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FIELD MEASUREMENTS OF SCC RHEOLOGY AND FORMWORK PRESSURES

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Abstract

Field measurements were made of the rheology and formwork pressures of 3 separate self-consolidating concrete (SCC) mixtures. Rheology measurements were made directly with the ICAR rheometer—a portable, vane-type rheometer—and indirectly with the slump flow test. An attempt was made to match the shear history of the concrete used for rheological measurements to that of the concrete in the forms. The maximum, recorded, lateral formwork pressures varied from 28% to 98% of hydrostatic pressure. The rate of increase of the static yield stress—measured either with the rheometer or slump flow test—was found to be important for evaluating formwork pressure. This rate of increase was affected by the loss of superplasticizer efficacy, hydration, and thixotropy. Concrete rheological properties were shown to be highly influenced by changes in mixture proportions, especially changes in admixture type and dosage. Increasing yield stress retention by varying the types and dosages of superplasticizer and retarder were beneficial for lengthening transport and placing times but resulted in significantly higher formwork pressures.

Keywords: self-consolidating concrete, form pressure, rheology, thixotropy

1. INTRODUCTION

A major issue for form designers and formwork suppliers is the lateral pressure exerted by self-consolidating concrete (SCC). However, published research on formwork pressures is inconsistent with some research concluding that forms should be designed for full hydrostatic pressure and other research showing significantly lower formwork pressures even for rates of placement as high as 120m/hr. While pressure measurements taken on one project may be valuable for checking the formwork on that site, the results cannot be used to develop a lateral pressure methodology unless the rheological (flow) characteristics of the concrete are determined in some manner. This paper reports rheological properties and formwork pressures measured on site during the construction of a hospital in Peterborough, Ontario. The objectives of the testing were to relate mixture proportions to rheological parameters and rheological parameters to formwork pressures.

2. SCC RHEOLOGY

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 such as oils, foods, inks, paints, polymers, clays, concrete, and asphalt. The common factor is that these materials exhibit some sort of flow and, therefore, can not be treated as solids. Fundamentally, the flow and stiffening characteristics of concrete are determined by aggregate shape and grading, paste composition and volume, water content, and chemical admixtures. However, given the vast number of different combinations and quantities of chemical admixtures that are available now and to be made available in the future, it would be impractical to develop lateral pressure guidelines based upon mixture proportions. Hence, recourse must be made by measuring the rheological flow and stiffening characteristics of the concrete. During the field testing described in this paper, various approaches for characterizing concrete rheology were evaluated, with some found to be preferable to others.

Fresh concrete is an age-stiffening, thixotropic material. After placing, without further agitation, concrete immediately begins to gain/regain its shear strength. This increase in shear strength with time is due to the build-up of the easily destroyed, at-rest (thixotropic) structure of SCC, the loss of admixture efficacy, and ongoing hydration. Conversely, concrete in a truck is agitated continuously, which destroys the built-up thixotropic structure and facilitates placement.

The at-rest concrete properties are of interest for formwork pressure considerations. In terms of rheology, the increase in static yield stress with time of undisturbed samples of concrete should be evaluated. The static yield stress reflects the amount of 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. The distinction between the static and dynamic yield stress is illustrated in Figure 1. The static and dynamic yield stresses are equal immediately after mixing. The dynamic yield stress increases due to the loss of admixture efficacy and hydration. The static yield stress of un-agitated SCC increases faster than the dynamic yield stress because of the build-up of an easily destroyed at-rest structure (thixotropy), which acts in addition to the effects of reduced admixture efficacy and hydration. After placement, however, the static yield stress increases—the rate of this increase is important for predicting formwork pressure.

In many studies of SCC formwork pressure in the literature, thixotropy and viscosity have been measured at high shear rates. To measure thixotropy at high shear rates, the breakdown area between upward and downward flow curves is commonly calculated (Figure 2). Such an approach was initially utilized in this research but was found not to be the best approach. Because formwork pressure is influenced by the behavior of concrete at rest in the forms, measurements near zero shear rates after periods of rest (namely static yield stress) should be more directly relevant to formwork pressure than breakdown area. It is the magnitude of the static yield stress (influenced by the loss of superplasticizer efficacy, hydration, and thixotropy) and not the amount of thixotropy per se that is relevant to formwork pressure. In Figure 2, the yield stress extrapolated from the upward flow curve (an indirect measure of static yield stress) increases faster than that from the downward flow curve (dynamic yield stress), partially reflecting the magnitude of thixotropy at low shear rates.

Static yield stress can be measured directly in a rheometer with a stress growth test, during which a very low shear rate is applied to the concrete and the build-up in stress is monitored (Figure 2). The maximum stress achieved is the static yield stress. The concrete sample for the stress growth test must be representative of the concrete in the form. For instance, concrete should ideally be sampled into separate rheometer containers at the time of placement, left undisturbed, and tested periodically to plot the static yield stress with time.

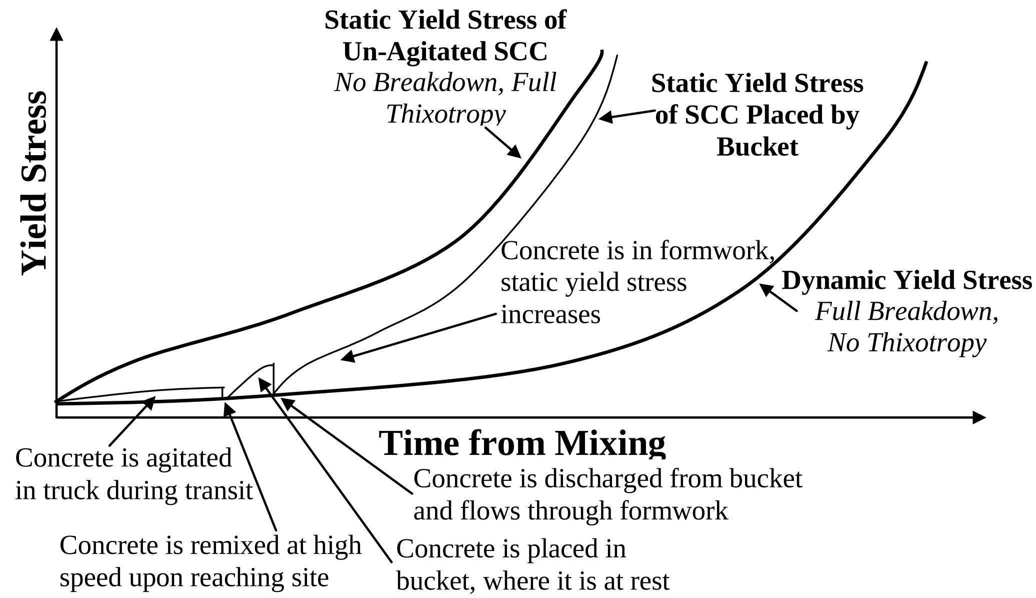

Figure 1: Conceptual Changes in Yield Stress with Time

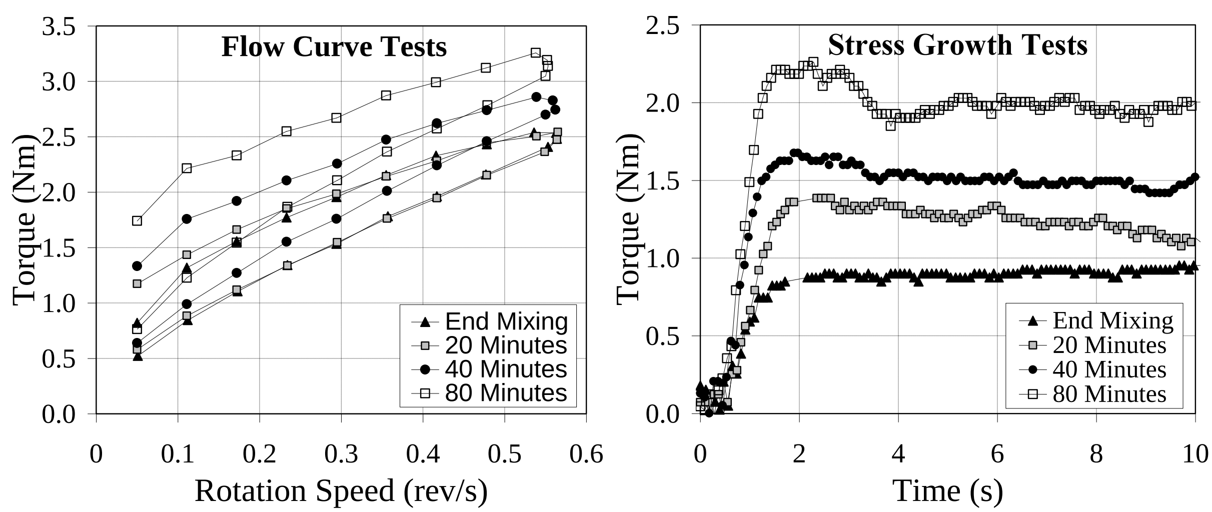

Figure 2: Breakdown Curves and Stress Growth Tests (Mixture 3, Laboratory Data)

As few contractors have access to concrete rheometers, rheological properties can be inferred from the slump flow test (ASTM C1611). Such an approach is not as precise as rheometer measurements because some breakdown of the built-up structure occurs during the slump flow test. For the slump flow test, concrete should be sampled at the start of placement and left undisturbed until the prescribed test times. In addition to the final spread, the time for the concrete to spread to diameters of 40 and 50 cm (T_{40} and T_{50}) should be measured.

3. FIELD TEST RESULTS

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 and 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 (a portable, vane type 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 slump flow measurements are not shown in this paper.

Figure 3 indicates that Mixtures 1 and 2 lost workability quickly, as indicated by the rate of increase in dynamic yield stress. Additionally, the thixotropy—which was measured as the breakdown area between upward and downward flow curves—increased rapidly in these 2 mixtures, which would be expected to increase the static yield stress. Consequently, the formwork pressures were much lower than hydrostatic pressure, as shown in Figures 4 and 5. 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 and 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.)

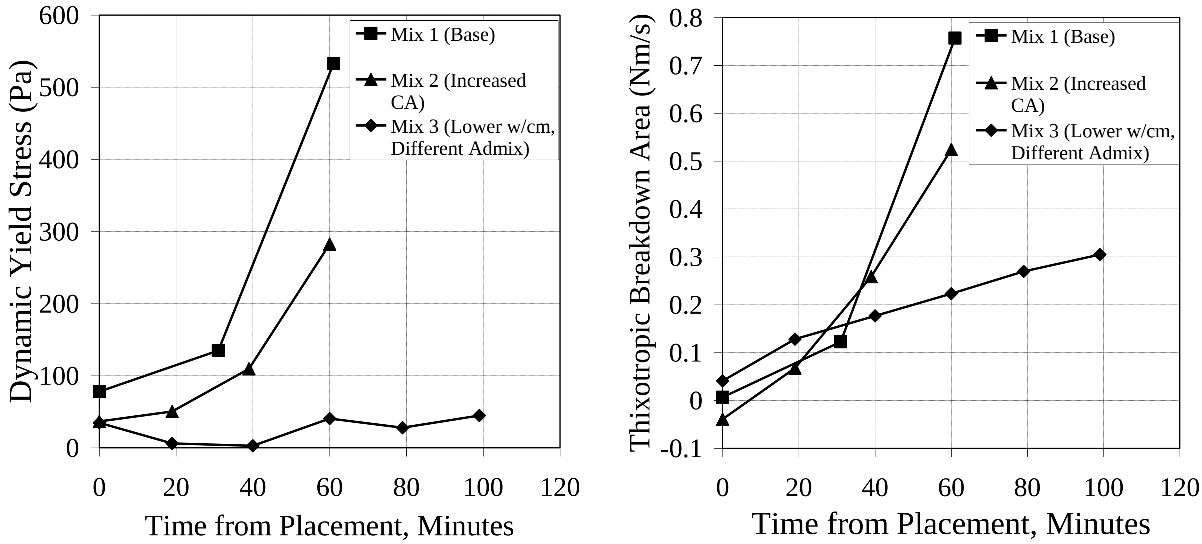

Figure 3: Changes in Rheology with Time

In contrast, the different retarder and superplasticizer used in Mixture 3 extended the workability retention and reduced the magnitude of thixotropy (Figure 3). As a result, the formwork pressures were much higher than in the first two mixtures and nearly approached hydrostatic pressure (Figure 6). 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 did not gain shear strength quickly.

The formwork pressure data for the 3 mixtures clearly confirm the diversity of pressure distributions reported in the literature for SCC. The rate of at-rest concrete stiffening significantly changed the maximum measured form pressure–large initial yield stress or large increases in yield stress with time reduced the maximum measured concrete pressures. Increases in yield stress were reflected in lower slump flow readings. Discontinuous placement, by bucket or programmed interruptions of pumping, allow the concrete to regain 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. Consequently SCC mixture design has to be done with care because admixtures can not be changed or substituted without diligent consideration. In addition changes to the water content 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.

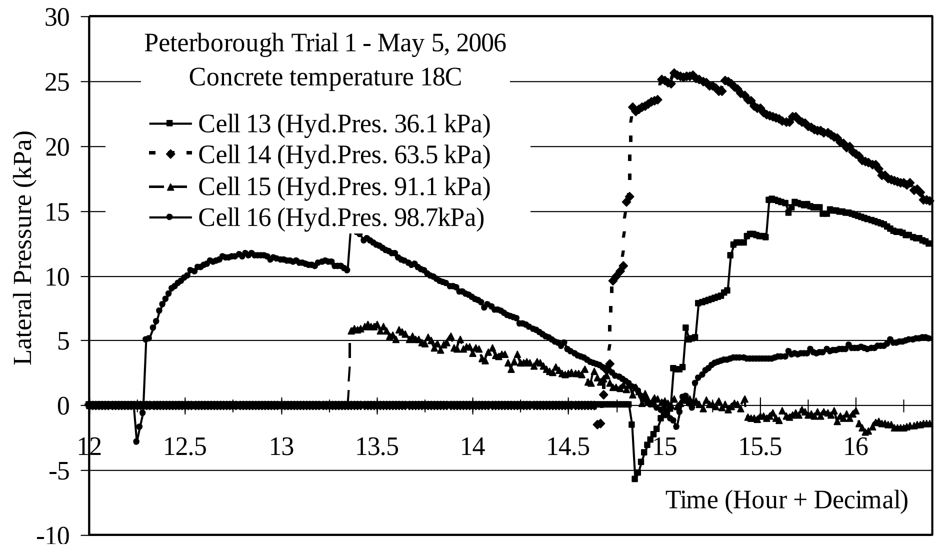

Figure 4: Formwork Pressure Measurements for Mixture 1

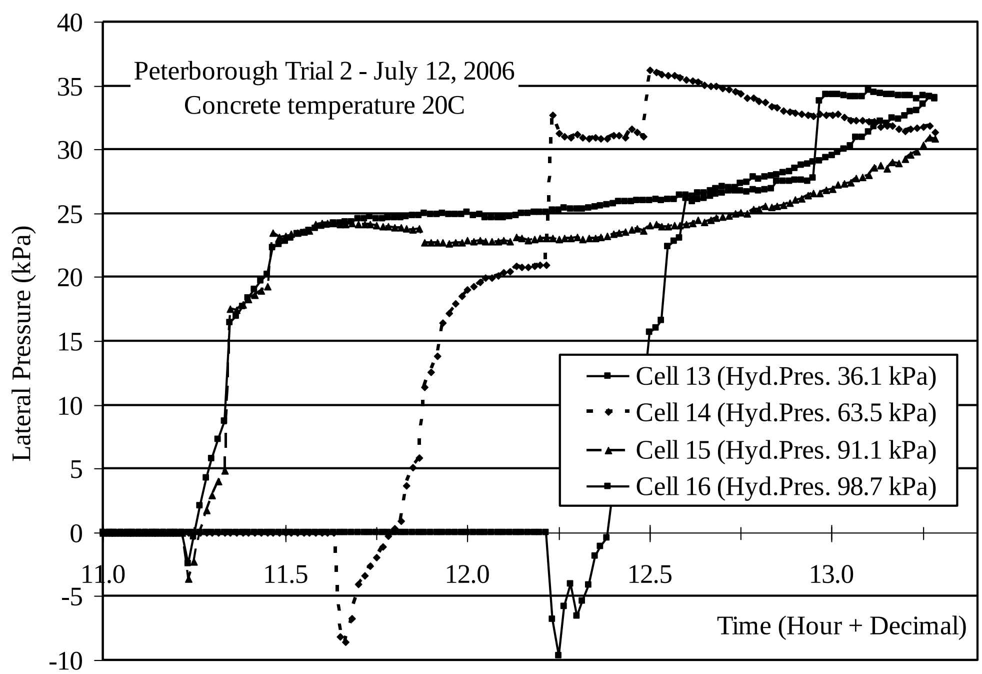

Figure 5: Formwork Pressure Measurements for Mixture 2

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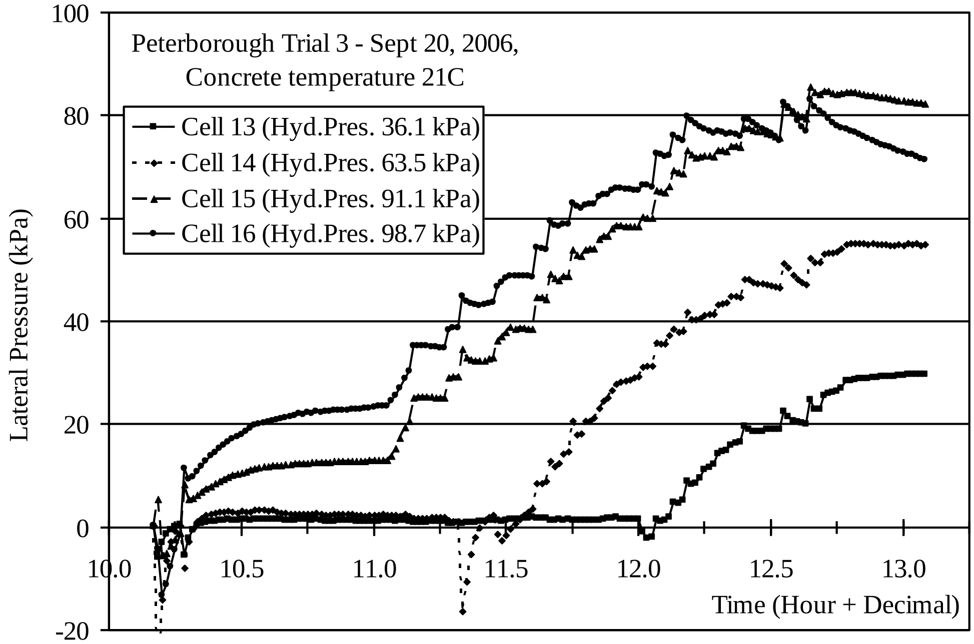

Figure 6: Formwork Pressure Measurements for Mixture 3

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the SCC field test results, the following conclusions can be reached:

- The rheological properties and formwork pressures associated with SCC can vary widely. In particular, the type of retarder and superplasticizer was found to be significant. The admixture combination for Mixture 3 extended workability retention and reduced thixotropy, resulting in significantly higher formwork pressures.
- The at-rest rheological properties of SCC are of interest in evaluating formwork pressures In particular, the static yield stress measured on an undisturbed sample of concrete representative of that in the formwork should be evaluated. Increases in static yield stress reflect the increasing shear strength of the concrete due to the reduction in superplasticizer efficacy, hydration, and the build-up of a thixotropic, at-rest structure.
- The increase in static yield stress with time can be utilized to reduce formwork pressures by allowing the concrete in lower lifts to gain/regain shear strength prior to the placement of higher lifts. The rate of placement needed to limit formwork pressures is a function of the rate at which the concrete gains/regains shear strength.
- To evaluate SCC formwork pressure data, a consistent databank of rheological test data should be collected. The authors recommend measuring the increase in static yield stress with time. For rheometer measurements, concrete should be sampled into separate rheometer containers at the beginning of placement, left undisturbed, and tested periodically with the stress growth test. If a rheometer is unavailable, the slump flow test can be conducted with undisturbed concrete samples in order to approximate static yield stress.

5. ACKNOWLEDGEMENTS

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