Field Investigation of Formwork Pressures Using Self-Consolidating Concrete

by N.J. Gardner, Lloyd Keller, Robert Quattrociocchi, and George Charitou

Although progress has been made, there is no widely accepted method for predicting formwork pressures developed by self-consolidating concrete (SCC).[1,2] Consequently, the common practice is to assume full liquid head when designing wall forms. While this practice helps to avoid malformed elements or formwork blowouts, it can also lead to overly conservative designs and higher costs. To optimize formwork designs, identifying and characterizing the flow/stiffening properties of SCC relevant to the magnitude of the lateral pressure envelope are required.

Characterization of Fresh Concrete

Fresh concrete is a thixotropic material. In other words, it's a semi-solid that can become liquid under high shear strain rates (vibration). Static yield strength, the stress needed to initiate flow in an at-rest thixotropic material, is relevant to formwork design. It can be measured directly in a rheometer using a strength growth test, during which a very low shear rate is applied to the concrete and the build-up in stress before flow is monitored. The static yield strength of concrete will increase with time; so, to be of use for formwork design, the initial state of the concrete samples used to measure static yield strength must be representative of the concrete in the form at the time of placement. Ideally, an initial concrete sample should be placed in multiple rheometer containers and left undisturbed until testing. The static yield strength can then be evaluated as a function of time by testing the individual samples at designated intervals.

Rheometers are not commonly used outside the research laboratory. Also, there is high variability in fundamental parameters measured using different types of rheometers.[3] We therefore investigated a more common test method to evaluate the build-up of static yield strength over time—the slump flow test per ASTM C1611, "Standard Test Method for Slump Flow of Self-Consolidating Concrete." In contrast to rheometric tests, the slump flow test is easy to perform on construction sites. Regardless of the test method, however, concrete should be sampled from a representative batch at the start of placement and left undisturbed until testing at designated intervals.

For the testing program described in this article, we tested the concrete every 20 to 30 minutes until the concrete slump flow had decreased from its specified value (typically, 600 to 700 mm [24 to 28 in.]) to 400 mm (16 in.), a characteristic value we selected as the end point for the slump flow testing.

Field Program

Field measurements of form pressures were taken at four sites and time periods:

- Charleston, SC, from June 2005 to February 2006;
- London, ON, Canada, from December 2005 to January 2006;
- Peterborough, ON, Canada, from May to September 2006; and
- Toronto, ON, Canada, from August 2007 to February 2008.

Mixtures were designed for a required initial slump flow of 600 to 700 mm (24 to 28 in.). In addition, the laboratory flow properties were determined using rheometers: an IBB rheometer for the Charleston and London mixtures and an ICAR rheometer for the Peterborough and Toronto mixtures. As the investigation progressed, more on-site material characterization was done by measuring the on-site slump flow and stiffening characteristics of the concrete. The test results emphasized the sensitivity of the

Ci online *More data for this study is included in the online version of this article at **www.concreteinternational.com**.*

Fig. 1: Geokon 4820 earth pressure cell at Peterborough, ON, site

Fig. 2: Crane view of the Citadel, Charleston, SC, site

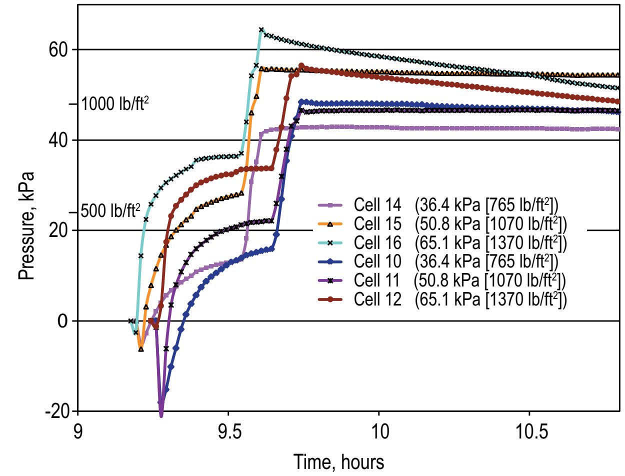


Fig. 3: Lateral pressure versus time from start of data logger for Citadel, Charleston, SC, with concrete temperature of 18°C (64°F) and mixture t_{400} of 122 minutes. Hypothetical hydrostatic pressures, based on fluid head above each cell, are provided in the legend

SCC stiffening behavior to variations in water content, temperature, and admixture types and dosages.

At all sites, lateral formwork pressures were measured using 125 mm (5 in.) diameter, Geokon 4820, vibrating wire pressure cells (Fig. 1). Pressure measurements were recorded using a scanning data logger. In-form concrete elevation data were taken by personnel using tape measures and stopwatches.

Citadel, Charleston, SC

Prior to construction, a baseline mixture, a mixture with a reduced water-cementitious material ratio (*w/cm*), a mixture with reduced paste, and a mixture with increased coarse aggregate were chosen to investigate the effects of proportions on formwork pressure. For all mixtures, the maximum aggregate size was 20 mm (3/4 in.). As the project progressed, modified mixtures were added to the program and other mixtures were abandoned without being used in the field. The project was a university residence hall with 150 and 400 mm (6 and 16 in.) thick shear walls. Placement heights were 3.5 m (11.5 ft) (Fig. 2).

A single residence unit between door blockouts, shown in Fig. 2, required about 5 m^3 (6 yd^3) of concrete. For such a small quantity of concrete, placement by pump could be completed in as few as 10 minutes, a rate of placement of 18 m/h (60 ft/h). Initially, two sets of four load cells in vertical rows were used to monitor form pressure. The maximum concrete head above the lowest gauge was 3.1 m (10 ft). Early results showed that the upper cells experienced only hydrostatic pressure, so the top cells were not installed for later placements.

After inspection of the results, the placement sequence was modified to reduce the rate of placement without excessively slowing down construction. Concrete placement was alternated between adjacent residence units so that the first lift was half of the form height. This lift was allowed to rest for about 20 minutes while concrete was placed in the forms for the adjacent unit. Eventually, two different mixtures were placed on the same day, using four sets of three load cells. Two instrumented forms were used for each mixture.

The results for the February 2, 2006, placement are shown in Fig. 3, along with the hypothetical hydrostatic pressures. The negative gauge readings are due to the load cell being only partially submerged during form filling. Most of the measured pressures were close to hydrostatic, regardless of the mixture proportions. Discontinuous placing (placing the concrete in lifts with a rest period between lifts) reduced the maximum pressures.

Labatt's Brewery, London, ON

Concrete was placed by bucket into 400 mm (16 in.) thick walls (Fig. 4), so the placement rate was a moderate 1.9 m/h (6 ft/h). Measured lateral pressure envelopes were similar to those expected for conventional concrete (Fig. 5), and maximum measured pressures were much less

Fig. 4: View of London, ON, site

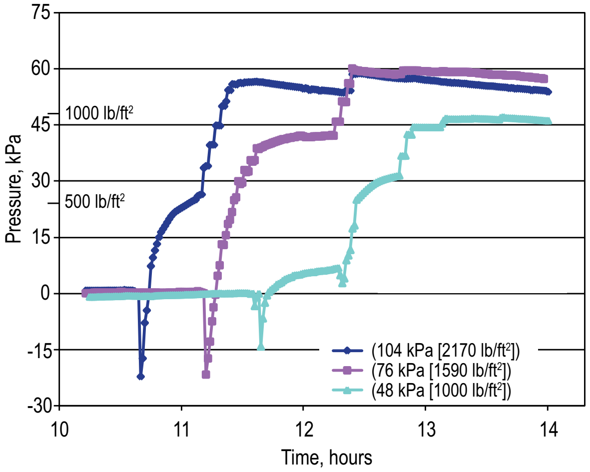


Fig. 5: Lateral pressure versus time from start of data logger for Labatt's Brewery, London, ON, with concrete temperature of 17°C (63°F). Hypothetical hydrostatic pressures are provided in the legend

than hydrostatic. We did not conduct on-site concrete rheometer or slump flow loss tests.

The results reinforce the observation that discontinuous placement (by bucket or programmed interruptions of pumping) allows the concrete to gain shear strength and thus reduces the maximum form pressures.

Regional Hospital, Peterborough, ON

By the time this project started, we had refined our ideas regarding the casting process and concrete conditioning before measurement. We also had gained access to an ICAR portable rheometer, which allowed on-site measurements. We also started measuring slump flow loss.

We installed pressure gauges in the forms for the stair/elevator core walls and measured pressures generated by three different mixtures. Mixture 1 was a baseline mixture; Mixture 2 had a higher coarse aggregate to total aggregate ratio; and Mixture 3 had a reduced *w/cm*. Mixture 3 required a larger dosage of high-range water reducing admixture (HRWRA) compared to Mixtures 1 and 2. We took on-site rheometric data and measured slump flow loss for both agitated and nonagitated concrete.

The walls were 4.27 m (14 ft) high and 300 mm (12 in.) thick. Two forms were instrumented with four vibrating wire pressure gauges at different elevations. The concrete head above the lowest gauge was 4.12 m (13.5 ft). Concrete was placed by bucket at a rate of about 2 m/h (7 ft/h). Concrete samples for rheology measurements and slump flow testing were taken from the

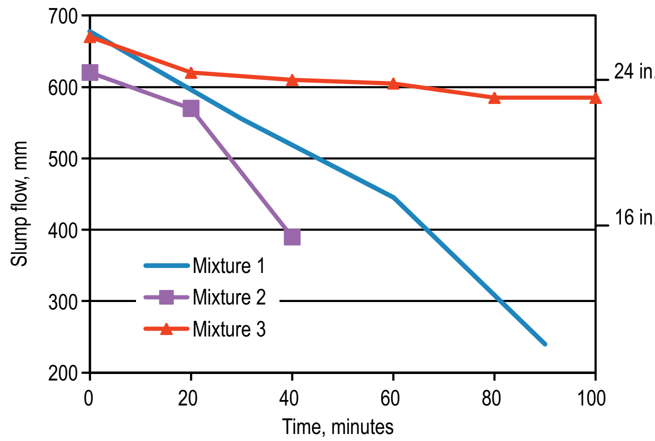
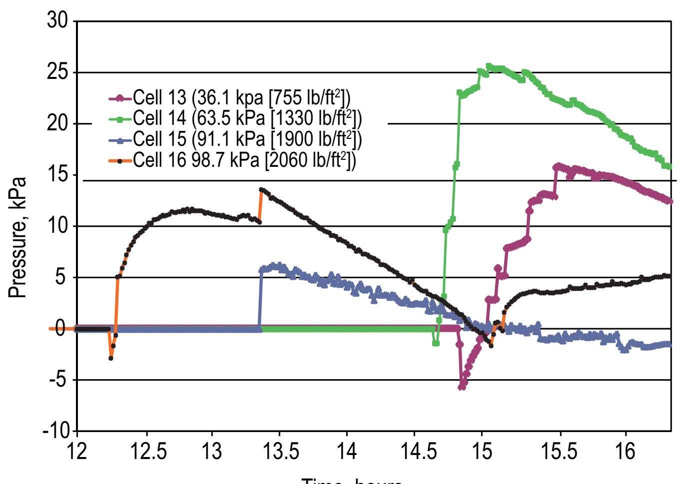


Fig. 6: Slump flow loss for mixtures for Regional Hospital at Peterborough, ON, site (1 mm = 0.04 in.)



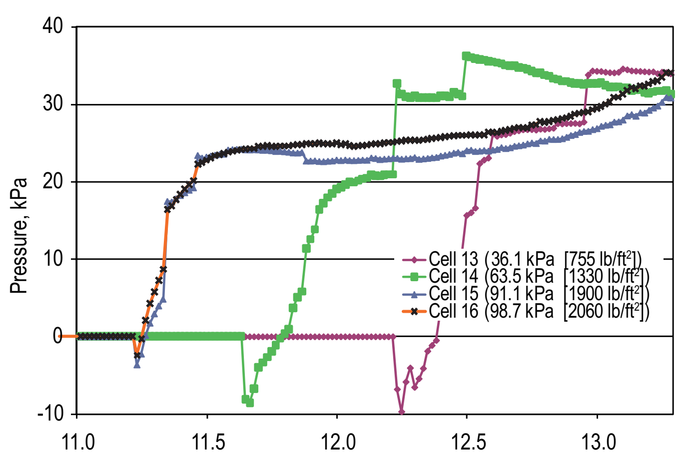
(a)

first truck at the beginning of placement. Concrete was placed in the rheometer container and left undisturbed until the time of testing. After testing, the concrete was remixed and left undisturbed in the 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. The results of the rheometer tests can be found in a previous publication.[4]

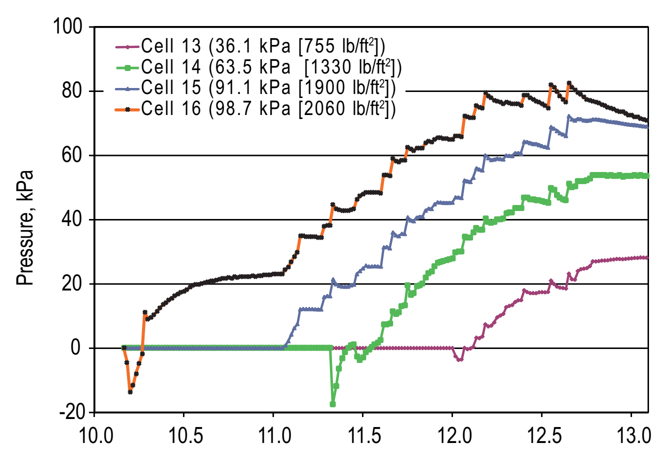
Figure 6 shows the on-site slump flow as a function of time for the three mixtures. As the data show, Mixtures 1 and 2 lost workability quickly. The retarder and HRWRA used in Mixture 3 significantly extended the workability, so the slump flow did not decrease significantly over the duration of the placement.

The lateral pressure measurements for Mixture 1 were compromised by the long delay in arrival between the first and second truck (Fig. 7(a)). The slump flow for Mixture 2 decreased at a much faster rate than the slump flow for Mixture 1 (Fig. 6). Form pressures were around 30 kPa (600 lb/ft²)—much lower than hydrostatic pressure (Fig. 7(b)). For either mixture, the pressure increased at the lower cells when concrete was first placed in the forms. As additional lifts were added, the pressure at the lower cells increased by a slight extent, if at all, because of the increased shear strength in the initial lift.

The retarder and HRWRA used in Mixture 3 extended the workability retention. As additional lifts were added, the pressures at the lower cells continued to increase significantly; and the formwork pressures were much higher than those measured for the first two mixtures (Fig. 7(c)). Although the pressures approached hydrostatic pressure, friction with the wall and reinforcing bars apparently prevented the development of true hydrostatic pressure.



(b)



(c)

Fig. 7: Lateral pressure versus time from start of data logger for Peterborough, ON. Hypothetical hydrostatic pressures are provided in the legends: (a) Mixture 1, placed on May 6, 2006, with concrete temperature of 18°C (64°F); (b) Mixture 2, placed on July 12, 2006, with concrete temperature of 20°C (68°F); and (c) Mixture 3, placed on Sept. 20, 2006, with concrete temperature of 21°C (70°F)

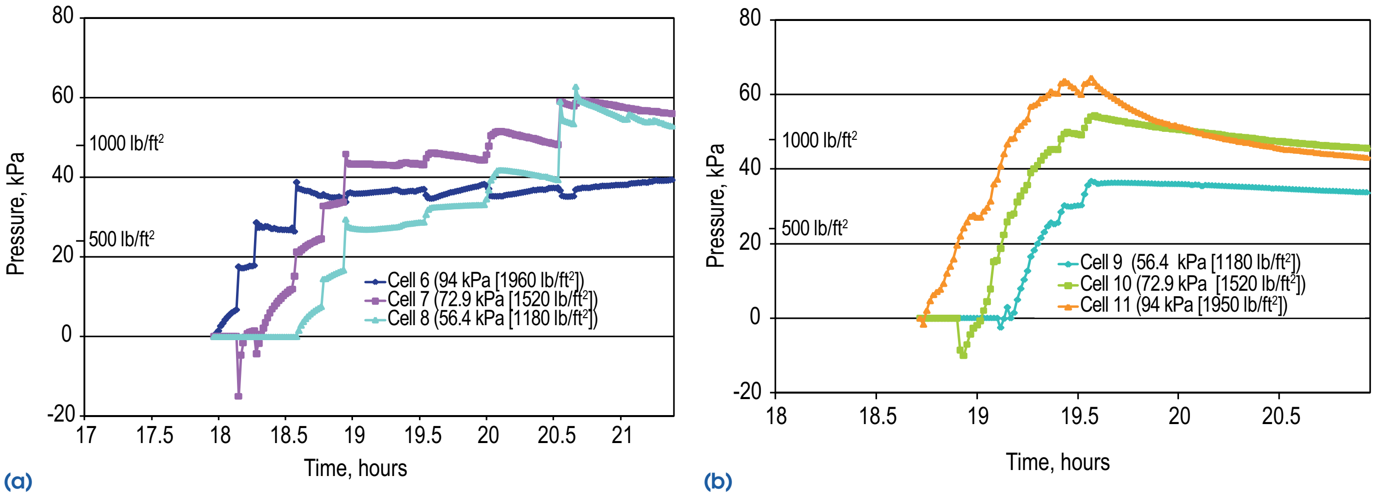


Fig. 8: Lateral pressure versus time from start of data logger for Bay-Adelaide, Toronto, ON, with concrete temperature of 19°C (66°F): (a) North wall, and (b) South wall. Hypothetical hydrostatic pressures are provided in the legends

Bay-Adelaide, Toronto, ON

Measurements were carried out on two walls for several floors of the concrete core for the 50-story Bay-Adelaide tower located in downtown Toronto, ON. The 33 x 20 m (100 x 65 ft) core was cast using a three-story self-climbing form. Pressures were measured on a 350 mm (14 in.) thick interior (south) wall and a 600 mm (24 in.) thick exterior (north) wall. The story heights were 4.17 m (13 ft 8 in.). The planned construction rate of one floor every 3 to 4 days required concrete strengths of 8 MPa (1160 psi) at 12 hours and 60 MPa (8700 psi) at 91 days. The same nominal concrete mixture was used for all floors.

Each wall placement took 4 to 5 hours and required about 380 m^3 (480 yd^3) of concrete supplied by 9 m^3 (12 yd^3) mixer trucks. The initial levels were placed using truck-mounted pump booms. When the core height exceeded the boom heights, the south wall concrete was placed by pumping from a central pump; and the north wall concrete was placed by bucket.

Typical results for the two instrumented wall forms are given in Fig. 8. As the measurements show, wall thickness had only a small effect on pressure readings.

Analysis of Field Data

All pressure measurements were recorded with time. Even though conceptually simple, it proved difficult to relate concrete head with the pressure records. The pressure records show that during the initial placement, the lateral pressure was hydrostatic. However, as additional concrete was placed, the lateral pressure increased at a lower rate than hydrostatic. The majority of maximum pressures recorded were less than hydrostatic.

Concrete placement rates can be estimated from the pressure records or the time to fill the form. For this study, the rate of placement was calculated for the cell that recorded the largest pressure. In Fig. 7(b), for example, the maximum pressure, recorded by Cell 14, was 36.3 kPa (760 lb/ft²) and the calculated rate of placement was 3.2 m/h (10.5 ft/h). However, the maximum head of concrete above Cell 14 was only 1.55 m (5 ft). The rate of placement calculated from the time to fill the form was 2.35 m/h (8 ft/h). Placement rate was a major factor. All but six of the 33 Citadel pressures (rate of placement greater than 3 m/h [10 ft/h] and maximum head of 2.77 m [9 ft]), were greater than 80% of hydrostatic. Conversely, only seven of 29 Bay-Adelaide pressures (rate of placement less than 2 m/h [7ft/h] and maximum head of 4 m [13 ft]) were above 80% hydrostatic.

Suggested Lateral Pressure Equation

Developing a lateral pressure equation from a limited filed study is difficult, but any such equation developed for SCC needs to include the rate of concrete placement and a material parameter characterizing the stiffening behavior of the concrete, and it should produce results that are asymptotic to hydrostatic pressure as placed.

Our pressure equations include a hypothetical time for the concrete mixture to reach zero slump flow t_0. Of course, t_0 is not physically measureable, so we estimate t_0 using the time required for the slump flow to drop to 400 mm (16 in.) t_{400} and the initial slump flow value in mm or in.:

$$t_0 = t_{400}\,[\textit{initial slump flow}/(\textit{initial slump flow} - 400 \text{ mm (16 in.)})] \qquad (1)$$

Other measurements of stiffening time (for example, those described in Reference 5) could also be used to develop estimates of t_0.

Based on our observations, we propose the following simple relationship to estimate the formwork pressure P as a function of time t after the start of placement:

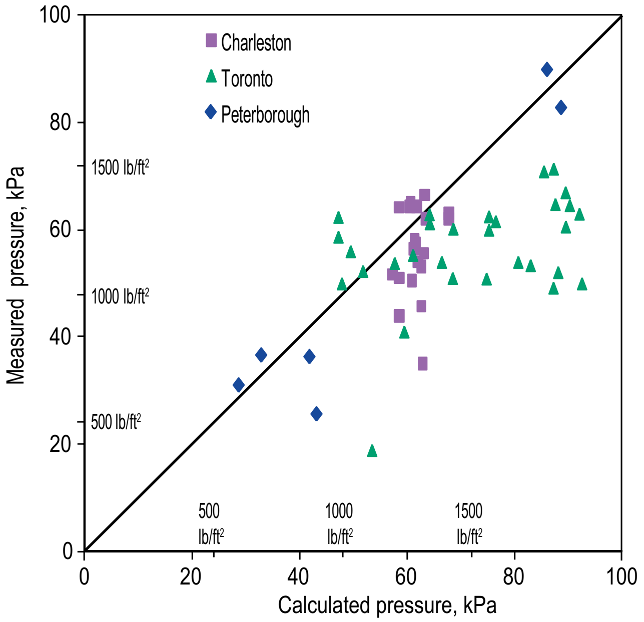


Fig. 9: Comparison of measured and predicted lateral pressures (1 kPa = 21 lb/ft²)

$$P = wR\left(t - \frac{t^2}{2t_0}\right); \quad t < \frac{t_0}{2} \qquad (2)$$

where w is the unit weight of the concrete in kN/m³ (lb/yd³) and R is the rate of placement in m/h (ft/h). The time t_h to reach a placement height h will be the quotient of h and R in hours. If t_h is less than t_0, t_h is substituted for t in Eq. (2), and the maximum pressure P_h is given by:

$$P_h = wR\left(t_h - \frac{t_h^2}{2t_0}\right) \qquad (3)$$

It should be noted that Eq. (2) doesn't have enough terms to be used for t greater than that required to achieve a maximum pressure P_{max}, given by:

$$P_{max} = wRt_0/2 \qquad (4)$$

For t greater than t_0, the pressure is assumed to remain constant at P_{max}.

In all equations, time is in hours and pressure is in kPa (lb/ft²). Field measured pressures and pressures calculated using these equations are compared in Fig. 9.

Conclusions and Recommendations

For SCC, the form pressures are determined by the rate of concrete placement relative to the rate of development of concrete stiffness. Reducing the rate of concrete placement allows the concrete to gain shear strength and reduces the maximum form pressures.

Mixture design and qualification should be done prior to start of construction. Testing for production, mixture selection/qualification, and formwork selection must be done simultaneously. Concrete control parameters have to be established to ensure compliance. Changes in 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 concrete plant.

Rigorous on-site quality control is required. When concrete arrives on site, if the initial slump flow is too low, it can be brought into compliance using HRWRA. This may change the stiffening behavior of the concrete and that could lead to higher maximum formwork pressures. Whether or not HRWRA has been added on site, the stiffening behavior of the concrete should be measured on one of the first batches of concrete delivered. An unresolved problem is reconciling laboratory values of t_{400} to site measured values.

We investigated various approaches for characterizing concrete rheology and found that flow parameters are sensitive to the conditioning of the concrete (agitated or not agitated) prior to measurement. The standard rheometric testing protocol at relatively high shear rates was found to be inappropriate for quality control during construction.

We recommend measuring the slump flow with time to evaluate the increase in static yield strength. The slump flow loss has to be determined from undisturbed concrete samples. Similarly, for rheometric measurements, a concrete sample taken at the beginning of a placement should be distributed into separate rheometer containers.

Although we were able to develop a simple set of equations for predicting formwork pressure based of slump flow loss, additional data (particularly from placements using taller forms) are required before the equations can be used for design.

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Note: Additional information on the ASTM International and AASHTO standards discussed in this article can be found at **www.astm.org** and **www.aashto.org,** respectively.

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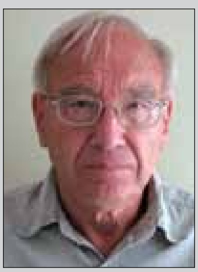

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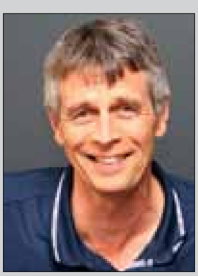

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Field Investigation of Wall Formwork Pressures using Self Consolidating Concrete.

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Abstract

Formwork pressures and concrete flow behaviour of Self Consolidating Concrete were measured at four construction sites during 2005 and 2008. The maximum, recorded, lateral formwork pressures varied from 45% of hydrostatic to hydrostatic. Flow measurements were made directly with a portable, vane-type rheometer and indirectly with the slump flow test. The shear history of the concrete used for flow measurements was matched to that of the concrete in the forms. Increasing slump flow retention by varying the types and dosages of superplasticizer and retarder is beneficial for lengthening transport and placing times but resulted in significantly higher formwork pressures.

The time for the slump flow to drop to 400 mm (16 ins.), t_{400}, was chosen as the material parameter characterizing stiffening/strength behavior of the concrete. An empirical equation was developed to fit the field measured lateral pressures to t_{400} .

Keywords: self-consolidating concrete, form pressure, rheology, slump flow loss

Biodata

ACI Fellow N. J. Gardner is a member of ACI Committees 209 Shrinkage and Creep, 231 Early-Age Properties of Concrete, 347 Formwork and 435 Deflection of Concrete Building Structures. His research interests are shrinkage and creep of concrete, early age loads due to the construction process, punching shear and formwork pressures.

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INTRODUCTION

Self-consolidating concrete (SCC), is concrete that can flow into every corner of reinforcement congested formwork without vibration - which may result in increased form pressures relative to vibrated concrete. Any increase in formwork pressures would be a concern for form designers and formwork suppliers. Published research on formwork pressures is inconsistent to the extent that one section of the Brite EuRam Contract Report #BRPR-Ct96-0366 on SCC concluded that forms should be designed for full hydrostatic pressure and, contrarily, another section concluded that the pressure exerted against the formwork could be less than hydrostatic even for rates of placement of 120m/hr (360 ft/hour) respectively.

Given the number of combinations of chemical admixtures that are available it would be difficult to develop lateral pressure guidelines based upon mixture proportions. Hence identifying and characterizing the flow/stiffening properties of the concrete appropriate to the magnitude of the lateral pressure envelope is required. A complication in measuring the mechanical properties of the fresh concrete is determining the initial state of the concrete, as a pseudo fluid (no shear resistance) or in a state where some shear resistance (but not necessarily at failure) has been developed. To establish a lateral pressure equation/method some measure of the early age, time stiffening/strength behavior of the concrete is required. Researchers have tended to use or modify existing methods and procedures. Most researchers have had access to only one piece of equipment so comparison between results is difficult as different concrete characterization information has been collected.

This paper reports the results of an investigation into formwork pressures exerted by SCC measured on four construction sites between 2005 and 2008. The object of the test program was to relate measured form pressures to either mixture proportions and/or flow parameters.

Research Significance

The maximum form pressures for formwork design for self Consolidating Concrete are determined by the rate of concrete placement relative to the rate/development of concrete stiffness/strength. To date there is conflicting information as to the formwork pressures developed on wall forms using self-consolidating concrete. Consequently it is standard practice to assume full liquid head when designing wall forms which may lead to overly conservative designs and, consequently, higher costs. Conversely an unconservative design could risk malformed elements, with the associated costs of making good, and even construction safety. Identifying and characterizing the flow/stiffening properties of the concrete relevant to the magnitude of the lateral pressure envelope is required.

Backgound

This is not meant to be an exhaustive literature review but an introduction to the concepts available. Most analyses of the concrete form pressure problem have assumed its behavior is similar to clay with internal friction, cohesion and pore pressure. For concrete these properties are time dependent on a time scale of one or eight hours (initial set) and hence temperature dependent. Theoretical treatments of formwork pressure, based upon soil mechanics principles, were developed by Schjodt (1955) (active pressure coefficient K_a), Alexandridis and Gardner (1981) and Gardner (1981) (at rest pressure coefficient K_o) for conventional concrete. Gregori, Ferron, Sun and Shah (2008) reported on a laboratory project simulating the formwork pressure exerted by various SCC mixtures by placing concrete in a cylinder, applying an axial load to the concrete and measuring the resulting lateral pressure – effectively a K_o test. They concluded that casting rate is the governing factor on formwork pressure development but mixture composition also plays a role. Assaad, Harb and Khayat(2009) reported on using the triaxial compression test on mortars to evaluate formwork pressure of SCC. Khayat and Omron (2010) summarized the results of a major study of the pressure exerted by SCC. They described a portable pressure column, similar in principle to that used by Gregori et al. Two field oriented tests were proposed; a portable vane test and an inclined plane test. A formwork pressure equation was proposed with an associated design aid. Kim, Beacraft, Kwon and Shah (2011) proposed a simple analytical model for formwork pressure of SCC.

A very early analysis of the pressures developed by granular fill in silos, a related problem, was published by Jansen (1885) who assumed that the fill material was in a state of failure allowing the Mohr-Coulomb theory to be used. The wall friction between the fill material and the wall must be determined or estimated. Vanhove, Djelal and Magnin (2004) and Proske and Graubner (2008) used silo theory to determine formwork pressure methods for Self Consolidating Concrete.

However the behavior of fresh concrete can better be described as thixotropic – liquid under high strain rates (vibration) but may solidify under a near zero strain rate. Flow occurs when the applied shear stress exceeds the material shear strength (Bingham flow).

Well-designed SCC has sufficient viscosity to ensure that the large particles can be transported/supported by the fine particle (cement, slag, fly ash, silica fume and limestone fines) paste – in this sense it behaves as a fluid. Rheology, the study of the deformation and flow of matter, describes the material properties of fluid and semi-solid materials. All rotational, vane or drum, rheometers operate in similar manners. Concrete is placed in the sample container, conditioned to prepare the sample by applying a low angular velocity (shear strain gradient) for several seconds, the velocity is then increased in steps to a chosen higher angular velocity and torque measurements are taken at every velocity step. The velocities are then decreased in steps to zero and torque measurements are taken at every velocity step. The characterization can be the intercept and slope of a straight line fitted to the decreasing velocity curve (Bingham assumption) or the difference between the increasing velocity and decreasing velocity curves (breakdown area). However the maximum velocity endpoint is arbitrary and rheometer characterizations done at high shear rates are not representative of the concrete placing process. Unfortunately fundamental parameters measured using different types of rheometers are different (Ferraris and Brower 2003).

Characterization of concrete no flow/flow properties

Fresh concrete is an age-stiffening, thixotropic material. Without agitation, concrete begins to gain/regain its shear strength. Concrete in a mixer or transit truck is agitated continuously, which destroys any tendency to build up a thixotropic structure, and remixed at high speed upon reaching the construction site. After concrete is discharged into the bucket it is at rest. Concrete is discharged from the bucket and flows into the form. For pumped construction, the concrete is agitated until it is in the forms. However after the concrete has reached its final position in the form it is not in a state of flow/failure.

Because formwork pressure is influenced by the behavior of concrete at rest in the forms, measurements at near zero shear rates (namely static yield strength or stiffness before flow), after periods of rest, are relevant to formwork pressure. The static yield strength reflects the stress needed to initiate flow in an at-rest material while the dynamic yield stress reflects the stress needed to maintain flow after the at-rest structure has been destroyed. Static yield strength can be measured directly in a rheometer in a strength growth test, during which a very low shear rate is applied to the concrete and the build-up in stress before flow is monitored. The initial state of the concrete sample for the stress growth test must be representative of the concrete in the form. Ideally concrete should be sampled into multiple rheometer containers at the time of placement, left undisturbed, and one sample tested at pre-chosen times to determine the development of static yield stress with time.

The standard test to measure the flow potential of SCC is the slump flow test (ASTM C1611) – easy to understand and perform on construction sites. The cconcrete should be sampled from a representative batch at the start of placement and left undisturbed until the prescribed test times**.** Measuring the slump flow on undisturbed samples allows the reduction in slump flow with time to be determined. As most SCC has a specified slump flow of 600-700 mm (24-27 ins.) the characteristic time was chosen to be the time for the slump flow to decrease to 400mm (16 ins.). Multiple samples are required to permit testing every 20-30 minutes or so until the flump flow decreases to less than 400mm (16 ins.). Cauberg, Desmyter and Pierard (2006). measured slump flow before and after casting (slump flow loss).

Field Program Field Program

Field measurements of form pressures were taken at four sites; Charleston (SC) (June 2005 –February 2006), London (Ontario) (Dec.2005-Jan 2006), Peterborough (Ontario) (May 2006-September 2006) and Toronto (Ontario) (August 2007-Febraury 2008). In addition to designing mixes for the required initial slump flow and strength, the laboratory flow properties of the Charleston and London concretes were determined using an IBB rheometer and those for Peterborough and Toronto using an ICAR rheometer. As the investigation progressed, more on-site material characterization was done measuring the on-site flow and stiffening characteristics of the concrete. The testing emphasized the sensitivity of the SCC stiffening behavior to variations in water content and admixture types and dosages.

Lateral pressures were measured using 125 mm (5 inch) diameter, vibrating wire earth pressure cells and recorded against time using a scanning data logger. The Peterborough installation is shown in Figure 1. In form concrete elevations with time were measured by personnel using tape measures and stop-watches.

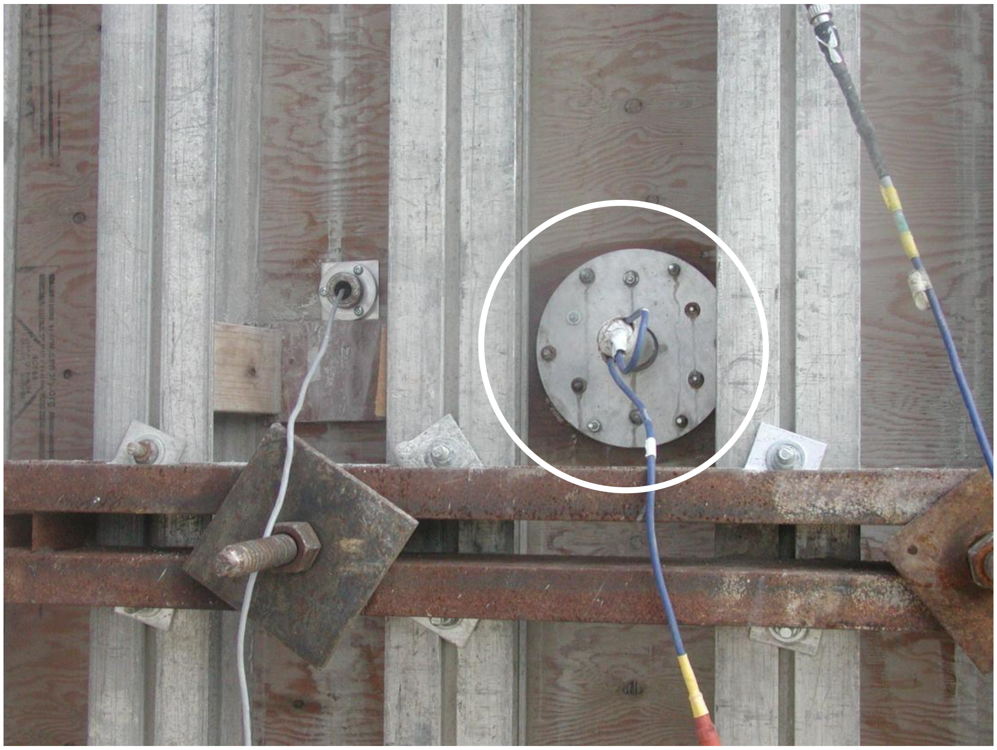

Figure 1 – Geokon 4820 earth pressure cell at Peterborough site

Citadel, Charleston SC 2005-2006.

Prior to construction, a base mix, a reduced w/cm mix, a reduced paste mix and an increased coarse aggregate mix were chosen to investigate their effect on formwork pressure. Maximum aggregate size was ¾ ins. (20 mm). As the project progressed, modified mixes were added to the program and others abandoned without field use. The project was a university residence with 150 mm (6ins.) and 400 mm. (16 ins) thick shear walls, 3.5 m (11.5 ft.) high,

Figure 2. A single residence unit between door blockouts, shown in Figure 2, required about 5 cubic metres (6 cubic yards) of concrete. For such a small quantity of concrete, placement by pump could be completed in as few as 10 minutes, a rate of placement of 18 metres/hour (60 ft/hour). Initially 2 sets of 4 load cells in vertical rows were used. The maximum concrete head above the lowest gauge was 3.1 metres (10 feet). As early results showed the upper, smaller head, cells only experienced hydrostatic pressure; the top cells were not installed for later pours giving three cells in a vertical line. After inspection of the results the placement sequence was modified to place half the height of concrete in adjacent residence units and placing the second lift some time (typically 20 minutes) later reducing the rate of placement in a form without excessively slowing down construction. Eventually two different mixes were placed on the same day with 4 sets of 3 load cells. To replicate the results two instrumented forms were used for each mix.

Figure 2 - Crane view of the Citadel site

The results for the February 2nd, 2006 placement are shown in Figure 3. The negative gauge results are due the load cell being only partially submerged as the concrete rises over the height of the cell. The potential hydrostatic pressures are indicated.

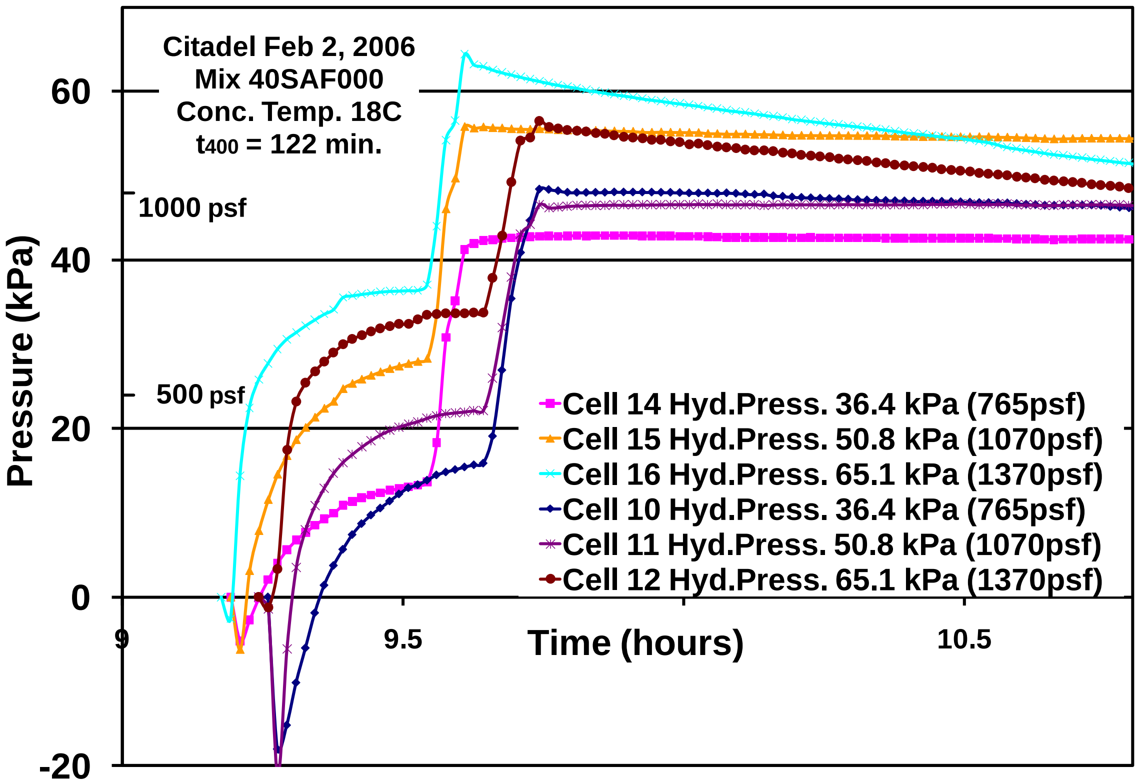

Figure 3 – Typical replicate lateral pressure measurements.

Most of the measured pressures were close to hydrostatic. Mix proportions did not seem to have much effect. Discontinuous placing, placing the concrete in lifts with a rest period between lifts, reduced the maximum pressures. All results are summarized in Table 1.

Labatt's Brewery, London, ON (Dec.2005-Jan 2006)

Concrete was placed by bucket into 400 mm (sixteen inch) thick walls, Figure 4, resulting in a moderate rate of placement 1.9 m/hr (6 ft/hr.). The measured lateral pressure envelopes, Figure 5, were similar to those expected for conventional concrete. The potential hydrostatic pressures are indicated. Maximum measured pressures were much less than hydrostatic. No on-site concrete rheometer or slump flow loss tests were done.

Figure 4 – View of London site

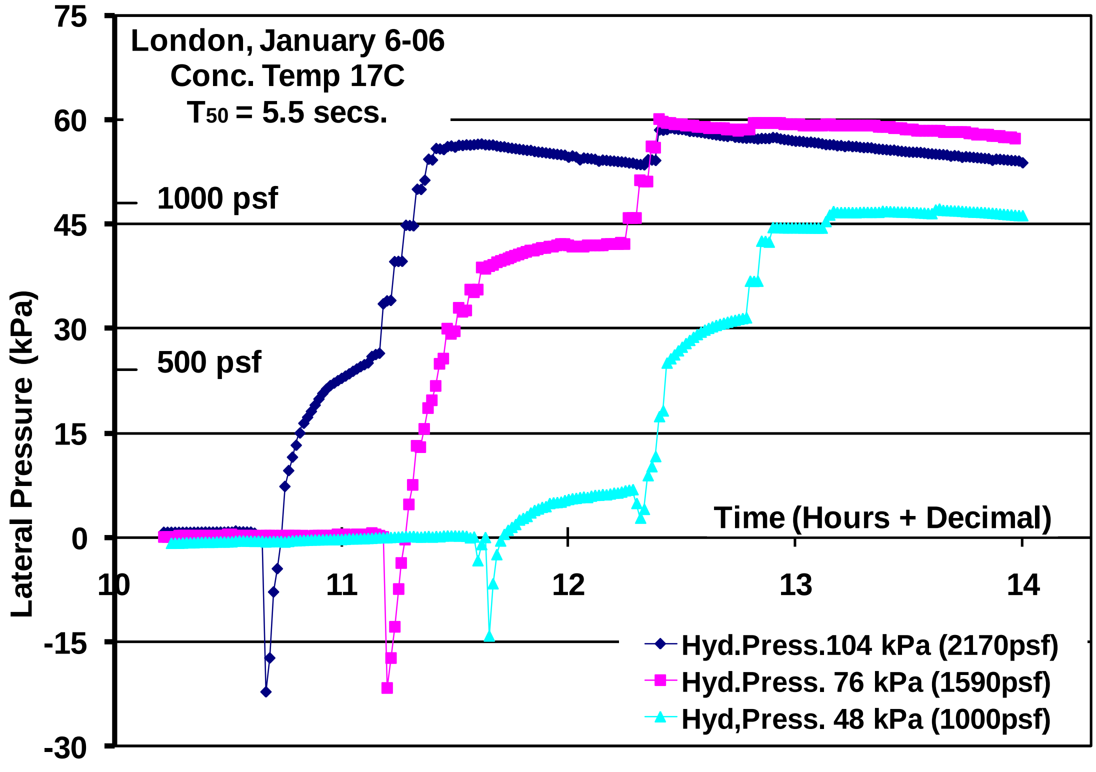

Figure 5 - January 6, 2006 pressure measurements

Discontinuous placement, by bucket or programmed interruptions of pumping, allows the concrete to gain shear strength reducing the maximum form pressures. The maximum pressure results are summarized in Table 1.

Regional Hospital, Peterborough ON (spring-summer 2006)

By this date the investigators had refined their ideas on the logic of the casting process, concrete conditioning before measurement and had access to an ICAR portable rheometer which allowed on-site rheometer measurements. Slump flow loss measurements were also made.

Pressures were measured on the wall forms for stairwell, elevator shear wall structures for the three different mixtures on separate days. Mixture 1 was a base mix; Mixture 2 had a higher coarse aggregate to total aggregate ratio; and Mixture 3, with its lower w/c ratio needed a higher dosage of HRWR compared to Mixes 1 and.2. On-site rheometer testing and slump flow loss were measured for both agitated and non-agitated concrete.

The walls were 4.27 m (14 feet) high, 300 mm (12 ins.) thick. The forms were instrumented with two sets of 4 vibrating wire pressure gauges. The head above the lowest gauge was 4.12 m (13.5 feet). Concrete was placed by bucket at approximately 2 m/hour (7 ft/hour). Concrete was sampled from the first truck at the beginning of placement, 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. The results of the rheometer tests can be found in Koehler, Keller and Gardner (2007).

Figure 6 shows the on-site slump flow measurements with time for the three mixtures. Mixtures 1 and 2 lost workability quickly, as indicated by the loss of slump flow with time. The retarder and superplasticizer used in Mixture 3 extended significantly its workability i.e. the slump flow did not decrease significantly over the duration of the pour.

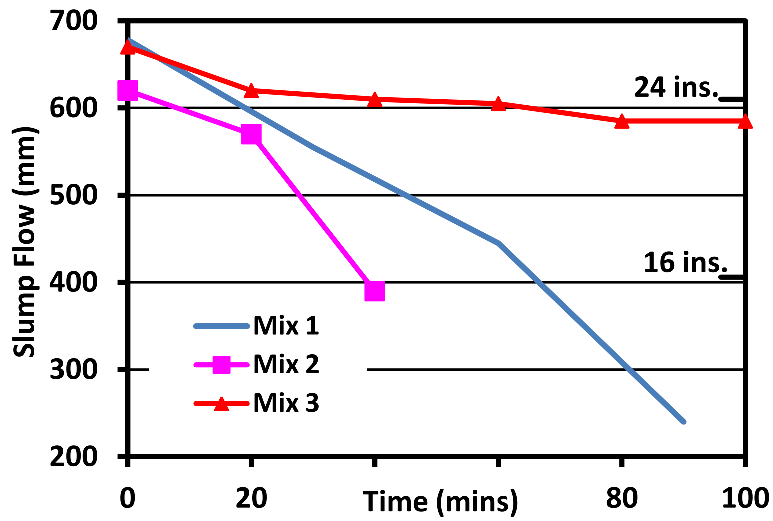

Figure 6 - Slump flow loss (Peterborough mixes)

The lateral pressure measurements for Mixture 1 were compromised, clearly illustrated in Figure 7, by the long delay in arrival between the first and second trucks.

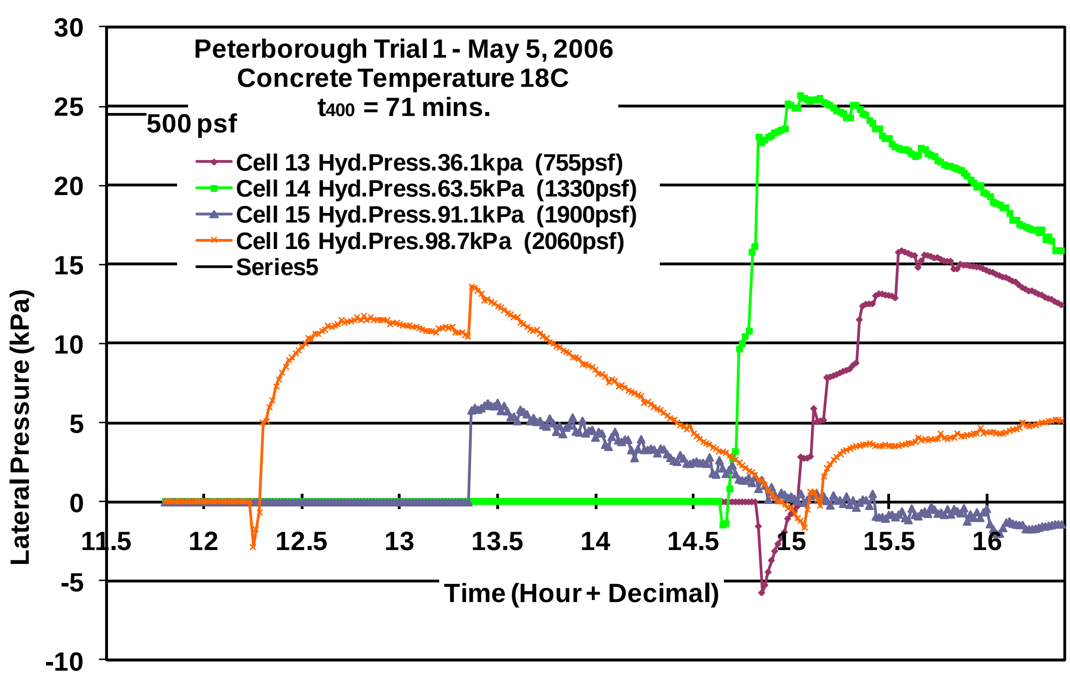

Figure 7 – Lateral pressure measurement Peterborough Mixture 1

Mixture 2, Figure 6, lost slump flow at a much faster rate than Mixture 1 resulting in form pressures, Figure 8, circa 30 kPa (600 psf), much lower than hydrostatic pressure. 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 - when pressures were registered on upper cells - the pressure at the lower cells increased only by a slight extent, if at all, because of the increased shear strength of the material at the lower cells. The increased shear strength, due to build-up of thixotropic structure, caused the rapid loss of workability and consequent lower form pressures.

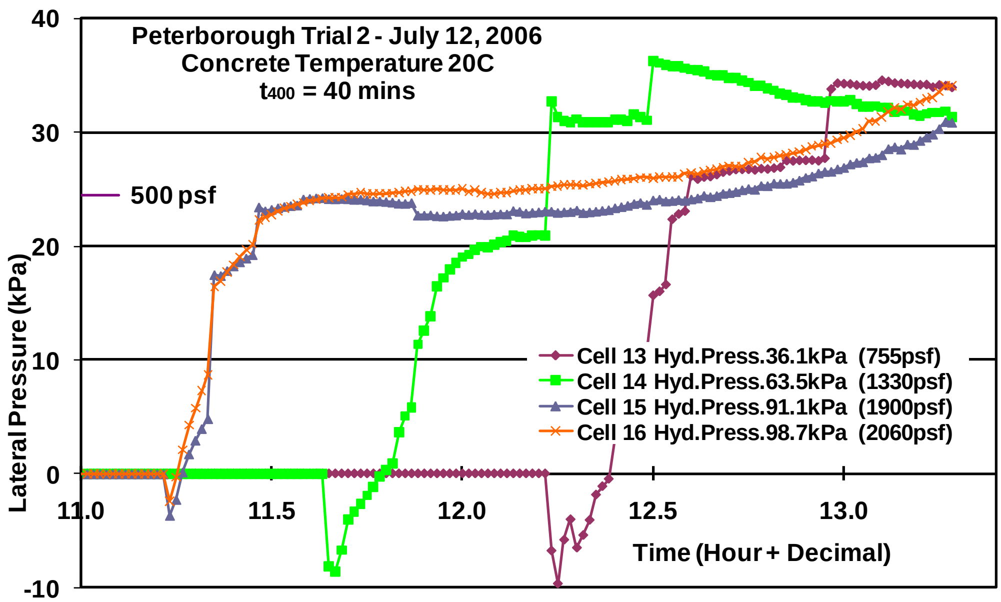

Figure 8 – Lateral pressure measurement Peterborough Mixture 2

The retarder and superplasticizer used in Mixture 3 extended the time the concrete could be self consolidated. 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. As a result, the formwork pressures, Figure 9, were much higher than in the first two mixtures and approached hydrostatic pressure. Wall friction will keep the measured lateral pressures less than true hydrostatic. All results are summarized in Table 1.

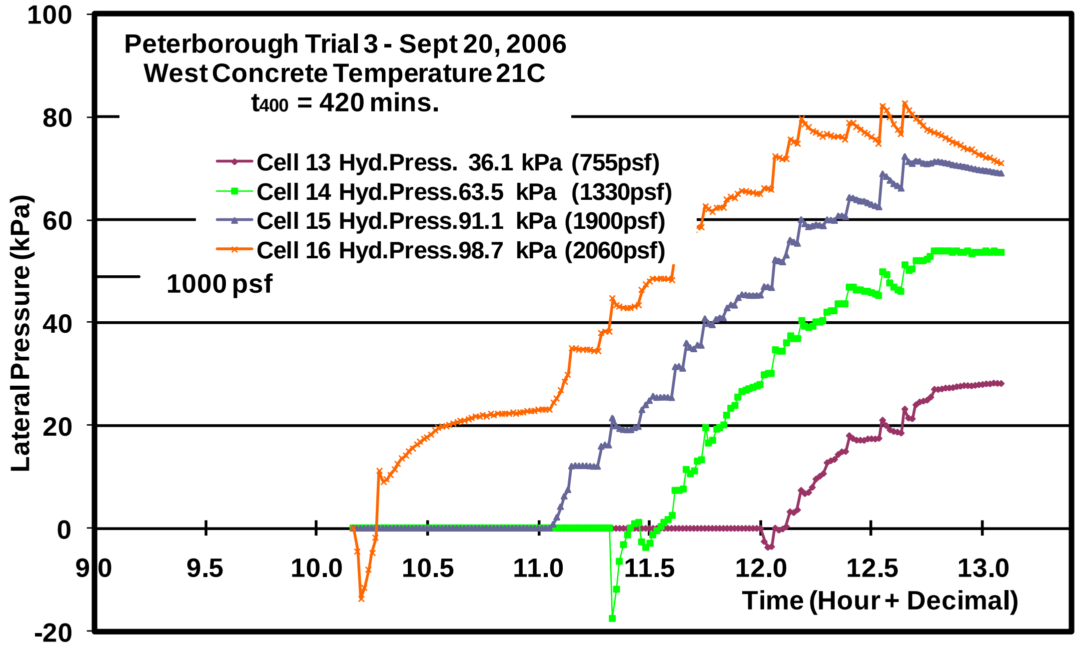

Figure 9 – Lateral pressure measurement Peterborough Mixture 3

The disparities in the formwork pressure envelopes for the 3 mixtures clearly illustrate the diversities of pressure distributions reported in the literature for SCC and the importance of the flow characteristics of the concrete.

Bay-Adelaide, Toronto

Measurements were carried out on two walls for several floors of the core structure of the 50 storey, steel frame concrete core Bay Adelaide tower located in downtown Toronto. The core was cast using a large, three storeys high, jump (self climbing) form for the core structure, Figures 13 and 14. Outside core dimensions were 33m x 20m (100 feet x 65 feet). The core had walls of various thicknesses but pressures were measured on a 350 mm (14 ins.) interior (South) wall and a 600 mm (24 ins.) exterior (North) wall. The wall heights were 4.17 metres (13 feet 8 inches). The planned construction rate of one floor (jump) every 3-4 days required concrete strengths of 8 MPa (1160 psi) at 12 hours and 60 MPa (8700 psi) at 91 days. The same nominal mixture was used for all floors.

Each wall pour required some 380 cubic metres i.e. 42 x 9 cubic metre trucks (480 cubic yards) of concrete and placement lasted 4 to 5 hours. At elevations above those that could be reached by truck based pumps, the south wall concrete was placed by pumping from a central pump and the north wall concrete by bucket.

Figure 10 – General view of construction

Figure 11 – Concrete placement by bucket

Typical results for the two instrumented wall forms are given below. Some small effect of wall thickness was observed. Logic would indicate the form pressure for the thicker wall should be slightly larger (effect of wall friction) for similar rates of pour. The potential hydrostatic pressures are indicated. All results are summarized in Table 1.

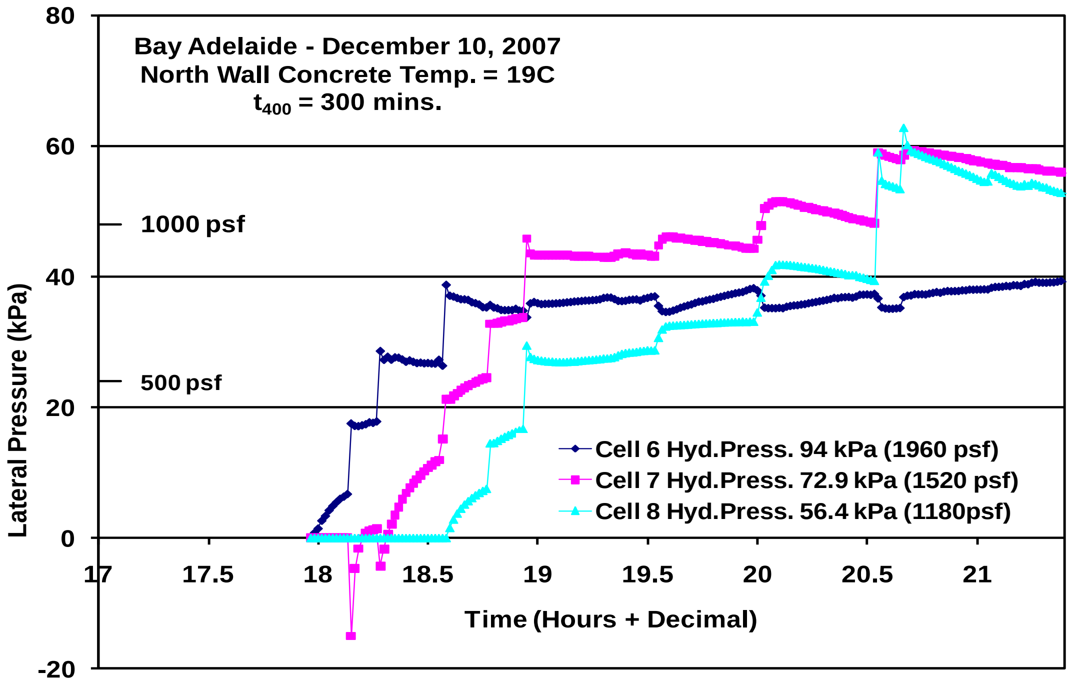

Figure 12 – Typical pressure results for North wall

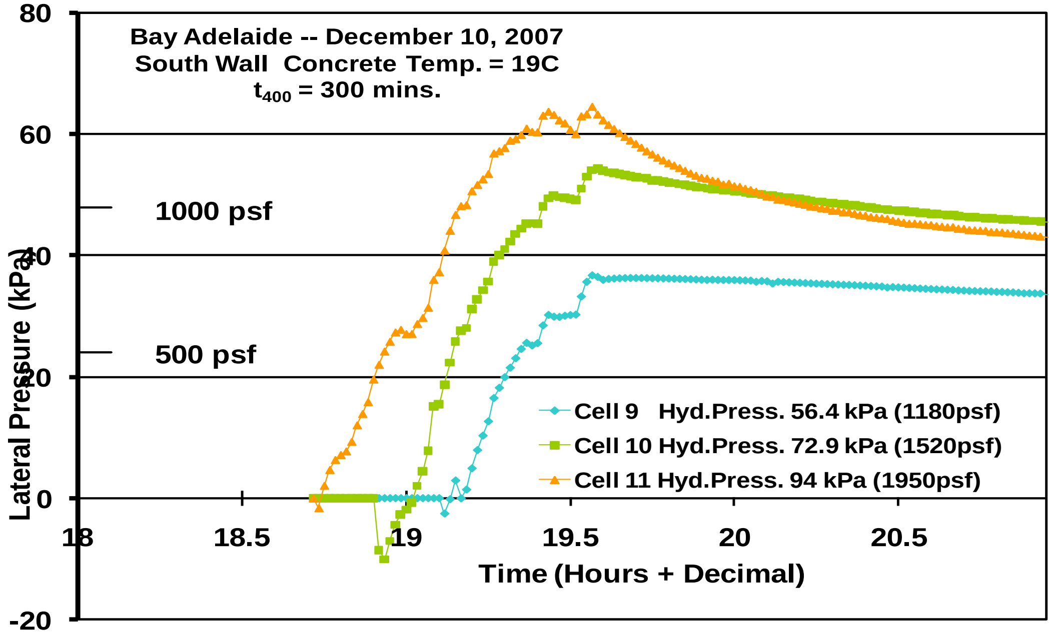

Figure 13 – Typical pressure results for South wall

Analysis of Field Data

All the pressure measurements were recorded with time. Even though conceptually simple, it proved difficult to relate concrete head with the pressure records. The pressure records show that initially, when placed, the lateral pressure is hydrostatic with head. However as further concrete was placed the lateral pressure increased but the increase was less than hydrostatic tending towards the conclusion that a limiting lateral pressure could be reached for a very tall form. A limiting pressure was not reached in any record but the majority of maximum pressures recorded were less than hydrostatic. The rate of placement was calculated for the cell that recorded the largest pressure.

Concrete placement rates are not uniform but can be estimated from the pressure records or the time to fill the form. Figure 7 illustrates some of the difficulties. In Fig. 8, for example,the maximum pressure, recorded by gauge 14, was 36.3 kPa (760 psf) and the calculated rate of concrete placement 3.2 m/hr. (10.5 ft/hr). However the maximum head of concrete above gauge 14 was only 1.55 m (5 feet). The rate of placement calculated from the time to fill the form was 2.35 m/hr (8 ft/hr). For this study, the rate of placement was calculated for the cell that recorded the largest pressure.

Placement rate is a major factor. All but six of the 33 Citadel pressures, rate of concrete placement greater than 3 m/hr (10 ft/hr) and maximum head 2.77 m (9 ft), were greater than 80% of hydrostatic. Conversely only seven of 29 Bay-Adelaide pressures, maximum head 4 m (13 ft), rate of placement less than 2 m/hr (7ft/hr), were above 80% hydrostatic.

The maximum pressure was recorded by gauge 14. The rate of placement for gauge 14 was very high but the maximum head of concrete above gauge 14 was only 1.55 m (5 feet) and the maximum pressure 35 kPa (700 psf).

All but six of the 33 Citadel pressures, maximum head 2.77 m (9 ft), rate of concrete placement greater than 3 m/hr (10 ft/hr), were greater than 80% of hydrostatic. Conversely only seven of 29 Bay-Adelaide pressures, maximum head 4 m (13 ft), rate of placement less than 2 m/hr (7ft/hr), were above 80% hydrostatic.

Suggested lateral pressure equation

Developing a lateral pressure development equation when few measured lateral pressures reached a limiting value is difficult. Any lateral pressure equation for SCC needs to include the rate of concrete placement, a measure of the time for the concrete to achieve strength /stiffness and asymptotic to hydrostatic as placed. The time for the slump flow to drop to 400 mm (16 ins.) was chosen as the material parameter characterizing the concrete. Cauberg, Desmyter and Pierard (2006). measured slump flow before and after casting but did not use slump flow loss as a characterising parameter. (with appropriate modifications other measurements of stiffening time, Assaad, Harb and Khayats's flow test or K_0 can be substituted for t_{400}). Equation (2) is a simple equation to describe the increasing lateral pressure development with time – the equation cannot be used for times greater than that required to achieve P_{max}. The form of the equation is similar to that of equation 6 of the paper by Kim et al 2011 with fewer terms,.

Defining t_0,the time to reach zero slump flow (not a physically measurable phenomena), as :

$$t_0 = t_{400}\ [\textit{initial slump flow}/(\textit{initial slump flow} - 400\textit{mm}(16\ \textit{ins.}))] \quad (1)$$

$$P = wR\left(t - \frac{t^2}{2t_0}\right) \qquad t < t_0 \qquad (2)$$

$$P_{max} = wRt_0/2 \qquad t > t_0 \qquad (3)$$

Maximum pressure $P_{max} = wRt_0/2$ occurs *at* $t = t_0$.

For $t > t_o$ the pressure is assumed to remain constant at the maximum value.

If the time to fill the form, t_h = height of form/R, is less than t_0, $t = t_h$ is used in equation (2).

$$P_h = wR\left(t_h - \frac{t_h^2}{2t_0}\right) \qquad (4)$$

h = height of placement m (ft)

P_h = limiting lateral pressure kPa (psf)

R = rate of placement m/hour (ft/hour)

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

$t_h = h/R$ hours

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

The comparison between the field measured pressures and those calculated using the above equation are shown in Figure 14. The experimental results are limited in that the maximum concrete head available to the authors was 4 metres (14 feet); implying hydrostatic pressures of 96kPa (2000 psf).

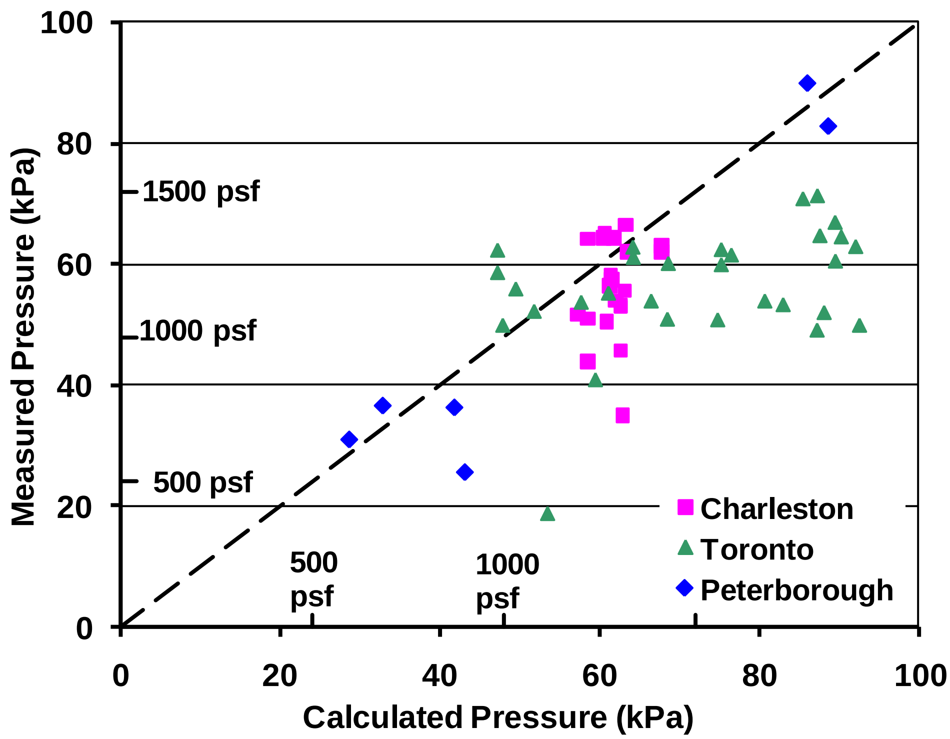

Fig 14 - Comparison of Measured and Predicted Lateral Pressures

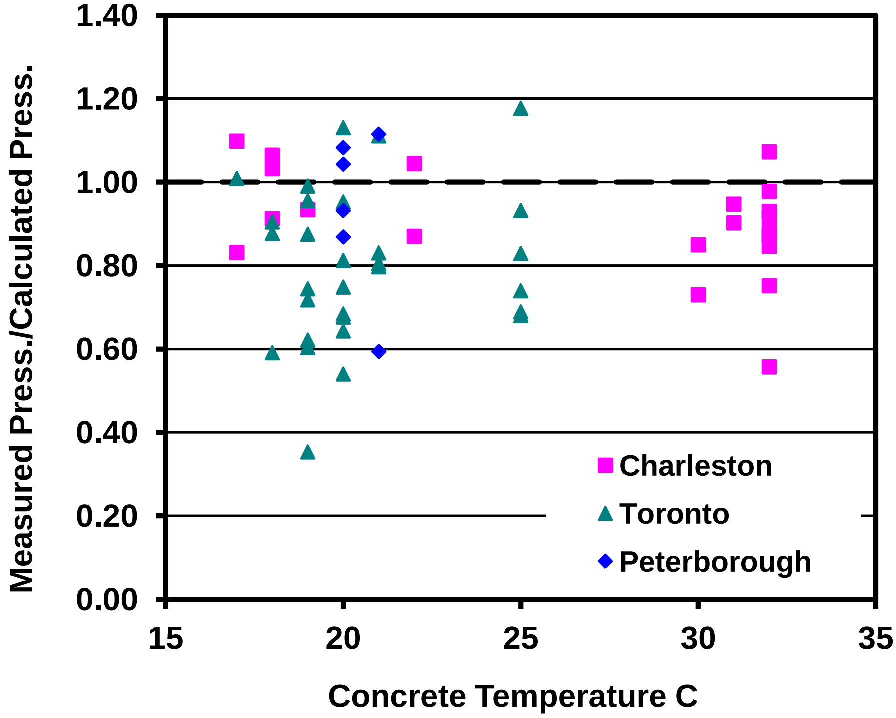

Fig 15 – Sensitivity of Measured/Predicted Lateral Pressures with Concrete Temperature

Figure 15 shows the sensitivity of the experimental/calculated pressures with concrete temperature. The lack of sensitivity of the concrete pressures to temperature is because the effect of temperature is accommodated in t_{400}.

CONCLUSIONS AND RECOMMENDATIONS

The lateral pressures developed by Self Consolidating Concrete are dominated by the performance of the admixtures. Form pressures are determined by the rate of concrete placement relative to the rate of development of concrete stiffness/strength. The rate of concrete placement must not be increased nor admixtures changed or substituted without consideration of their effects on formwork pressure. Reducing the rate of concrete placement by scheduled placement i.e. bucket or programmed interruptions of pumping, allows the concrete to gain shear strength, reducing the maximum form pressures.

Mix design and qualification should be done prior to start of construction. Testing for production, mixture selection/qualification and formwork selection must be done in concert and concrete control parameters established to ensure compliance. Changes in 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. An unresolved problem is reconciling laboratory values of t_{400} to site measured values.

Rigorous on-site quality control is required to ensure mix compliance and consistency. When concrete arrives on site, if the initial slump flow is too low it can be brought into compliance using High Range Water Reducer (HRWR). However this may change the stiffening behavior of the concrete which would change the maximum formwork pressures. Whether or not HRWR has been added on site, the stiffening behavior of the concrete should be measured on one of the first batches of concrete delivered.

During the field testing described in this paper, various approaches for characterizing concrete rheology were tried. The flow parameters are sensitive to the conditioning of the concrete, agitated or not agitated, prior to measurement. The standard rheometer testing protocol at relatively high shear rates was found not appropriate for quality control during construction.

For formwork design appropriate load factors need to be chosen as design philosophy changes from working stress design to limit states design. Current ACI load factors are 1.2 on Dead Load and 1.6 on Live Load. It is suggested that the lateral pressure envelope need not exceed 1.2 times the hydrostatic envelope.

A databank of formwork pressure data and rheological test data should be collected; in particular results are needed for taller forms. The authors recommend measuring the slump flow with time and, if the apparatus is available, the increase in static yield strengths with time. As the state of the concrete before testing dominates the measured properties it is critical the pretesting state of the concrete is appropriate. The slump flow loss has to be determined from undisturbed concrete samples. Similarly for rheometer measurements, concrete should be sampled into separate rheometer containers at the beginning of placement.

Given the difference between the active and passive pressure properties of granular materials, consideration should be given to developing and using zero displacement load cells.

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Table 1 – Summary of Results (100 kPa = 2100 psf.)

Site Date (y/m/d)	Mix	Wall	wall thick (mm)	Max. Head (m)*	Conc. Temp C	Initial Flow (mm)	T400 (mins)	Rate (m/hr)	Meas. Press. (kPa)	Calculated Pressure (kPa)
Charleston										
2005/6/9	F457	L	400	3.07	32	610	60	8.7	62	67.8
		R	400	3.07	32	610	60	8.7	63	67.8
2005/7/21	F457	6E	150	2.77	32	610	60	6	51	58.5
	F457	16E	400	2.77	32	610	60	6	44	58.5
		16W	400	2.77	32	570	55	13	35	62.8
2005/9/15	F648	East1	150	2.77	32	690	92	5.5	65	60.6
	F648	East	150	2.77	32	690	92	10	53	62.6
	T688	West	150	2.77	32	690	135	8.4	55.6	63.1
	T688	West1	150	2.77	32	690	135	10	62	63.4
2005/9/27	F457	1	150	2.77	30	650	60	5	45.7	62.6
	F457	2	150	2.77	30	650	60	5	53.2	62.6
2005/11/8	F691	3	150	2.77	31	690	55	5.3	51.7	57.3
	F691	4	150	2.77	31	690	55	11	58.1	61.3
2005/12/16	F000	1	150	2.77	17	650	90	2.5	50.6	60.9
	F648	2	150	2.77	17	650	57	4.2	64.2	58.5
2005/12/21	F648	1	150	2.77	15	710		1.6	57.1	
	F648	2	150	2.77	15	710		2.9	69.5	
	F648	3	150	2.77	15	710		3.3	74.5	
2006/1/11	F688.1	1	150	2.77	22	560		4.2	31.9	
	F688.1	2	150	2.77	22	560		4.7	49.2	
	T688	3	150	2.77	22	560	92	4.95	57.8	62.1
	T688	4	150	2.77	19	560	92	5.1	57.4	61.5
2006/1/19	F688.1	1	150	2.77	19	660		3.54	60.1	
	F688.1	2	150	2.77	19	660		3.34	69.9	
	F691.1	3	150	2.77	18	710		3.6	65.3	
	F691.1	4	150	2.77	18	710		3.6	67.1	
2006/1/26	T688.1	1	150	2.77	17	560		7.7	67.9	
	T688.1	2	150	2.77	17	560		4.95	60.7	
	T688.1	3	150	2.77	17	560		1.53	54.2	
2006/2/2	F000	1	150	2.77	18	660	122	6.4	64.4	62.4
	F000	1	150	2.77	18	660	122	5.5	56.5	61.9
	F648.1	1	150	2.77	22	660	270	6.1		
	F648.1	1	150	2.77	22	660	270	5.5	66.5	63.7
2006/2/26	F000	1	150	2.77	18	740	90	6	64.4	60.5

*Head above gauge that measured highest pressure

Table 1 (cont.)

Site Date y/m/d	Mix	Wall	wall thick (mm)	Max. Head (m)*	Conc. Temp C	Initial Flow (mm)	T400 (mins)	Rate (m/hr)	Meas. Press. (kPa)	Calculated Pressure (kPa)
Peterborough										
2006/5/5		N	400	1.71	21	620	71	1.4	36.6	32.8
		E	400	2.17	21	620	71	1.1	25.5	35.9
2006/7/12		N	400	1.53	20	620	40	2	31	28.6
		E	400	2.17	20	620	40	3.2	36.3	41.8
2006/9/20		S	400	3.88	20	620	400	1.8	89.9	86.2
		W	400	4.04	20	620	400	1.6	82.8	88.9
Toronto										
2007/8/8		N	600	4	25	585	62	3	50.9	74.8
		S	300	4	25	585	62	1.55	41	59.5
2007/8/20		N	600	4	21	680	310	0.8	60	75.3
		S	300	4	21	680	310	0.8	62.5	75.3
2007/9/1		N	600	3.1	19	720	240	2.9	51	68.5
		S	300	2.4	19	550	240	1.6	18.9	53.5
2007/9/13		N	600	4	25	730	240	2.5	70.9	85.5
		S	300	4	25	690	240	3.1	64.8	87.6
2007/9/24		N	600	4	21	750	110	2.8	61.6	76.5
		S	300	3.1	25	750	110	1.9	53.8	57.7
2007/10/19		N	600	4	19	730	450	1.4	54	86.9
		S	300	2.4	19	730	450	1	50	52.3
2007/10/26		N	600	2.4	25	620	500	0.85	62.4	53.0
		S	300	2.4	21	620	500	0.81	58.7	52.8
2007/11/26		N	600	3.1	18	750	190	1.5	52.1	79.1
		S	300	3.1	18	750	190	1.25	60.2	62.0
2007/12/10		N	600	3.1	19	705	275	1.14	62.9	63.5
		S	300	4	19	705	275	4.44	64.6	90.0
2008/1/7		N	600	4	19	750	260	1.63	71.4	81.6
		S	300	4	19	750	260	1.62	49.2	81.5
2008/1/29		N	600	3.1	20	650	215	1.41	61.2	64.0
		S	300	3.8	20	650	215	2.9	53.4	82.1
2008/2/26		N	600	3.1	20	705	240	1.4	54.5	66.6.
		S	300	2.4	20	705	320	0.8	56	49.5
2008/3/20		N	600	4	20	740	535	4	63	92.1
		S	300	4	20	740	535	2	60.6	89.6
2008/4/7		N	600	4	20	720	590	1.9	67	89.5
		S	300	4	20	720	590	6	50	92.6

*Head above gauge that measured highest pressure.

Addendum - Submission on Form Pressures due to SCC to CSA S269 September 23rd 2011

INTRODUCTION

Self-consolidating concrete (SCC), is concrete that can flow into every corner of reinforcement congested formwork without vibration - which may result in increased form pressures relative to vibrated concrete. Any increase in formwork pressures would be a concern for form designers and formwork suppliers. Published research on formwork pressures is inconsistent to the extent that one section of the Brite EuRam Contract Report #BRPR-Ct96-0366 on SCC concluded that forms should be designed for full hydrostatic pressure and, contrarily, another section concluded that the pressure exerted against the formwork could be less than hydrostatic even for rates of placement of 120m/hr (360 ft/hour) respectively.

Given the number of combinations of chemical admixtures that are available it would be difficult to develop lateral pressure guidelines based upon mixture proportions. Hence identifying and characterizing the flow/stiffening properties of the concrete appropriate to the magnitude of the lateral pressure envelope is required. A complication in measuring the mechanical properties of the fresh concrete is determining the initial state of the concrete, as a pseudo fluid (no shear resistance) or in a state where some shear resistance (but not necessarily at failure) has been developed. To establish a lateral pressure equation/method some measure of the early age, time stiffening/strength behavior of the concrete is required. Researchers have tended to use or modify existing methods and procedures. Unfortunately most researchers have had access to only one piece of equipment so comparison between results is difficult as different, or incomplete, characterization information was collected.

Backgound

Research in form pressures has not followed a single chronological or logical path. This introduction attempts to separate the various trains of thought. This is not meant to be an exhaustive literature review but an introduction to the concepts available. Most analyses of the concrete form pressure problem have assumed its behavior is similar to clay with internal friction, cohesion and pore pressure. For concrete these properties are time dependent on a time scale of one or eight hours (initial set) and hence temperature dependent. Theoretical treatments of formwork pressure, based upon soil mechanics principles, were developed by Schjodt (1955) (active pressure coefficient K_a), Alexandridis and Gardner (1981) and Gardner (1981) (at rest pressure coefficient K_o) for conventional concrete. Gregori, Ferron, Sun and Shah (2008) reported on a laboratory project simulating the formwork pressure exerted by various SCC mixtures by placing concrete in a cylinder, applying an axial load to the concrete and measuring the resulting lateral pressure – effectively a K_o test. They concluded that casting rate is the governing factor on formwork pressure development but mixture composition also plays a role. Assaad, Harb and Khayat(2009) reported on using the triaxial compression test on mortars to evaluate formwork pressure of SCC. Khayat and Omran (2010) summarized the results of a major study of the pressure exerted by SCC. They described a portable pressure column, similar in principle to that used by Gregori et al. Two field oriented tests were proposed; a portable vane test and an inclined plane test. A formwork pressure equation was proposed. Kim, Beacraft, Kwon and Shah (2011) proposed a simple analytical model for formwork pressure of SCC.

A very early analysis of the pressures developed by granular fill in silos, a related problem, was published by Jansen (1885) who assumed that the fill material was in a state of failure allowing the Mohr-Coulomb theory to be used. The wall friction between the fill material and the wall must be determined or estimated. Vanhove, Djelal and Magnin (2004) and Proske and Graubner (2008) used silo theory to determine formwork pressure methods for Self Consolidating Concrete.

Characterization of the placement process of Self Consolidating Concrete

Fresh concrete is an age-stiffening, thixotropic material. Without agitation, concrete begins to gain/regain its shear strength. Concrete in a mixer or transit truck is agitated continuously, which destroys any tendency to build up a thixotropic structure, and remixed at high speed upon reaching the construction site. After concrete is discharged into the bucket it is at rest. Concrete is discharged from the bucket and flows into the form. For pumped construction, the concrete is agitated until it is in the forms. However after the concrete has reached its final position in the form it is not in a state of flow/failure.

Because formwork pressures are influenced by the behavior of concrete at rest in the forms, measurements at near zero shear rates (namely static yield strength or stiffness before flow), after periods of rest are relevant to formwork pressure. The static yield strength reflects the stress needed to initiate flow in an at-rest material while the dynamic yield stress reflects the stress needed to maintain flow after the at-rest structure has been destroyed. Static yield strength can be measured directly in a rheometer in a strength growth test, during which a very low shear rate is applied to the concrete and the build-up in stress before flow is monitored. The initial state of the concrete sample for the stress growth test must be representative of the concrete in the form.

TOPICS RELATED TO FORM PRESSURE PROBLEM

Initially research on Self Consolidating Concrete, SCC, was directed to developing mix proportions and tests to measure/identify various indicators of the properties of fresh SCC. These properties included slump flow, segregation index, time to flow to 500 mm, and various blockage tests. Various researchers used the concepts of “rheology”, the study of the deformation and flow of matter, to investigate/describe the behaviour of fresh concrete. However the anticipated increase in the lateral pressures is a concern for form designers, formwork suppliers and contractors. Several organizations have sponsored or performed investigations to relate the lateral pressured exerted by SCC to measured fresh concrete properties – unfortunately the fresh concrete properties measured were determined by the equipment available to the research group and different concrete charactistics were measured.

Measurement of Field Formwork Pressures

Lateral pressures have been measured with small diameter, commercially available, pressure transducers, various earth pressure cells, tie force measurements or strain in form elements. Papers by

Cauberg, Desmyter and Pierard (2006) and McCarthy and Siwerbrand (2011) have shown that the named measurement systems give similar results. Rate of pour, concrete consistency uniformity are problematic in field investigations. Concrete head is difficult to measure and maximum head is limited by the project. Many projects have not measured the changes in concrete behaviour over the pour durations, typically 4-5 hours or less.

Simulated form pressures

Because of the measurement difficulties, lack of technical support, concrete consistency problems and the cost of field form research, many researchers have resorted to laboratory investigations measuring pressures in a closed, small head square or tubular form and applied a vertical load (pressure) using hydraulic or fluid pressure to simulate a predetermined rate of placement. The lateral pressures are measured using, usually, small diameter pressure transducers. Several researchers emphasize the decay of the lateral pressure, to cancellation, after the maximum value has been reached.

Rheology

The study of the deformation and flow of matter, describes the material properties of fluid and semi-solid materials. All rotational, vane or drum, rheometers operate in similar manners. Concrete is placed in the sample container and conditioned by applying a low angular velocity (shear strain gradient) for several seconds. The velocity is then increased in steps to a chosen higher angular velocity and torque measurements are taken at every velocity step. The velocities are then decreased in steps to zero and torque measurements are taken at every velocity step. The characterization can be the intercept and slope of a straight line fitted to the decreasing velocity curve (Bingham assumption) or the difference between the increasing velocity and decreasing velocity curves (breakdown area). However the maximum velocity endpoint is arbitrary and rheometer characterizations done at high shear rates are not representative of the concrete placing process. Unfortunately fundamental parameters measured using different types of rheometers are different (Ferraris and Brower 2003).

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LATERAL PRESSURE EQUATIONS

Form pressures exerted by SCC are determined by the rate of concrete placement relative to the rate of development of concrete stiffness/strength. The development of concrete stiffness/strength is dominated by the performance of the admixtures. Mix qualification and formwork design, are done prior to start of construction. As changes in the water content of the aggregates or admixture doses can significantly affect the stability of the mixture, and possibly increase the lateral pressure, a site verification method is required. A problem, common to all three methods, is reconciling laboratory values of measured behavior indicators to site measured values.

Given the number of combinations of chemical admixtures that are available it would be difficult to develop lateral pressure guidelines based upon mixture proportions. Hence identifying and characterizing the flow/stiffening properties of the concrete appropriate to the magnitude of the lateral pressure envelope is required. A complication in measuring the mechanical properties of the fresh concrete is determining the initial state of the concrete, as a pseudo fluid (no shear resistance) or in a state where some shear resistance (but not necessarily at failure) has been developed. To establish a lateral pressure equation/method some measure of the early age, time stiffening/strength behavior of the concrete is required. Researchers have tended to use or modify existing methods and procedures. Most researchers have had access to only one piece of equipment so comparison between results is difficult as different, or incomplete, characterization information was collected.

The lateral pressures developed by Self Consolidating Concrete are determined by the rate of concrete placement relative to the rate of development of concrete stiffness/strength. Consequently any prediction method should be capable of being easily checked on site using on-site measurements. Methods that meet this requirement are DIN 18218 (based upon the research of Proske and Graubner), Khayat and Omran (2010, 2011) and Gardner, Keller, Charitou and Quattrociocchi (2011).

DIN 18218:2010-01 (Proske and Graubner 2008)

DIN 18218 uses a pressure envelope that is hydrostatic from the free surface to a limiting value. The limiting formwork pressures, including SCC and vibrated, high slump concrete, are given in terms of the concrete consistency (DIN 12350-5).

For SCC the limiting pressure can be calculated from the following equation which requires the 10MPa (1450 psi) Vicat setting time on the sieved mortar using 1.13 mm. diam. Vicat needle for a penetration of 2.5 mm. Alternatively, DIN 18218(2010) allows the setting bag test to determine the setting time for SCC.

$$P_{max} = (1.0\ m + 0.26\ Rt_E)w > 30\ kPa \qquad (1)$$

P_{max} = limiting lateral pressure kPa

R = mean rate of placement m/hour

t_E = setting time for concrete (using 1.13 mm. diam. Vicat needle at

10MPa for a penetration of 2.5 mm)

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

Din 18218 uses a load factor of 1.5 on both the hydrostatic and the limiting pressure.

Khayat and Omran (2011, 2010)

Khayat and Omran suggested two methods to measure the on-site shear strength of SCC, namely the Portable Vane Test (PV) and the Inclined Plane (IP) test. The static yield strengths PVτ and IPτ (in Pa) are measured after 15 minutes of rest at 22C. The pressure envelope is hydrostatic from the free surface to a limiting value given by one of the following equations.

$$P_{max}= wh\{112.5 -3.8\, h + 0.6R - 0.6T + 10D_{min} - 0.021PV\,\tau_{0rest@15min@T=22C}\}\, f_{MSA} f_{wp} \quad (2)$$

$$P_{max}= wh\{12.0 -3.83\, h + 0.6R - 0.6T + 10D_{min} - 0.023IP\,\tau_{0rest@15min@T=22C}\}\, f_{MSA} f_{wp} \quad (3)$$

D_{min} = minimum form dimension $(0.2 < D_{min} < 0.4)$ m

f_{MSA} = factor for maximum agregate size

fwp = factor for delay in successive lifts

h = height of placement m

P_{max} = limiting lateral pressure kPa

R = mean rate of placement m/hour

T = concrete temperature

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

$PV\,\tau_{0rest@15min@T=22C}$ = static yield strength (Pa) measured using inclined plane test, Pa

$IP\,\tau_{0rest@15min@T=22C}$ = static yield strength (Pa) measured using vane test, Pa

Gardner, Keller, Charitou and Quattrociocchi (2011)

The time for the slump flow to drop to 400 mm was chosen as the material parameter characterizing the concrete. Equation (4) is a simple equation to describe the lateral pressure development with time – the equation cannot be used for times greater than that required to achieve P_{max}.

The time, t_0, to reach zero slump flow (not a physically measurable phenomena), is defined as:

$$t_0 = t_{400}\,[\textit{initial slump flow}/(\textit{initial slump flow} - 400mm))] \quad (4)$$

$$P = wR\left(t - \frac{t^2}{2t_0}\right) \qquad t < t_0 \quad (5)$$

$$P_{max} = wRt_0/2 \qquad t > t_0 \quad (6)$$

Maximum pressure $P_{max} = wRt_0/2$ occurs *at* $t = t_0$.

For $t > t_o$ the pressure is assumed to remain constant at the maximum value.

If the time to fill the form, $t_h = h/R$, is less than t_0, $t = t_h$ is used in equation (2).

$$P_h = wR\left(t_h - \frac{t_h^2}{2t_0}\right) \quad (7)$$

h = height of placement m

P_h = limiting lateral pressure kPa

R = rate of placement m/hour

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

$t_h = h/R$ hours

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

Characteristic time

The characteristic time should be measured on concrete subjected to the same conditioning regime as the concrete will experience on site; namely agitated before discharge from the truck and placed in the form. As some modern admixture combinations enable concrete to be fluid as placed and then stiffen rapidly, the characteristic time selected must be short enough to be able to estimate the early age, fresh concrete properties. This could well be different from the setting time.