Final Report CRC Project #40

Formwork pressures for Self Consolidating Concrete.

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Effectively this project has been on hold since 2008. The project depended upon access to construction projects of the co-investigators (Ellis-Don Construction) using Self Consolidating Concrete. Unfortunately the current construction situation has not resulted in any suitable projects.

The results to date were summarized in a presentation at Los Angeles (spring 2008). A pdf of the presentation, titled LosAngeles4, is attached. All figures in this report are taken from the Los Angeles presentation.

The major, labor intensive and expensive part of the project involved measuring form pressures at 4 sites operated by Ellis-Don Construction in Charleston, London Ontario, Peterborough Ontario and Toronto. Obviously industry is most interested in the maximum form pressures for formwork design; which are determined by the rate of concrete placement versus the rate/development of concrete stiffness/strength. Unfortunately the term “Self Consolidating Concrete” is a non-unique, generic description. Indentifying and characterizing the flow/stiffening properties of the concrete relevant to the magnitude of the lateral pressure envelope would be very useful. Material characterization evolved over the course of the project. Mix design and qualification should be done prior to start of construction. However on-site quality control is required to ensure mix compliance and consistency.

Preconstruction mix testing is usually limited to ensuring that specified strength and slump flow can be achieved using the available materials and admixtures. Slump flow loss and rheometer tests can be done conveniently, in the luxury of a laboratory environment, at this time.

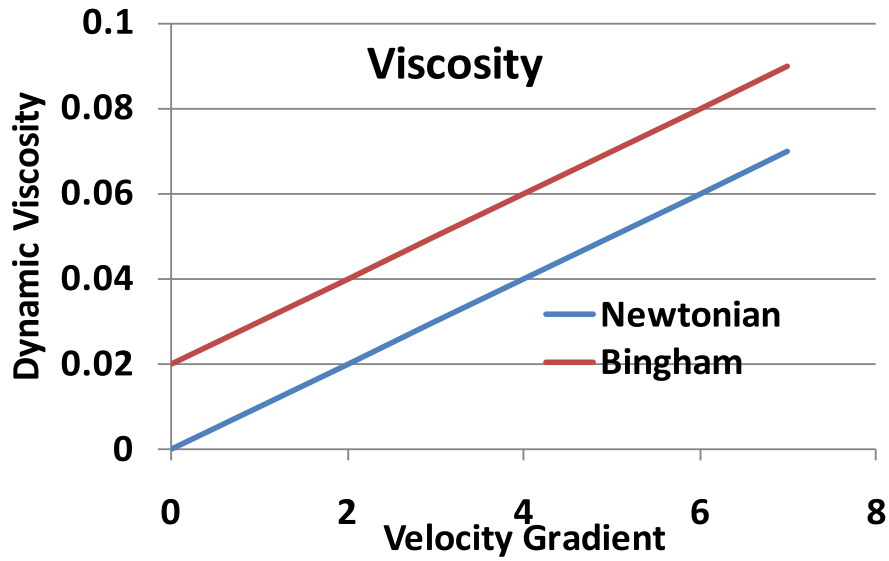
Lessons learned

Discontinuous placement, by bucket or programmed interruptions of pumping, allows the concrete to gain shear strength, reducing the maximum form pressures. For formwork pressure purposes, the ideal admixture combination would produce a concrete that flows under agitation and immediately stiffens when agitation ceases. The SCC mixture design has to be done with care and admixtures can not be changed or substituted without diligent consideration. In addition changes to the water content of the aggregates can significantly affect the stability of the mixture and strict control for moisture compensation needs to be instituted at the ready-mix plant. Testing for production, mixture selection/qualification and formwork selection must be done in concert and concrete control parameters must be established to ensure compliance.

Rheometer Studies

Flow behaviors are measured by devices called a rheometers. Measurements can be taken using linear movement (falling ball),or axisymetric, planetary or annular rotational movement.

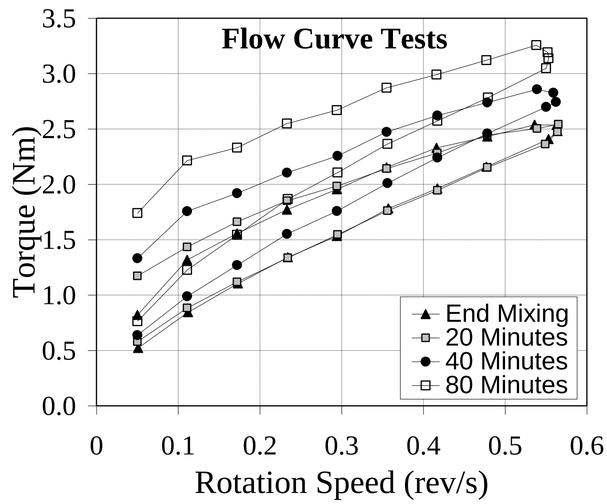
Flow occurs when the applied shear stress exceeds the material shear strength. Traditionally fluids were described as Newtonian – resistance to flow proportional to velocity gradient. More recently Bingham proposed that a flow regime in which an initial shear stress has to be applied to initiate flow.



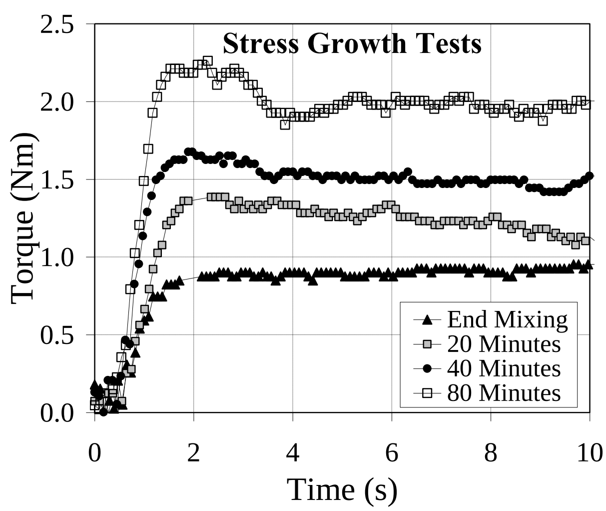
At its fundamental, a rheometer has to give data at sufficient points to determine the initial yield strength and the dynamic viscosity. Naturally flow of real particulate materials is more complicated.

ICAR rheometer

The ICAR rheometer uses a paddle rotating in the test material. The motor applies a chosen rotational speed and measures the torque required. The process is repeated at different angular velocities. Concrete is conditioned, to remove initial perturbations in the sample, by applying a low angular velocity for several seconds, the velocity is then increased to a chosen higher velocity and then the velocities are decreased to zero. Torque measurements are taken at pre-selected velocities. The figure below shows measured results for a trial SCC taken at different ages after mixing. The angular velocity was increased in steps, to enable the torque to be measured, from 0.05 rotations/second to 0.55 rotations/second and then decreased with torque measurements also taken at the same rotations. The increasing rotation speed torques are higher than the decreasing speed torques. The decreasing torque speed curves approximate a straight line (Bingham) with an intercept (yield strength) and a slope (dynamic viscosity).



As concrete in a form is at rest the zero rotation behavior is of most of interest – initial conditioning of the concrete is a complication. Using different control settings the ICAR rheometer can also measure the minimum displacement (yield) stress growth during conditioning.



Slump Flow Loss

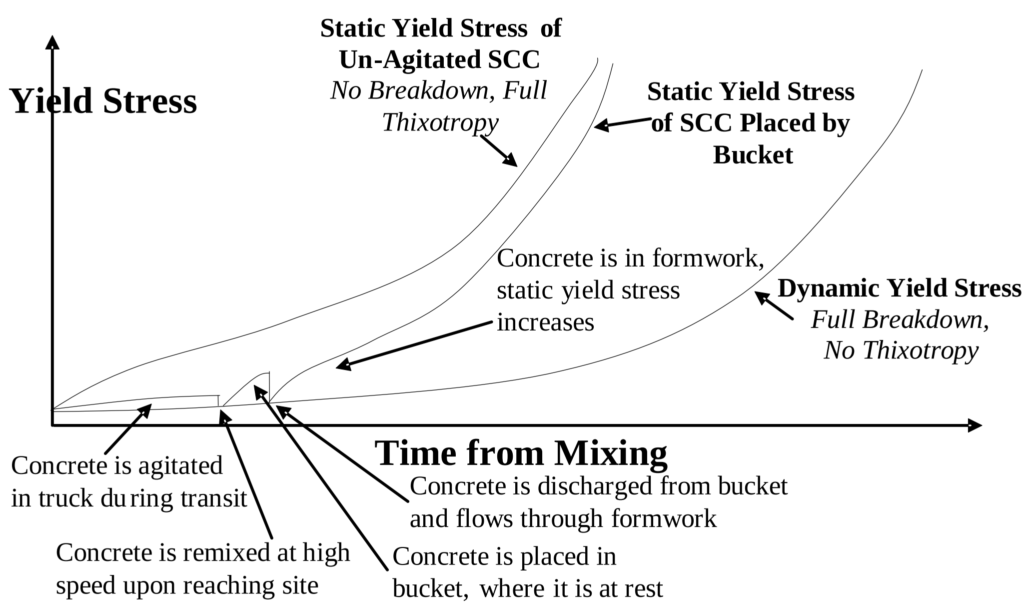
The standard test to measure the flow potential of SCC is the slump flow – easy to understand and possible to do on construction sites. Multiple samples are required to permit testing every 20-30 minutes or so during the time needed to cast a concrete element. As most SCC has a specified slump flow of 600mm (24 ins.) the loss point was chosen to be 400mm (16 ins) and the time for the flump flow to reach 400mm was taken as the characteristic. The slump flow loss has been correlated to the ICAR fundamental rheological properties (which are rheometer dependent).

Visualization of Casting Process

The figure below, also shown in the LosAngeles4 pdf, is a visualization of the placing process to determine the required characterization properties. Concrete is agitated in the truck during transport and remixed at high speed upon reaching the construction site. Concrete is placed into the bucket where it is at rest. Concrete is discharged from the bucket and flows into the form. When the concrete is at rest, inter-particle bonds form creating shear strength. When the concrete is poured into the form the bonds are broken.

However after the concrete has reached its final position in the form it is not in a state of flow/failure. The formwork supplies sufficient lateral constraint to hold the concrete in place. As more concrete is poured it is supported by the lower concrete partly by the shear strength of the previously placed concrete is due to cohesion and internal friction. Neither of conventional rheometer characterizations is an appropiate representation of the concrete placing process.

Figure 1 Visualization of the casting process



With the aging of concrete during placement multiple undisturbed samples of concrete are required.

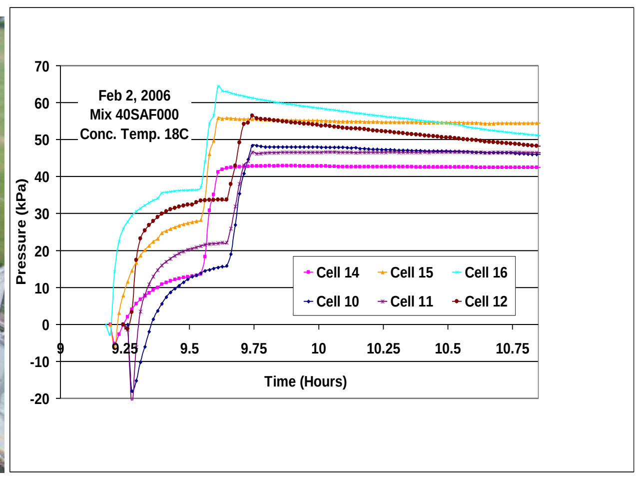
As an alternative measure of flow behavior the slump flow loss test was devised – also requiring multiple undisturbed samples.

Field Program

Field measurements of form pressures were taken at four sites pressures at 4 sites operated by Ellis-Don Construction in Charleston, London Ontario, Peterborough Ontario and Toronto.

Citadel, Charleston SC 2005-2006.

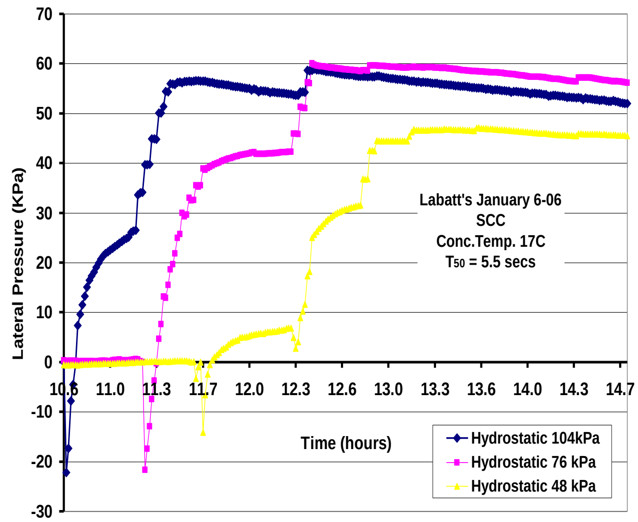
Base mix design, including use of an IBB rheometer, was completed before the PI got involved with Ellis-Don. A base mix, a reduced w/cm, a reduced paste mix and an increased coarse aggregate mixes were chosen. As the project progressed modified mixes were added and others abandoned without field use. The project was a university residence with 6ins. and 16 ins. thick shear walls. A single residence unit required about 6 cubic yards of concrete placed by pump. With SCC the concrete placement could be completed in as few as 10 minutes – the form pressure envelope was hydrostatic. With time the placement sequence was modified to place half the height of concrete in successive residence units and the placing the second lift some time (20 minutes) later.



Most of the measured pressures were close to hydrostatic. Mix proportions did not seem to have much effect. Splitting the pouring into lifts with a rest period between lifts did reduce the maximum pressures.

Labatts Brewery, London, ON (Dec.2005-Jan 2006)

Sixteen inch thick walls for a service shaft placed by bucket resulting a moderate rate of placement. No rheometer tests were done. Maximum measured pressures much less than hydrostatic.



Regional Hospital, Peterborough ON (spring-summer 2006)

Field testing was conducted on 3 mixtures on separate days. Mixture 1 was a base mix; Mixture 2 had a higher coarse aggregate to total aggregate ratio; and Mixture 3 had lower w/cm and different retarder and superplasticizer. The walls were 4.27 m high, 300 mm thick and were instrumented with 4 vibrating wire pressure gauges (4.12 m maximum head above lowest gauge). Concrete was placed into forms by bucket at approximately 2 m/hr. At the beginning of placement, concrete was sampled for rheology measurements with the ICAR rheometer and the slump flow test. For the rheometer, concrete was placed in the rheometer container and left undisturbed until the time of testing. After testing, the concrete was remixed and allowed to remain undisturbed in the rheometer container until the next test. For the slump flow test, an undisturbed sample of concrete was stored in a wheelbarrow and tested at times corresponding to the rheometer measurements. For brevity, the rheometer measurements are not shown in this paper.

Figures indicates that Mixtures 1 and 2 lost workability quickly, as indicated by the loss of slump flow. Consequently the formwork pressures were much lower than hydrostatic pressure, as shown. When concrete was first placed into the forms for these two mixtures, the pressure increased at the lower cells. As further lifts of concrete were added to the initial lifts—as seen when pressures were registered on higher cells—the pressure at the lower cells increased by a slight extent, if at all, because of the increased shear strength of the material at the lower cells. The fast loss of workability or build-up of thixotropic structure contributed to this increased shear strength. (The results for Mixture 1 were compromised by the long delay in arrival between the first and second trucks, illustrating the problems of field research.)

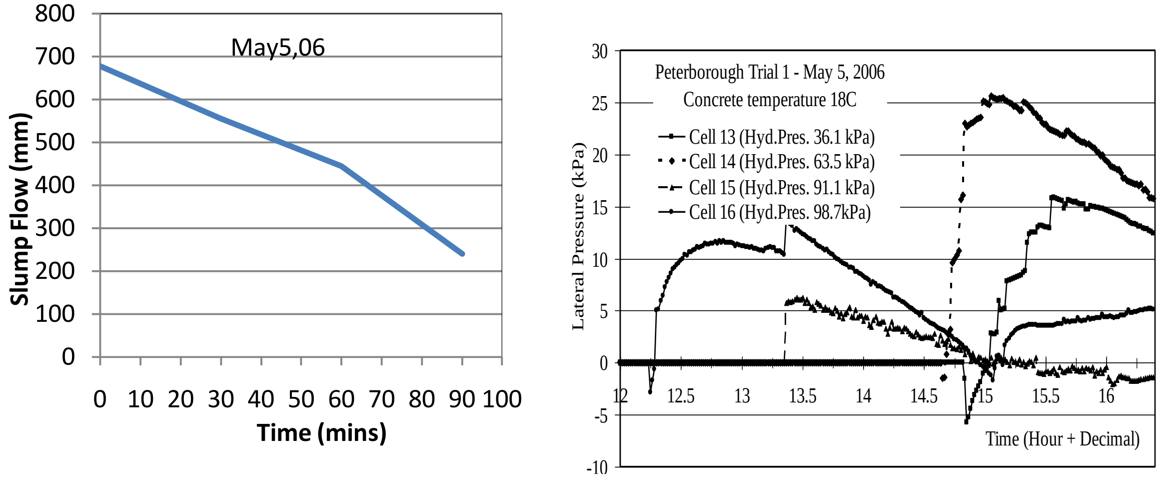


Figure 4: Formwork Pressure Measurements for Peterborough Mixture 1

Second concrete truck got lost allowing earlier concrete to set up.

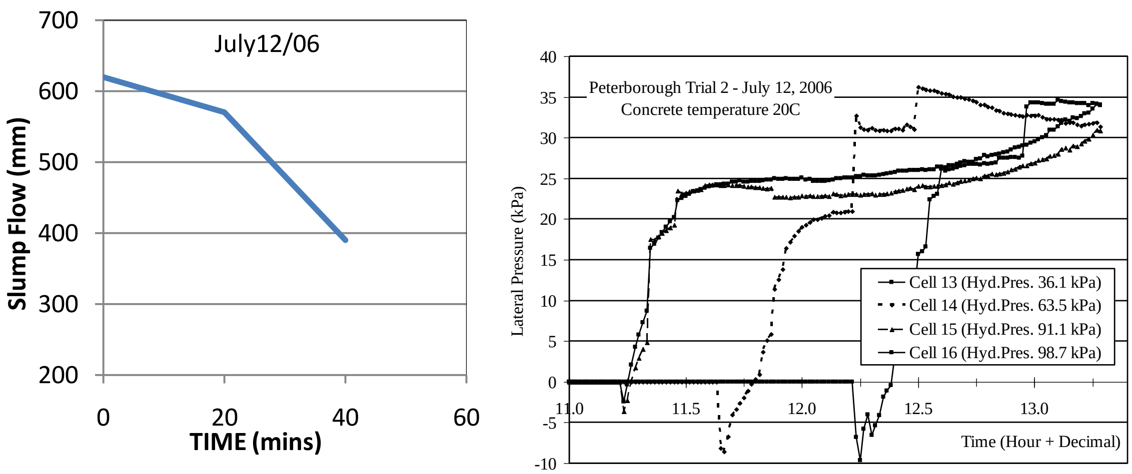


Figure 5: Formwork Pressure Measurements for Mixture 2

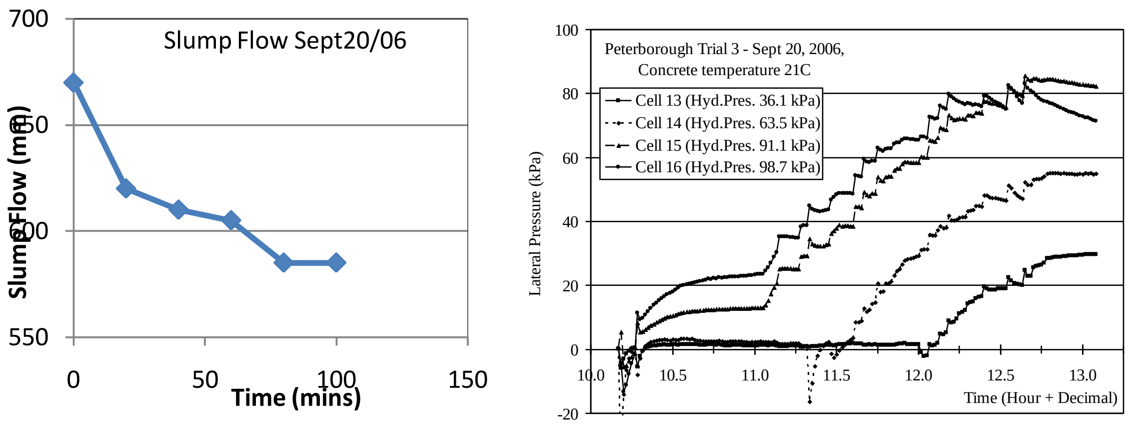


Figure 6: Formwork Pressure Measurements for Mixture 3

The different retarder and superplasticizer used in Mixture 3 extended the workability retention. As a result, the formwork pressures were much higher than in the first two mixtures and nearly approached hydrostatic pressure. As further lifts of concrete were added to the lower lifts, the pressures at the lower cells continued to increase significantly because the lower concrete had not gained shear strength.

The formwork pressure data for the 3 mixtures clearly confirm the diversity of pressure distributions reported in the literature for SCC.

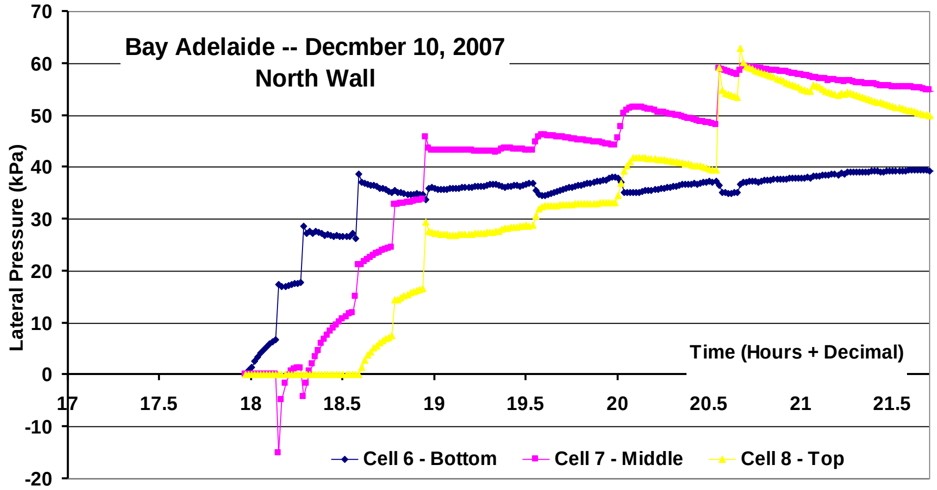
Bay-Adelaide, Toronto

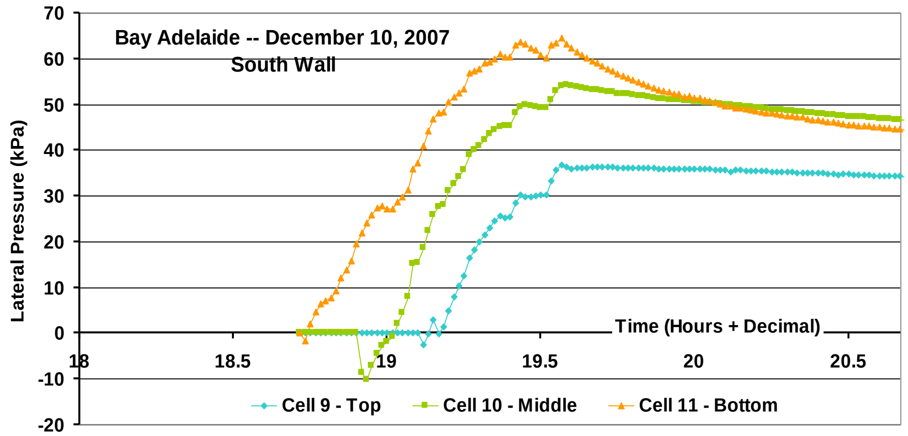
Measurements were carried out on several floors of the core structure of the 50 storey Bay Adelaide tower.

Large jump (self climbing) form for the core structure. Outside core dimensions 33m x 20m (100 feet x 65 feet). Various wall thicknesses but pressures measured on 350 mm (14 ins) and 600 mm (24 ins.) walls. Height of lift 4 metres (13 feet).

Very large pour of some 380 cubic metres (42 x 9 cubic metre trucks) lasting 4 or 5 hours. South wall concrete placed by pumping and north wall by bucket

Typical results for the two instrumented wall forms are given below. Some small effect of wall thickness – providing the rate of placements are the same logic would indicate the form pressure for thicker wall should be slightly larger.





Lessons learned

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Suggested lateral Pressure Equation

The following equation was developed to fit the field measured lateral pressures. Note the experimental results were limited in that the maximum concrete head was 4 metres (14 feet).

SI units

$$P_{\max} = 2w\left(\left(\frac{d}{500}\right)^{1/8}\right)\left(\left(R*\left(\frac{t_{400}}{60}\right)\right)^{1/4}\right)\left(\left(\frac{50}{18+T_c}\right)^{1/2}\right)$$

P_{max} = limiting lateral pressure (kPa)

w = unit **weight** of concrete (kN/m^3)

d = minimum lateral form dimension (mm)

R = rate of placement (m/hour)

T_c = concrete temperature (Celcius)

t_{400} = time for slump flow to drop to 400 mm

US units

$$P_{\max} = 5w\left(\left(\frac{d}{20}\right)^{1/8}\right)\left(\left(R*\left(\frac{t_{400}}{60}\right)\right)^{1/4}\right)\left(\left(\frac{90}{T_F}\right)^{1/2}\right)$$

P_{max} = limiting lateral pressure (psf)

w = unit **weight** of concrete (lbs/ft^3)

d = minimum lateral form dimension (ins)

R = rate of placement (ft/hour)

T_F = concrete temperature (Fahrenheit)

t_{400} = time for slump flow to drop to 400 mm (16 ins)

The figure below shows the comparison between the field measured pressures and the above equation.

Comparison of Measured Predicted Lateral Pressures

(100 kPa = 2100 psf)