An Insight into Formwork Pressures Using Self-Consolidating Concrete

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“Self consolidating concrete (SCC), also known as self compacting concrete, is a highly flowable, non-segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation, but lack of knowledge of formwork pressure is a concern and reason for not using SCC in large scale in developing countries”.

Utilization of Self-Consolidating Concrete (SCC) in cast-in-place concrete has been relatively slow to progress in developing countries partly due to the lack of understanding of pressures exerted on formwork systems. It is generally understood that the pressure is greater than ordinary (nonflowing) concrete, but quantification and prediction of the pressure has been difficult due to the many types of SCC available and the various construction methods used during placement. Without adequate prediction methods, the only options left to the engineer, according to ACI 347, are to either design for full hydrostatic pressure or to monitor pressure during placement and adjust the rate of placement accordingly. The assumption of full hydrostatic pressure would generally create formwork that is too costly to justify the use of SCC. Since formwork pressure is a life-safety related issue, with significant construction collapse as a consequence, the only viable option remaining is to monitor the form pressure during placement until prediction models can be developed and validated. The monitoring performed in this study is intended to be used for validation of prediction models and to promote understanding of the factors that influence lateral formwork pressure during construction with SCC.
Factors Affecting Formwork Pressure

(A) Materials

Formwork pressure exists as long as the concrete is in a plastic state, and its rate of decay is related to the rate of the stiffening of the concrete mixture. It follows that the lower the yield stress and plastic viscosity of the concrete are (i.e. high flowability), the greater the initial lateral pressure. Conversely, a faster rate of stiffening brings about a faster rate of decay of the lateral pressure. As is evident, SCC can be formulated in various ways and consequently does not have any specific composition. Researchers have found that any of following parameters aggregate content and size, w/cm, cement type and content, silica fume, fly ash, slag, ground limestone filler, superplasticizer type and content, and VMA type and content can affect the lateral pressure characteristics. To be more specific, they have found that increasing aggregate content and size gives rise to a lower initial lateral pressure. In contrast, rich concrete mixes develop greater pressure than normal and lean mixtures. This is attributed to internal friction of coarse aggregate carrying some of the hydrostatic load. However, if the content of the fines (the paste component of the concrete) is increased, the ability of the coarse aggregate to carry loads decreases, and the lateral pressure is increased. Increasing the w/cm or/and superplasticizer content increases the lateral pressure and vice versa. However, different superplasticizers have been found to affect differently both the initial lateral pressure and its rate of drop after casting. Researchers also observed that addition of supplementary cementitious materials (SCM), such as fly ash, silica fume, or granulated blast-furnace slag, affect the lateral pressure and more specifically its rate of decay. This is attributed to the thixotropic nature of the concrete that changes with the inclusion of these materials. However, the literature mainly provides qualitative information on the effects of the various ingredients listed above and occasionally, disagreements on the effects of some ingredients are encountered.

(B) Placement Conditions

The placement rate is a critical parameter for formwork pressure of SCC. The higher the rate of placing, the higher the lateral pressure is, and to reiterate, this pressure may be as high as full hydrostatic pressure. Conversely, if placement rates are reduced, the concrete mixture, especially that possessing thixotropic properties, undergoes structural build-up, and the pressure is reduced. Similarly, the placement method has a significant effect on formwork pressure. Concrete pumped into the formwork from the bottom of the form exhibits higher pressures than that placed from above. These effects are to a great extent related to the shearing forces to which the plastic concrete is subjected to during placement, being greater once the concrete is pumped into the forms from the bottom up. Since the mechanical properties of concrete are temperature dependant, the higher the initial temperature of the concrete and/or the ambient temperature, the lower the lateral pressure is. Subsequently, a higher rate of pressure decay is recorded. This is attributed to a faster rate of structure build-up and hydration takes place at higher temperatures. The set time of concrete has similar effects. After placement, mixtures with longer setting times display longer lateral pressure cancellation time.

(C) Formwork Characteristics

There is little data pertaining to the effects of formwork dimensions and formwork pressure. Few researcher have showed that smaller cross-sections exhibit lower maximum pressure. It was explained that this relationship was due to an arching effect that limits lateral pressure. The presence of reinforcement theoretically helps to decrease the formwork pressure because it can hold part of the concrete load, although this may be a negligible effect in SCC. Research also has shown that the type of formwork used has an effect on formwork pressure. Specifically, rigid and smooth formwork materials result in higher lateral pressure and lower rate of pressure drop after placement. The roughness of the forms also plays a role due to the dynamic friction that develops upon concrete placement. It was shown that the application of demolding agents, such as oil, to the formwork can decrease friction and lead to an increase in lateral pressure.

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.

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. 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.

Some Field Measurement Studies

(Source Concrete International Journal January 2012, article by by N.J. Gardner, Lloyd Keller, Robert Quattrociocchi, and George Charitou) Field The field investigation of form pressure in Charleston, SC, from June 2005 to February 2006 is discussed here for general information of the reader on the article insight.

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. 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 SCC stiffening behavior to variations in water content, temperature, and admixture types and dosages. The lateral formwork pressures were measured using 125 mm (5 in.) diameter, Geokon 4820, vibrating wire pressure cells (Refer Figure 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) (Refer Figure 2).

A single residence unit between door blockouts, shown in Figure 2, required about 5 m3 (6 yd3) 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 Figure 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.

Form Pressure Models

Numerous models and code regulations aiming at predicting form pressure are reported in the literature. However, in most cases the models do not pertain to SCC. The models available include the following input parameters: pore water pressure, rate of casting, vibration, setting time, consistency, form permeability and surface texture, form dimensions, coarse aggregate, temperature, and concrete unit weight. Of the few models pertaining to SCC, thixotropy has been identified as a main factor that affects the lateral pressure and its rate of decay. Accordingly, both the Sherbrooke and Northwestern research groups have shown that thixotropy can be monitored and quantified by measuring the area confined in the hysteresis loop (of shear rate vs. shear stress plot) obtained by studying the rheological characteristics of the mixture or by evaluating the drop in shear stress between initial and equilibrium states determined at different shear rates. The resulting area in the hysteresis loop or in the drop in shear stress vs. shear rate is used to quantify the energy required for structural breakdown during mixing and the ensuing structure build-up once the mixture is at rest. Indeed, Khayat and his coworkers successfully implemented this concept and made a connection between the rate of pressure decay and the degree of thixotropy.

Conclusion

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. 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.

Reference

- The National Ready-mix Concrete Research Foundation And The Strategic Development Council, American Concrete Institute
- Field Investigation of Formwork Pressures Using Self-Consolidating Concrete, by N.J. Gardner, Lloyd Keller, Robert Quattrociocchi, and George Charitou, Concrete international January 2012.