State-of-the-Art Review of Form Pressure Exerted by Self-Consolidating Concrete

Executive Summary

Kamal H. Khayat, P. Eng., Ph.D.
Professor

A. Omran
Ph.D. Candidate

Department of Civil Engineering
Université de Sherbrooke
Sherbrooke, Québec, Canada

SCC Formwork Pressure

EXECUTIVE SUMMARY

Submitted to:

THE READY MIXED CONCRETE RESEARCH & EDUCATION FOUNDATION
and
THE STRATEGIC DEVELOPMENT COUNCIL, AMERICAN CONCRETE INSTITUTE

By:
P.I.: Kamal Henri Khayat, Université de Sherbrooke
Subcontractors: 1- Surendra Shah, Northwestern University
2- CTLGroup

Submitting Agency

UNIVERSITÉ DE SHERBROOKE

Kamal Henri Khayat, *Professor,* Kamal.Khayat@USherbrooke.ca
Ahmed F. Omran, *Ph.D.,* Ahmed.Omran@USherbrooke.ca

EXECUTIVE SUMMARY

1. Introduction

Self-consolidating concrete (SCC) is an emerging technology that utilizes flowable concrete and eliminates the need for consolidation. The advantages of SCC lie in a remarkable reduction of the casting time, facilitating the casting of congested and complex structural elements, and the possibility of reducing labor demand, elimination of mechanical vibrations and noise, improvement of surface appearance, and production of better and premium concrete products.

While SCC has been successfully used in North America in the precast industry, a certain number of technical issues have slowed down its use in cast-in-place applications, in particular the lack of knowledge of the lateral pressure exerted by SCC on formwork systems. This prompts contractors and engineers, as recommended by ACI 347R-03 (Guide to Formwork for Concrete), to design the formwork to withstand full hydrostatic pressure, which increases construction cost and compromises profitability.

2. Objectives

This project undertaken in this research project seeks to:

- Capture existing knowledge regarding formwork pressure exerted by SCC and make recommendations for current practice;
- Devise portable apparatus for measuring and predicting lateral pressure of SCC;
- Devise test method for field evaluation of relevant plastic properties of SCC that control formwork pressure;
- Identify the role of material constituents, mix design, concrete placement factors (casting rate), geometry of formwork, and fresh concrete temperature that have major influence on formwork pressure exerted by SCC;
- Relate the maximum lateral pressure and rate of decay in pressure to the initial plastic properties of the concrete;
- Propose effective ways to reduce lateral pressure by developing formulation expertise and providing practical guidelines to reduce SCC lateral pressure ; and
- Propose design equations to predict SCC formwork pressure for column and wall elements.

3. Test protocol

3.1   Devices for evaluating formwork pressure of SCC during mixture prequalification

Two devices were developed in this project, as detailed below: (i) portable pressure device and (ii) a 1.2-m (3.9-ft) high sacrificial column.

3.1.1   Portable pressure column (U*of*S2 pressure device)

A portable pressure column refered here as the U*of*S2 pressure device was developed for use in evaluating formwork pressure of SCC and is suitable for laboratory and field use. The device enables to quantify lateral pressure exerted by SCC. The pressure device has a circular cross section measuring 200 mm (7.9 in.) in internal diameter, 700 mm (27.6 in.) in height and with a wall thickness of 10 mm (0.4 in.), as shown in Fig. 1. The device is filled to a height with 500 mm (19.7 in.) of concrete at the targeted casting rate. The top of the pressure device is then sealed, and overhead air pressure is introduced at a given rate from the top to simulate pressure increase at the desired placement rate. The device can enable simulation the casting of concrete height up to 13 m (42.7-ft). A pressure sensor is set flush with the fresh concrete surface near the base of the pressure device to record lateral pressure exerted by the plastic concrete. Another transducer is fixed above the concrete surface at 625 mm (24.6 in.) from the base to determine the net overhead pressure inside the pressure device. The pressure device should be demolded few hours after the end of casting simulation prior to concrete hardening.
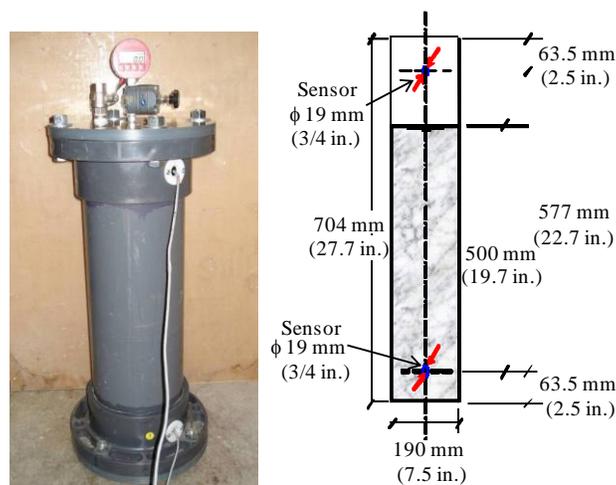

Fig. 1 - U*of*S2 pressure device

A pressure transducer supplied by Honeywell is used for the measuring system. The sensor is extremely accurate with relative error of 0.25% over a wide range of temperatures. The sensor

has a capacity of 1380 kPa (200 psi) and measures 19 mm (3/4 in.) in diameter. It can operate over a temperature range varying from -54 to +93°C (-65.2 to 200 °F) and is excited using 5 V dc current. The sensor is connected to a data acquisition system to monitor pressure variations at 90-s interval. In addition to the pressure sensor, a digital dial-gauge (manometer) is fixed in a small regulating chamber attached to the top of the UofS2 pressure device to control the overhead air pressure on top of the concrete surface.

The results of UofS2 pressure device can be presented in three forms: (i) variations of lateral pressure with time, or pressure decay, (ii) variations of the maximum lateral pressure, P_{max}, with casting depth, H, and (iii) variations of relative lateral pressure, K_0, with H. Examples of the first two cases are shown in Fig. 2.
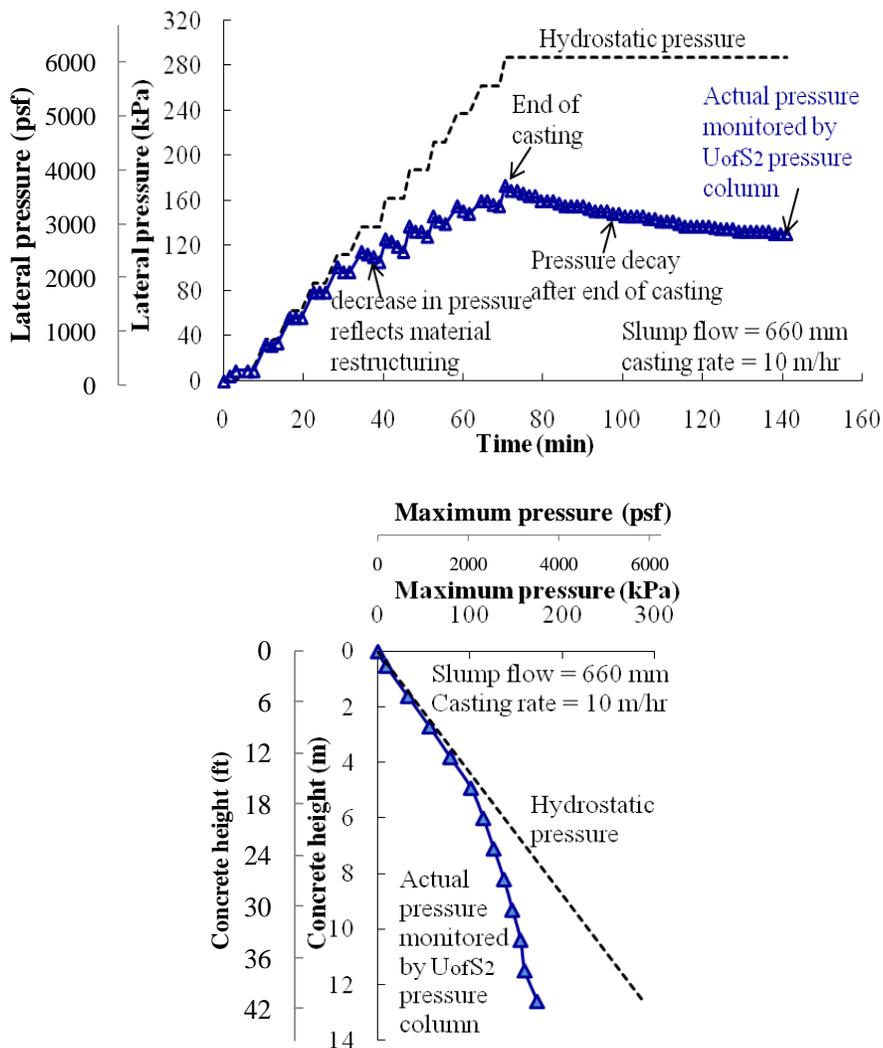

Fig. 2 - Variations of lateral pressure with time (left) and variations of the maximum lateral pressure, P_{max}, with casting depth, H, (right) using UofS2 pressure device

3

The repeatability of the UofS2 pressure device was determined using one SCC mixture prepared and tested four times. The results of the relative error, RE, for the K_0 values at various H values are given in Table 1. The results indicate high precision of the pressure measurements.

The lateral pressure characteristics of SCC mixtures determined using the UofS2 device filled with 0.5 m (1.6 ft) and overhead pressure to simulate a head of concrete of 3 m (3.8 ft) were compared to measurements obtained from a free standing column of 3 m (3.8 ft) of fresh concrete cast in a rigid PVC column of the same diameter. Good agreement was obtained between both systems in terms of initial lateral pressure and pressure decay. From the comparison between the UofS2 pressure device and a 1.2-m (3.9-ft) high sacrificial column, described in the following section, the UofS2 pressure device is shown to enable the evaluation of the decay in lateral pressure up to 2 hours after the end of casting; the results of the pressure decay are similar to those obtained using the 1.2-m (3.9-ft) high sacrificial PVC column.

The UofS2 pressure device was also validated using SCC mixtures made with various material characteristics, mix designs, and casting rates. Findings from the pressure device were found to be quite comparable to those reported in the literature.

Table 1 - Relative error, RE, in predicting relative lateral pressure values, K_0, using the UofS2 pressure device

Casting depth; H, m (ft)	Relative error; RE (%)
1 (3.3)	± 0.7
4 (13.1)	± 2.4
8 (26.2)	± 2.3
12 (39.4)	± 4.0

3.1.2 *Use of sacrificial column for evaluating pressure decay*

A rigid PVC with 10 mm (0.4 in.) wall thickness measuring 200 mm (7.9 in.) in diameter and 1.2 m (3.9 ft)in height is proposed to monitor lateral pressure variations until pressure cancellation (Fig. 3), which corresponds to concrete hardening. The column has a smooth inner surface which should be coated with a layer of formwork release agent prior to each use. The PVC column has a seam along its height to facilitate demolding and is tightened using four radial ties. The concrete is cast continuously at the desired rate from the top without any vibration. The concrete pressure is monitored using three pressure sensors of 100-kPa (43.5-psi) capacities mounted at 1.0, 0.8, and 0.6 m (39.4, 31.5, and 23.6 in.) from the top concrete surface.

Fig. 3 - Sacrificial column for evaluating pressure decay

3.2 Devise test method for field evaluation of relevant plastic properties of SCC that control formwork pressure

Two field-oriented test methods are proposed for the characterization of the structural build-up SCC that affects form pressure. These tests consist of the portable vane and the inclined plane methods. The study clearly demonstrates that structural build-up at rest of SCC has a signifiucant impact on the magnitude of the macimum lateral pressure exerted by the concrete and its decay in time.

3.2.1 Portable vane test

The portable vane, PV, test (Fig. 4) is inspired from the in-situ test of measurement of shear strength of clay soil. Four-blade vanes of different sizes (Table 2) were manufactured from stainless steel to enable using a torque-meter of high precision to capture shear strength of plastic concrete subjected to various times of rest; typically 15, 30, 45, and 60 minutes. The largest vane is used for the weakest structure, i.e., shortest resting time, and vice versa.
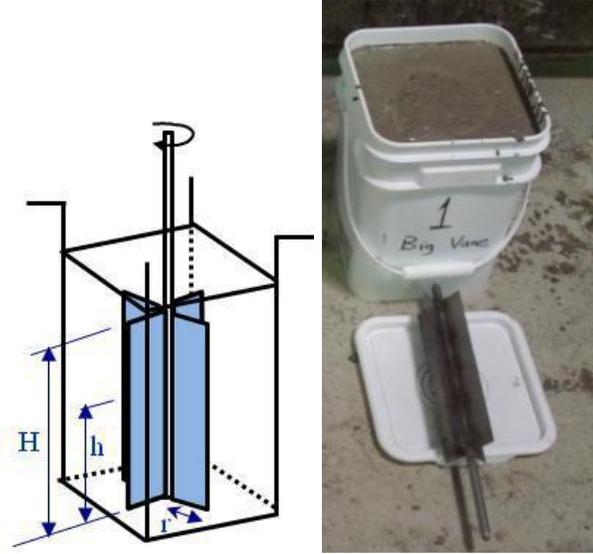
Fig. 4 - portable vane test

Table 2 - Vane dimensions for the portable vane test

Vane	Vane dimensions, mm (in.)	
	r	H
Vane # 1 (large vane)	37.5 (1.48)	250 (9.84)
Vane # 2	37.0 (1.46)	200 (7.87)
Vane # 3	37.5 (1.48)	150 (5.91)
Vane # 4 (small vane)	37.5 (1.48)	100 (3.94)

Immediately after mixing, the four vanes are centered vertically in the containers, and the containers are filled with SCC to a given *H,* indicated in Table 2. It is important to note that the immersion height, h, can be decreased from the total immersion height, H, indicated in Table 2 by controlling the concrete volume in the container. The containers are then covered. At the given time of rest, the torque-meter is attached to the axis of the vane and turned slowly (10 to 15 s for a quarter turn). The maximum torque needed to breakdown the structure is then noted. The torque values are converted to static shear stress, $PV\tau_{0rest}$, using Eq. 1.

$$PV\tau_{0rest} = \frac{T}{G} \qquad where: \ G = 2\pi r^2 \left(h + \frac{1}{3} r \right) \tag{1}$$

where *T* is the measured torque, r is the radius of the vane, and h is the immersion depth of the vane in the concrete.

Variations of $PV\tau_{0rest}$ with time of rest for typical SCC mixtures designed with different thixotropic characteristics are shown in Fig. 5. The $PV\tau_{0rest}$ at 15 min time of rest, $PV\tau_{0rest@15min}$, the time-dependent change of $PV\tau_{0rest}$ with time of rest, $PV\tau_{0rest}(t)$, as well as the couple effect of

6

the initial and rate of change in static yield stress, $PV\tau_{0rest@15min} \times \tau_{0rest}(t)$ can be used as indices for the structural build-up at rest of the concrete.
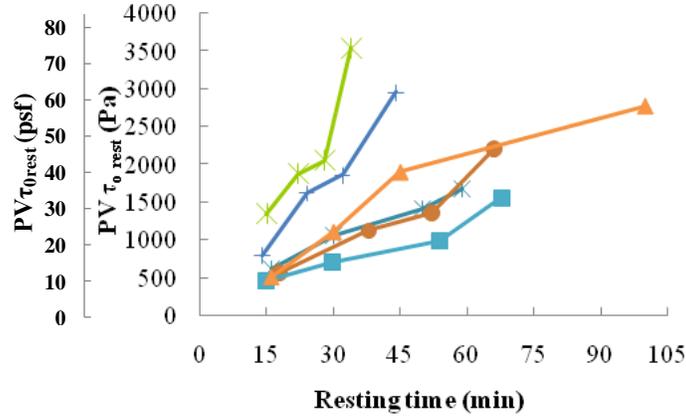

Fig. 5 - Variation of static yield stress with time obtained using portable vane test

3.2.2 Inclined plane test

The inclined plane, IP, test involves placing concrete in a cylindrical mould measuring 120 mm (4.7 in.) in height and 60 mm (2.4 in.) in diameter, onto a horizontal plate of a given roughness, then lifting the plate slowly (over 10 s) to initiate the flow of the material, as illustrated in Fig. 6. The corresponding angle necessary to initiate the flow is used to determine the static yield stress, $IP\tau_{0rest}$ in Pa (1 Pa = 0.0209 psf), as follows:

$$IP\tau_{0rest} = \rho.g.h.sin\alpha \tag{2}$$

where; ρ is unit weight of tested material in kg/m³ (1 kg/m³ = 0.0624 Ib/ft³), g is the gravitation constant that equals 9.81 m/s² (32.2 ft/s²), h is the characteristic mean height in mm (1 mm = 0.039 in.) of the slumped sample, and α is the critical angle of the inclined plate (in degree) when the sample starts to flow. The h value is the mean of five heights of the slumped sample; four at the circumference of a middle circle of the slumped spread, and one at the center. Four tests are performed after different periods of rest to evaluate the rate of increase in $IP\tau_{0rest}$ at rest. For SCC of relatively low thixotropy, the times of rest can be 15, 30, 45, and 60 minutes. For high thixotropy mixture, these rest times can be decreased to 5, 10, 15, and 20 minutes.

7

Fig. 6 - Inclined plane test

Typical variations of $IP\tau_{0rest}$ with time of rest for SCC mixtures of different structural build-up rates are shown in Fig. 7. Similar to the PV test, three indices for expressing the structural build-up at rest of SCC can be evaluated, namely the $IP\tau_{0rest@15min}$, $IP\tau_{0rest}(t)$, and $IP\tau_{0rest@15min} \times \tau_{0rest}(t)$.
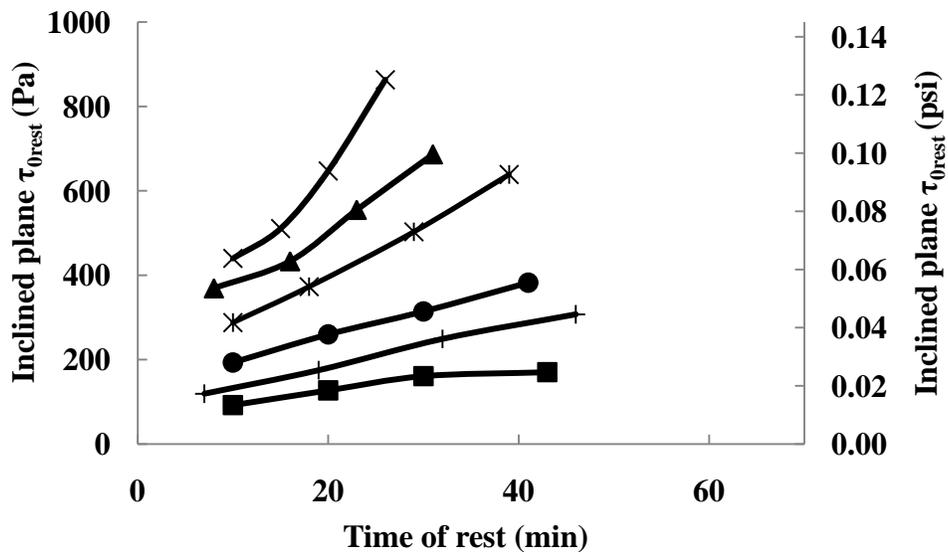

Fig. 7 - Variation of static yield stress with time obtained using inclined plane test

Validation of PV and IP test methods

A summary of the various indices to reflect the change in the rate of structural build-up at rest of concrete-equivalent mortar (CEM) and then SCC determined using the PV and IP test methods are presented in Table 3.

Table 3 - Various thixotropic indices obtained from the empirical test methods

Thixotropy index	Portable vane	Inclined plane
Initial response at 15 min of rest	$PV\tau_{0rest@15min}$	$IP\tau_{0\ rest@15min}$
Time-dependant change of response *(slope)*	$PV\tau_{0\ rest}(t)$	$IP\tau_{0\ rest}(t)$
Couple effect of initial and slope responses	$PV\tau_{0rest@15min} \times PV\tau_{0rest}(t)$	$IP\tau_{0\ rest@15min} \times IP\tau_{0rest}(t)$

The PV and IP test methods showed good repeatability and low relative error, RE, when used to assess structural build-up at rest of CEM and SCC of low and high thixotropy. The indices representing the structural build-up at rest obtained using the PV and IP test methods were validated against various indices obtained using the rheometric concrete measurements; static yield stress at rest, τ_{0rest}, drop in apparent viscosity at rotational frequency of 0.7 rps, $\Delta\eta_{app@N=0.7rps}$, and breakdown area, Ab_1. The validation was formulated using 42 SCC mixtures of different compositions. The compared parameters were measured initially and with respect to time of rest. The correlation coefficients (R^2) for these correlations are summarized in Table 4.

Table 4 - R^2 values for correlations between PV and IP tests versus concrete rheometer

	Initial response at 15 min	Time-dependent response
$PV\tau_{0rest}$ vs. $IP\tau_{0rest}$	0.82	0.85
$PV\tau_{0rest}$ vs. Rheometerτ_{0rest}	0.82	0.96
$IP\tau_{0rest}$ vs. Rheometerτ_{0rest}	0.82	0.93
$PV\tau_{0rest}$ vs. $\Delta\eta_{app@N=0.7rps}$	0.81	0.96
$IP\tau_{0rest}$ vs. $\Delta\eta_{app@N=0.7rps}$	0.67	0.93
$PV\tau_{0rest}$ vs. Ab_1	0.87	--
$IP\tau_{0rest}$ vs. Ab_1	0.70	--

4. Analytical models for formwork pressure prediction relating lateral pressure to plastic properties of SCC

Several parameters that influence formwork pressure and thixotropy of SCC were investigated in laboratory using the UofS2 pressure device and the PV and IP test methods. The data obtained from the study, approximately 800 points, were successfully used to establish analytical models *(UofS models)* to predict formwork pressure for SCC.

4.1 Investigated parameters affecting formwork pressure and thixotropy of SCC

Mixture proportions, casting characteristics, concrete temperature, and minimum formwork dimension were studied as main factors affecting lateral pressure and thixotropy of SCC. The

parameters and their ranges are given in Table 5. In the study, the mix design parameters were identified by relevant thixotropy indices.

Table 5 - Modeled parameters in the prediction models of SCC formwork pressure

Parameter	Range of tested parameters
• Initial slump flow (ϕ) • Volume of coarse aggregate (V_{ca}) • Paste volume (V_p) Sand-to-total aggregate ratio (S/A)	were expressed by thixotropy indices (T.I.) in the prediction models and have two identifications: • T.I.$_{@T=22\pm2°C}$ at ambient temperature of $22 \pm 2°C$ ($71.6 \pm 3.6°F$) • T.I.$_{@Ti}$ at concrete temperature of 12 to 32°C ($53.6 \pm 89.6°F$)
Casting depth (H)	1 - 13 m (3.3 – 42.7 ft)
Placement rate (R)	2, 5, 10, 17, 24, and 30 m/hr (6.6, 16.4, 32.8, 55.8, 78.7, and 98.4 ft/hr, respectively)
Concrete temperature (T)	• 12, 22, and $30 \pm 2°C$ (53.6, 71.6, and $89.6 \pm 3.6°F$, respectively)
Minimum lateral dimension of formwork (D_{min})	200, 250, 300, and 350 mm (7.9, 9.8, 11.8, and 13.8 in., respectively)
Maximum-size of aggregate (MSA)	10, 14, and 20 mm (0.39, 0.55, and 0.78 in., respectively)
Waiting period between successive lifts (WP)	▪ Continuous 30 min at middle of casting ▪ Two periods of 30 min

4.2 Analytical models for prediction of maximum formwork pressure, P_{max}

The prediction models of the maximum formwork pressure, P_{max}, were derived as function of casting depth, H, placement rate, R, concrete temperature, T, minimum lateral dimension of formwork, D_{min}, and thixotropy index, T.I. The effects of waiting period between successive lifts, WP, and maximum-size of aggregate, MSA, were also considered. Thixotropy indices are determined using the PV and IP test methods. The thixotropic indices can be either evaluated at various concrete temperatures, T.I.$_{@Ti}$, or at a reference concrete temperature of $22 \pm 2°C$ ($71.6 \pm 3.6°F$), T.I.$_{@T=22\pm2°C}$. For the latter, a temperature correction function is introduced to account for the actual fresh concrete temperature.

The recommended prediction models for P_{max} in kPa (1 kPa = 20.9 psf) that resulted in the best correlation between predicted-to-measured responses and with the highest R^2 are:

Structural build-up at rest determined using the PV test method:

for thixotropy index determined at fixed concrete temperature of 22 ± 2 °C ($71.6 \pm 3.6°F$), T.I.$_{@T=22\pm2°C}$:

$$P_{max} = \frac{\rho g H}{100,000}[112.5 - 3.8\,H + 0.6\,R - 0.6\,T + 10\,D_{min} - 0.021\,PV\tau_{0rest@15\,min@T=22\pm2°C}] \times f_{MSA} \times f_{WP} \quad (3)$$

🦐 for thixotropy index determined at various concrete temperature (T.I.$_{@Ti}$):

$$P_{max} = \frac{\rho g H}{100,000}[98 - 3.82\,H + 0.63\,R + 11\,D_{min} - 0.021\,PV\tau_{0rest@15min@Ti}] \times f_{MSA} \times f_{WP} \quad (4)$$

where, P_{max}: maximum lateral pressure, kPa;

ρ: unit weight of concrete, kg/m^3;

g: gravitational acceleration, m/s^2;

H: concrete height, m;

R: casting rate, m/h;

T: concrete temperature, ºC;

D_{min}: minimum formwork dimension, m;

$PV\tau_{0rest@15min@22\pm2°C}$: static yield stress after 15 min of rest obtained using the PV test at concrete temperature of 22 ± 2 ºC, Pa.

$PV\tau_{0rest@15min@Ti}$: static yield stress after 15 min of rest obtained using the PV test at various concrete temperatures, Pa.

f_{MSA} : correction factor for MSA. The f_{MSA} is considered as *1.0* except for MSA = 10 mm (0.39 in.), low thixotropic SCC of $PV\tau_{0rest@15min} \leq 700$ Pa (14.6 psf), and H = 4 - 12 m (13.1 - 39.4 m), which is calculated as:

$$f_{MSA}\text{ (dimensionless)} = 1 + \frac{1.26\,H - 5.04}{100} \qquad \textit{H is expressed in (m)}$$

$$f_{MSA}\text{ (dimensionless)} = 1 + \frac{0.384\,H - 5.04}{100} \qquad \textit{H is expressed in (ft)}$$

f_{WP} : correction factor for WP, and can be determined from Fig. 8, dimensionless.
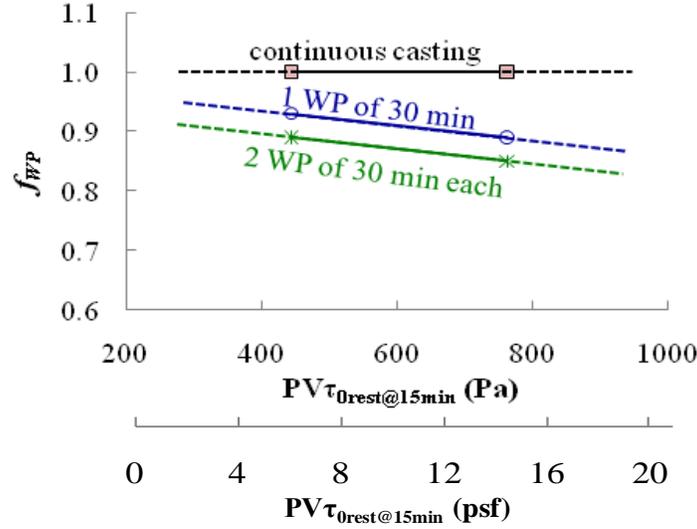
Fig. 8 - Correction factor for waiting period versus initial static yield stress obtained using portable vane test

Excellent agreement is found between the two recommended prediction models of P_{max} that include $T.I._{@T=22\pm2°C}$ and $T.I._{@Ti}$, respectively. They correlated in a 1:1 relationship with R^2 value of 1.0.

Structural build-up at rest determined using the IP test method:

🔴 for thixotropy index determined at fixed concrete temperature of 22 ± 2 °C (71.6 ± 3.6°F), $T.I._{@T=22\pm2°C}$:

$$P_{max} = \frac{\rho gH}{100,000} [112 - 3.83\,H + 0.6R - 0.6\,T + 10\,D_{min} - 0.023\,IP\tau_{0rest@15min@T=22\pm2°C}] \tag{5}$$

🔴 for thixotropy index determined at various concrete temperatures ($T.I._{@Ti}$):

$$P_{max} = \frac{\rho gH}{100,000} [98.4 - 3.8\,H + 0.6\,R + 11\,D_{min} - 0.0227\,IP\tau_{0rest@15min@Ti}] \tag{6}$$

where, $IP\tau_{0rest@15min@22\pm2°C}$: static yield stress after 15 min of rest obtained using the PV test at concrete temperature of 22 ± 2 °C, Pa.

$IP\tau_{0rest@15min@Ti}$: static yield stress after 15 min of rest obtained using the PV test at various concrete temperatures, Pa.

The above prediction models for P_{max} are valid for the ranges: $H = 1 - 13$ m (3.3 - 42.6 ft), $R = 2 - 30$ m/hr (6.6 - 98.4 ft/hr), $T = 12 - 30 \pm 2$ °C (53.6 - 89.6 $\pm$ 3.6°F), $D_{min} = 0.2 - 0.35$ m (7.87 - 13.8 in.), $PV\tau_{0rest@15min} = 0 - 2000$ Pa (0 - 41.8 psf), $PV\tau_{0rest}(t) = 0 - 125$ Pa/min (0 - 2.61 psf/min), $IP\tau_{0rest@15min} = 0 - 1200$ Pa (0 - 25 psf), $IP\tau_{0rest}(t) = 0 - 30$ Pa/min (0 - 0.627 psf/min)

4.3 Prediction models for lateral pressure decay

The prediction models recommended for estimating lateral pressure decay are:

i) During the first hour from the end of casting

$$\Delta K(t)(0\text{-}60 \text{ min}) = [0.1092 + 0.000112 \times PV\tau_{0rest@15min}] \times f2_{Dmin} \tag{7}$$

ii) During the time to pressure cancelation $\tag{8}$

$$\Delta K(t)(0\text{-}t_c) = [0.1491 + 0.000000657 \times PV\tau_{0rest@15min} \times \tau_{0rest}(t)] \times f2_{Dmin}$$

<u>where</u>: $f2_{Dmin} = 1.260353 - 1.302\,D_{min}$ $\tag{9}$

$\Delta K(t)(0\text{-}60 \text{ min})$ and $\Delta K(t)(0\text{-}t_c)$ are expressed in *%/min*; $PV\tau_{0rest@15min}$ in *Pa*;

$PV\tau_{0rest@15min} \times \tau_{0rest}(t)$ in *Pa²/min*; $f2_{Dmin}$ in *dimensionless*; and D_{min} in *mm*.

4.4 Two-function model to predict formwork pressure

The 'two-function model' presented here divides the lateral pressure into an instantaneous and a delayed response that result from the application of a vertical pressure, as shown in Fig. 9. When the vertical pressure has the increment of $d\sigma_V(\tau)$ at loading time τ, the instantaneous response can be expressed by $\beta(\tau)$, and the delayed response with the duration $(t\text{-}\tau)$ is expressed by $\alpha(\tau,t)$.

Two examples of predictions resulting from the use of the two-function model are illustrated in Fig. 10: (1) the lateral pressure profile and (2) the change of lateral pressure over time are shown in Fig. 10.
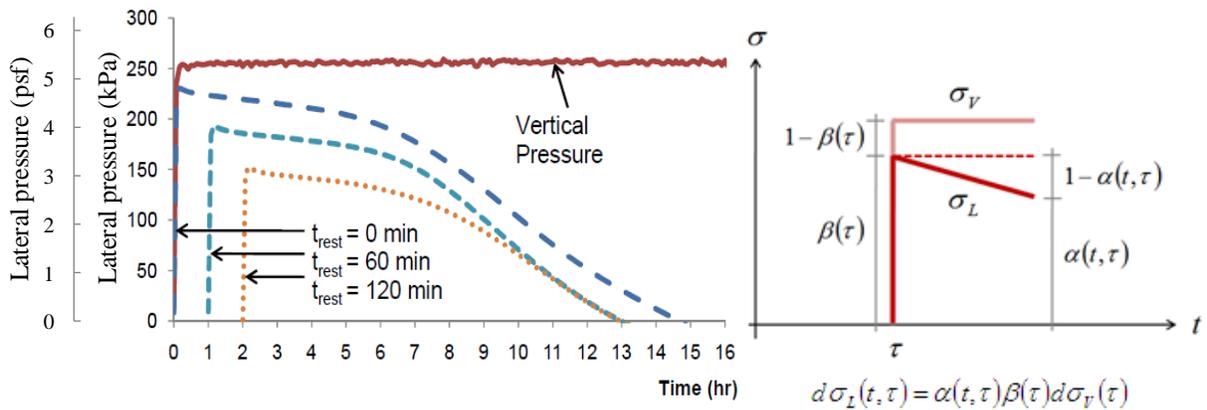

Fig. 9 - Lateral pressure variation obtained using pressure device proposed by Northwestern University
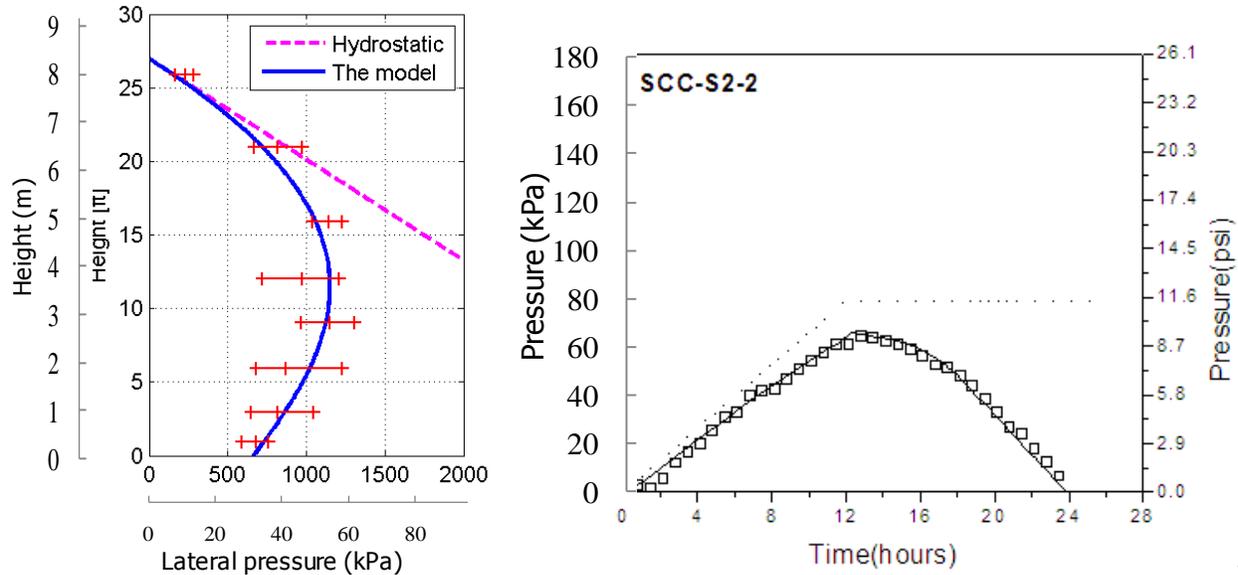
Fig. 10 - Lateral pressure profile (left) and change of lateral pressure over time (right) predicted using the two-function model

4.5 Field validation of the *UofS formwork prediction models*

Actual field measurements on large large-scale elements were measured and used to validate the *UofS models*. The lateral pressure characteristics obtained using the UofS2 pressure device and the 1.2-m (3.9-ft) high PVC column were compared to those obtained from the field measurements. Eight wall elements cast during the construction of the "Integrated Research Laboratory on Materials Valorization and Innovative and Durable Structures" at the Université de Sherbrooke in Quebec, were used in the first series of field validation. The second validation involved casting eight column elements at the Materials Laboratory of CTLGroup in Illinois. In the full-scale wall and column elements, the effect of different mix designs and casting characteristics were tested, similar to those investigated in the laboratory. This validation resulted in the following conclusions:

1. The proposed *UofS form pressure models* were successfully validated using wall and column elements. The relationship between the measured-to-predicted P_{max} values resulted in high R^2 value of 0.97.

2. The *UofS models* for lateral pressure decay during the first 60 min following the end of casting and that over the pressure cancellation period resulted in adequate estimates for the majority of the wall and column elements.

14

3. The U$_{of}$S2 pressure device resulted in similar variations of lateral pressure with casting depth to those obtained from the actual casting in wall and column elements. The U$_{of}$S2 pressure device reflected well the effect of casting rate and other mixture proportioning.

4. Pressure decay obtained from the small-scale PVC column was proven to be similar to that obtained from the wall and column castings. Therefore, the PVC column can be used to reflect the effect of mixture composition and concrete temperature on the variations in lateral pressure with time.

5. Both of the portable vane and the inclined plane test methods are shown to be successfully employed to determine the structural build-up of SCC at rest. Such index can be used to differentiate between different SCC mixture proportionings to better select mix design capable of reducing the lateral pressure exerted on formwork systems.

The validation of the *UofS models* was extended to include comparisons with published guidelines. As expected, the equations proposed in the ACI-347, German Standard DIN 18218 models [1980], and Roussel and Ovarlez [2005] showed overestimation for the K$_0$ values. The results of P$_{max}$ determined from the *UofS models* correlate well to the model proposed by Khayat and Assaad [2005A]. However, the former *model* considers wider range of casting conditions and can be applied using the PV and IP tests to estimate thixotropy.

5.   Guidelines to minimize formwork pressure of SCC

5.1   Guidelines to concrete producers for design of SCC

The following section offers some statistical design models, contour diagrams, and guidelines to help the concrete producers to better select SCC mix design that could exert less lateral pressure on the formwork.

A.   Statistical models for estimating lateral pressure characteristics and thixotropy of SCC based on key SCC mix design characteristics

Statistical models can enable the evaluation of formwork pressure and relevant rheological characteristics of SCC from its mixture composition. These models could help in better selecting the concrete constituents that exhibit high thixotropy and exert lower lateral pressure on the formwork system. Six statistical models to predict various lateral pressure characteristics and 10 other models to estimate thixotropic properties were established. The mix design parameters are slump flow, ϕ, sand-to-total aggregate ratio, S/A, and coarse aggregate volume, V$_{ca}$. The derived

models are shown to have high R^2 values varying between 0.84 and 0.99. Selections of these models are shown below.

$$K_{0@H=8\,m} (\%) = 67.2 - 4.7275\ V_{ca} + 4.0675\ \text{slump flow} + 1.96\ S/A + 1.1775\ \text{slump flow}.\ V_{ca} \quad (8)$$

$$\Delta K(t)(0\text{-}t_c)\ (\%/min) = 0.16 - 0.00625\ \text{slump flow} + 0.0044\ S/A + 0.0006\ V_{ca} \quad (9)$$

$$t_c\ (min) = 587.7 - 48.5625\ V_{ca} + 38.0625\ \text{slump flow} + 24.1875\ S/A + 9.9375\ \text{slump flow}.S/A\ (10)$$

$$PV\tau_{0\ rest@15min}\ (Pa) = 537.5 + 220.125\ V_{ca} - 155.375\ \text{slump flow} - 127.875\ S/A \quad (11)$$

where: slump flow is expressed in *mm*, V_{ca} and S/A are *ratios*.

The statistical models compare the effect of the mixture parameters and their interactions on the modeled responses; formwork pressure characteristics and thixotropic properties. The sign of the parameters (+/-) indicates the type of effect of the given parameter on the considered response. For example, the increase of slump flow and S/A (+) can lead to increase in $K_{0@H=8m}$, while the increase of V_{ca} (-) can reduce $K_{0@H=4m}$. The statistical models also offer indication of the relative significance of the various parameters and their interactions. For example, the $PV\tau_{0rest@15min}$ is affected mainly by the changes in V_{ca} followed by slump flow, then S/A.

B. Contour diagrams

Contour diagrams were established as a simple interpretation of the derived statistical models. They can be used to compare trade-off between the effects of different mixture parameters on the considered responses. The contour chart illustrated in Fig. 9 shows how the relative pressure response at 8 m in height, $K_{0@H=8\,m}$, varies with the variation of two parameters, slump flow and V_{ca}, at a time for a given value of the third parameter, S/A of 0.44. In this diagram, the increase in slump flow results in an increase in the $K_{0@H=8m}$. On the other hand, increasing the V_{ca} ratio leads to a reduction in $K_{0@H=8m}$. Other diagrams were also demonstrated for the various formwork pressure characteristics and thixotropic properties are shown in the report.
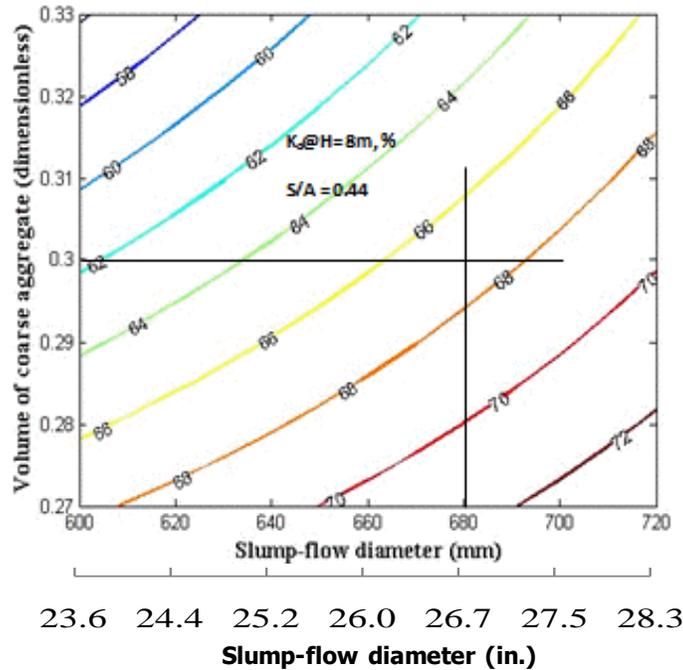
16

Fig. 9 - Trade-off of different parameters affecting $K_{0@H=8m}$

C. Concluding remarks to reduce formwork pressure and enhance thixotropy of SCC

Factors affect initial maximum pressure

1. At shallow depths, K_0 is typically close to 100%. However, beyond 3-m (9.8-ft) depth, the pressure envelop diverged from P_{hyd}. K_0 values decrease linearly with the increase in concrete depth. For example, at H of 1, 3, and 7 m, (3.3, 9.8, and 23 ft, respectively) SCC38 mixture cast at 5 m/hr (16.4 ft/hr) and 22°C (71.6°F) resulted in K_0 values of 81%, 73%, and 58%, respectively.

2. K_0 values increases with the increase in placement rate. For a very high R value of 30 m/hr, K_0 approaches 100% especially at shallow depths. A significant reduction in K_0, even at shallow castings, is obtained at slow rate; R = 2 m/hr (6.6 ft/hr).

3. The maximum formwork lateral pressure decreases with increase in the thixotropy level. The $K_{0@Hi}$ can correlate to various thixotropic indices determined using concrete rheometer or empirical tests. Abacuses were established to facilitate the estimate of K_0 vs. thixotropy for various R values.

4. The P_{max} exerted by SCC is lower than that of the hydrostatic pressure, P_{hyd}. Large deviation from P_{hyd} can be observed with the increase in thixotropy. For example, SCC30 with

$PV\tau_{0rest@15min}$ of 815 Pa (17 psf), cast at 10 m/hr (32.8 ft/hr) and 22ºC (71.6°F), can have a K_{0i} value at 12 m (39.4 ft) depth as low as 30%.

5. The increase in slump flow of SCC due to the addition of HRWRA (the same mix design) increases lateral pressure. For example, increasing the slump flow from 600 and 720 mm (23.6 and 28.3 in., respectively) resulted in $K_{0@H=8m}$ values of 71% and 77% (SCC27 and SCC32 mixtures).

6. The increase in coarse aggregate volume, V_{ca}, can decrease P_{max}.

7. For the same paste volume, increasing the sand-to-total aggregate ratio leads to a reduction in coarse aggregate content and results in higher lateral pressure.

8. Increasing the MSA reduces lateral pressure. A correction factor, f_{MSA}, as function of H is proposed to account for the effect of MSA other than 14 mm (0.55 in.) on lateral pressure of SCC. The f_{MSA} is 1.0 for relatively high thixotropy SCC, $PV\tau_{0rest@15min} > 700$ Pa (14.6 psf) or for low thixotropic SCC, $PV\tau_{0rest@15min} < 700$ Pa (14.6 psf) and proportioned with MSA of 20 mm (0.78 in.). On the other hand, for low thixotropic SCC with 10 mm (0.39 in.) MSA, the f_{MSA} is on order of [1 + (1.26H-5.04)/100].

9. The increase of concrete temperature results in lower lateral pressure. At T of 12 °C (53.6 °F), SCC38 exhibited pressure close to P_{hyd}. However, the increase in T to 22 °C (71.6 °F) and then to 30 °C (89.6 °F) displayed significant deviation from P_{hyd}. At T of 12, 22, and 30 °C (53.6, 71.6, and 89.6 °F, respectively), K_0 values, at depth of 7 m (23 ft) for SCC cast at 5 m/hr (16.4 ft/hr), are 71%, 58%, and 42%, respectively.

10. Interruption of concrete casting for a waiting period, WP, of 30 min can reduce K_0 by up to 10 %, especially for highly thixotropic SCC.

11. K_0 increases with the increase in minimum formwork dimension. A correction factor, fl_{Dmin}, for K_0 is derived to account for changes due to variations of D_{min} between 200 to 350 mm (7.9 to 13.8 in., respectively), as follows ($fl_{Dmin} = 0.000968\ D_{min} + 0.806332$).

Factors affect pressure decay

1. The lateral pressure decay is sharper initially than the average decay until pressure cancellation. For example, SCC with $PV\tau_{0rest@15min}$ of 740 Pa (15.5 psf), showed an initial decay over 60 min, $\Delta K(t)(0-60\ min)$, of 0.22 % per minute compared to 0.17 % per minute for the mean rate of pressure decay until pressure cancellation, $\Delta K(t)(0-t_c\ min)$.

2. The increase in initial slump flow of SCC due to the addition of HRWRA (the same mix design) is shown to delay pressure decay.

18

3. The lateral pressure decays at a slower rate when the coarse aggregate volume is increased or when the paste volume is reduced, as shown below.

Mixture	V_p, l/m^3 (ft^3/yd^3)	V_{ca}, l/m^3 (ft^3/yd^3)	$\Delta K(t)(0\text{-}t_c)$ (%/min)
SCC36	340 (9.18)	319 (8.61)	0.177
SCC38	370 (9.99)	305 (8.24)	0.265
SCC39	390 (10.53)	295 (7.97)	0.312

4. The pressure decay increases with the increase in concrete temperature. At T of 12, 22, and 30 °C (53.6, 71.6, and 89.6 °F, respectively), the SCC38 cast at 5 m/hr (16.4 ft/hr) had $[\Delta K(t)(0\text{-}t_c)]$ values of 0.20, 0.21, and 0.35 %/min respectively.

5. The pressure decay decreases with the increase in minimum formwork dimension. At D_{min} of 200, 250, 300, and 350 mm (7.9, 9.8, 11.8, 13.8 in., respectively), the $[\Delta K(t)(0\text{-}t_c)]$ values at H of 1.45 m (4.8 ft) for SCC38 were 0.33, 0.30, 0.27, and 0.25 respectively. Correction factor, $f2_{Dmin}$, for $\Delta K(t)(0\text{-}t_c)$ accounting for the changes in D_{min} can be calculated as: $f2_{Dmin} = 1.260353 - 0.0001302\ D_{min}$.

6. The casting rate and waiting period between two successive lifts are shown to have no influence on pressure decay.

Factors affect time of pressure cancellation

1. Increasing concrete temperature reduces pressure cancellation time. At T of 12, 22, and 30 ± 2 °C (53.6, 71.6, and 89.6 ± 3.6°F, respectively), SCC38 cast at 5 m/hr (16.4 ft/hr) and had t_c values of 470, 385, and 230 min, respectively.

2. The value of t_c increases with the increase in D_{min}. For SCC38, increasing D_{min} from 200 to 350 mm (7.9 to 13.8 in., respectively) led to an increase in t_c of about 110 min. At a given concrete depth, the t_c measured from the sensors mounted in the two lateral dimensions were found to be same.

3. The R and WP values are shown to have no influence on the duration to pressure cancellation.

Factors affect thixotropy of SCC

1. The increase in initial slump flow of SCC due to the addition of HRWRA (the same mix design) is shown to reduce thixotropy. This can be illustrated from SCC27 and SCC31 had slump flow values of 600 and 720 mm (23.6 and 28.3 in.), respectively, as shown below.

Mixture	slump flow, mm (in.)	$PV\tau_{0\ rest@15min}$, Pa (psf)
SCC27	600 (23.6)	327 (6.8)
SCC31	720 (28.3)	210 (4.4)

2. Decreasing the paste volume or increasing the coarse aggregate volume leads to an increase in thixotropy, as shown below.

Mixtures	V_p, l/m^3(ft^3/yd^3)	V_{ca}, l/m^3(ft^3/yd^3)	Ab_1, J/m^3.s (Ibf.ft/yd^3.s)
SCC36	340 (9.19)	319 (8.61)	543 (306)
SCC38	370 (9.99)	305 (8.24)	440 (248)
SCC39	390 (10.53)	295 (7.97)	230 (130)

3. Proportioning SCC with coarse aggregate of larger MSA leads to higher thixotropy.

Work carried on on cement past showed that the structural rebuilding power, defined as the area under a shear stress vs. strain rate flow curve, increases over time. Thixotropic of the paste gains resistance to an external shear loading with time. The structural rebuilding was found to be highly affected by changes in mixture proportioning as observed in concrete mixtures. The rate of structural rebuilding decreased as the alkali and C_3A contents of the cement increased. A correlation between the rate of rebuilding and ionic strength, pH, and concentrations of K, Na, S, and OH ions was established. Increasing the initial fluidity resulted in a decrease in the structural rebuilding. However, for a given fluidity level the structural rebuilding was higher if the fluidity level was obtained by increasing the dosage of HRWRA rather than increasing the water content. Different structural rebuilding was obtained based on the type of HRWRA in use, such as synthetic- and polycarboxylate-based HRWRAs. Mixtures proportioned with VMA did not show any difference in structural rebuilding compared to those made without any VMA. However, the results suggest that VMA increases yield stress of the paste by binding some of the water phase.

Replacement of portions of the cement with silica fume was shown to increase the rate of structural rebuilding. This effect was more significant than reducing the w/c. The effect of replacing part of the cement with fly ash on thixotropy was found to be dependent on the type of cement. Slight improvements in the rate of structural rebuilding were noted seen when the fly ash was used with low alkali or low C_3A cement. However, these effects are quite limited, and in general fly ash was found to reduce the structural rebuilding.

5.2 Guidelines to reduce SCC formwork pressure

A. Abacuses for lateral pressure prediction

The prediction models for the relative initial maximum lateral pressure, K_0 (%) = 100,000×P_{max}/ ρgH (with the respect of the dimensions mentioned earlier: P_{max} in kPa, ρ in kg/m^3, g in m/s^2, and H in m), exerted by SCC are used to propose simple abacuses for formwork pressure prediction, as shown in Fig. 10. In such abacuses, K_0 values at different casting depths,

H, are correlated to the various thixotropic indices determined using the PV and IP test methods as well as the concrete rheometer values. The abacuses were constructed for given values of R, T, D_{min}, WP, and MSA. The values of the fixed parameters are indicated in each figure.
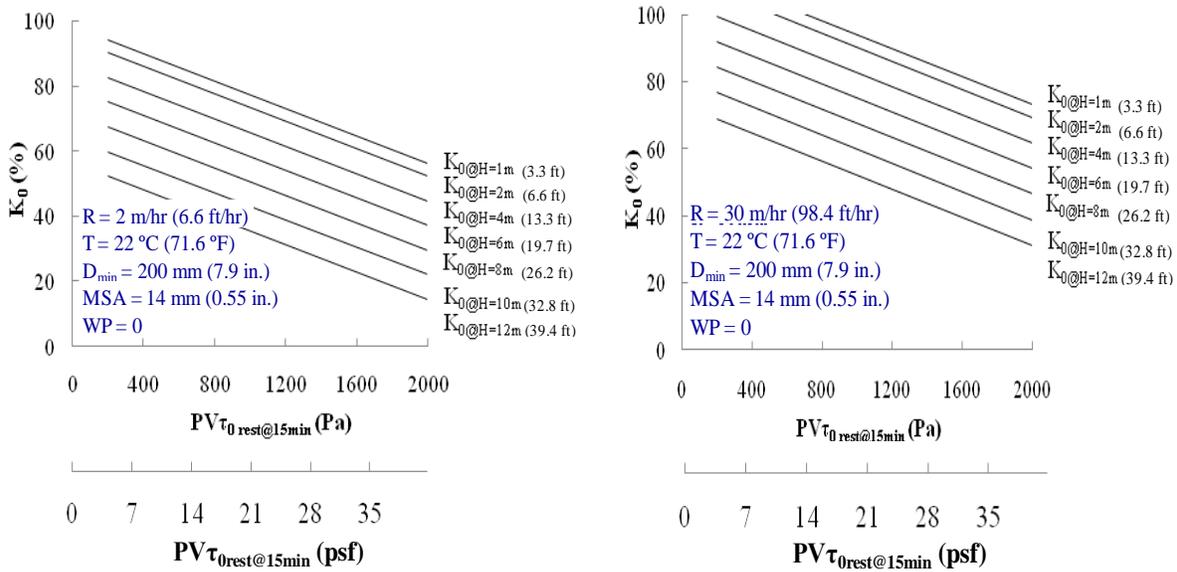

Fig. 10 - Correction between K_0 and $PV\tau_{0rest@15min}$

B. Design Tables

The rate of structural build-up at rest, placement rate, R, and casting depth, H, are found to be the most effective parameters governing the lateral pressure exerted by SCC on formwork systems. Therefore, the proposed prediction model for P_{max} (Eq. VII-91) was employed to calculate P_{max} at different thixotropy indices determined using the PV test method, $PV\tau_{0rest@15min}$, placement rates, R, and casting depths, H. Samples of P_{max} values predicted at different R and H values for a given $PV\tau_{0rest@15min}$ value of 200 Pa (4.2 psf) , are shown in Table 6. Other tables were established for different thixotropy levels. These tables were constructed for typical SCC mixtures used in cast-in-place applications that proportioned with MSA of 14 mm (0.55 in.) and has unit weight, ρ, of 2350 kg/m^3 (146.7 Ib/yd^3). The formwork minimum dimension, D_{min}, was also considered as 200 mm (7.8 in.). The concrete was assumed to be continuously cast without any waiting period, WP, at concrete temperature, T, of 22 ± 2 ºC (71.6 ± 3.6ºF).

Table 6 is divided into intervals characterized by certain colors according to P_{max} values. The pressure intervals can be suitable for formwork panels of different strength ratings. These tables can be used to design formwork after taking into consideration a certain factor of safety.

21

Table 6 - P_{max} in kPa (psf) values for formwork

$PV\tau_{0rest@15min}$ = 200 Pa (4.18 psf)								
H, m (ft)	R, m/hr (ft/hr)							
	1 (3.3)	2 (6.6)	5 (16.4)	10 (32.8)	15 (49.2)	20 (65.6)	25 (82)	30 (98.4)
0 (0)	0	0	0	0	0	0	0	0
1 (3.3)	22 (459)	22 (459)	22 (459)	23 (480)	23 (480)	24 (501)	25 (522)	26 (543)
2 (6.6)	41 (856)	42 (877)	42 (877)	44 (919)	45 (940)	47 (982)	48 (1003)	49 (1023)
3 (9.8)	59 (1232)	60 (1253)	61 (1274)	63 (1316)	65 (1358)	67 (1399)	69 (1441)	71 (1483)
4 (13.1)	76 (1587)	76 (1587)	78 (1629)	81 (1692)	83 (1733)	86 (1796)	89 (1859)	92 (1921)
5 (16.4)	90 (1880)	91 (1901)	93 (1942)	96 (2005)	100 (2089)	103 (2151)	107 (2235)	110 (2297)
6 (19.7)	103 (2151)	104 (2172)	106 (2214)	110 (2297)	114 (2381)	119 (2485)	123 (2569)	127 (2652)
7 (23)	114 (2381)	115 (2402)	118 (2464)	123 (2569)	127 (2652)	132 (2757)	137 (2861)	142 (2966)
8 (26.3)	123 (2569)	124 (2590)	128 (2673)	133 (2778)	139 (2903)	144 (3008)	150 (3133)	155 (3237)
9 (29.5)	131 (2736)	132 (2757)	136 (2840)	142 (2966)	148 (3091)	154 (3216)	161 (3363)	167 (3488)
10 (32.8)	136 (2840)	138 (2882)	142 (2966)	149 (3112)	156 (3258)	163 (3404)	170 (3551)	177 (3697)
11 (36.1)	140 (2924)	142 (2966)	147 (3070)	154 (3216)	162 (3383)	169 (3530)	177 (3697)	185 (3864)
12 (39.4)	143 (2987)	144 (3008)	151 (3154)	158 (3300)	166 (3467)	174 (3634)	183 (3822)	191 (3989)
13 (42.7)	143 (2987)	145 (3028)	154 (3216)	159 (3321)	168 (3509)	177 (3697)	186 (3885)	195 (4073)
ρ = 2350 kg/m^3(146.7 Ib/yd^3), T = 22ºC (71.6 ºF), D_{min} = 0.2 m (7.8 in.), WP = 0, MSA = 14 mm (0.55 in.).								

Color	Intervals of P_{max} values, kPa (psf)
	< 50 (1044)
	50 (1044) - 80 (1671)
	80 (1671) - 110 (2297)
	110 (2297) - 140 (2924)
	140 (2924) - 170 (3551)
	>170 (3551)