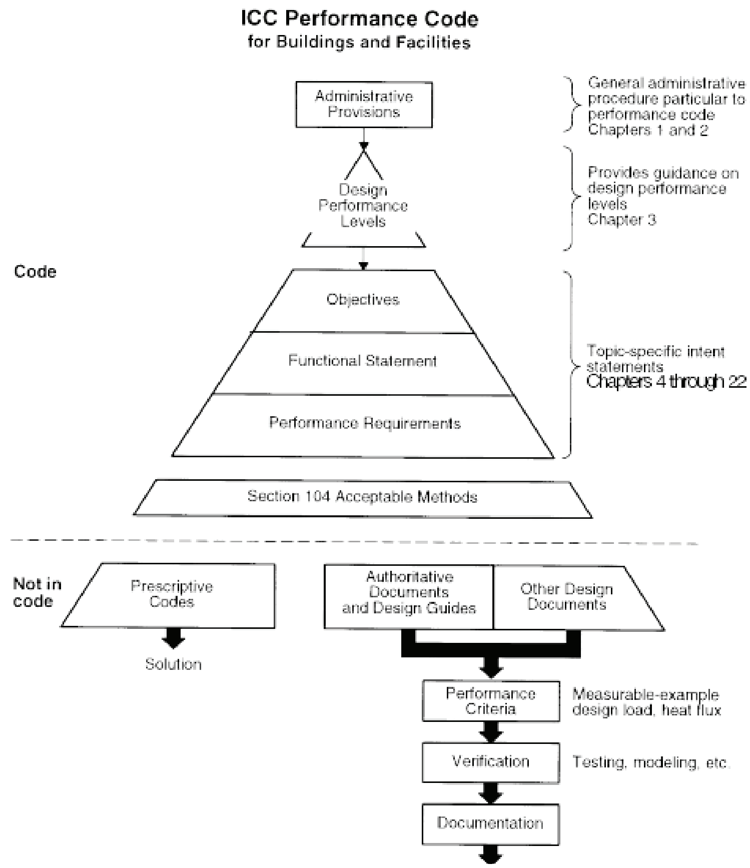


Figure 3.3.1: Summary of process and relationship between US-based International Code Council (ICC) prescriptive Codes versus ICC Performance Code [7].

design and specification has emerged globally in response to the following simply expressed statements:

- "Interest in performance-based requirements is fueled by the changes in practice that have evolved to enhance concrete durability and sustainability" [6].
- "Concrete producers are often required to make concrete according to a customer's recipe, even though they know that they could make concrete that can attain a better performance at a lower price" [8].

In application, performance-based design could mean that a structure could be designed with more innovation and creativity, without preestablished materials and systems for a given structural, durability, or sustainability challenge. A performance-designed structure is then explicitly evaluated to predict its performance, and specifically the risk of not meeting its performance objectives, and uncertainty is calculated. If the performance objectives are not met, then the design or performance objectives are revised [3]. Performance-based design, therefore, directly targets these requirements for concrete structures, and involves specification of required performance objectives, such as compressive strength for structural performance, and durability parameters such as resistance to chloride penetration and freeze-thaw durability but leaves the specific mixture proportions or constituents up to the materials supplier or other party (e.g., sustainability consultant). A materials supplier would then develop a concrete mixture design to satisfy the minimum performance requirements, and submit prequalification testing results or perform new testing to verify performance. Performance-based design relies on the concrete materials supplier's experience, familiarity with locally available materials, and industry standards.

This approach emerged within the last 50 years as a systematic process that allows project teams to consider a range of solutions for a project, rather than a predetermined one [7]. Fire, seismic events, and other extraordinary circumstances and the need for predictable, reliable, durable performance during these events drove the development of this approach. Thus, within performance-based design, ensuring the reliability of a

Table 3.1: Designing with the end in mind, Table 303.3 of 2003 IPC PC correlates permitted damage (mild to severe) to a given performance group of structure to the magnitude of event [7].

TABLE 303.3
MAXIMUM LEVEL OF DAMAGE TO BE TOLERATED BASED ON PERFORMANCE GROUPS AND DESIGN EVENT MAGNITUDES

		INCREASING LEVEL OF PERFORMANCE → PERFORMANCE GROUPS			
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV
MAGNITUDE OF DESIGN EVENT (INCREASING MAGNITUDE OF EVENT ↑)	VERY LARGE (Very Rare)	SEVERE	SEVERE	HIGH	MODERATE
	LARGE (Rare)	SEVERE	HIGH	MODERATE	MILD
	MEDIUM (Less Frequent)	HIGH	MODERATE	MILD	MILD
	SMALL (Frequent)	MODERATE	MILD	MILD	MILD

1. Performance Group I structures include temporary buildings, agricultural facilities, and some storage groups.
2. Performance Group II buildings are those that are not I, III, or IV.
3. Performance Group III buildings are schools, health care facilities, jails, etc. where groups of people congregate and “failure represents a substantial hazard.”
4. Performance Group IV are essential buildings and facilities like hospitals, emergency shelters, water treatment plants, etc.

given system to meet the performance objectives is based upon durability and service life prediction. Advances in concrete-making materials, service life modeling and increased demand for enhanced concrete durability fueled the recent development of performance-based design in the construction industry. With this durability design methodology, the design professional identifies the long-term performance requirements necessary to achieve the desired service life. In this way, necessary concrete mixture performance requirements such as freeze-thaw resistance, resistivity, permeability, and sorptivity are determined directly, rather than assuming these performance requirements will be met if prescriptive requirements are met. Based on the defined criteria, concrete mixture designs are developed that meet or exceed the specific performance requirements.

It is important to note that a design professional can elect to adopt a hybrid design methodology, where the design methodology selected for one aspect of durability is prescriptive, while the design methodology selected for another aspect of durability is performance-based. In this way, the design professional can optimize the durability design by determining performance requirements where necessary and relying on prescriptive design where more specific performance requirements are not necessary. An example of a hybrid design methodology is one where a design professional elects to determine rapid chloride permeability testing (RCPT) requirements in accordance with ASTM C1202 for chloride-induced corrosion resistance but also specified a percentage of air entrainment for freeze-thaw durability, rather than determining the required resistance to rapid freezing and thawing in accordance with ASTM C666. Alternately, a design professional may require different concrete mixture designs depending upon location in the structure.

Both prescriptive and performance-based design methodologies will have required testing to confirm properties of concrete delivered to a site to verify compliance with the design intent. Typical on-site testing will include a measure of consistency (slump test), air content and compressive strength specimens. ACI 318-14, a life-safety prescriptive design Code, requires sampling and testing of fresh concrete for measurement of air content and compressive strength. Acceptance of the in-place material is solely based upon compressive strength test results, consistent with its life-safety framework. If a project team requires that more information is required to evaluate performance, additional tests are not prohibited by ACI 318-14, but there is no formal Code guidance. Additional testing may be used in a performance-based design methodology for confirmation of durability parameters (e.g., chloride penetration verification after a period of time). However, the large criticism of performance-based methodologies is the "lack of reliable, consistent, and standardized test procedures for evaluating concrete performance", and "performance tests can be expensive, are time-consuming, and lack desired precision" [6].

3.3.2 Specification Formats – Prescriptive vs. Performance-Based Specifications

Similar to durability design methodologies, concrete materials specifications can be prescriptive, performance-based, or hybrid. Prescriptive specifications define the requirements for composition and proportioning of the materials used in the concrete mixture. Key features of a prescriptive durability specification include minimum cementitious material contents and maximum water to cementitious materials (w/cm) ratios, among other properties. To confirm adherence to specified mixture proportions, prescriptive specifications incorporate quality control requirements for fresh and hardened concrete properties. The design professional is responsible for the selection of the target performance of the concrete mixture and the confirmation of the suitability of the specified materials and proportions to produce a concrete mixture that satisfies intended project goals. The responsibility of the contractor or supplier is limited to satisfactory compliance with the prescribed specifications and production of consistent concrete batches that satisfy quality control requirements defined by the design professional. Durability is then thought to be achieved by previous successful historic experience with these prescriptive requirements, but durability is not guaranteed. This approach is appropriate for common applications and environments but can be limiting for special applications and more aggressive environments.

In contrast, performance-based specifications define performance requirements against which concrete mixtures are measured. Determination of specific concrete mixture proportions, constituents, and construction means and methods is left up to the contractor or material supplier. A performance-based durability specification may include requirements for shrinkage, corrosion resistance, freeze-thaw resistance, sulfate resistance, or heat of hydration, among other properties. These requirements can also serve as quality control measures if they are specified on an ongoing basis. Based on the defined criteria, the contractor develops concrete mixture designs that meet or exceed the performance requirements. In this specification format, the contractor or supplier is held responsible for the performance and adequacy of the concrete used in the project. Thus, it is critical for the design professional to specify appropriate quality control measures to ensure that the contractor or supplier is continually meeting performance goals. An advantage in this approach is that special applications and environments can leverage the concrete producers' knowledge in addition to the design professional in selecting and evaluating options. In addition, it is easier to consider newer materials and innovative options in this framework.

Hybrid specifications are specifications incorporating both prescriptive and performance-based requirements. Most important in development of hybrid specifications is ensuring that the prescriptive and performance-based requirements do not conflict. ACI 132R-14 "Guide for Responsibility in Concrete Construction" states:

> *The licensed design professional has a responsibility to specify the exposure conditions, concrete properties, and any aspects of the constituent materials, placement, and curing plans that will materially affect the work. These can be specified by a prescriptive method or by establishing performance criteria. The responsibility of the licensed design professional in a combined performance and prescriptive specification is to specify criteria that are consistent, compatible, and possible to perform.*

Allocation of responsibilities for concrete mixture performance is difficult when utilizing a hybrid specification format. While the contractor or supplier is required to meet performance requirements, various prescriptive requirements have myriad effects on fresh and hardened concrete properties. As such, care must be taken during development of prescriptive or hybrid specifications to ensure that all project goals are met, rather than improving one characteristic to the detriment of others. For example, specification of an excessively high cementitious material content and an excessively low w/cm ratio will improve durability but can result in concrete mixtures with insufficient workability. Insufficient workability can lead to honeycombing, which reduces durability, the very characteristic meant to be improved. Ultimately, responsibility of performance must be compatible with the authority to design and adjust concrete mixtures.

Typically, the format of project specifications follows the selected design methodology, though such conformity is not necessary. Prior to construction, a design professional may elect to determine performance-based requirements to assist in specifying prescriptive requirements for use during construction. However, prescriptive durability design will always result in prescriptive concrete mixture specifications.

Prescriptive, performance-based, and hybrid specifications exhibit a number of differences in the overall structure, responsibility allocation, and nature of technical requirements. During the durability design process, it is imperative for the design professional to identify the specification format and provisions that would best meet the project goals. Without an appropriate specification, the most sophisticated durability design prior to construction may result in a completed concrete structure that lacks durability. Furthermore, selection of the quality control measures and associated limits that will reliably and adequately define expected performance is critical for the successful implementation of any specification.

3.4 Durability Challenges for Concrete Structures

Concrete is a composite, multi-phase construction material that is produced from a combination of manufactured materials (portland cement and chemical admixtures), processed naturally-occurring materials, and water, with industrial by-products / residual materials commonly used. Reinforcing steel and other reinforcement materials add to the complexity of the durability problem. Durability challenges for reinforced concrete structures can originate with the concrete materials, reinforcing steel or from the exposure. A brief list of possible deterioration and damage mechanisms are listed in Table 3.2, and specific durability considerations for concrete structures include:

- Like any other building material, concrete changes with time, reacting to its environment and deteriorates at some rate, accelerated in warmer temperatures and exterior exposure.
- Consensus in defining fundamental durability requirements, like the maximum allowable amount of chlorides in fresh concrete, is a challenge even for a leading developer and distributor of concrete information like ACI [9]. No less than 12 ACI documents refer to chloride limits without harmonization as to what they should be.
- Construction materials are constantly improving (or changing), hampering attempts to predict service life for new structures or members. As service life expectations increase, traditional prescriptive specification requirements might not assure durability.
- New environments can change a structure from performing as expected to being deficient.
- Changing service loads change the performance requirements. If demands exceed capacity, then unacceptably poor performance can arise.
- Level of maintenance can change the expected service life.

Table 3.2: Typical deterioration challenges for structures.

MATERIALS	STRUCTURAL SYSTEMS
Corrosion • Chloride-induced • Carbonation-induced	Structural overload & cracking
Freeze-Thaw Damage	Unanticipated thermal and moisture gradients
Leaching	Shrinkage and creep
Salt Crystallization	Improper drainage
Alkali-aggregate reactions	
Chemical attack (acid, sulphate)	

4 Significant Investigative Findings

4.1 General

The review of global Codes and standards for durability design revealed substantial variations in how durability design is approached and implemented. Tables 4.1 to 4.4 present a summary of the documents reviewed (4.1) and how the various documents approach durability design (4.2 - 4.4).

4.2 Terminology

A review of the collected terms in Appendix A indicates that although there are differences in phrasing or scope, global documents and standards generally have consensus about the content and expression of a given term, with some exceptions (e.g., service life). The investigators observed, however, that for many of these critical terms there are numerous definition variations used within ACI documents, depending upon the focus of the document. As an example, "service life" is routinely stated within ACI documents (ACI 318-Commentary only, ACI 350, etc.), and often is not defined in their terms and definitions list, or there is a reference to ACI 365.1, to cover how the term might be interpreted. Global standards, ACI 365.1, and ACI 562 refer to "design service life" as this refers to a specific period of time in a particular service environment when major repairs are not anticipated. In contrast, "service life" can mean almost anything. Imprecise or conflicting terminology can lead to confusion in document comprehension and problems in Code-interpretation for design professionals and Code officials.

Table 4.1: Brief summary of technical focus area of reviewed documents.

Document	Year	Document Title	Region	Focus Area[1]	Code / Standard/ Guideline/ Report
AASHTO LRFD Design	2017	LRFD Bridge Design Specifications, 8th edition	International	New Design	Code
ACI 201.2R	2016	Guide to Durable Concrete	International	General Durability	Guideline
ACI 222R	2001	Protection of Metals in Concrete Against Corrosion	United States	Corrosion	Guideline
ACI 301	2016	Specifications for Structural Concrete	United States	Specification	Standard
ACI 318	2014	Building Code Requirements for Structural Concrete	International	New Design	Code
ACI 350	2006	Code Requirements for Environmental Engineering Concrete Structures	United States	New Design	Code
ACI 350.4R	2004	Design Considerations for Environmental Engineering Concrete Structures	United States	Environmental Structures	Guideline
ACI 350.5	2012	Specifications for Environmental Concrete Structures	United States	Specification	Guideline
ACI 357.3R	2014	Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures	United States	Marine/Coastal Structures	Guideline
ACI 362.1R	2012	Guide for the Design and Construction of Durable Concrete Parking Structures	United States	Parking Structures	Guideline
ACI 365.1R	2017	Report on Service Life Prediction	United States	Service Life Modeling	Guideline
ACI 562	2016	Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary	International	Repair	Code
AS 3600	2018	Concrete Structures	Australia	Design	Code
CIA Z7/01	2014	Durability Planning	Australia	Durability Planning	Guideline
CIA Z7/04	2014	Good practice through Design, Concrete Supply and Construction	Australia	General Durability	Guideline
CIA Z7/06	2017	Concrete Cracking and Crack Control	Australia	Cracking	Guideline
CIA Z7/07	2015	Performance Tests to Assess Concrete Durability	Australia	Durability Testing	Guideline
CSA A23.1-14/A23.2-14	2014	Concrete materials and methods of concrete construction / Test methods and standard practices for concrete	Canada	New Design	Standard
CSA A23.3	2004	Design of Concrete Structures	Canada	New Design	Standard
CSA A23.4	2016	Precast Concrete – Materials and Construction	Canada	Design	Standard
CSA S413	2014	Parking Structures	Canada	Design	Standard

Table 4.1: Brief summary of technical focus area of reviewed documents (cont'd).

Document	Year	Document Title	Region	Focus Area[1]	Code / Standard/ Guideline/ Report
CSA S448.1	2010	Repair of Reinforced Concrete in Buildings and Parking Structures	Canada	Repair	Standard
CSA S478	2007	Guideline on Durability of Buildings Structures (Design)	Canada	Design	Standard
EN 1990	2002	Eurocode – Basis of structural design	Europe	Design	Code
EN 1992-1-1	2004	Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings	Europe	Design	Code
EN 1992-3	2006	Eurocode 2: Design of concrete structures – Part 3: Liquid retaining and containment structures	Europe	Design	Code
EN 206	2013	Concrete – Specification, performance, production and conformity	Europe	Specification	Standard
fib MC2010	2010	Model Code for Concrete Structures 2010	International	Design	Code
fib Bulletin No. 34	2006	Model Code for Service Life Design	International	Service Life-based Design	Code
GB/T 50476	2008	Code for Durability Design of Concrete Structures[2]	China	Design	Code
ISO 13823	2008	General principles on the design of structures for durability	International	Design	Standard
ISO 15686	2008-2017	Buildings and constructed assets – Service life planning	International	Service Life	Standard
ISO 16204	2012	Durability – Service life design of concrete structures	International	Design	Standard
ISO 16311-1 through -4	2014	Maintenance and repair of concrete structures	International	Repair	Standard
ISO 19338	2014	Performance and assessment requirements for design standards on structural concrete	International	Code Evaluation	Standard
JSCE Guidelines for Concrete No. 15	2007	Standard Specifications for Concrete Structures – 2007 "Design"	Japan	Design	Standard
JSCE Guidelines for Concrete No. 16	2007	Standard Specifications for Concrete Structures – 2007 "Materials and Construction"	Japan	Specification	Standard
MarCom WG 162	2016	Recommendations for Increased Durability and Service Life of New Marine Concrete Infrastructure	International	Marine/Coastal Structures	Guideline
TCVDVN 318	2004	Concrete and Reinforced Concrete Structures, Guide to Maintenance	Vietnam	Maintenance	Standard
UFGS-03 31 29	2012	Unified Facilities Guide Specifications	United States	Marine/Coastal Structures	Standard
USBR Concrete Manual	1981	US Bureau of Reclamation Concrete Manual	United States	Water Infrastructure	Guideline

1) A Focus Area of "Design" indicates that the document applies to new and existing structures, while "New Design" and "Repair" indicate that the document applies to new and existing structures, respectively.

2) A non-official English translation of this Code was reviewed, in concert with summaries of content contained in (1).

Table 4.2: Durability requirements within Codes and specifications.

Document	Prescriptive, Performance-based, or Hybrid	f'c	w/cm Ratio	Concrete Cover	Cementitious Materials Content	Air Content	Cement Type	Chloride Content Limits	Performance Requirements
AASHTO LRFD Design	Typically prescriptive, with some performance classes	Yes	Yes	Yes	Yes	Yes	Yes, by reference to other AASHTO stds	Yes, by reference to other AASHTO stds	As specified by user
ACI 301	N/A – Specification relying upon prescriptive requirements from design professional.	-	-	-	-	-	-	-	-
ACI 318	Prescriptive, with select provisions containing performance alternatives	Yes	Yes	Yes	Yes	Yes	Yes	Yes	ASTM C1012 in lieu of sulfate exposure cement type restrictions.
ACI 350	Based upon ACI 318 with changes related to environmental structures.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
ACI 350.5	N/A – Specification relying upon prescriptive requirements from design professional	-	-	-	-	-	-	-	-
ACI 562	Performance-based, relying upon characteristics of existing structure and design professional requirements	NA	NA	NA	NA	NA	NA	NA	Design for durability shall consider the repair area, surrounding concrete and the interaction of the repair with the surrounding structure.
AS-3600	Typically prescriptive but allows for one concrete class to be entirely performance-based	Yes	No	Yes	No	Yes	No	Yes	Class U concrete properties are specified by the user "to ensure durability under the particular exposure environment."
CSA A23.1/A23.2	Typically prescriptive but allows all prescriptive requirements to be superseded by performance requirements.	Yes	Yes	Yes	No	Yes	Yes	Yes	A23.2-23C Testing (RCPT) for concrete classes C-XL, A-XL, C-1, and A-1.

Table 4.2: Durability requirements within Codes and specifications (cont'd).

Document	Prescriptive, Performance-based, or Hybrid	f'c	w/cm Ratio	Concrete Cover	Cementitious Materials Content	Air Content	Cement Type	Chloride Content Limits	Performance Requirements
CSA A23.3	N/A – References other A23 documents for durability requirements	-	-	-	-	-	-	-	-
CSA A23.4	N/A – references A23.1 for mixture proportions/durability and A23.3 for structural design	-	-	Yes, as it is reduced from cast-in-place concrete.	-	-	-	-	References A23.1
CSA S413	Hybrid – references A23 documents with some modifications	Yes	Yes	Yes	No	Yes	Yes	Yes	A23.2-23C Testing (RCPT) for concrete classes C-XL, A-XL, C-1, and A-1.
CSA S448.1	N/A – References A23 documents for durability requirements	-	-	-	-	-	-	-	-
CSA S478	N/A – references A23 documents for specific materials and systems. This is a building standard, not specific to concrete.	-	-	-	-	-	-	-	-
EN 1990	N/A – Umbrella Code for all structural materials. Requires that durability be considered but refers to EN 1992 through EN 1999 for specific recommendations	-	-	-	-	-	-	-	-
EN 1992-1-1	N/A – Umbrella concrete requirements and discusses general framework of how durability should be treated but refers to EN 206 for more specific methods.	-	-	-	-	-	-	-	-
EN 1992-3	N/A – Liquid containment structures specific	-	-	-	-	-	-	-	Adds additional requirement to EN 1992-1-1 that abrasion should be considered
EN 206	Hybrid – allows for entirely prescriptive or entirely performance-based concrete classes	Yes	Yes	No	Yes	Yes	Yes	Yes	No specific requirements or methods listed.
fib MC2010	Hybrid—allows entirely prescriptive or entirely performance-based concrete classes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No specific requirements or methods listed.
GB/T 50476	Prescriptive	Yes	Yes	Yes	Yes	Yes	--	Yes	--

Table 4.2: Durability requirements within Codes and specifications (cont'd).

Document	Prescriptive, Performance-based, or Hybrid	f'c	w/cm Ratio	Concrete Cover	Cementitious Materials Content	Air Content	Cement Type	Chloride Content Limits	Performance Requirements
JSCE Guidelines for Concrete No. 15	Performance limit states, with informative prescriptive means by which the performance requirements can be met	No	No	No	No	No	No	No	All durability requirements are performance-based.
JSCE Guidelines for Concrete No. 16	Performance limit states, with informative prescriptive means by which the performance requirements can be met	No	Max. 0.65	No	No	Limited to assume air-entrainment	No	Limited to max. 0.3 kg/m^3	All durability requirements are performance-based, with limited max requirements.
TCVDVN 318	Performance-based, relying upon characteristics of existing structure and design professional requirements	NA	NA	NA	NA	NA	NA	NA	Design for durability shall consider the repair area, surrounding concrete and the interaction of the repair with the surrounding structure.
UFGS-03 31 29	Specification with some prescriptive and performance-based requirements.	No	No	No	No	No	No	Yes	Includes drying shrinkage and freeze-thaw requirements, and requires durability modeling by proprietary software.

Table 4.3: Key attributes of Codes and standards with respect to durability.

Document	Design Service Life (excl. or ranges)	Modeling Requirements	Performance Metric Verification	Construction Requirements & QA/QC	Maintenance/Repair[1]
NBC	N/A	N/A	N/A	N/A	N/A
AASHTO LRFD Design	75 years	No	No	No	No
ACI 301	No	No	No	Yes	No
ACI 318	No	No	No	Yes	No
ACI 350	50-60 years	No	No	Yes	None, except for reference that some assembly components will need replacement sooner than 50-60 years.
ACI 350.5	No	No	No	Yes	No
ACI 562	To be selected by design professional with Owner	No	No	Yes	No
AS-3600	40-60 years	No	No	Yes	No
CSA A23.1-14/A23.2-14	Yes, by reference to other Canadian stds	Yes, for special concretes.	N/A	Yes	No
CSA A23.3	Yes, by reference to other Canadian stds	Yes, for special concretes.	N/A	No	No
CSA A23.4	Yes, by reference to other Canadian stds	Refers to A23.1 and A23.3	Refers to A23.1 and A23.3	Transportation and installation yes, but no specific QA/QC.	Repair only, both aesthetic and structural. Maintenance is considered in Appendix as part of environmental sustainability.
CSA S413	Yes, by reference to other Canadian stds	Yes, for special concretes.	N/A	Yes	Yes
CSA S448.1	Yes, by reference to other Canadian stds	Yes, for special concretes.	N/A	Yes	Yes
CSA S478	Yes, as categories for buildings and parking structures.	--	--	Yes	Yes
EN 1990	To be specified by user	No	Yes	Yes	Yes
EN 1992-1-1	To be specified by user	No	Yes	Yes	Yes

Table 4.3: Key attributes of Codes and standards with respect to durability (cont'd).

Document	Design Service Life (excl. or ranges)	Modeling Requirements	Performance Metric Verification	Construction Requirements & QA/QC	Maintenance/Repair[1]
EN 1992-3	To be specified by user	No	N/A – refers to EN 1992-1-1	Yes	Yes
EN 206	To be specified by user	No	N/A – verification governed by EN 1990 and EN 1991-1-1	Yes	Yes
fib MC2010	To be specified by user	Yes	Yes	Yes	Yes
fib Bulletin No. 34	N/A—to be specified by use in *fib* MC 2010	Yes	Yes	Yes	Yes
GB/T 50476	Yes, 30/50/100 years	No	No	Yes, but also references GB 50204 for acceptance criteria.	No
ISO 13823	Yes	Yes	Yes, reliability approach.	No	Yes – can be used for existing structures.
ISO 15686-1 through -10	Yes	Yes	Yes, reliability approach.	Yes	Yes
ISO 16204	Yes	Yes	Yes	Yes	Yes
ISO 16311-1 through -4	Yes	Yes	Yes (16311-1; others refer to 16311-1)	Yes, 16311-3 and I6311-4	Yes
ISO 19338	Yes	Yes – permits them.	Yes – permits them.	Yes	Yes
JSCE Guidelines for Concrete No. 15	To be specified by user	No	Yes	Included as part of JSCE Guidelines for Concrete No. 16	Included as part of JSCE Guidelines for Concrete No. 17
JSCE Guidelines for Concrete No. 16	To be specified by user	No	Yes	Yes	Included as part of JSCE Guidelines for Concrete No. 17
TCVDVN 318	To be selected by design professional with Owner	No	No	Yes	Yes
UFGS-03 31 29	To be specified by user	Yes	N/A	Yes	No, only for new construction non-compliant work.

1) Maintenance and repair activities refers to work performed during operational service life of the structure, and not that needed to accept a new structure or member.

Table 4.4: Key attributes of guides and reports.

Document	Design Service Life (excl or ranges)	Modeling Requirements	Performance Metric Verification	Construction Requirements & QA/QC	Maintenance/Repair[1]
ACI 201.2R	No	No	No	No	No
ACI 222R	No	No	No	Limited	Yes, references ACI 222.3 for additional information
ACI 350.4R	No	No	No	Limited	No
ACI 357.3R	Yes, indicates modeling service life could be useful.	No	No	No	Yes
ACI 362.1R	No	No	No	Limited	No
ACI 365.1R	No, includes methodology to perform service life prediction.	Yes	Sensitivity analysis.	No	Yes
CIA Z7/01	Yes	Limited, refers to Z7/06	N/A	Yes	Yes
CIA Z7/04	No, refers to Z7/01	No	No	Yes	Yes
CIA Z7/06	No, refers to Z7/01	Yes	Yes	Yes	Yes, of cracks.
CIA Z7/07	No, refers to Z7/01	No	No	Yes	No
MarCom WG 162	Yes, in that 100 or 150 year service life calculations are referenced, without a mandate.	Yes	Yes	Yes	Yes
USBR Concrete Manual	No	No	No	Yes	Yes

1) Maintenance and repair activities refers to work performed during operational service life of the structure, and not that needed to accept a new structure or member.

4.3 Categories of Design Service Life

Unlike the ACI's Codes and standards for buildings, Australia, Canada, China, Europe's EN 1990, and *fib* Model Code 2010 have design service life categories embedded in Codes and standards. As an example, Canada's categories for buildings, including parking structures, are shown in Table 4.5. Chinese durability Code GB/T 50476 also has provisions that discriminate between plates/walls and beam/column members in a concrete structure, shown in Table 4.6.

For bridges, there is limited design guidance or requirements, however, Australia's CIA Z7/01 stipulates bridge systems require a design service life of 100 years (CIA Z7/01, Table 4.1) while AASHTO's LFRD design manual stipulates 75 years.

Without any reference to categories, ACI's Code for environmental structures, ACI 350, instead prescribes using the provisions of ACI 318 with the assumption that 50 to 60 years of service life will be achieved for the structural concrete. ACI's concrete repair Code, ACI 562, does not list design service life categories, either, and instead requires a design service life for a given repair or rehabilitation program be set in consultation with the Owner.

Table 4.5: Canadian categories of design service life for buildings (CSA S478, Table 2).

Table 2
Categories of Design Service Life for Buildings
(See Clauses 5.2.3 and 6.2.)

Category	Design service life for building	Examples
Temporary	Up to ten years	• non-permanent construction buildings, sales offices, bunkhouses • temporary exhibition buildings
Medium life	25 to 49 years	• most industrial buildings • most parking structures*
Long life	50 to 99 years	• most residential, commercial, and office buildings • health and educational buildings • parking structures below buildings designed for long life category*
Permanent	Minimum period, 100 years	• monumental buildings (eg, national museums, art galleries, archives) • heritage† buildings

** Parking structures should have a design service life at least equal to the building they serve, except parking structures serving long life category buildings may be designed for medium life provided they are not located directly under the long life superstructure or provided deterioration of the parking structure would not adversely affect the building served. See CSA Standard S413.*

† Buildings are not designed as a heritage structures but may be assigned the designation by virtue of their historical significance. One purpose of applying such a designation to a building is to ensure that, henceforth, it will be preserved permanently. The concepts contained in this Guideline will be of assistance in establishing appropriate maintenance and repair programs for designated buildings.

Table 4.6: Design service life and durability requirements adjusted according to building member type (GB/T 50476, Table 7.3.2).

Table 7.3.2 the Minimum Thickness C of Concrete Material and Reinforced Protective Layer Under Chemical Corrosion Environment (mm)

Environmental action grades \ Design service life		100 years			50 years		
		Concrete strength grades	The maximal water to binder ratio	c	Concrete strength grades	The maximal water to binder ratio	c
Surface shape structures such as plate and wall	V-C	C45	0.40	40	C40	0.45	35
	V-D	C50	0.36	45	C45	0.40	40
		≥C55	0.36	40	≥C50	0.36	35
	V-E	C55	0.36	45	C50	0.36	40
Stripped structures such as beam and column	V-C	C45	0.40	45	C40	0.45	40
		≥C50	0.36	40	≥C45	0.40	35
	V-D	C50	0.36	50	C45	0.40	45
		≥C55	0.36	45	≥C50	0.36	40
	V-E	C55	0.36	50	C50	0.36	45
		≥C60	0.33	45	≥C55	0.36	40

Note: 1 Protective layer thickness of precast members may be reduced by 5mm than that in the table;

2 Protective layer thickness of prestressed reinforcement complies with Article 3.5.2 of this code.

4.4 Durability Planning

Within the listed global resources, Australia, Canada, Japan, and ISO have standards or guides that specifically detail conceptually or in great detail how to plan for durability:

- Australia's CIA Z7/01 delineates key roles, activities, and best practices by stage of construction from concept to construction administration and during operation.
- Canada's CSA S478 combines the concepts of durability, design service life, and apportions activities by construction stage from design and construction to operation, maintenance, repairs, and renovation.
- Japan's JSCE No. 15 and No 16 treat durability as a process with limit states confirmed at each construction stage with verification steps of key criteria before a design professional or constructor can advance to the next stage (e.g., anticipated crack width is monitored with respect to a limit state for risk of chloride ingress).
- ISO has multiple documents, ISO 13823, ISO 15686, and ISO 16204 which address a comprehensive review of durability planning with respect to service life.

Other documents, like MarCom WG 162 from the US, offer recommendations targeted to new marine infrastructure and include guidance for lifecycle costing, selection of design service life, prescriptive versus performance durability approaches, but is not written in mandatory language and would require work to harmonize with buildings. Of greatest importance is that these standards and guides often coordinate durability design into the quality assurance process, such as that shown in Table 4.7 from Canada's CSA S478.

Table 4.7: Quality assurance activities are tied to durability design (CSA S478, Table 1).

Table 1
Quality Assurance and the Building Process
(See Clause 5.1.)

Stage in Building Life Cycle	Quality Assurance Activity	Reference Clauses
Conception	• establish appropriate levels of *performance* for building and *components*	4, 6
Design – detail – specify	• prescribe *performance* criteria for materials, *components*, and *assemblies* • confirm acceptability and achievability of *performance* • specify test options (prototype, in situ, etc)	6, 7, 8, 10
Tendering	• review design documents, including *performance* specifications • accept requirements (contractor) • accept tender(s) (owner)	8, 9
Construction	• control through • review of process and product • sampling and testing • correction of deficiencies • certification of work	5, 8, 9
Handover	• commissioning • verification of *performance* of completed building by testing under operational loads	10, 11
Operation and Maintenance	• monitor *performance* • inspect for deterioration or distress • investigate problems • certify work	10, 11, 12
Renovation	• same as for Conception and Design, above	13

Overall, there appears to be a wealth of global consensus information in both guide and standards formats, but ACI does not appear to have similarly formatted information except as discrete documents that might not reference once another.

4.5 Comparison of ACI Codes and Standards with Global Documents

The review of global Codes and standards identified a number of features that are not present in ACI Codes and standards. Some of the common features identified (beyond concrete material requirements) in global Codes and standards that impact durability include:

- Design approaches that addresses durability design as part of a multi-disciplinary process
- Explicit consideration that durability design requirements change with design service life
- Consideration that maintenance and repair of structures will be required during the service life
- Use of service life modeling as a predictive tool for durability
- Performance based requirements for concrete materials

Current ACI documents, including ACI 318, all incorporate some of the items listed above, however the documents are not integrated to create a unified approach to durability design or framed as a planning exercise (e.g., CIA Z7/01). In particular, the ACI documents tend to be siloed, as they provide detailed information about a particular topic or type of structure but lack the integration needed for durability through the service life of a structure. Some of the features that are notable in the ACI documents related to durability include:

- ACI design Codes for new construction and repair, ACI 318 and 562, respectively, do not explicitly address or define the expected service life of a structure. ACI 318 specifically excludes "preventative maintenance". ACI 562 does reference a "design service life" be selected in consultation with the Owner of a structure (i.e., the Owner's expected service life), and this is coordinated with the corresponding maintenance plan, also agreed upon with the Owner.
- ACI 201 provides a detailed review of concrete durability from a mechanistic approach but does not provide significant content for a design professional interested in design for an extended service life.
- ACI 365 describes the mechanisms of calculations needed to model service life for a number of approaches, but does not provide guidance similar to a design method such that standardized, reproducible results can be obtained.
- ACI 318 allows for use of stainless steel and other types of corrosion resistant reinforcement, but only provides limited information on when use of corrosion resistant reinforcement is warranted. ACI 562, Chapter 8, requires that a licensed design professional "consider" corrosion implications, but does not provide a rationale for stainless steel selection and refers to other references within ACI documents.
- ACI 318 separates design requirements for durability of steel reinforcement (Section 20.6) from the design requirements for durability of concrete materials (Section 19.3) rather than designing a durable reinforced concrete structure.
- ACI 318 provides no information on future maintenance requirements or planning for future repairs for a structure. ACI 562 does mandate development of a maintenance plan.

4.6 Interview Comments & Discussions

For the purposes of understanding global perspectives, the investigative team sought personal opinions and feedback on their respective country's Codes, standards, and general guidance from Australia, Canada, China, Japan, and United States. Of these, only Canada and US responded in sufficient numbers to present a more comprehensive viewpoint, such that one respondent did not respond for all. The investigators sought information from design professionals, academics (educators), Code developers, contractors, and concrete producers. Interviews were conducted with a focus on how durability provisions within these global Codes and standards are taught, implemented, and understood within the concrete industry. In addition, interviewees were asked about drawbacks of durability provisions within these global documents and ways in which the durability provisions could be improved. Only a limited number of contacts were possible, and even so, only representatives of Canada and the USA responded during the investigative timeframe. The following general consensus topics emerged. A consolidated summary of the questions and responses is presented in Appendix C.

Even with durability provisions embedded in their Codes (Canada, USA), the first instinct of a structural engineer is to rationalize compressive strength (f'c), and what the structural performance requirements are. Durability is a secondary consideration and the role of a separate design professional, if the need for one is recognized.

In neither country did it seem that an experienced structural engineer was also an expert in durability, unless they were also experienced in repair and rehabilitation of concrete structures. Conversely, for "special or complicated structures", it appears customary that a durability-focused expert is included in the design team.

Much of the education related to durability design is received on-the-job, rather than as a student. Typically, structural design courses are not integrated with concrete materials courses. Moreover, durability classes at college or university are limited and likely only graduate level courses.

It is possible for a design professional to design, document, and seal a set of drawings without truly understanding the following concrete parameters: water/cement ratio, air-entrainment, and supplementary cementitious materials, even if these parameters are prescribed in Codes. It appears that if durability and service life requirements are discussed in the Codes, structural engineers could seek to conform with the requirements. However, it appears that even with Code requirements, non-conformance to the Codes is not unusual. Poor or incomplete contract documents, adding water for workability onsite, and acceptance of sub-standard concrete because of schedule constraints, are examples of non-conformance to the Codes.

There is no evidence that contractors consider the durability and service life requirements, unless specifically obligated to do so, and the construction and payment schedule is paramount. They might not be privy to the Owner's Project Requirements or Conceptual design documents, where such information could be documented; they only see the administrative and technical requirements. Even so, they will only build what they are contractually obligated to do, or even less: concrete producers in Canada report routine use of the "request for information" process to clarify what mixture proportions and additives are required for any given placement, and too often, concrete that does not meet the Code requirements is purchased and delivered. In Canada, concrete producers are in the habit of overdesigning mixtures for strength and workability, at their expense, to compensate for a lack of engineering design and poor construction practices onsite by contractors that damage the concrete (e.g., adding additional water pre-placement, not prescribed by the concrete plant).

Concrete is a highly sophisticated, engineered material, for both structural design and durability design requiring expertise from contractors and the concrete supplier to execute properly.

In the US, there can be specialty guides and reports for wastewater treatment plants, nuclear structures, and infrastructure, but for the average building, Code requirements are not tailored. Unless those specialized documents exist, it is difficult for a design professional to know what they do not know. Design professionals might not recognize that exposed structures like a high-rise condominium on a beach in Miami, Florida, or a parking structure in Philadelphia, PA, might need additional requirements beyond generic Code minima to be durable for a period of time specified by the Owner. Moreover, an Owner has trouble discriminating amongst a field of design professionals to discern who is a generalist and who is a specialist for a given application.

5 Discussion

5.1 General

The review of global design Codes and standards revealed diverse methods for addressing durability and achieving some framework of service life (i.e., design or working service life, or a long-term expected service life). Some documents, such as JSCE Guidelines for Concrete No. 15, Canada's S-series standards, and Australia's CIA documents provided rigorous treatment of durability concepts. In other documents, durability could simply refer to getting drainage of water off of a member or structure (e.g., ACI 357.3, ACI 362.1, GB/T 50476) and maintaining prescriptive requirements for concrete. The review demonstrated significant differences between the ACI 318 design standard and comparable international documents. Durability design via ACI 318 is intended to be achieved via tailoring of the concrete mixture design and cover based upon the expected service environmental exposure, and consideration of the environmental exposures is typical of all Codes. No consideration is given in ACI 318 to the expected design service life of the structure, or future maintenance that may be required.

More in-depth Codes and their accompanying supporting standards and reports include design service life and service life prediction as part of design, either prescriptively "deem-to-satisfy" or through modeling "limit states", or both. Model verification is also included, and durability design is integrated into structural serviceability states. However, the literature review showed that, even in the more in-depth documents, best-practices for durability continue to be sought. Durability design is most straight-forward for simple structures and challenging for more complicated structures and environments.

The reviewed global Codes and standards typically approached durability design with a more holistic approach than ACI. The concept of durability design and planning is perhaps best stated in Section 4.9 of CIA Z7/01:

> There is real value in reviewing performance outcomes from previous projects to understand how acceptable durability was achieved and to identify mistakes that should be avoided (i.e. include lessons learnt feedback from past projects with stakeholder review workshops).
>
> Concrete durability is significantly influenced by the structural form plus the quality/composition of all concrete mix design materials and workmanship available in the specific locality.
>
> Furthermore, the design and construct method of project delivery can exacerbate the situation as the drive to come up with the most cost effective design and lowest construction costs can result in robust solutions being pared down to the extent that the durability performance is compromised or cannot be realised to the asset owner's preferred intent. Again, it is the performance of existing structures that can provide the best assessment of 'what works in practice and what does not'.

The overall concept embodied above is that long-term durability design involves more than selection of concrete materials that are appropriate for the project location. Long-term durability for new structures originates with the understanding of Owner intent for expected service life, design details that minimize potential durability problems, appropriate material selection and understanding of expected future maintenance.

The holistic approach for Codes to allow for the creation of structures with extended service lives in aggressive environments needs to be balanced with the recognition that many structures will be located in "ordinary or non-aggressive environments" and may not require an extended service life. The Code user survey generally agreed with this assessment, with many users stating a preference for prescriptive requirements for the majority of the work they perform. The need for Codes to address both situations highlights the value of a durability planning document such as CIA Z7/01.

Globally, the role of the structural engineer in durability varies. Australian guidance questions whether a structural engineer should be responsible for durability without "training or relevant experience" (CIA) and indicates that durability design can be a separate role. Japanese experts believe it is not possible to design a new structure or repair an existing one without durability considerations, however, it is the authors' observation that environmental/durability engineers can be distinct from structural engineers (i.e., the Japanese already have an integrated design process with both structural and "environmental" engineers working together).

In the United States, monumental or special projects may involve a separate durability consultant; however, for most projects, durability design is left up to the structural engineer. Despite this responsibility, many design professionals in the United States indicate that durability design education is primarily conducted on-the-job, rather than through formal courses. Further development of ACI Codes and Standards will encourage further education and awareness of durability concerns.

The comparison of ACI and international building Codes also identified a difference in perception on the origin of durability in concrete structures. In simple terms, a durable concrete structure is one that has the following overall characteristics, when applicable:

- Designed and constructed to promote drainage from the structure;
- Limited number and width of cracks of exposed surfaces under service conditions;
- Concrete with low drying shrinkage to limit the potential for crack to form and crack widths;
- Concrete with a low permeability and high resistance to chloride ion penetration;
- Adequate air-void system to prevent freeze-thaw damage;
- Concrete with suitable aggregates and cementitious materials to limit alkali-aggregate reactions;
- Concrete that is resistant to sulfate attack; and
- Redundancy of mechanisms for corrosion protection in critically exposed areas.

ACI design Codes focus on concrete materials requirements, and concrete cover for durability. Recent changes in ACI 318 have eliminated consideration of expected cracks widths during the design process, and have trended towards members designed to be cracked in service (class C prestressed concrete members). Other global Codes have retained these criteria and it is subject to verification procedures in performance-oriented Codes. The systematic approach to durability design is not captured in current ACI documents.

5.2 Focus Area

The reviewed documents provided a wide variety of focus areas and target audiences. The Codes and standards were generally focused on design, construction, and maintenance or some combination of the three. The guidelines and reports, on the other hand, were typically much more focused in scope, with emphasis placed on one aspect of concrete durability such as planning or service life modeling.

Codes and standards differ from reports and guidelines in that they contain mandatory language and can be adopted by legal authorities. Thus, Codes and standards are much more widely used in design, whether new or existing, because design professionals are legally obligated to meet their requirements. However, Codes and standards typically lag behind the state-of-the-art in concrete design and construction. Reports and guidelines, on the other hand, are typically produced and updated as concrete technology evolves. As such, of the reviewed documents, the reports and guidelines were most reflective of the current state of durability design.

Many of the ACI technical reports and guidelines had comparable counterparts from other countries. However, one noticeably absent subject matter missing from ACI documents was a rigorous treatment of durability planning, such as that contained within ISO 15686 or CIA Z7/01. Such documents create awareness within design professionals that durability should be considered at the beginning of design and should consider the entire life of the structure, not just the beginning of service.

Much of the potential further development of ACI Codes and Standards as it pertains to durability are already contained within existing industry guidelines and reports, such as ACI 201.2R, ACI 365.1R, CIA Z7/01, and CIA Z7/04. The existing framework of ACI Codes and Standards does not need to be completely abandoned. However, it is clear that many of the reports and guidelines and some other Codes and Standards are more sophisticated in their treatment of durability than the current ACI Codes and Standards.

5.3 Prescriptive, Performance-based, or Hybrid

Prescriptive, performance-based, and hybrid requirements each provide unique advantages and disadvantages. Traditionally, industry Codes have handled durability through prescriptive requirements like w/cm, crack control, air-entrainment, and cement type and content. Indeed, most of the industry Codes examined provided prescriptive requirements, though to varying degrees. In instances where prescriptive requirements were not provided, optional prescriptive means to meet performance requirements were provided, such as in JSCE Guidelines for Concrete No. 15. Prescriptive requirements are convenient in that they typically have a proven track record and are widely applicable to various structure types and exposure conditions, and a concrete producer likely has produced mixtures suitable for a given standard and is rigorously tested. For simple structures with typical exposures, prescriptive requirements are generally more than sufficient to ensure durability. However, prescriptive requirements may be insufficient in more complicated design scenarios (e.g. manufacturing and extreme environments), certain types of structures (e.g. tanks, chimneys, water containment, and nuclear), long service lives (e.g. bridges, monuments), and planning for maintenance/repair/rehabilitation.

Prescriptive requirements provide the design professional with the opportunity to utilize project resources in areas other than durability design. All examined documents provided recommendations for at least one prescriptive-only concrete class. However, it is important to note that prescriptive requirements typically correlate with, but do not guarantee, durability. Traditional methods of indirectly addressing durability through prescriptive means may not be sufficient for achieving the required durability.

Performance requirements, on the other hand, directly address concrete durability. By allowing durability performance requirements, industry Codes provide the best opportunity for concrete mixture optimization. This is especially true given recent advances in concrete mixture design and the widespread usage of supplementary cementitious materials and admixtures. Performance requirements are the preferred method for structures facing unusual exposure conditions or with extraordinary project goals. The Codes from Europe, Australia, Japan, Canada, and fib all had provisions allowing for a fully performance-based concrete class. In some instances, these documents provided concrete classes with mostly performance-based requirements and only minimal prescriptive requirements.

Hybrid requirements were common in the reviewed industry documents. Hybrid requirements can take two different forms: additive or alternative. For example, CSA A23.1-14 concrete exposure class C-1 requires a maximum w/cm ratio of 0.40 and a chloride ion permeability of less than 1000 coulombs within 91 days, representing hybrid requirements that are additive. ACI 318 exposure class S3, on the other hand, has a Type V cement requirement, but allows for alternative cements complying with ASTM C1012 sulfate expansion requirements, representing hybrid requirements that are alternative.

Alternative hybrid requirements allow the design professional to select the most appropriate durability design method and specification format to match overall project goals. Performance requirements undoubtedly provide the most effective means to optimize concrete mixtures for durability, especially as concrete technology evolves; however, prescriptive requirements are also beneficial in that they provide a minimum expected durability performance without the need for extensive concrete mixture design development. Adopting alternative hybrid performance requirements in Codes and Standards also encourages adoption into project specifications. In that way, the benefits of having alternatives during durability design are also realized during construction. Contractors and suppliers can determine their preferred method of demonstrating durability and the design professional is ensured a minimum level of durability.

EN 206 provides a model framework for adoption of alternative requirements. Article 5.3.1(1) of EN 206 states:

> *Requirements for the concrete to withstand the environmental actions are given either in terms of limiting values for concrete composition and established concrete properties (see 5.3.2), or the requirements may be derived from performance-related methods (see 5.3.3). The requirements shall take into account the design working life of the concrete structure.*

Being a multinational umbrella Code, Section 5.3.2 does not provide specific prescriptive requirements, but rather lists the prescriptive criteria that should be specified. Similarly, Section 5.3.3 does not provide specific performance criteria. Specific prescriptive and performance requirements are instead intended to be specified in the national annexes applicable to individual countries within Europe.

Another model framework is provided in JSCE Guidelines for Concrete No. 15. The Japanese Concrete Code specifies performance-based durability limit states in Chapter 8, requiring the design professional to quantitatively check durability performance with analytical equations. Equations to check include depth of carbonation and chloride ion concentration at the depth of reinforcing steel. These equations also include characteristic safety factors for each particular deterioration mechanism. In Part 3 of the Standard Methods section of JSCE Guidelines for Concrete No. 15, optional prescriptive requirements are provided that are deemed to satisfy the performance criteria in Chapter 8. In that way, a design professional can elect to perform a performance-based or prescriptive design. An example of that approach is shown in Figure C3.3.1 of the JSCE Guidelines for Concrete No. 15, shown here as Figure 5.1.

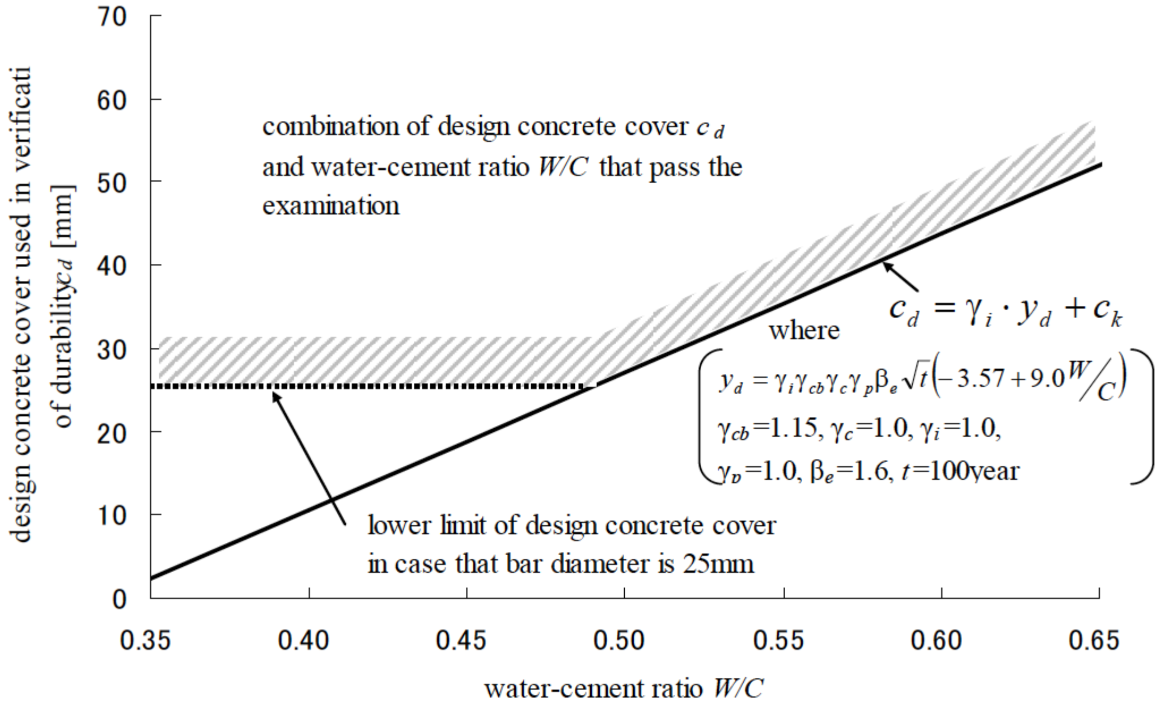


Fig. C3.3.1 A sample relation between the thickness of carbonated concrete and water-cement ratio

Figure 5.1: Performance approach for verification of concrete cover with respect to carbonation-induced corrosion from JSCE Guidelines for Concrete No. 15, Fig. C.3.3.1.

By keeping the existing methods in place and adding alternative performance requirements, design professionals can take advantage of the latest in concrete technology without sacrificing the simplicity of existing prescriptive requirements. Such a framework could be adopted into ACI Codes and standards with little adjustment needed for the typical design professional. As the existing state of built concrete structures continues to age and deteriorate, the focus of the concrete community has shifted towards durability design and the need for Codes to address the demands of structures in service.

5.4 Design Service Life

The examined documents typically take one of three approaches for addressing design service life: 1) explicitly specify an expected or design service life; 2) direct the user to select a design service life and design accordingly; or 3) do not specify or discuss design service life. Directing the user to select a design service life is typical of documents that allow for performance-based durability design such as Eurocode and the JSCE Guidelines for Concrete.

The documents that either did or did not specify a design service life were more typically fully prescriptive. However, this generalization has notable exceptions. For instance, Canada's A23.1-14 contains concrete classes with durability performance requirements and allows for complete supersession of prescriptive requirements by performance-based requirements, yet A23.1-14 does not discuss design service life and directs the design professional CSA C478.

The most effective method to addressing design service life seems to be to direct the user to select it based on the anticipated needs of the project. This allows users to select service lives for a wide range of structures, ranging all the way from temporary to monumental. Table 2.1 of Eurocode EN 1990, shown here as Table 5.1, provides an example of allowing users to select a design service life based upon the anticipated use of the structure.

Intended to be adapted to regional use, Eurocode does not provide specific prescriptive or performance-based requirements, but rather specifies the requirements that should be considered by a design professional. Nonetheless for documents that allow users to select the design service life but also have specific prescriptive or performance-based requirements, requirements should not be fixed but, rather, should be based on design service life. An example of such a framework is given in JSCE Guidelines for Concrete No. 15. This Code is performance-based but provides prescriptive alternatives that, if met, constitute conformance with performance-based requirements. These prescriptive alternatives are variable, however, and change based upon the design professional specified design service life. One example of the variable prescriptive requirements is given in Table 5.2 (Table C3.2.1 of JSCE Guidelines for Concrete No. 15). While the diffusion coefficient values presented in this Table represent performance requirements, the JSCE Guidelines for Concrete No. 15 allow for calculating diffusion coefficients using specified crack width and w/cm ratio.

While it is advantageous to allow the user to select design service life, none of the examined Codes and standards provide sufficient means by which to account for the effects of maintenance and repair on design service life during initial design if a prescriptive design approach is taken. Many of the documents provide maintenance requirements and provide means by which extension of service life through repair can be calculated; however, this is not easily translated to a design service life during prescriptive design of new structures. Ideally, a design professional should be able to present an owner with several different options on durability design within the context of a maintenance and repair schedule and still satisfy prescriptive Code requirements. For example, it may be advantageous from an initial material cost standpoint for an owner to decide to decrease a minimum cementitious material content with the assumption that yearly maintenance and repair will occur.

In general, the examined Codes and standards that provide a design service life do not explicitly state the considered limit state for each aspect of durability. For example, while AS 3600 states a service life of between 40-60 years, it is not clear whether this time frame considers corrosion initiation to be the end of service life or whether it includes some amount of corrosion propagation. One notable exception is JSCE Guidelines for Concrete No. 15, which explicitly defines the end of service life criterion for each aspect of durability through performance limit states. Without explicit limit states, design professionals and owners alike are left with uncertainty as to what condition a structure may be at the end of the design service life without further durability analysis.

Table 5.1: Many international bodies provide guidance or requirements for Design Working Life or Design Service Life, depending upon the type of structure. Table 2.1 of Eurocode EN 1990 is a representative example.

Table 2.1 - Indicative design working life

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures (1)
2	10 to 25	Replaceable structural parts, e.g. gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, and other civil engineering structures
(1) Structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary.		

Table 5.2: Excerpt from JSCE Guidelines for Concrete No. 15 (Table C 3.2.1) lists design diffusion coefficients for chloride ingress.

Table C 3.2.1 Maximum design diffusion coefficient for passing the examination for chloride ingress D_d (approximate value)

splash zone (C_0=13kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	-	-	-	0.123	0.192	0.276	0.376	0.767	1.72	3.07
30 year	-	-	-	-	0.128	0.184	0.25	0.511	1.15	2.04
50year	-	-	-	-	-	0.11	0.15	0.307	0.69	1.23
100year	-	-	-	-	-	-	-	0.153	0.345	0.613

near shoreline (C_0=9kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	-	-	0.115	0.15	0.235	0.338	0.46	0.939	2.11	3.75
30 year	-	-	-	0.1	0.156	0.225	0.307	0.626	1.41	2.5
50year	-	-	-	-	-	0.135	0.184	0.375	0.845	1.5
100year	-	-	-	-	-	-	-	0.188	0.422	0.751

0.1km from coast (C_0=4.5kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	-	0.14	0.191	0.249	0.389	0.561	0.763	1.56	3.5	6.23
30 year	-	-	0.127	0.166	0.26	0.374	0.509	1.04	2.34	4.15
50year	-	-	-	-	0.156	0.224	0.305	0.623	1.4	2.49
100year	-	-	-	-	-	0.112	0.153	0.311	0.7	1.25

0.25km from coast (C_0=3kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	0.15	0.216	0.295	0.385	0.601	0.866	1.18	2.4	5.41	9.62
30 year	0.1	0.144	0.196	0.256	0.401	0.577	0.785	1.6	3.61	6.41
50year	-	-	0.118	0.154	0.24	0.346	0.471	0.962	2.16	3.85
100year	-	-	-	-	0.12	0.173	0.236	0.481	1.08	1.92

0.5km from coast (C_0=2kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	0.288	0.414	0.564	0.737	1.15	1.66	2.26	4.61	10.4	18.4
30 year	0.192	0.276	0.376	0.491	0.768	1.11	1.5	3.07	6.91	12.3
50year	0.115	0.166	0.226	0.295	0.461	0.663	0.903	1.84	4.14	7.37
100year	-	-	0.113	0.147	0.23	0.332	0.451	0.92	2.07	3.68

1km from coast (C_0=1.5kg/m^3)	design concrete cover (mm)									
life time	25	30	35	40	50	60	70	100	150	200
20 year	0.62	0.893	1.22	1.59	2.45	3.57	4.86	9.92	22.3	39.7
30 year	0.413	0.595	0.81	1.06	1.65	2.38	3.24	6.61	14.9	26.4
50year	0.248	0.357	0.486	0.635	0.992	1.43	1.94	3.97	8.93	15.9
100year	0.124	0.179	0.243	0.317	0.496	0.714	0.972	1.98	4.46	7.93

5.5 Service Life Modeling Requirements

While service life modeling is a common activity in durability guidelines and reports, modeling requirements are not typically specified in Codes and standards (UFGS-03 31 29 is the exception). Service life modeling capabilities have seen major advances in recent years, with probabilistic (as opposed to deterministic) models seeing widespread use. However, these advances have not been significantly incorporated into existing Codes and standards.

Most closely resembling an explicit requirement for service life modeling in a Code document are the performance limit states to be satisfied in Japan's JSCE Guidelines for Concrete No. 15 and the fib Model Code. Satisfying the durability performance limit states does not require service modeling; however, the limit states to be satisfied closely resemble the output of service life models. For example, design professionals are required to check that the carbonation depth and chloride threshold concentration do not reach the depth of the reinforcing steel. Similar checks would be performed as part of service life analysis.

Undoubtedly, service life modeling requires expertise, yet these models also represent the best mechanism to translate durability design choices into service life estimates. Service life modeling also provides a fair and reproducible process to evaluate the impact of design choices. However, the effort to execute these models is not warranted in many structures for various reasons, including non-aggressive environments (e.g., typical office interior), short design service lives (e.g., temporary structures intended to last less than 20-25 years), or common elements that have been extensively installed in similar environments (e.g., residential foundations, sidewalks, curbs, etc.).

If considered for a given project, it is commonly recognized that different service life models often produce different results depending upon calculation procedures and model assumptions. As such, development of a mandatory-language standard practice for developing service life modeling requirements is warranted. Creation of a service life modeling standard will establish the minimum requirements for creation of a independently-reproducible service life model to be documented, and such a standard is already underway within the committee work ACI 365[1]. International versions of a similar document already exist (i.e., fib Bulletin No. 34, ISO 16204), however, the framework and terminology of these documents is not readily compatible with the ACI family of documents. Thus, a goal of ACI 365 is to create a document that can be easily incorporated by reference into ACI Code documents and other standards.

5.6 Concrete Durability Parameters

The parameters by which the examined documents measure durability vary depending on the durability design method used. The examined Codes and standards typically contain some form of prescriptive means by which a design professional can select durability performance requirements, denoted "deemed-to-satisfy" in *fib* Model Code 2010, as an example. The most common prescriptive parameter specified is maximum w/cm ratio, which is commonly thought of as one of the most effective ways in which to provide durable concrete because limiting unit water content (i.e., a lower w/cm ratio) reduces shrinkage, thermal heat rise, and chloride-penetrability. Other common methods by which durability is prescribed include requirements for compressive strength, concrete cover, cementitious materials content, air content, cement type, and maximum chloride ion content. In contrast, many of the examined guidelines discuss the important prescriptive parameters to consider when durability is desired yet also discuss the performance metrics by which durability can actually be measured.

Of the examined Codes and standards with performance-based criteria, specific performance testing methods are rarely specified, with these Codes and standards more often leaving the decision up to the user. For example, Australia's AS 3600 specifies the performance-based Class U concrete for particularly aggressive environments, but Class U concrete properties are specified by the user "to ensure durability under the particular exposure environment." One notable exception is Canada's A23.1-14, which specifies A23.2-23C Testing (substantially equivalent to ASTM C1202 RCP Testing) for concrete classes C-XL, A-XL, C-1, and A-1. It is important to note that many performance tests for concrete durability, such as ASTM C1202 RCP Testing, involve longer testing periods in excess of 28 days. Longer testing periods for concrete mixture acceptance can negatively affect construction scheduling and extend payment schedules.

It is important to note that many of the common prescriptive means by which durability is specified can have unintended consequences on other aspects of concrete mixture behavior. Parameters such as w/cm ratio and cementitious materials content directly affect workability. Cement type and cementitious materials content will affect heat of hydration. All material requirements are also subject to local market availability. Overdesigned concrete mixtures can lead to the excessive use of admixtures. Concrete mixtures are complex, and adjustments to a single parameter can have myriad effects on fresh and hardened concrete properties.

Thus, any changes or updates to ACI Codes and standards regarding durability must keep the overall goal of well-placed, good quality concrete at the forefront. For simple structures with typical service lives and non-

1 *Marcotte is a member and past-chair of ACI 365. She is a chapter lead in the new ACI 365 standard practice document currently in development under the leadership of Dr. Kyle Stanish.*

aggressive environments, the current prescriptive concrete durability parameters do not represent a burden on constructability. However, for structures in aggressive environments or with long design service lives, a balance needs to be struck between provisions too simple to ensure sufficient durability and provisions too complex such that other concrete properties are negatively affected. As discussed, preferably this balance would be realized through utilization of alternative performance requirements, as well as variable prescriptive or performance-based requirements accounting for design service life. Current requirements do not allow for optimization of concrete mixtures in accordance with the latest advances in concrete technology.

Ideally the design professional would also be given options to modify prescriptive requirements. Not only should design service life be taken into account, but a design professional should be able to, for example, increase the w/cm ratio if concrete cover is also increased, if chloride-induced corrosion resistance is the main concern. Different solutions would be needed for freeze-thaw or sulfate-attack concerns. Overall, any changes to current ACI Codes and Standards should be with the goal of providing more flexibility to design professionals in terms of concrete durability parameters.

5.7 Performance Metric Verification & Reliability

For some documents, performance metric verification is assumed given prescriptive concrete durability parameters are met. Other documents require verification through testing of actual concrete mixtures to be used. Still other documents leave performance metric verification completely up to users by simply stating that users are to specify durable concrete based upon project requirements. The means by which that is achieved are, thus, left up to the user.

Three examples of how performance metric verification and reliability are integrated into Codes and Standards are the *fib* Model Code, JSCE Guidelines for Concrete No. 15, and ISO 13823. The fib Model Code is unique of the three in that it provides four different methods by which performance can be verified. This document will not discuss the "avoidance-of-deterioration" approach. The fib Model Code and JSCE Guidelines for Concrete No. 15 both present limit state equations (called "partial safety factor format" in fib) for design professionals to calculate if, for example, the carbonation depth at the end of the design service life is less than the concrete cover. Unlike the other two, ISO 13823 provides a framework for a given durability parameter to be evaluated with respect to reliability but does not discuss specific parameters. However, the framework provided by ISO 13823 is similar to the probabilistic methods presented in the fib Model Code.

Incorporating design limit state or probabilistic equations to verify performance is significantly different from the current approach used in ACI Codes and Standards, which is to assume performance if prescriptive requirements are met. Because of this difference, any inclusion of an equation-based method into ACI Codes and Standards would simultaneously need updates to education. It is the authors' understanding from interviews with practitioners that education on durability design is typically on-the-job, rather than through schooling. As such, integration of formalized equations might require significant changes to how practitioners are taught durability design.

As previously discussed, prescriptive requirements are the preferred method for specifying durability for simple structures in nonaggressive environments. Any addition of performance metric verification to ACI Codes and Standards should keep in mind that many structures do not require extensive verification. The fib Model Code allows for performance verification through a prescriptive, "deemed-to-satisfy" approach, but provides little guidance on specific parameters. The JSCE Guidelines for Concrete No. 15, on the other hand, provides specific ways in which performance-oriented limit state equations may be satisfied with prescriptive requirements.

Future development of ACI Codes and Standards should include performance metric verification; however, the manner in which this is included should not represent a significantly different design philosophy than that contained in current ACI documents. As such, the best solution may be to keep current prescriptive requirements in place and let design professionals and/or contractors modify the prescribed mixtures if performance is verified through testing. Reliability concepts can also be included with any performance test.

5.8 Construction Requirements and QA/QC

Levels of construction requirements differ in prescriptive vs. performance-oriented Codes and standards and differ with the relative importance of the structure and its design service life. For example, a temporary structure in a standard atmosphere would not require the same QA/QC as a bridge or monumental building with a 75+ year design service life in a severe environment. Similarly, improved construction and QA/QC should directly lead to improved durability. ACI 318 inherently recognizes the expected quality control benefit of concrete members produced in a manufacturing plant (compared to field construction) by allowing lower cover in these situations.

Concrete cover can be used as an example of the importance of construction on durability. Service life models commonly predict the time to corrosion of reinforcing steel based upon the time to ingress of chlorides to the reinforcing steel. The depth of the reinforcing steel can be assumed to be located at the design cover depth or at design cover depth minus a construction tolerance. Corrosion will typically initiate at locations with the least cover, and therefore these areas serve as limiting factors to long-term durability.

The concept of construction quality as a durability parameter is mentioned in Appendix A of CIA Z7/01. However, the concept of improving construction quality to improve long-term durability has not been adequately explored in any of the reviewed documents. Updates to ACI Codes and Standards should consider the effect of construction requirements and QA/QC. Consideration may be as simple as requiring, for instance, additional cover to account for increased tolerances if QA/QC is not rigorous. More rigorous treatment of curing requirements is also to be desired. Currently, ACI 318 allows accelerated curing if it produces equivalent durability to standard curing but does not require any specific measures to validate equivalency.

5.9 Maintenance, Repair, and Dismantlement

The concept of repair and maintenance of an existing structure is not present in ACI 318, which is in contrast to the global documents examined in this study. The lack of provisions for repair and maintenance in ACI 318 is rooted in the focus of US Codes and standards on new construction. Existing structures in US practice are largely dealt with by a separate building Code (International Existing Building Code (IEBC) versus International Building Code) or a property maintenance Code (International Property Maintenance Code).

The poor performance of some concrete structures in the US with respect to durability has created a substantial market in the US for repair of existing structures, which is estimated to represent 20% of US construction spending. The US repair industry has been proactive in the development of guides, codes and standards for the repair of existing structures. Specifically, ACI 562 provides code requirements for assessment, repair and rehabilitation of existing structures, and ACI 563 provides standard specifications for concrete repair. Other ACI documents (ACI 364.1R-01 and ACI 546R-16 in particular) present detailed information on how to assess and design repairs to existing structures. The ACI repair documents were developed to satisfy the needs of design professionals and contractors involved with existing structures and were developed independent of ACI design Codes.

Globally, ISO, *fib*, and EN have all created standards for repair of existing structures. The global approach tends to be geared towards a more integrated approach that maintenance and future repair are expected as part of the service life of the structure. With respect to terminology, maintenance is generally considered to be routine practice / operation while repairs are events that occur in addition to or outside the scope of routine maintenance in US practice; Japanese and Canadian practice considers minor repairs within the scope of maintenance. Maintenance, especially, is a critical part of the service life of a structure. In many instances, routine maintenance can significantly reduce or delay repairs, leading to a structure that is more economical through its life.

To move ACI Codes and standards forward, an implicit understanding needs to be developed by US design professionals that routine maintenance and repairs are a part of the service life of a structure. It is interesting to note, that inclusion of a requirement in ACI 562 that future maintenance and inspection requirements be documented as a part of repair design was cited as a reason for opposition during the IEBC adoption process, and continues to represent an uphill battle. Clearly, an evolution in US thought process may be required for ACI Codes and standards for new construction to include consideration of future repair and maintenance. Alternately, widespread adoption and use of the ACI 562 Code as the "post-construction standard" will allow for repair and rehabilitation to be completed on existing structures without impacting the design Code.

5.10 Feedback and Practicalities of working with Durability Design Codes, Standards, and Guides

Although preliminary and with only a few respondents from Canada and the US, the limited number of conversations within the context of this investigation was highly revealing:

1. There is a valid perception that Codes and standards support successful design, execution, and repair of concrete structures. However, the presence of minimum Code requirements does not guarantee that a successful structure will be constructed, arising from any number of contributing factors: absence of Owner's Project Requirements for concrete durability, faulty design or poor documentation, contract and schedule constraints, workmanship issues, and incomplete maintenance.
2. There were any number of comments attributing concerns with achieving better durability and longer service lives to inadequate education of design professionals, lack of design consensus and documentation for durability and service life prediction, poor contractor awareness, poor construction QA/QC, and lack of Owner knowledge.

Ultimately, the investigators consider this data collection process to be limited and will amend this feedback discussion as additional information becomes available.

5.11 USA versus the world's perceptions of concrete durability requirements

Despite the importance of durability in concrete structures, it is the authors' perception that a typical design professional in the United States does not consider durability to be of primary consideration. Instead, they are most concerned with satisfying compressive strength to satisfy calculated structural demands, then will consider Code-mandated requirements, and ultimately the final cost per volume of material will decide what is placed. A typical design professional would be one that is educated and experienced in structural design but might not belong to professional societies related to concrete or become specialized in the nuances of concrete, even in their region of practice. While concrete is often perceived as a low-level, ubiquitous material that can be installed by anyone, in reality, it is a highly engineered product that requires expertise and skill to design and install well, regardless of the intended design service life. Furthermore, repair and rehabilitation require additional specialization and expertise to optimize design service life against costs and time for asset management, and this can be burdensome and mystifying for Owners. For concrete repair, Marcotte and Emmons (2019) drafted an anecdotal distribution curve to express these challenges for both design professionals and contractors, shown in Figure 5.11. Thus, for a typical design professional in the US, Code requirements in simple terms will have the greatest chance of being properly documented in design. More complex requirements with "grey areas" subject to interpretation are likely to be missed or ignored.

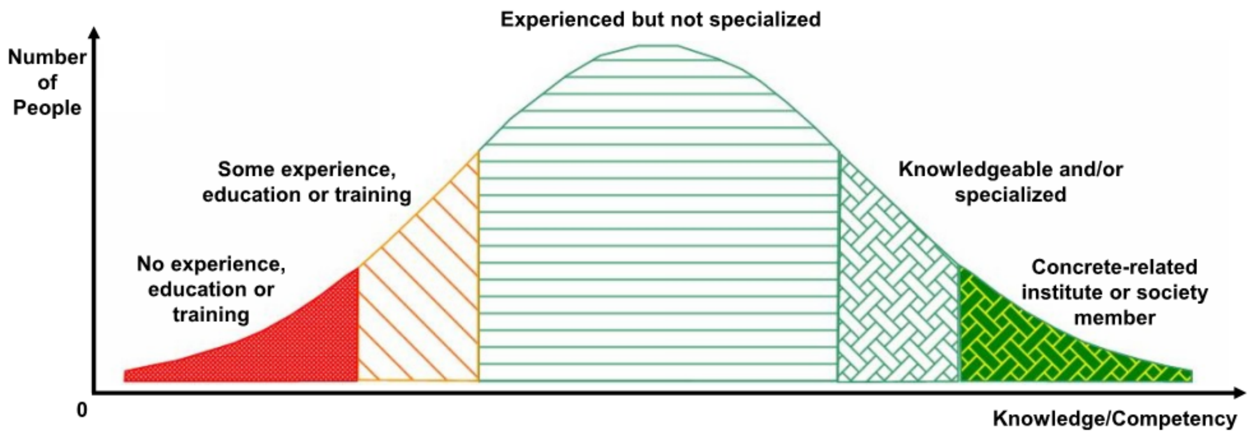


Figure 5.11: Perceived distribution of engineers and contractors, adapted from [10].

This is an untenable situation, however. In our opinion, for any material other than concrete (e.g., steel), we believe that a US design professional would immediately question durability if the structure were placed outside without an enclosure. Even poorly executed concrete can provide some protection and durability, and this might be part of the reason why US design professionals are perceived to undervalue the importance of durability in concrete construction. US design professionals recognize that ACI Codes and Standards provide minimum requirements for design of structures, yet, at the same time, design professionals have a significant fear of providing something greater than the Code minimum. Concern about exceeding minimum requirements is likely rooted in fear of producing non-competitive designs or adding additional construction costs. Concerns about exceeding minimum requirements are a significant impediment to extended service lives and greater durability.

Documentation and feedback from international authorities indicates that durability design is recognized as a distinct specialization and this role is incorporated into important or specialized structures (e.g., nuclear and wastewater plants, government structures, infrastructure, monuments, etc.). Whether this role is fulfilled by an experienced structural engineer or a separate durability engineer is immaterial; it is simply important that this role is filled. To facilitate consistency and harmonize industry practices, documents from CIA, CSA, ISO, etc., presented as part of this investigation, have been developed. Within the US, ACI 562 has durability considerations (i.e., not specific requirements as no standards exist to support them) and is supporting the development of supporting standards in expert committees (ACI 201, ACI 365) to strengthen and improve its Code provisions.

6 Conclusions & Recommendations

6.1 Conclusions

Globally, ACI Codes and Standards are the most widely used documents for design of concrete structures, with ACI 318 used as a design standard in over 40 countries and regions. The next generation of ACI Codes and Standards are being developed, and these documents will be used for both design and the education of concrete design professionals and allied professions working both in the US and internationally. The review of global Codes and standards for design of concrete structures identified a wide range of practices for durability design, with many of the global Codes providing a more in-depth and systematic approach to durability design compared with ACI documents. Differences in approach to durability design were highlighted by informal interviews with US and international practitioners, academics and professionals involved in Code development. US design professionals generally indicated they had limited familiarity with durability outside of prescriptive ACI 318 Code requirements and questioned if ACI 318 requirements were adequate for aggressive environments. Further, US design professionals' knowledge was reported to be obtained in practice, outside of their formal education.

For ACI to remain the global leader in the development and dissemination of concrete knowledge, the next generation of ACI Codes and standards will need to focus upon *comprehensive design of structures* (i.e., not "structural design") to satisfy structural, durability, and other requirements for ordinary structures in a non-aggressive environments, but also structures that can be more complex, or require an extended service life in aggressive environments. For many structures, ordinary ones where the concrete is protected, current ACI 318 durability requirements will produce a structure that is fully capable of achieving a satisfactory service life at an acceptable cost. Looking ahead, challenges for the next generation of ACI Codes and Standards include:

1. Can the next generation of ACI Codes and standards improve durability design without significantly impacting ease of interpretation or cost of construction?
2. How can ACI 318 be modified to better integrate the durability of concrete and steel components as a system?
3. How should ACI 318, a prescriptive and life-safety oriented Code, address durability: prescriptively, performance-oriented, or both? Should ACI 318 contain only prescriptive durability provisions, and another Code document be developed for performance-oriented durability?
4. Determining a rational dividing line between structures that require "ordinary" levels of durability and those that require more design and construction effort to achieve durability in a given environment for a set period of time.
5. Development of a balance between a Code that provides minimum Code requirements for "ordinary" structures and a Code that can produce a structure with an extended service life in an aggressive environment. As an example, CSA A23.1 accomplishes this by having both C-1 and C-XL classes of concrete (or A-1 and A-XL) for different (but undefined) periods of resistance to the same exposure.
6. Numerous international Codes and standards recognize that maintenance and future repairs will be required during the service life of a structure. How can ACI better integrate documents developed for new design and existing structures?
7. Interviews with US design professionals indicated that concepts of durability design were learned in practice, outside of formal education. What materials can be developed to educate design professionals that are "experienced but not specialized" about durability design concepts?
8. How can ACI maintain the current ease of use of ACI 318 and other ACI Code durability provisions such that the "experienced but not specialized" design professional can implement the provisions correctly with confidence?

6.2 Recommendations for ACI Document Development and Improvement

The review of global documents related to durability design revealed significant differences between current ACI Codes and Standards and global documents. When compared to ACI Codes and Standards, the global Codes and standards typically addressed durability design in a more integrated manner than ACI documents and presented more detailed durability requirements. Many of the global documents reflected the reality that repair and maintenance will be required during the service life of concrete structures.

To maintain ACI as the preeminent source for concrete knowledge related to durability design, ACI Codes and standards can be improved and new documents created, as follows:

1. The simplest improvement that can be made is to standardize durability and service life prediction terms and definitions across ACI's families of documents, using Appendix A as a starting point. This contributes to better comprehension of concepts within ACI, communication outside the institute, and harmonization within ACI's knowledge base.
2. Another straightforward improvement would involve better integration of the information contained in existing ACI documents related to durability of concrete structures (ACI 201, 222, 224, etc.) with the design Code for new construction (ACI 318). ACI 318 currently addresses durability prescriptively through minimum concrete cover requirements and limited concrete mixture design

requirements. Creation of an enhanced durability commentary (referencing other ACI documents) in ACI 318 that describes mechanisms to create more durable structures by exceeding the minimum ACI requirements is a possible path forward.

3. In addition to improving existing ACI Codes and Standards, new documents that likely would enhance ACI's family of documents include:
    - Standard practice for durability design – ACI 201 (concept approved)[2].
    - Standard practice for service-life prediction – ACI 365 (concept approved)[3]
    - Planning guide for durability design – possible ACI 201, 546, or 562 document that provides similar information to CIA Z7/01.
    - Guide for Durable Construction – ACI 201

    Creation of these documents outside of the ACI 318 committee will allow ACI 318 to focus on providing minimum requirements, while providing design professionals required information for enhanced durability design. Two of the documents have already been approved by ACI TAC to be developed. The planning guide for durability design is ideally produced by ACI members with experience in the evaluation of existing structures, such as members of the durability, repair or repair Code committee, ACI 562. These members have the firsthand experience with existing structures needing repair to identify what works and what does not.

    Creation of the documents described would provide ACI with a backbone of documents for design professionals to use when designing structures in aggressive service environments and for extended service lives. Further, the documents would provide the basis for performance-based design of structures for extended services lives in aggressive environments which is the focus of ACI 562 (Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary).
4. There is a need for a unified approach for chloride limits, tailored for the importance and type of structure. Recommend that ACI focus on creating consensus amongst its committee documents on key durability provisions like "chloride content" that affect so many structures.
5. In addition to new document creation, the authors recommend conducting a more formalized survey, expanding upon the interviews conducted for the purposes of this report. The survey should go beyond engineers and include owners, contractors, and concrete producers. The recommendations issued in this report were informed by the survey results, and a more expansive and comprehensive survey would help inform any further needs to be addressed by ACI Code and Standard development.
6. Other documents to support the construction side or address the practicalities of concrete installation and QA/QC or tools would also be welcome from affiliated organizations to ACI, like PCI and ICRI.

6.3 Recommendations for Education and Outreach

The development of new design documents related to performance-based durability and service life design will not improve practices until the design procedures are implemented and new structures created. The efforts toward implementation will require direct outreach to end users, including:

- Owners who need to be educated on the benefits of performance-based durability designs;
- Design professionals on how to design durable structures;
- Contractors on mechanisms to improve construction quality; and
- Concrete producers on what types of concrete materials will be required and the level of quality

2 *"Standard Practice" does not currently exist as a document type in the ACI Technical Committee Manual, but the authors envision this as a document with mandatory language requirements and commentary that when followed, will provide the durability design, repair, or maintenance of a structure. March 2020 update: ACI approved the creation of a new ACI Committee 321 to develop a durability Code in lieu of originally proposed ACI 201 Standard Practices.*

3 *Similar to the Standard Practice for durability design, a standard practice for service life prediction is envisioned as a mandatory language document with a commentary that will allow service life prediction practitioners to perform and document service life prediction activities for use with the design, repair, or maintenance of a structure.*

control required.

Beyond the need for individualized education and outreach to the various parties, additional education is needed for all parties on how to integrate durability design into each phase of the life cycle of a structure. The best approach for robust, sustainable, and economical structures is to further educate on the benefits of durability and durability design.

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Appendix A: Terminology

A1. General

The following references have definitions relevant to durability design. This list is a representative sample from the documents reviewed. Definitions are summarized in Table A1.

- ACI CT 2018: Concrete terminology
- ACI TCM 2018: Technical committee manual
- ACI 132R-14 Guide for Responsibility in Concrete Construction
- ACI 318-14 Building Code Requirements for Structural Concrete and Commentary
- ACI 365.1R-17 Report on Service Life Prediction
- ACI 562-16 Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary
- AS 3600:2018 Australian Standard Concrete structures
- CIA Z7/01 2014 Recommended Practice Concrete Durability Series – Durability Planning
- CIA Z7/04 2014 Recommended Practice Concrete Durability Series Good Practice Through Design, Concrete Supply and Construction
- CSA A23.1/A23.2 (2014) Concrete materials and methods of concrete construction/Test methods and standard practices for concrete
- CSA S478 (2016) Guideline on Durability of Buildings Structures (Design)
- EN 206:2013 Concrete – Specification, performance, production, and conformity
- EN 1990:2002+A1 Eurocode – Basis of Structural Design
- *fib* Model Code for Concrete Structures 2010
- ISO 13822:2010 Bases for design of structures — Assessment of existing structures
- ISO 13823:2008 General principles on the design of structures for durability
- ISO 15686-1:2011Buildings and constructed assets — Service life planning — Part 1: General principles and framework
- ISO 15686-8:2008 Buildings and constructed assets — Service-life planning — Part 8: Reference service life and service-life estimation
- ISO 16204:2012 Durability — Service life design of concrete structures
- ISO 16311-1:2014 Maintenance and repair of concrete structures — Part 1: General principles
- ISO 16311-3:2014 Maintenance and repair of concrete structures — Part 3: Design of repairs and prevention
- ISO 55000:2014 Asset management — Overview, principles and terminology

Table A1: Summary of relevant durability design and service life terms.

TERM	DEFINITION(S)
assessment	• Refer to "condition assessment" • set of activities performed in order to verify the reliability of an existing structure for future use (ISO 13822, ISO 16311-2) • (structural assessment) the process of investigating by systematically collecting information that affects the performance of an existing structure; evaluating the collected information to make informed decisions regarding the need for repair or rehabilitation; detailing of findings as conclusions and reporting recommendations for the examined structural concrete work area (member, system, or structure) (ACI 562). • (condition assessment) A process of reviewing information gathered about the current condition of a structure or its components, its service environment and general circumstances, whereby its adequacy for future service may be established against specified performance requirements for a defined set of loadings and/or environmental circumstances. (CIA Z7/01)
asset management	• coordinated activity of an organization to realize value from assets (ISO 55000) » *Note 1 to entry: Realization of value will normally involve a balancing of costs, risk, opportunities and performance benefits.* » *Note 2 to entry: Activity can also refer to the application of the elements of the asset management system.* » *Note 3 to entry: The term "activity" has a broad meaning and can include, for example, the approach, the planning, the plans and their implementation.* • (Asset management (of structures)) Processes and procedures adopted for the maintenance, inspection, testing, assessment and repair or other remedial action of structures in order to provide effective control against (pre-determined) criteria to ensure the continued safe operation of individual structures or wider groupings of the inventory and related assets. Asset management of structures often involves conflicting requirements and objectives, which invariably requires compromise and judgment about the action to be taken or not taken due to limitations in the available resources. (CIA Z7/01)
basis of design	• Technical description of the implementation of service criteria agreement (*fib* Model Code)
capacity	• the strength, stiffness, ductility, energy dissipation and durability, of a material, member or system as determined by analysis or testing (ACI 562)
characteristic service life	• Refer to "design service life" or "service life" • value of a predicted service life chosen either on a statistical basis, so that it has a specified probability of being more unfavourable (i.e. lower), or on a non-statistical basis, for instance based on acquired experience (ISO 13823)

TERM	DEFINITION(S)
condition assessment	• Refer to "assessment" • A process of reviewing information gathered about the current condition of a structure or its components, its service environment and general circumstances, allowing a prognosis to be made of current and future performance, taking into account active deterioration mechanisms and, if appropriate, predictions of potential future damage. (*fib* Model Code)
consequence level	• expression of seriousness of consequences related to a defined reference level (ISO 16311-2)
damage	• changes in the capacity of an existing structure resulting from events, such as loads and displacements (ACI 562) • unfavorable change in the condition of a structure that can affect structural performance (ISO 13822)
defect	• fault, or deviation from the intended level of performance of a structure or its parts (ISO 15686-1)
degradation	• process whereby an action on an item causes a deterioration of one or more properties (ISO 15686-8) » NOTE Properties affected can be, for example, physical, mechanical or electrical.
demand	• the force, deformation, energy input, and chemical or physical attack imposed on a material, member, or system which is to be resisted (ACI 562)
designed concrete	• concrete for which the required properties and additional characteristics if any are specified to the producer who is responsible for providing a concrete conforming to the required properties and additional characteristics (EN 206)
designer	• Refer to "engineer" and "Licensed Design Professional" • the person or company responsible for the durability design and hence the specification of durability requirements. Frequently this will be the durability consultant who may be independent of the structural designer. (CIA Z7/04)
deterioration	• Worsening of condition with time, or a progressive reduction in the ability of a structure or its components to perform according to their intended specifications. (CIA Z7/01) • Worsening of a condition with time, or a progressive reduction in the ability of a structure or its components to perform according to their intended functional specifications (fib Model Code) • process that adversely affects the structural performance, including reliability over time due to » naturally occurring chemical, physical or biological actions, » repeated actions such as those causing fatigue, » normal or severe environmental influences, » wear due to use, or » improper operation and maintenance of the structure (ISO 13822)

TERM	DEFINITION(S)
design service (or working) life	• Refer to “characteristic service life” or “service life” • (design life)—period for which a structure or structural member is to remain fit for use for its designed purpose with maintenance (AS 3600) • (design working life) - assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary (EN 1990; EN 206) • (specified (design) service life) the period during which the required performance must be achieved, used in the design of new structures (fib Model Code) • (design life) Specified period of time for which a structure or a component is to be used for its intended purpose without major repair being necessary. (ISO 13823) • (design service life) --assumed period for which a structure or a part of it is to be used for its intended purpose with anticipated maintenance, but without major repair being necessary (ISO 16204) • (design service life (of a building, component, or material))—the period of time after installation or repair during which the performance satisfies the specified requirements if routinely maintained but without being subjected to an overload or extreme event (ACI 365, ACI 562) • (design service life) – the service life specified by the designer in accordance with the expectations (or requirements) of the owners of the building. For given materials and constructions exposed to identical loads, the design service lives for similar buildings are adjusted depending upon the amount and nature of maintenance that the owners commit to carry out during the lives of the completed buildings (CSA S478). • (design service life) - specified period of time for which a structure or its members is to be used for its intended purpose without major repair being necessary (ISO 16311-1) • (Design service life or design life (specified)) The term “design life” is often used to convey the same intent as “design service life” and both terms are acceptable to convey the same intent. The period in which the required performance shall be achieved, used in the design of new structures. The specified (design) service life is related to the required service life, as given by the stakeholders (i.e. owners, users, contractors, society) and to the other implications of service criteria agreement (e.g. with regard to structural analysis, maintenance and quality management). See also service life (operational, required and residual). (CIA Z7/01)

TERM	DEFINITION(S)
durability	• ability of a material or structure to resist weathering action, chemical attack, abrasion, and other conditions of service and maintain serviceability over a specified time or service life (ACI 562) • Ability of a structure and its component members to perform the functions for which they have been designed, over a specified period of time, when exposed to their environment (AS 3600) • The ability of a building or any of its components to perform its required functions in its service environment without unforeseen cost for maintenance or repair (CSA S478). • The capability of structures, products or materials of continuing to be useful after an extended period of time and usage. In the context of performance-based design of structures, durability refers to the fulfilment of the performance requirements within the framework of the planned use and the foreseeable actions, without unforeseen expenditure on maintenance and repair. (CIA Z7/01) • The capability of structures, products or materials of continuing to be useful after an extended period of time and usage. (fib Model Code) • capability of a structure or any of its members to satisfy, with planned maintenance, the required performance over a specified period of time under the influence of environmental action (ISO 13823)

durability limit state (DLS)	• Refer to “initiation limit state” and “limit state”
	• A limit state used to define the end of the service life of a structure. The limit state may be a condition, performance or operational limit state. Most commonly it is a condition limit state. For example, for reinforced concrete structures subjected to deterioration caused by corrosion of reinforcing steel, one or more of the following durability limit state levels may be used to define the end of service life:
	  » Depassivation of the reinforcing steel (or initiation of corrosion).
	  » Cracking of the cover concrete.
	  » Spalling of the cover concrete.
	  » Loss of section (and reduced structural capacity).
	  » Collapse of the structure.
	• The operational service life can be extended beyond the design service life. (CIA Z7/01)

engineer	• Refer to “licensed design professional” and “designer” • A person in the engineering profession with specific expertise in either or both of (a) concrete materials and methods of concrete construction; or (b) principal test methods for hardened and freshly mixed concrete and for concrete materials, and who is licensed to practice in a jurisdiction in Canada (CSA A23.1)
initiation limit state (ILS)	• Refer to “durability limit state” and “limit state” • state that corresponds to the initiation of significant deterioration of a component of the structure (ISO 13823)

TERM	DEFINITION(S)
licensed design professional	• Refer to “designer” and “engineer” • an individual who is licensed to practice structural design as defined by the statutory requirements of professional licensing laws of the state or jurisdiction in which the project is to be constructed, and who is in responsible charge of the structural design (ACI 318) • (1) an engineer or architect who is licensed to practice structural design as defined by the statutory requirements of the professional licensing laws of a state or jurisdiction; (2) the engineer or architect, licensed as described, who is responsible for the structural design of a particular project (also historically engineer of record) (ACI 562)
limit state	• Refer to “durability limit state” and “initiation limit state” • Limiting condition at which the structure ceases to fulfill its designated function (AS 3600) • state beyond which the structure no longer satisfies the relevant performance criteria (fib Model Code) • state beyond which the structure no longer satisfies the relevant design criteria (ISO 16204) • state beyond which a structure or component no longer satisfies the design performance requirements (ISO 13823)

TERM	DEFINITION(S)
maintenance	• A set of planned (usually periodic) activities performed during the service life of the structure intended to either prevent or correct the effects of minor deterioration, degradation or mechanical wear of the structure or its components in order to keep their future serviceability at the level anticipated by the designer. Maintenance activities involve recurrent or continuous measures which enable the structure to fulfil the requirements for reliability. The term "maintenance" is commonly applied in the context of building fabric components with a limited life, components associated with water management and rainwater run-off, items where regular intervention is required to maintain their effective operation, etc. The term "maintenance" is commonly applied to ancillary items such as gutters, drains, sealants, movement joints, bearings, etc. (CIA Z7/01) • The actions and measures taken periodically to maintain a desired level of performance. Maintenance includes a planned program of cleaning, repair, or replacement of components such as paint or gaskets (CSA S478). • A set of planned (usually periodic) activities performed during the service life of the structure intended to either prevent or correct the effects of minor deterioration, degradation or mechanical wear of the structure or its components in order to keep their future serviceability at the level anticipated by the designer. (fib Model Code) • combination of all technical and associated administrative actions during the service life to retain a building, or its parts, in a state in which it can perform its required functions (ISO 15686-1) • Set of activities taken to check, evaluate the performance of a structure, and preserve/restore it so as to satisfy performance requirements in service (ISO 16311-1) • set of activities that are planned to take place during the service life of a structure in order to fulfil the requirements for reliability (ISO 16204)
performance	• The behaviour of a building or any of its components as related to use (CSA S478). • The behaviour of a structure or structural element as a consequence of actions to which it is subjected or which it generates. (fib Model Code) • qualitative level of a critical property at any point in time considered (ISO 15686-1)
prescribed concrete	• concrete for which the composition of the concrete and the constituent materials to be used are specified to the producer who is responsible for providing a concrete with the specified composition (EN 206)
preservation	• the process of maintaining a structure in its present condition and arresting further deterioration.(ACI CT 2018)

TERM	DEFINITION(S)
prevention	• remedial action to prevent or slow down further deterioration of a structure or structural member and reduce the possibility of damage to the user or any third party, inhibiting the progress of deterioration, and proactively preventing deterioration (ISO 16311-3)
rehabilitation	• repairing or modifying an existing structure to a desired useful condition (ACI 562) • the process of repairing or modifying a structure to a desired useful condition (ACI CT 2018) • Intervention to restore the performance of a structure or its component parts that are in a changed, defective, degraded or deteriorated state to the original level of performance, generally without restriction upon the materials or methods employed. (CIA Z7/01) • Intervention to restore the performance of a structure or its components that are in changed, defective, degraded or deteriorated state to the original level of performance, generally without restriction upon the materials or methods employed. (fib Model Code)
reliability	• The ability of a structure or a structural member to perform its intended function satisfactorily (from the viewpoint of the customer) for its intended life under specified environmental and operating conditions. Reliability is usually expressed in probabilistic terms. In the context of performance-based design of structures, reliability refers to the ability of a structure or a structural member to fulfil the performance requirements during the service life for which it has been designed at a required failure probability level corresponding to a specified reference period. (CIA Z7/01) • Ability of a structure or a structural member to perform its intended function satisfactorily (from the viewpoint of the stakeholder) for its intended life under specified environmental and operating conditions. Reliability is usually expressed in probabilistic terms. (*fib* Model Code)

TERM	DEFINITION(S)
repair	• the reconstruction or renewal of concrete parts of an existing structure for the purpose of its maintenance or to correct deterioration, damage, or faulty construction of members or systems of a structure (ACI 562) • to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure (ACI CT 2018) • Intervention to reinstate to an acceptable level the current and future performance of a structure or its components which are either defective, deteriorated, degraded or damaged in some way so their performance level is below that anticipated by the designer; generally without restriction upon the materials or methods employed. (CIA Z7/01, fib Model Code) • Action taken, including replacement, to bring the level of performance to a level acceptable to the level of the designer and the Owner. It may be a part of the planned maintenance program for a building (e.g., patching and painting of walls in access corridors) or may be initiated to remedy unexpected damage (e.g., repair of parking slab resulting from premature failure of part of a protective membrane (CSA S478). • activities performed to preserve or to restore the function of a structure that fall outside the definition of maintenance (ISO 16204)
risk	• the combination of the likelihood of occurrence of a particular hazard and its consequences (CIA Z7/01; fib Model Code) • effect of uncertainty on objectives (ISO 55000) • Note 1 to entry: An effect is a deviation from the expected — positive and/or negative. • Note 2 to entry: Objectives can relate to different disciplines (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process (3.1.19)). • Note 3 to entry: Risk is often characterized by reference to potential "events" (as defined in ISO Guide 73:2009, 3.5.1.3) and "consequences" (as defined in ISO Guide 73:2009, 3.6.1.3), or a combination of these. • Note 4 to entry: Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated "likelihood" (ISO Guide 73:2009, 3.6.1.1) of occurrence. • Note 5 to entry: Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood.
robustness	• An indication of the ability of a structure to mobilise alternative load paths around an area of local damage. It is related to the strength and form of the structural system, particularly the degree of redundancy. (CIA Z7/01) • The ability of a structure, subject to accidental or exceptional loading, to sustain local damage to some structural components without experiencing a disproportionate degree of overall stress or collapse. (*fib* Model Code)

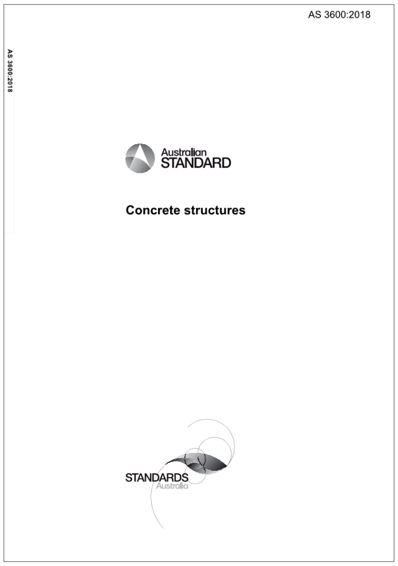
TERM	DEFINITION(S)
serviceability	• structural performance under service loads (ACI 562) • serviceability refers to the ability of the structural system or structural member to provide appropriate behavior and functionality under the actions affecting the system. Serviceability requirements address issues such as deflections and cracking, among others (ACI 318-14, R4.7 Commentary)
Serviceability limit state (SLS)	• State that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met. (CIA Z7/01; *fib* Model Code)
service life	• Refer to "characteristic service life" or "design service life" • an estimate of the remaining useful life of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions without repairs. (ACI 365) • (Service life (operational))-The period in which the required performance of a structure or structural element is achieved, when it is used for its intended purpose and under the expected conditions of use. It comprises design service life and prolonged service lives (see Figure 1 and design service life). (CIA Z7/01) • (Service life (required)): The stakeholders (i.e. owners, users, contractors, society) stated period in which the required performance shall be achieved after construction (see Figure 1 and design service life). (CIA Z7/01) • (Service life (residual)): The remaining period in which the required performance shall be achieved from current time until the design service life is achieved (see Figure 1 and design service life). (CIA Z7/01) • (service life): the time during which the structure performs its design function without unforeseen maintenance and repair. (CSA A23.1) • (service life) the actual period of time during which the building or any of its components performs without unforeseen costs or disruption for maintenance and repair (CSA S478).
service life planning	• design process of preparing the brief and the design for the building and its parts to achieve the design life (ISO 15686-1) Note 1 to entry: Service life planning can, for example, reduce the costs of building ownership and facilitate maintenance and refurbishment.
specification	• (specifications) the written document that details requirements for Work (ACI TCM 2018) • (project specification) project-specific document describing the requirements applicable for the particular project (ISO 22966:2009)
Ultimate Limit State (ULS)	• State associated with collapse or with other similar forms of structural failure. Generally the ultimate limit state corresponds to the maximum load-carrying resistance of a structure or structural member. (CIA Z7/01) • state associated with collapse, or with other similar forms of structural failure (ISO 13823)

Appendix B: Codes, Standards, and Guideline Document Summaries

B1. General

This Appendix provides snapshot summaries of key documents from the range of documents available globally (i.e., outside the US). No representation is made to suggest that these snapshots are comprehensive, and the intent was to provide only a sample of the durability information available. The following documents are summarized:

- AS 3600:2018 Australian Standard Concrete structures
- CIA Z7/01 2014 Recommended Practice Concrete Durability Series – Durability Planning
- CIA Z7/04 2014 Recommended Practice Concrete Durability Series Good Practice Through Design, Concrete Supply and Construction
- CSA A23.1/A23.2 (2014) Concrete materials and methods of concrete construction/Test methods and standard practices for concrete
- EN 206:2013 Concrete – Specification, performance, production, and conformity
- EN 1990:2002+A1 Eurocode – Basis of Structural Design
- EN 1992-1-1
- EN 1992-3
- *fib* Model Code for Concrete Structures 2010
- ISO 13823:2008 General principles on the design of structures for durability



Australian Standard Concrete Structures - 2018

Standards Australia

"The principal objective of this Standard is to provide users with nationally acceptable unified rules for the design and detailing of concrete structures and members, with or without steel reinforcement or prestressing tendons, based on the principles of structural engineering mechanics. The secondary objective is to provide performance criteria against which the finished structure can be assessed for conformance with the relevant design requirements." Additional Standards Australia standards, and ISO/EN references are used to execute this Standard.

Revision + Adoption Cycle
Not known.

Region(s) of Use
Australia

Publication Language(s)
English

Key Feature 1: Applies to new structures and members, and per subclause 1.3, shall be applied to existing structures for evaluations of strength and serviceability.

UNDERSTOOD THAT HISTORICAL MATERIALS MIGHT NOT CONFORM TO THIS STANDARD, BUT THAT GENERAL PRINCIPLES WOULD APPLY. STRUCTURAL TESTING OF MEMBERS AND STRUCTURES IS SPECIFIED IN MANDATORY (NORMATIVE) APPENDIX B, AND APPLIES TO BOTH NEW AND EXISTING STRUCTURES.

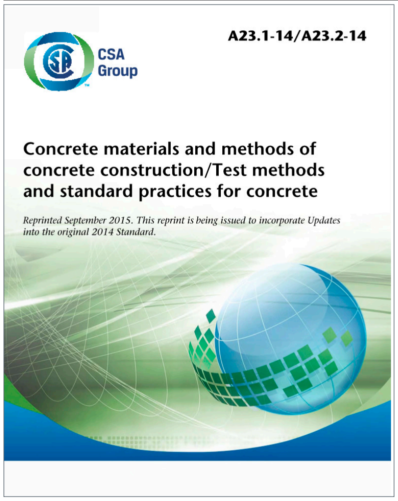
Key Feature 2: Subclause 2.1, "Design Procedures" outlines several design topics, presented to appear be of same importance: strength and serviceability, earthquake actions, robustness and structural integrity, durability and fire resistance, fatigue, and materials properties.

SUBSEQUENT SECTIONS PROVIDE SPECIFIC REQUIREMENTS FOR IDENTIFIED TOPICS.

Table of Key Provisions

REF	DESCRIPTION
4.1	Section 4 (Design for Durability) applies to structures and members with a design life of 50 yrs +/- 20%. Notes indicate that longer planned design lives (i.e., monumental structures) could require more stringent requirements, and these requirements can be relaxed for temporary structures.
4.2	"Method of Design for Durability" requires determining the exposure classification per Clause 4.3, conforming with the concrete quality (Clause 4.4.) and curing (Clause 4.5), plus considering traffic abrasion (Clause 4.6), freezing and thawing (Clause 4.7), exposure to aggressive soils (Clause 4.8), susceptibility to alkali aggregate reactions (Ref, Standards Australia Handbook 79 *Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia*), and for reinforced members, concrete shall conform to Clause 4.9, and the cover to tendons shall conform to Clause 4.10.
4.3.1	Exposure classifications are listed in Table 4.3 and Figure 4.3, and the most stringent requirements for a range of exposures is to be selected. Members that do not contain reinforcement are automatically classified as A1.
4.3.2	If a member is only exposed on one surface, a lower grade of concrete can be selected provided the cover depth is increased by 20 mm or 15 mm, depending upon the type of formwork and compaction per 4.10.3.2 and 4.10.3.3.
4.4	"Members subject to exposure classifications A1, A2, B1, B2, C1 and C2 shall have minimum f'_c" and "cured as specified" in Table 4.4. B2, C1 or C2 concrete is deemed special and is governed by AS 1379 *Specification and Supply of Concrete*.
4.10	Cover is prescriptively defined by exposure classification, and is required to be satisfactorily placed around reinforcement, etc. per 17.1.3 (Handling, Placing and Compacting of Concrete) and Tables 4.10.3.2 and 4.10.3.3.

CANADA A23.1/A23.2



Concrete materials and methods of concrete construction/Test methods and standard practices for concrete - 2014 (2015 Update)

CSA Group

The first two parts of a four-part series of technical documents addressing concrete construction and test methods. Other CSA A23 documents address the design of concrete structures (A23.3) and Precast Concrete -Materials and Construction (A23.4). Canadian concrete codes provisions are intended to address social goals of safety, health, accessibilty, structural performance, sustainabilty, minimizing greenhouse gas emissions, etc. CSA A23 documents rely upon CSA standards as well as ASTM standards for testing of materials and concrete products.

Revision + Adoption Cycle

Revision cycle has varied by is subject toreview every 5 years; Adoption is individually regulated by provinces and territories.

Region(s) of Use

Canada

Publication Language(s)

English, French

Key Feature 1: Proprietary materials or methods of construction may be permitted by the owner, provided the quality meets the min. requirements of this Standard.

Key Feature 2: A23.1 is a framework document for the A23.2 document and its 45 test procedures and methods, related to A23.1. A23.1 only addresses cast-in-place concrete and field precast concrete. A23.4 governs plant manufactured precast concrete. For parking structures, additional requirements of CSA S413 apply. Repair of concrete structures is governed by CSA 448.1.

Key Feature 3: Subclause 4.1.1 defines prescriptive durability requirements, but emphasizes use of high-quality materials, effective quality control, and good execution of the concrete. Historical data is permitted for qualification of materials and concrete mixes.

Table of Key Provisions

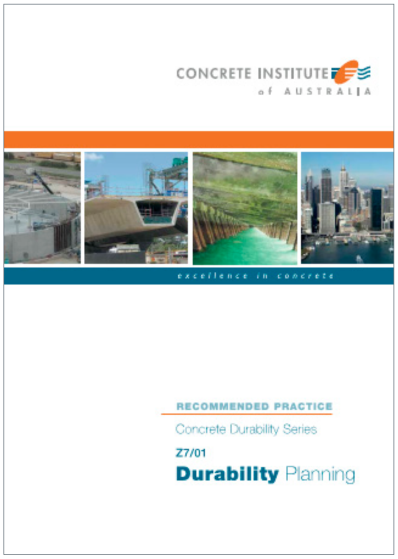
REF	DESCRIPTION
4.1.1.1.1	"Concrete that will be subjected in service to weathering, sulphate attack, a corrosive environment, or any other process of deterioration covered by this Standard shall meet the requirements of Clauses 4.1.1.1 to 4.1.1.10 and 7.4 and Tables 1 to 4 and 19, as appropriate."
8.1.3	"When specified, special performance or material requirements shall supersede other relevant clauses of this Standard. Selection of mix materials, proportions, concrete quality, production of concrete, placing, and/or curing shall be addressed in each relevant clause, where appropriate."
Multi clauses	Tables 1-4, and 17 define different classes of concretes and requirements, generally prescriptive. Table 5 indicates alternate specification options, incl. owner directed options, eliminating the engineer.

EXCERPT

Table 1
Definitions of C, F, N, A,S and R classes of exposure
(See Clauses 3, 4.1.1.1.1, 4.1.1.1.3, 4.1.1.5, 4.1.1.8.1, 4.1.2.3, 4.4.4.1.1.1, 4.4.4.1.1.2, 6.1.4, 6.6.7.5.1, 8.12.1, 9.1, L.3, and R.1, Tables 2, 3, and 17, and Annex L.)

C-XL	Structurally reinforced concrete exposed to chlorides or other severe environments with or without freezing and thawing conditions, with higher durability performance expectations than the C-1 classes.
C-1	Structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. Examples: bridge decks, parking decks and ramps, portions of structures exposed to seawater located within the tidal and splash zones, concrete exposed to seawater spray, and salt water pools. For seawater or seawater-spray exposures the requirements for S-3 exposure also have to be met.
C-2	Non-structurally reinforced (i.e., plain) concrete exposed to chlorides and freezing and thawing. Examples: garage floors, porches, steps, pavements, sidewalks, curbs, and gutters.
C-3	Continuously submerged concrete exposed to chlorides, but not to freezing and thawing. Examples: underwater portions of structures exposed to seawater. For seawater or seawater-spray exposures the requirements for S-3 exposure also have to be met.
C-4	Non-structurally reinforced concrete exposed to chlorides, but not to freezing and thawing. Examples: underground parking slabs on grade.
F-1	Concrete exposed to freezing and thawing in a saturated condition, but not to chlorides. Examples: pool decks, patios, tennis courts, freshwater pools, and freshwater control structures.
F-2	Concrete in an unsaturated condition exposed to freezing and thawing, but not to chlorides. Examples: exterior walls and columns.
N	Concrete that when in service is neither exposed to chlorides nor to freezing and thawing nor to sulphates, either in a wet or dry environment. Examples: footings and interior slabs, walls, and columns.
N-CF	Interior concrete floors with a steel-trowel finish that are not exposed to chlorides, nor to sulphates either in a wet or dry environment. Examples: interior floors, surface covered applications (carpet, vinyl tile) and surface exposed applications (with or without floor hardener), ice-hockey rinks, freezer warehouse floors.
A-XL	Structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas might be generated, with higher durability performance expectations than A-1 class.
A-1	Structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas might be generated. Examples: reinforced beams, slabs, and columns over manure pits and silos, canals, and pig slats; and access holes, enclosed chambers, and pipes that are partially filled with effluents.
A-2	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freeze-thaw exposure. Examples: reinforced walls in exterior manure tanks, silos and feed bunkers, and exterior slabs.
A-3	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freeze-thaw exposure in a continuously submerged condition. Concrete continuously submerged in municipal or industrial effluents. Examples: interior gutter walls, beams, slabs, and columns; sewage pipes that are continuously full (e.g., forcemains); and submerged portions of sewage treatment structures.
A-4	Non-structurally reinforced concrete exposed to moderate manure and/or silage gases and liquids, without freeze-thaw exposure. Examples: interior slabs on grade.

(Continued)



Durability Planning - 2014

Concrete Institute of Australia Z7/01

One part of a multi-part series of guides documenting recommended practices "that provide deemed to satisfy requirements applicable to all concrete structure types based on standard input parameters for design life, reliability and exposure. This Part focuses on a durability planning process from initial Owner conversations to operational maintenance during the service life of the concrete, including maintenance and repair." Durability planning is "cost effective selection and usage of materials combined with design processes, construction methods and detailing to achieve the asset owner intended service life without premature unexpected operational maintenance. "

Revision + Adoption Cycle

Revision TBD. As a guideline, no adoption cycle.

Region(s) of Use

Australia

Publication Language(s)

English

Key Feature 1: A broad range of concrete structures are recommended for durability planning, but not simple residential ones.

RECOMMENDED STRUCTURES ARE MAJOR CIVIL AND BUILDING STRUCTURES, PRECAST CONCRETE WITH COMPLEX METAL COVERS, BUILDINGS WITH UNUSUAL EXPOSURES (E.G., INDOOR SWIMMING POOLS), INDUSTRIAL SITES, CONCRETE MEMBERS WITH CRITICAL LEAKAGE REQUIREMENTS, AND STRUCTURES IN CORROSIVE ENVIRONMENTS.

Key Feature 2: Structural performance is accepted by all and is formally designed, but durability performance is expected by all and is not formally designed.

SECTIONS 2.4.1 AND 2.4.2 RATIONALIZE A COMPARISON BETWEEN STRUCTURAL AND DURABILITY DESIGN. THE STRUCTURAL ENGINEER CANNOT BE REASONABLY OBLIGATED TO DURABILITY DESIGN WITHOUT TRAINING AND/OR EXPERIENCE.

Table of Key Provisions

REF	DESCRIPTION
1.4	Durability knowledge is well documented and progressively updated with new developments throughout the world. However, design, construction and maintenance processes have not adopted the level of durability planning to minimise the risk of premature deterioration.
2.1	A durability philosophy throughout the project delivery will provide capital investment optimisation, safety from no unexpected damage and sustainability by appropriate design, construction and maintenance measures to achieve the asset owner's intended service life and level of service.
2.3	Design and construction to National or International Standards may not achieve the asset owner's required design life in aggressive exposure conditions. A durability review is required as Codes do not cover all environmental exposure conditions and specifc location micro exposure conditions can be more severe than the general exposure conditions.
2.6	Outline lists of key tasks at different stages of project development and execution related to durability best practices.
3	Purpose and benefitsof durability planning (Asset Owner, Designer, Contractor, Operator/Maintainer of Asset) outlined for stakeholders.
4	The difference between design life versus servicelife is summarized in Table 4.1 with Australian standards, and guidance as to how to rationalize what structures merit longer service lives and more detailed planning, shown in Table 4.2.
5-8	Detailed presentation of goals, potential pitfalls, and opportunities for each stage of design and construction briefly noted in Section 3.
App. A	Examples of Key durability deliverables and process are presented.
App. B	A durability checklist example is presented.
App. C	Incorporation of reliability into durability design is presented.

Good Practice Through Design, Concrete Supply and Construction - 2014

Concrete Institute of Australia Z7/04

One part of a multi-part series of guides documenting recommended practices "that provide deemed to satisfy requirements applicable to all concrete structure types based on standard input parameters for design life, reliability and exposure." This Part focuses on "more general concrete design and construction as well as concrete requiring specifically higher levels of durability. Specifications, the impact of design and constructability is discussed in detail to aid in comprehensive durability planning for the entire project team."

Revision + Adoption Cycle

Revision TBD. As a guideline, no adoption cycle.

Region(s) of Use

Australia

Publication Language(s)

English

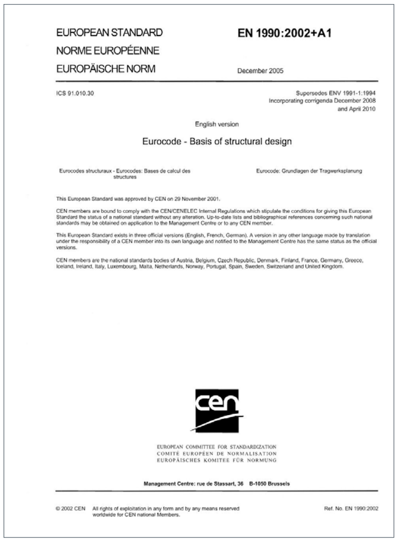
Key Feature 1: Detailed guidance for implementing durability practice into procurement, design and construction for a range of materials and concrete systems.

Key Feature 2: Guidance attempts to rationalize a well-designed, durable outcome with Owner costs.

Key Feature 3: Specific detailing and recommendations for countering common concrete configurations, navigating through reinforcement corrosion protection, and best practices in forming cast-in-place, precast, or sprayed concrete.

Table of Key Provisions

REF	DESCRIPTION
2	Contractual aspects outlines best practices in developing prescriptive or performance specifications that are sufficiently detailed and well-written to communicate to the concrete producer, avoiding additional costs during construction to achieve durability performance requirements. Alternatively, underspecified durability requirements, if not countered during construction, can lead to additional unanticipated maintenance.
3	Critical areas of design detailing are outlined: minimum cover, tolerances, cover and aggregate size, cover and bar or tendon size, quality control of cover concrete, testing of the exposure, configuration and congestion of reinforcement, dissimilar types of metals, member profiles, and so on.
4	Pre-pour planning involves a preconstruction effort to review communication, "buildability", concrete sourcing, preparing for weather contigencies, curing, etc.
5	Quality of concrete describes critical properties to test and assess (e.g., permeability, water sorption and iffusion), and what limitations exist (i.e., lack of test for "penetratability" for deleterious species).
6	Concrete materials, supply and construction section describes the materials comprising concrete, and notes that Australian Codes do not attempt to provide guidance on different systems. The reader is directed to other documents in the Concrete Durability series of documents.
7	Concrete supply provides an overview of the topics related to the producer, the most important of which is that the designer indicate prescriptive and performance requirements essential to durability.
8	Reinforcement and prestressing steel describes the interrelationship of corrosion resistance of reinforcement (e.g., Table 8.1) and the concrete cover in a given environment.
9	Construction describes training, supervision, and responsibilities in concrete.
10	Cast Insitu concrete discusses specific types of members and durability concerns.


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1990:2002+A1

December 2005

ICS 91.010.30

Supersedes ENV 1991-1:1994
Incorporating corrigenda December 2008
and April 2010

English version

Eurocode - Basis of structural design

Eurocodes structuraux - Eurocodes: Bases de calcul des structures

Eurocode: Grundlagen der Tragwerksplanung

This European Standard was approved by CEN on 29 November 2001.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Management Centre has the same status as the official versions.

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COMITÉ EUROPÉEN DE NORMALISATION
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Ref. No. EN 1990:2002

Eurocode: Basis of structural design - 2002 (2005 Amendment)

European Committee for Standardization

EN 1990 (informally, "Eurocode 0") is an umbrella document that "describes the Principles and requirements for safety, serviceability and durability of structures. It is based on the limit state concept used in conjunction with a partial factor method." It is intended to be used in conjunction with tailored documents for new construction (i.e., EN 1991 through EN 1999) for actions on structures (EN 1991), and various construction materials like concrete (EN 1992), and so on. EN 1990 can also be used for the structural appraisal of existing construction for repairs or alterations, or considering change of use.

Revision + Adoption Cycle

Revision TBD. Adoption by member bodies with existing national standards withdrawn.

Region(s) of Use

European Union member bodies.

Publication Language(s)

English, French, German (official); others permitted by CEN members with notification.

Key Feature 1: EN 1990 can be applied to new or existing construction.

Key Feature 2: Design working life is to be specified at the outset, and is intrinsically tied to the structural design requirements for a broad range of construction materials.

FRAMEWORK OF STRUCTURAL DESIGN REQUIREMENTS ASSUMES MATERIALS PROPERTIES, SERVICE ENVIRONMENTS, AND DETERIORATION MECHANISMS WILL BE CONSIDERED, EVEN AS LIMIT STATES IN THE DESIGN.

Key Feature 3: A structure will be designed to meet its structural requirements for its design working life.

Table of Key Provisions

REF	DESCRIPTION
1.3 (2)	The general assumptions of EN 1990 include that the structure will be adequately maintained.
2.3 (1)	Design working life should be specified; Table 2.1 gives examples.
2.4 (1)P	The structure shall be designed such that deterioration over its design working life does not impair the performance of the structure..., having due regard to its environment and the anticipated level of maintenance.
2.4 (2)	To achieve an adequately durable structure, the following should be taken into account: the intended or foreseeable use of the structure; the required design criteria; the expected environmental conditions; the composition, properties and performance of the materials and products; the properties of the soil; the choice of the structural system; the shape of members and the structural detailing; the quality of workmanship, and the level of control; the particular protective measures; the intended maintenance during the design working life.
2.4 (3)P	The environmental conditions shall be identified at the design stage so that their significance can be assessed in relation to durability and adequate provisions can be made for protection of materials used in the structure.
2.4 (4)	The degree of any deterioration may be estimated on the basis of calculations, experimental investigation, experience from earlier constructions, or a combination of these considerations.
4.1.7 (1)P	The environmental influences that could affect the durability of the structure shall be considered in the choice of structural materials, their specification, the structural concept and detailed design.
4.1.7 (2)	The effects of environmental influences should be taken into account, and where possible, described quantitatively.
4.2 (1)	Properties of materials or products should be represented by characteristic values.
4.2(2)	When a limit state verification is sensitive to the variability of a material property, upper and lower characteristic values of the material property should be taken into account.

TABLE 2.1 EXCERPT

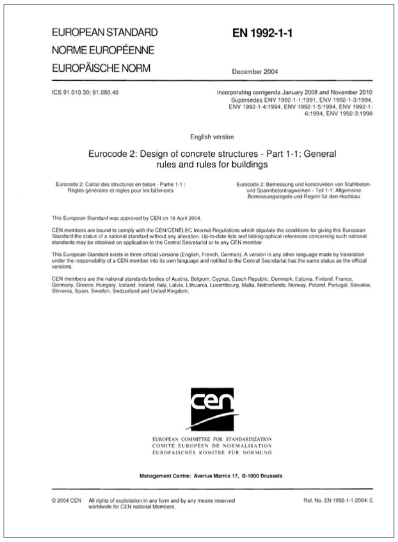
2.3 Design working life

(1) The design working life should be specified.

NOTE Indicative categories are given in Table 2.1. The values given in Table 2.1 may also be used for determining time-dependent performance (*e.g.* fatigue-related calculations). See also Annex A.

Table 2.1 - Indicative design working life

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures [(1)]
2	10 to 25	Replaceable structural parts, e.g. gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, and other civil engineering structures
(1) Structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary.		



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1992-1-1

December 2004

ICS 91.010.30; 91.080.40

Incorporating corrigenda January 2008 and November 2010
Supersedes ENV 1992-1-1:1991, ENV 1992-1-3:1994, ENV 1992-1-4:1994, ENV 1992-1-5:1994, ENV 1992-1-6:1994, ENV 1992-3:1998

English version

Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings

Eurocode 2: Calcul des structures en béton - Partie 1-1 : Règles générales et règles pour les bâtiments

Eurocode 2: Bemessung und konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau

This European Standard was approved by CEN on 16 April 2004.

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Ref. No. EN 1992-1-1:2004: E

Eurocode 2: Design of concrete structures Part 1-1 General rules and rules for buildings - 2004

European Committee for Standardization

Eurocode 2 is a four-part series of documents addressing the design of buildings and civil engineering works in plain, reinforced and prestressed concrete. I

Revision + Adoption Cycle

Revision anticipated 2020. 2004 version adopted by member bodies according to their national timetables.

Region(s) of Use

European Union member bodies

Publication Language(s)

English, French, German (official); others permitted by CEN members with notification

Key Feature 1: National Annex Parameters

MEMBER BODIES TAILOR THIS FRAMEWORK TO SUIT NATIONAL STANDARDS OR REQUIREMENTS.

Key Feature 2: Exposure Classes governed by EN 206-1 Concrete – Part 1: Specification, performance, production and conformity

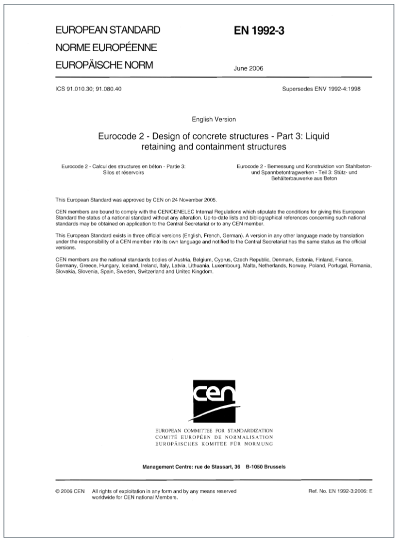
ONLY BRIEFLY SUMMARIZED WITHIN EN 1992-1-1: RISK LEVEL OF CORROSION IS ASSIGNED BUT THEN DISCRIMINATED INTO CARBONATION, GENERAL CHLORIDES, OR CHLORIDES FROM SEA WATER. OTHER EXPOSURE CLASSES ADDRESS FREEZE-THAW CONDITIONS OR CHEMICAL ATTACK.

Key Feature 3: Design working life, durability, and quality management governed by EN 1990, Section 2.

WITHIN EN 1992-1-1, STRUCTURAL CLASSES ARE RECONCILED WITH KEY CRITERIA LIKE 100 YR DESIGN SERVICE LIFE, ENVIRONMENTAL CLASSES, SLAB GEOMETRY, QUALITY CONTROL OF CONCRETE PRODUCTION, AND MINIMUM COVER IN TABLES 4.3N, 4.4N, AND 4.5N.

Table of Key Provisions

REF	DESCRIPTION
4.1 (1)P	A durable structure shall meet the requirements of serviceability, strength and stability throughout its design working life, without significant loss of utility or excessive unforeseen maintenance.
4.1 (2)P	The required protection of the structure shall be established by considering its intended use, design working life, maintenance programme and actions.
4.1 (4)	Corrosion protection of steel reinforcement depends on density, quality and thickness of concrete cover (see 4.4) and cracking (see 7.3). The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content (see EN 206-1) and may be related to a minimum strength class of concrete..
4.1(5)	Where metal fastenings are inspectable and replaceable, they may be used with protective coatings in exposed situations. Otherwise, they should be of corrosion resistant material.
4.1(6)	Further requirements to those given in this Section should be considered for special situations (e.g. for structures of temporary or monumental nature, structures subjected to extreme or unusual actions etc.).
4.3	Requirements for durability requires that the structural and materials requirements are harmonized, along with other parameters, to achieve the design service life.
4.4.1.2	Minimum cover is defined for structural, durability, and fire resistance, and can be reduced if stainless steel reinforcement is used. This parameter can be tailored by national annexes.
7.3.1(P)	Cracking shall be limited to an extent that will not impair the proper functioning or durability of the structure or cause its appearance to be unacceptable.



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1992-3

June 2006

ICS 91.010.30; 91.080.40

Supersedes ENV 1992-4:1998

English Version

Eurocode 2 - Design of concrete structures - Part 3: Liquid retaining and containment structures

Eurocode 2 - Calcul des structures en béton - Partie 3: Silos et réservoirs

Eurocode 2 - Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 3: Stütz- und Behälterbauwerke aus Beton

This European Standard was approved by CEN on 24 November 2005.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

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Ref. No. EN 1992-3:2006: E

Eurocode 2: Design of concrete structures - Part 3: Liquid retaining and containment structures - 2006

European Committee for Standardization

Eurocode 2 is a four-part series of documents addressing the design of buildings and civil engineering works in plain, reinforced and prestressed concrete. I

Revision + Adoption Cycle
Not known.

Region(s) of Use
European Union member bodies

Publication Language(s)
English, French, German (official); others permitted by CEN members with notification

Key Feature 1: Specific durability provisions add abrasion effect of stored materials to containment or retaining structure, i.e., chemical, physical, or mechanical.

SUBCLAUSE 4.3 SPECIFIES CONSIDERATIONS SPECIFIC TO CONTAINMENT STRUCTURES AND REFERENCES MAIN PROVISIONS FROM EN 1990-1-1 FOR THE BASE CONSIDERATIONS.

Table of Key Provisions

REF	DESCRIPTION
4.3	Indicates requirements for brasion resistance of concrete arising from: (1) mechanical attack from filling and discharging stored materials; (2) chemical attack from reaction between the stored material and concrete; and (3) physical effects from erosion and corrosion, including temperature effects and moisture. Concrete is expected to remain serviceable for the design working life.

Concrete - Part 1: Specification, performance, production and conformity - 2013

European Committee for Standardization

EN 206 is an umbrella standard (Table 1) for a broad range of EN materials standards, testing standards, and assessment. It specifies classes of concrete for "different climatic and geographical conditions, levels of protection, and well-established regional traditions and experience" and serves as the basis for EN 1992 (Eurocode 2)

Revision + Adoption Cycle
Not Known.

Region(s) of Use
European Union member bodies

Publication Language(s)
English, French, German (official); others permitted by CEN members with notification

Key Feature 1: Standardizes concrete classes and constituents for buildings and civil structures, but is also flexible, allowing regional provisions to be used if deemed valid.

MULTIPLE PROVISIONS PROVIDE FUNDAMENTAL REQUIREMENTS BASED ON STANDARDIZED MATERIALS AND TEST METHODS VERIFIED USING EN STANDARDS.

Key Feature 2: Defines tasks and technical responsibilities for the specifier, producer, and user from the initial design of the concrete mixture to placement by the user.

CLAUSES 6 AND 7 INDICATE REQUIREMENTS FOR THE SPECIFIER, PRODUCER, AND USER WITH SUPPORTING MANDATORY (NORMATIVE) ANNEXES C AND D FOR ADDITIONAL TASKS AND TESTS IN SPECIFICATION, CONFORMITY, INSPECTION, AND CERTIFICATION.

Key Feature 3: Relies upon prescriptive limit states, and is working toward performance-based concepts.

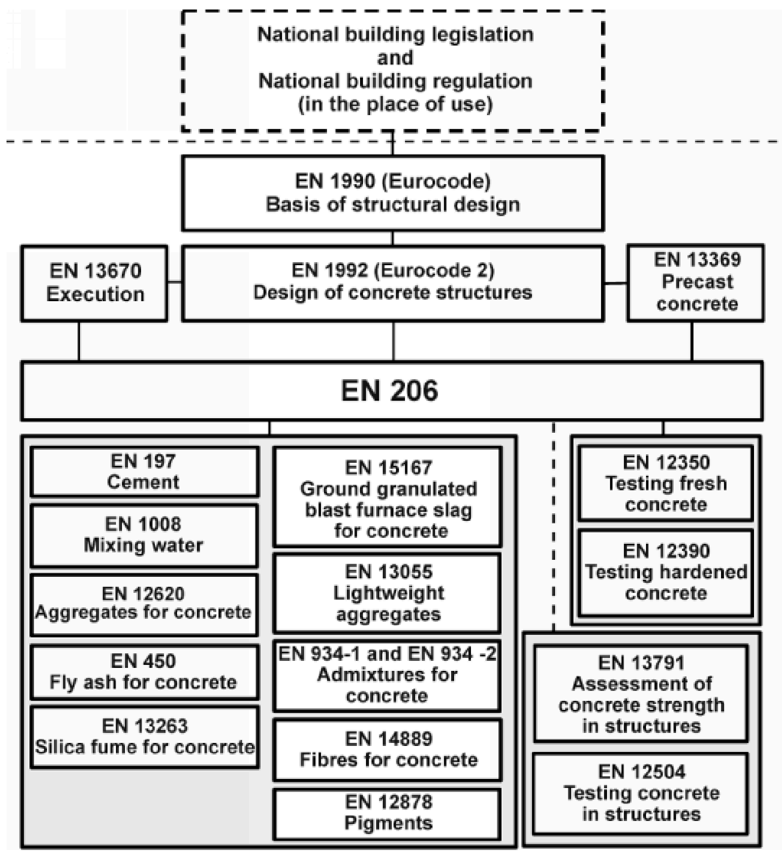


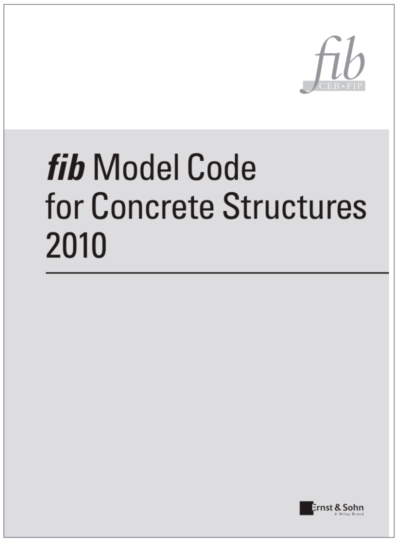
Figure 1 — Relationships between EN 206 and standards for design and execution, standards for constituents and test standards

EUROPE EN 206:2013 cont'd

Table of Key Provisions

REF	DESCRIPTION
4.1	Table 1 is an informative summary of proposed exposure classes, and can be modified for conditions in the place of use. More than one of the exposure classes may be relevant for a particular application and should be considered. Chemical exposure conditions are not included but the specifier is instructed to evaluate situations where the environment might be outside the limits of Table 2, and consider local practices.
5.1.1	General requirements for concrete constituents - for example, constituents with established suitability for the intended use. Also gives guidance on establishing suitability.
5.1.1 (3)	Constituents shall not contain harmful ingredients in such quantities as may be detrimental to the durability of the concrete of cause corrosion of the reinforcement and shall be suitable for the intended use in concrete.
5.2.1 (1)	The concrete composition and the constituents for designed or prescribed concrete shall be selected (see 6.1) to satisfy the requirements specified for fresh and hardened concrete, including consistence, density, strength and durability, taking into account the production process and the intended method of execution of concrete works.
5.2.1 (2)	Where not detailed in the specification of concrete, the producer shall select types and classes of constituents from those with established suitability in provisions valid in the place of use for the specified environmental conditions.
5.2.1 (4)	In the case of designed concrete, the limiting values shall be specified in terms of minimum or maximum values and in the case of prescribed concrete, the composition shall be specified by target values.
5.2.1 (5)	For standardized prescribed concretes, the provisions valid in the place of use shall specify the prescription and list the types and categories of constituent materials with established suitability. These prescriptions shall satisfy the criterion for adoption of initial tests given in A.5.
5.2.2 (1)	Cement shall be selected from those for which the suitability is established, taking into account the: execution of the work; intended use of concrete; curing conditions (e.g. heat treatment); dimensions of the structure (the heat development); environmental conditions to which the structure is to be exposed (see 4.1); potential reactivity of aggregate to the alkalis from the constituents.
5.2.3.5 (1)	Where aggregates contain varieties of silica susceptible attack by alkalis and the concrete is exposed to humid conditions, actions shall be taken to prevent deleterious alkali-silica reaction using provisions valid in the place of use.
5.2.4 (1)	Water recovered from processes in the concrete industry on its own or combined with potable water or ground water conforming to EN 1008 may be used as mixing water for concrete with or without reinforcement or embedded metal and also for prestressed concrete, provided the requirements according to EN 1008 are met.
5.2.5.1	Use of additions is prescribed in terms of initial tests and conformance with requirements, and introduces the k-factor perfomance requirement of 5.2.5.1 (3).
5.2.5.1 (3), (4), (5), (6)	The suitability of the k-value concept and the principles of the equivalent performance concepts (equivalent concrete performance concept (ECPC), equivalent performance of combinations concept (EPCC)) are established and reference additional sections in 5.2.5.2.2, 5.2.5.2.3 and 5.2.5.2.4..
	The k-value concept is a prescriptive concept. It is based on the comparison of the durability performance of a reference concrete with cement "A" against a test concrete in which part of cement "A" is replaced by an addition as function of the water/cement ratio and the addition content.
	The k-value concept permits type II additions to be taken into account: by replacing the term “water/cement ratio” with “water/(cement + k × addition) ratio”; and the amount of (cement + k × addition) shall not be less than the minimum cement content required for the relevant exposure class.
5.2.8	Chloride content requirements are specified and summarized in Table 15.
6.1 (3)	Concrete shall be specified either as designed concrete referring in general to classification or target values or as prescribed concrete by prescribing the composition. The basis for designing or prescribing a concrete composition shall be results from initial tests or information obtained from long-term experience with comparable concrete.

fib Model Code for Concrete Structures 2010



fib Model Code for Concrete Structures 2010

International Federation for Structural Concrete (fib)

Produced by 44 countries from 5 continents, this model Code is considered "pre-normative" in that it is envisioned as a globally harmonized basis for future Codes, and presents " new developments with regard to concrete structures, related structural materials and new ideas... for optimum behaviour." Model Code 2010 "includes the whole life cycle from design and construction to conservation (assessment, maintenance, strengthening) and dismantlement, in one Code for buildings, bridges, and other civil engineering structures."

Revision + Adoption Cycle
Planned for 2020. Adoption is not typical, although provisions are considered for individual projects.

Region(s) of Use
Global outreach, although not an operational Code.

Publication Language(s)
English

Key Feature 1: Divided into 5 parts, MC2010 begins with Principles, and this is followed by parts that address the general life cycle of a structure: Design Input Data, Design, Construction, and Conservation and Dismantlement.

Key Feature 2: Durability is considered an "inherent aspect of serviceability and structural safety, and the performance verification must be conducted with proper consideration of change of performance over time."

THE CONCEPT OF "PERFORMANCE OVER TIME" REQUIRES SPECIFYING SERVICE LIFE (3.3.2.1) FOR NEW OR EXISTING STRUCTURES, AND VERIFICATION OF SERVICE LIFE (3.3.2.2).

Key Feature 3: Defines three categories of performance that must be met: serviceability, structural safety, and sustainability.

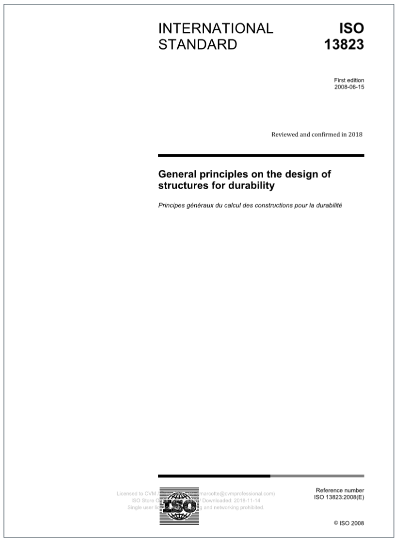
TABLE 3.2-1 PROVIDES AN EXAMPLE OF PERFORMANCE REQUIREMENTS AND REFERENCES EN 1990, ANNEXES B AND C FOR ADDITIONAL INFORMATION.

Key Feature 4: Performance-based design broadly outlined for new and existing structures.

EVALUATION IS BASED ON VERIFICATION OF PERFORMANCE REQUIREMENTS AND SATISFACTORY BEHAVIOUR IS DEMONSTRATED WITH RESPECT TO SERVICEABILITY, STRUCTURAL SAFETY, AND SUSTAINABILTY.

TABLE OF KEY PROVISIONS

REF	DESCRIPTION
3.1.1	(Leveis of Performance) "Structures and structural members must be designed, constructed and maintained in such a way that they perform adequately and in an economically reasonable way during construction, service life and dismantlement. In general: – structures and structural members must remain fit for the use for which they have been designed – structures and structural members must withstand extreme and/or frequently repeated actions and environmental influences liable to occur during their construction and anticipated use, and must not be damaged by accidental and/or exceptional events to an extent that is disproportional to the triggering event; – structures and structural members must be able to contribute positively to the needs of humankind with regard to nature, society, economy and well-being."
3.2.1	"Using a performance-based approach, a structure or a structural component is designed to perform in a required manner during its entire life cycle. In the case of existing structures, by using a performance-based approach we can assess whether the actual performance of an existing structure or structural members andtheir performance during the residual life satisfies the demands of the stakeholders."
3.2.2	"Performance requirements are established by means of the performance criteria and the associated constraints related to service life and reliability. The performance requirements are satisfied if all relevant performance criteria are met during the service life at the required reliability level."
3.2.2	"Constraints related to service life are given by means of a specified (design) service life (relevant for the design of new structures) or a residual service life (relevant for the re-design of existing structures)."
3.3	Performance criteria for serviceability and structural safety considers serviceability limits, ultimate limit states, and robustness.
3.3.2.1	"For new structures, the specified service life defines the period during which the structure has to satisfy the performance criteria agreed. For existing structures the specified residual service life defines the period during which the structures have to meet the performance criteria agreed." Table 3.3-1 is a broad overview and may not represent the true economic drivers of a particular building or structure.
3.3.2.2	Verification of service life requires time-dependent deterioration and other effects be considered in the change of performance over time.
3.3.3.1	Target reliability levels take into account the risk of failure and are used to evaluate design service life. Table 3.3-2 lists failure probabilities from EN 1990:2002, while Tables 3.3-3 through 3.3-6 indicate various scenarios for target reliability levels, comparing reference periods of 50 years to 1 year, and new versus existing structures..


INTERNATIONAL STANDARD | ISO 13823

First edition 2008-06-15

Reviewed and confirmed in 2018

General principles on the design of structures for durability

Principes généraux du calcul des constructions pour la durabilité

Reference number ISO 13823:2008(E)

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ISO 13823 General principles on the design of structures for durability - 2008 (Reapproved 2018)

ISO

This International Standard addresses materials-related failure and verification of durability of structures, and is envisioned as a companion document to ISO 2394 General principles on reliability for structures, which uses limit-states to verify resistance of a structure to gravity, wind, snow, and earthquakes. ISO 13823 standardizes "the evaluation and design of structures for durability by the incorporation of building-science principles into structural-engineering practice.

Revision + Adoption Cycle

All standards are considered for revision at least every 5 years. No adoption cycle.

Region(s) of Use

Global standard; used wherever referenced.

Publication Language(s)

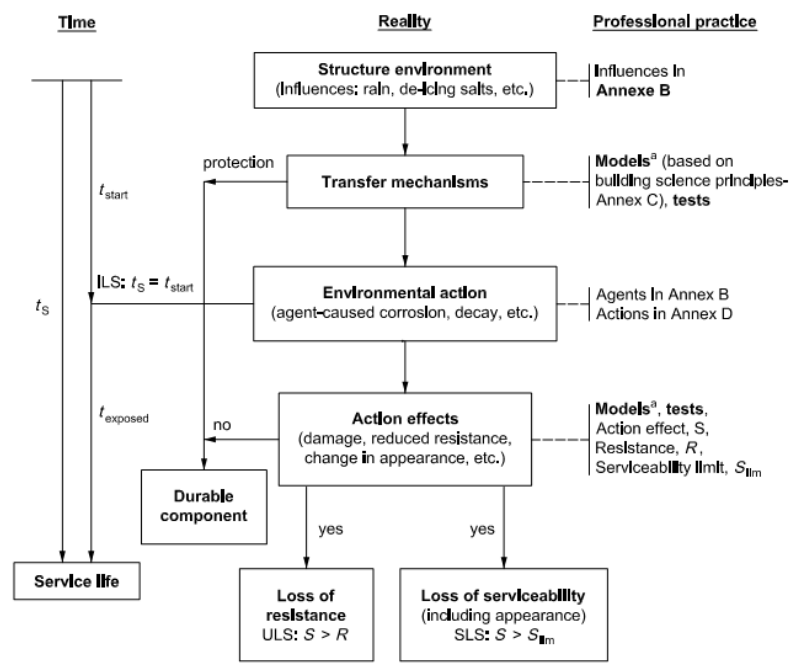
English, French

Key Feature 1: Ties materials deterioration into structural reliability analysis to predict the failure of a component.

Key Feature 2: Relies upon service life prediction of ISO 15686 and deterioration testing or modeling of durability.

Key Feature 3: Applies to structures whenever a minimum service life is needed, either new or existing structures. Can also be applied to non-structural components that can affect the durability of the structural system.

CAN BE IMPLEMENTED IN THE DESIGN PHASE, AS WELL AS PLANNING MAINTENANCE, REPAIR AND REPLACEMENT WORK. EXISTING STRUCTURES CAN HAVE ADDITIONAL TESTING AND DOCUMENTATION THAT INFORMS USERS OF THIS STANDARD REGARDING THE PERFORMANCE OF THE STRUCTURE VERSUS THE ORIGINAL DESIGN INTENT. ISO 13822 - BASES FOR DESIGN OF STRUCTURES - ASSESSMENT OF EXISTING STRUCTURES IS USEFUL TO ASSIGN LOWER TARGET RELIABILITY LEVELS.



a Both conceptual and mathematical.

Figure 1 — Limit-states method for durability

GLOBAL ISO 13823 cont'd

TABLE OF KEY PROVISIONS

REF	DESCRIPTION
1.	"This ISO specifies general principles and recommends procedures for the verification of durability of structures subject to known or foreseeable environmental actions, including mechanical actions, causing material degradation leading to failure of performance."
6.1	"This International Standard recommends the use of the limit-states method shown in Figure 1 for the design and verification of structures for durability. For any component of the structure, this requires an understanding of the structure environment (6.2), the transfer mechanisms (6.3), the environmental action (6.4), leading to action effects (6.5) that can result in the failure of the component"
6.6	" Limit States: (1) Ultimate limit state: failure, (2) Service: local damage, change in appearance, and relative displacements that affect function or appearance, (3) Initiation Limit State: the initiation of deterioration that precedes the occurrence of the serviceability or ultimate state."
7.1	"The service life of the structure and its components shall meet or exceed the design life."
7.2.1	"The basic durability requirement from 7.1 shall be checked either by service-life format (7.2.2) or limit-states format (7.2.3)."
7.2.3.1	"The basic requirement for the ultimate limit state (ULS) defined in 6.6.1 at any time t during the design life of the component, td, is given by equation 5, the resistance capacity, R(t), is greater or equal to the action effect, S(t)."
7.2.3.2	"The basic requirement for the serviceability limit states (SLS)at any time, t, during the design life of the component, td, is given by Equation (7), the serviceability state Slim > than the action effect, S(t)."
7.2.3.3	"The basic requirement for the initiation limit state can be evaluated in accordance with the ULS or SLS by assuming that exposure (Y1,t) = 0"
8.1	"The design life of a structure should be agreed with the client and appropriate authority. Table 1 in ISO 2394:1998 gives typical design life categories."
8.2	"The design life of a component should be determined considering: the design life of the structure (8.3), exposure conditions, difficulty and cost of maintenance or replacement (8.4), the consequences of failure of the component in terms of costs of repair, disruption and operation, and the hazard to users or other (8.5 and Table 1), current and future availability of suitable components, and technical or functional obsolescence."
9.1.1	"The predicted service life of the components or the structure shall be assessed taking into account: experience (9.2), modelling (9.3) and testing (9.4)."
9.2	Prediction based on experience relies on data and inspection of existing facilities per ISO 15686-2, as well as local experience with similar structures and environmental actions. If sufficient experience is not attainable, then modeling and research per 9.3 is necessary.
9.3	Modeling can be conceptual (based on Figure 1), mathematical using materials models, or testing (standard tests based on principles of Figure 1).
10.	Summarizes the durability design strategy using service life planning, execution of quality construction and verification of details, and a general plan to design all materials and components in an assembly to exceed the desired design life, without maintenance and repair. Even so, a maintenance plan and assumptions made in the design phase should be considered, and finally, at what point replacement is merited.
Annex A.3	Within non-mandatory (informative) annex, example of service life of concrete structure determined by carbonation-induced corrosion is included. Both the limit-states approach (A.3.2, Figure A.7) and service life format (A.3.3) are described.
Annex D	Non-mandatory (informative) annex decribes examples of environmental actions for structural materials and their control. Table D.1 contains suggestions for concrete and steel corrosion in concrete environment.
Annex E	Non-mandatory (informative) annex includes Table E.1 - Example of procedures and communications for ensuring durability.

Appendix C: Interview Responses

C1. General

To facilitate a broader understanding of how durability concepts are perceived or approached by Codes and standards developers or users of the information (e.g., academics, design professionals, concrete producers, contractors), the following questions were developed and distributed by email to Australia, Canada, China, Japan, and the United States. Philosophically, the investigators were interested in feedback from country representatives with well-documented durability provisions to compare and contrast these views with the United States. The investigators were also interested in more general, open-ended questions that would allow the respondent to answer as freely as possible. Any specific references to their location, place of work, or branded products have been replaced with generic terms in parentheses.

At the time of this report, responses to these questions were returned in written form, or the investigators conducted approx. 45-60 minute interviews of the respondent. Not all requests for information have been returned at the time of report issue; only respondents from Canada and the United States have returned their information.

If an interview was performed, the process took on more of a discussion format, and only questions pertinent to the respondent were covered, and occasionally additional follow-up questions were asked.

Given the non-statistical approach to this questionnaire and the lack of demographic analysis, the following responses to the questions should be considered anecdotal and the sole opinion of the respondent. Nevertheless, the investigators believe that this preliminary information could serve as a starting point for a broader, more statistically rigorous process, one that would solicit feedback from the following groups:

- Countries with and without building Code concrete durability provisions
- A range of concrete producers and users, including but not limited to: concrete and base materials producers, academics, Code officials, consultants, design professionals---both new construction and repair and rehabilitation specialists, "typical" structural engineers that might not belong to a professional society related to concrete, concrete contractors, Owners, and more.
- Different ranges of time or experience as design professionals within the concrete community, either in new construction or repair and rehabilitation.

Responses are summarized in Table C1.

Table C1: Summary of durability design questions and responses.

1. Do you think the current (insert country) durability design provisions are effective – i.e., will a structure designed to Code achieve the expected design service life with minimal future interventions or repairs?
• (Canada) With A23.1, the intent to provide flexibility in concrete production for both design professional and concrete producer. It works, but yes and no. It is used more as a guide – not set in stone. Provinces and municipalities can vary adoption practices, accepting, changing or deleting provisions. It is the case that CSA will indicate a higher strength or requirement, and provinces and municipalities will make these less or more stringent. The CSA does not dictate what happens. • (Canada) ACI – woefully inadequate for durability. ACI 201 was more state of the art. ACI code committee contain mostly structural engineers, with few materials people. Specifically: » ACI 318 addresses chlorides, w/c, and f'c ; no permeability. Not state of art. » *fib* 2010 – maybe too far except for major structures. Attempts to model everything for major structures. » CSA A23.1 – in between *fib* 2010 and ACI 318. Permeability requirements are related to rapid chloride permeability testing. Moving to a more advance code with more flexibility, i.e. design professional can choose between different options such as increasing cover, reducing permeability, or using a different type of steel. » ACI is the bottom end of the scale. • (Canada) There are at least four relevant standards here: Canadian Standards Association (CSA) A23.1 "Concrete Materials and Methods of Concrete Construction"; A23.3 "Design of Concrete Structures"; CSA S6 "Canadian Highway Bridge Design Code"; CSA S413 "Parking Structures". I am a member of the technical committees responsible for A23.3 and S6 standards. Most of the durability provisions for concrete in buildings are given in A23.1. I think they are effective. The S413 Parking Structures standard was created because parking structures constructed to A23.1/A23.3 were not durable in the mid '90s when the first edition of the standard was published. The durability provisions in the latest (2019) edition of CHBDC (Canada Highway and Bridge Design Code) are intended to encourage bridge owners to require more durable structures – many read like white papers, and will be difficult for engineers to follow in practices. • (Canada) Most places (US and Canada) it is superficial. Positive movement in the direction (of better durability). Most things are prescriptive. » 20 years ago in Canada - durability provisions for parking garages were added with multiple levels of protection. Forces people to think about it. » US – biggest thing – FHWA policy paper for 75 year design life for new bridges. Forced issue in US. Not in actual AASHTO – prescriptive code only. Policy is 75 years. Real change in bridge market is in process. • (United States) Service life of 50 years? In conditioned, or minimally exposed, environments – yes. Exposed to the elements or other corrosive environments – no. • (United States) In non-exposed environments there is a long history of good performance. While my experience is with buildings/garages. I tend to find when I deviate from local experience things are much worse. I worry over specification by designers makes things worse. • (United States) Yes, I believe they are effective, however, all structures require maintenance. And it is with the proper maintenance that you can achieve or exceed the expected service life. • (United States) I think the provisions are effective. On projects I have worked on the durability issues are almost always due to field changes – workers adding water on site for workability, batch plant forgets to add air entraining admix, etc.

2. Do you think design professionals (currently in practice) understand and are comfortable with implementing the durability provisions contained in the design Codes?

• (Canada) No, it is common to encounter structural engineers that assume the concrete plant knows what to supply for the concrete, and even fundamentals like air-entrainment for freeze-thaw resistance, or managing mass concrete are not understood at all. There are too many cut and paste specifications out there. There is little to no academic training in durability.
• Canada) Our provincial engineers follow Code, and there is some level of durability from following the Code. However, if you follow code without understanding – no flexibility. Conflicts inherent associated with lack of understanding. Mass placements are problematic for any Code: example - chloride exposure may require high cementitious material content, but that increases heat production.
• (Canada) For special structures, design professionals will engage an experienced durability consultant.
• (Canada) Basic durability questions – yes. Most design professionals accept maximum w/c (or w/b) ratios, minimum cover, and similar requirements. Most also are aware of the need to proactively manage water travel across a bridge or building exterior to minimize durability concerns.
• (Canada) Code provisions – people are okay. Less comfortable with FHWA mandate. Mandate is for an outcome, not design checklist.
• (United States) I assume this means concrete mixes, concrete cover, maximum bar spacing, and the like. If so – yes.
• (United States) I think those in infrastructure do, but typical building structural engineers have very low technical knowledge.
• (United States) Yes, the Exposure Categories and Classes in the Code are explicit and the provisions are relatively easy to follow.
• (United States) My company performs approximately 5-10 peer reviews of structural designs each year for contractors as part of their risk mitigation process. In our experience the drawings and specs we are reviewing are all over the map in regards to consistency with the ACI Code – w/c ratios not conforming to ACI recommendations, air entrainment percentages not conforming, not specifying exposure categories and classes in the Construction Documents, etc.
   » Generally speaking, structural engineers want to have something to refer back to… "Why did you do that?" "Because ACI 318 recommended/required it."
   » In my opinion structural engineers would make more of an effort to conform to the ACI Code if they were familiar with the durability requirements. I think many engineering firms use the same Structural Notes and Specifications that they have always used and don't put the effort into updating them to match currently adopted Codes.
   » Not durability related but emphasizing my point, I would guess there are very few structural engineers who are aware that ACI 318 recommends more 4"x8" compressive strength cylinders than 6"x12" cylinders. I was speaking to a structural testing and inspecting firm engineer on Friday asking him to refer to my Structural Notes and make more 4"x8" as part of their onsite testing. I forwarded him the ACI 318 section suggesting (3)-4"x8" cylinders. He said the quantity of cylinders his firm sees on drawings varies widely. He said the latest strange requirement that he saw on Drawings was for a 13-story condo unit in Florida which required (4)-4"x8" cylinders be made and tested as follows: (1) 28-day and (3) 56-day breaks.
   » All of this to say I don't think it's intentional non-conformance but rather ignorance of the Code provisions.
• (United States) Yes, specialists in utility structures, wastewater, nuclear, and even parking garage specialists understand what it takes to make an exposed structure. However, for the buildings, it is hard for an Owner to know if someone is qualified and experienced in these structures, and non-specialized engineers can design poorly without an understanding of the durability requirements.

3. Are the durability provisions for design consistent with the state of construction practice? What needs more improvement – the state of design or state of construction practice?
• (Canada) Hard for me to answer – I'm not particularly familiar with the state of construction practice. There are Canadian examples of exceptionally durable structures: the Confederation Bridge between New Brunswick and Prince Edward Island is, for example, a remarkably durable structure constructed in the mid '90s using high-performance concrete. The precast surfaces still have the sheen of being cast in metal forms. • (Canada) Inspection and quality control practice is the limiter on durability. Contractor motivation is to get job completed. Lack of quality control is major factor in durability and is similar for both US and Canadian practice. Someone has to be prepared to pay for inspection. Owner paying for quality control is better path. • How can QC process be improved – get more people involved in QC process. We take cylinders, but do not necessarily measure cover slopes, cover, etc. • (United States) Both. I think any reinforced concrete not in a conditioned environment needs an admixture like (water penetration admixtures) to obtain real corrosion resistance for steel reinforcement. Unless it's prestressed. My perception is that the general quality of CIP concrete construction is not good (formwork, bar placement, voids and vibrating practices, concrete mix/delivery issues). • (United States) State of design for common buildings/garage is ok, good contractors are great, low performing contractors are a nightmare. Can we focus on 'raising the bottom 10%' somehow? • (United States) In my opinion the provisions are consistent with the state of construction practice. I think the state of design is adequate, so it is really up to the inspections and testing provided by the special inspectors during construction to ensure that what is provided meets what is specified. • (United States) Yes, they are consistent. The construction practice needs more improvement. Unfortunately, the Contractor will typically place concrete that arrives on site, even if it's out of spec, rather than rejecting it in order to stay on schedule. It also doesn't seem to matter how many times a foreman or I tell a worker not to add water to plastic concrete, they still do it.

4. Are contractors concerned about the expected durability of the structures they are constructing?
• (Canada) Builders seem to not be concerned about end result—they care about making the construction schedule and getting paid. The concrete producer can only go so far to counter what a builder will do onsite (e.g., watering down the concrete rather than buying a mid-range water reducer or superplasticizer). • (Canada) What you do not see, does not harm you. Personally, not heavily involved in construction stage and not on site often. Not qualified to answer. People in construction do not know better, though, than the durability experts. • (Canada) Hard for me to answer but I think generally yes. Reputable contractors care about their reputations! • (Canada) Not in new construction segment and not in sense of durability. Get project completed and signed off. Not thinking about what will happen 20 years in the future. • (United States) I'm sure there are some, but again, my perception is generally no. • (United States) In typical buildings/garages I think they are not. As engineers (and codes even) increase restriction it gives them more room to 'blame the code' or 'blame the designer'. Is a 'certification model' like that done for post-tensioning contractors somehow make sense? This bring focus on best practices, gives engineers more confidence in areas they generally lack knowledge, and lets them cut costs where most appropriate. • (United States) In our practice, most contractors are primarily concerned with providing only what is required by the Construction Documents, and how it can be achieved with the least amount of cost. • (United States) I would say Contractors are concerned with the expected durability but it takes a back seat to construction schedule. They are more likely to adhere to it when it's convenient.

5. What additional guidance or tools are missing from durability design processes?
• (Canada) ACI durability guide (ACI 201) is a useful document. *fib* model code a bit too complicated. Durability standard that 201 creates may be useful??? Hard to see how it will unfold. Followup question: Are designers aware of ACI 201? Most people are not involved in ACI and perhaps information is not getting out. • (Canada) Properly classifying exposure is critical. Nothing in ACI 318. Chloride resistance values in ACI 318 are out of step with rest of ACI documents. • (Canada) More on the need to proactively manage water travel. The most important number in this regard is a “quarter inch per foot” • (Canada) Inspection is missing. Ultimately – testing and confirmation of parameters that we are achieving durability. Test for strength, but not typically permeability. Measure critical factors for permeability. Slope and drainage are critical for durability – not measured. • (United States) Simple, easy-to-obtain, universal guidance in one source: concrete cover + admixtures + fiber reinforcement and their combined effect in varying quantities to cracking and durability. • (United States) Not sure. • (United States) I don’t think anything is missing from the process, it is preferred that everything is in one place and that would be in the Code. • (United States) Making structural engineers open the early chapters of ACI 318 so they are aware of the requirements and recommendations.
6. What are the lessons learned from implementation of advanced durability Codes and standards?
• (Canada) CSA has exposure classes similar to ACI 318. Sulfates are similar to 318. CSA has permeability limit. CSA instructive on limiting exposure to ASR. There is also twenty-plus years of experience with ASR. ASR guidance in CSA similar to ASTM C1778, AASHTO T80. • (Canada) See previous comment on the CHBDC (Canada Highway and Bridge Design Code) provisions – they are somewhat of a “motherhood” variety and will be difficult for practitioners to demonstrate that they have been successfully met. • (United States) I have little experience with these. • (United States) I have not implemented ‘advanced’ standards. • (United States) That good testing and inspections during construction is crucial. • (United States) I don’t think the effects of ACI’s expanded requirements and recommendations will be realized for years but for me personally, it’s nice to have the information and guidance available to include in my Construction Documents, I just have to know where to look.

7.	**How important to you is it, philosophically, that durability is performance-oriented? Or can durability be achieved via prescriptive requirements for structural design, concrete materials, reinforcing steel and construction requirements?**
•	(Canada) Durability must be performance oriented. But it has to be a combination of performance observation and prescriptive requirements – we have to continue to identify and specify best practices and minimum requirements.
•	(United States) Performance oriented is best, with alternative prescriptive requirements (if the owner doesn't know any better).
•	(United States) (Consistent with my previous) responses, performance-based approaches are a win-win for the contractor and engineer IF the contractor is experienced and competent (i.e. certification).
•	(United States) I believe that it can be achieved via prescriptive requirements.
•	(United States) I've read the article in Concrete International (August 2015) which recommends not specifying w/c ratios and other prescriptive properties but rather outlining the performance requirements and letting the concrete supplier design a mix accordingly. I think this works on the largest and highest profile projects but not for 90% of the projects I work on. I think prescriptive requirements are more likely to be followed because concrete suppliers do not have the resources available to tailor a concrete mix for a project which may only receive 150 cy total.

8.	**Is the state of durability design practice improving? What are barriers to improvement?**
•	(Canada) Contract law can be a barrier to improving durability: payments are processed usually on a monthly schedule. Some durability requirements like tests for rapid chloride permeability testing need 90 days to complete, and yet the 28 day payment schedule will sometimes trigger non-scientifically oriented acceptance criteria to be set. There appears to be a fundamental lack of respect for science. To improve practice, recommend design professionals spend time with an actual concrete producer.
•	(Canada) Practice is improving with time. Reasons – not sure. Expectations for structures are improving. 75-100 year design life is becoming the norm. Education is getting a bit better, but more education on durability is necessary.
•	(Canada) I think yes – owners are gradually becoming more aware of the need to consider the lifetime cost of a structure, not just the first cost. I was on a committee that worked with the architect/engineer design team that designed a new engineering building at (my university) (100,000 sq. ft.): the participants from (my university)'s Facility Management group were very concerned about durability in virtually every aspect of the construction. Given we have a provincial premier who announced a 10% tuition cut last week with no additional funding to the universities, it is the only perspective to have!
•	(Canada) Again, it's about inspection and the need to verify durability parameters during construction, like drainage. Five years ago – different answer. FHWA expected performance. More powerful that it was expected to be. Policy statement for expected durability. Repair code – requires consideration of design service life. Should be stated and agreed to by Owner and Design Professional. Pass the information along to contractor, etc.
•	(United States) My sense is that too much is proprietary (e.g. admixtures and fiber reinforcement). They should go the route of post-installed anchors: keep the products proprietary to promote innovation, but the results from product testing feed into a common platform for design by engineers.
•	(United States) Not sure.
•	(United States) I think it is definitely improving, the durability provisions in the Code are far advanced from when I started designing structures in the 1980s.
•	(United States) Yes, it is improving. The main barrier is informing designers, contractors, and the concrete subs (placers, finishers, etc.).

9. From an educational perspective, how are students learning about durability design in (insert country), if at all?

• (Canada) Lots of durability conferences, but preaching to the choir. A lot of improvements – financial institutions are putting weight onto durability. Most DOTs are using multiple lines of defense to corrosion. In my province – high performance concrete, membrane, and corrosion inhibitor are required for every element above the bearing level. Girders, deck, barrier walls all have additional level of corrosion protection.
• (Canada) At (my university), we have separate concrete and concrete materials courses and they are not terribly integrated. I teach steel design and try to integrate material information with structural design requirements.
• (Canada) Most students – deer in headlights about durability design. My daughter, in a Canadian engineering masters program, is taking concrete durability class. Class is atypical. Students have interest, but may not have access to classes. Tie to sustainability and environment. We cannot afford from any perspective for concrete structures to last 20 years and need to be replaced. Need concepts of immunity in design and design by avoidance:
  » Immunity design – use FRP rebar in chloride environment, etc.
  » Avoidance – eliminate potential hazards, eliminate joints, etc.
• (United States) On the job. Not in my experience.
• (United States) Principles are taught, but how they inform code is not well addressed. Bridging this gap helps reinforce the code.
• (United States) It has been a long time since I've been in school, so I don't know the answer to this one.
• (United States) I don't remember durability courses when I was in school. My training has been while working for structural engineering design companies.

10. Is there a single comment that you would like to make about concrete construction in your area?
• (Canada) There is a problem with CSA development: not enough producers in the document development process. Too many consultants and academics are involved and not contractors or enough producers. • (Canada) Not really. It is reasonably well done. No post-tensioned buildings in our part of the world – I gather a contractor tried one over a quarter of a century ago and lost his shirt! • (Canada) Need mandate – to get people aware. Be aware of fake math in service life models. Europeans have gone this way, and it may be bad direction. Anomalies and construction problems make these models less than useful. • (United States) CIP concrete leaves a lot to be desired in the constructed result, from a design point of view. • (United States) We see fully enclosed buildings in SF using fully-encapsulated post-tensioned systems because the industry decided it was appropriate for initial and long-term durability despite added costs; yet we see regular durability problems with exposed concrete due to cracking then corrosion of steel. Contractor blames engineer for a bad spec and designer blames contractor for poor construction. How is it one industry 'self-advances' with fully encapsulated systems while others cut-cost and performance due to fiscal pressure? • (United States) Based on our practice, the cost of construction is very competitive, and an extra dollar is not spent unless it is required. Therefore, the durability design has to be in the form of Code provisions, otherwise its use will be very limited. • (United States) The lack of carpenters has driven the price of concrete up.

11. Who else do you think we should talk to about this topic?
• (Canada) Concrete producers and the cement association • (Canada) Cement association and the current chair of the Canada Highway and Bridge Design committee on durability. • (Canada) Bridge designer. • (United States) Concrete subcontractors. • (United States) Ask structural spec writers at firms to specifically respond. At the moment we do not have one, but most firms do. • (United States) Possibly Architects and Owners/Developers. • (United States) Structural testing and inspecting firms.
12. If you were designing a "new condominium building in Miami, Florida" and the Owner wanted "75 yrs of design service life" for the exposed concrete features, what would you do?
• (United States) 20 yrs ago – I would go to the Code and make sure I'm compliant with that. I assumed that the Code would help me with some sensible guidance about how to proceed. I would not know how to assure anyone how to achieve 75 yrs. In the last 20 yrs - I now know that there are ways to design and model (tools) for durability, and I would explore those to meet the 75 yr design service life.

cvm

PIVOT

ENGINEERS