

Evaluation of SCC Formwork Pressure

By Kamal Henri Khayat, Ahmed F. Omran
Université de Sherbrooke, Sherbrooke, QC, Canada

INTRODUCTION

Self-consolidating concrete (SCC) is a new class of high-performance concrete that can flow readily under its own weight and consolidate without mechanical vibrations and with minimum risk of segregation. SCC has been successfully used in North America in the precast industry; however, the use of SCC in cast-in-place applications has been hindered by some technical issues, including formwork pressure exerted by SCC. Lack of information regarding formwork pressure variations during casting and pressure decay following placement has prompted contractors and engineers, as recommended by ACI 347 (Guide to Formwork for Concrete), to design for full hydrostatic pressure. Unfortunately, this leads to cost increase of the formwork system that compromises profitability due to rapid placements and possible labor savings associated with SCC.

This paper presents a summary of an extensive research project that aimed at developing formulation expertise and guidelines to lower lateral pressure of SCC. The project was sponsored by the RMC Research & Education Foundation and the Strategic Development Council of the American Concrete Institute. The paper highlights the development of a pressure column device that can be used to predict lateral pressure exerted by SCC as well as empirical test methods to determine the structural build up at rest of SCC, which is shown to significantly affect formwork pressure. The role of material constituents, mix design, concrete casting rate, formwork geometry and temperature on SCC form pressure are highlighted. Proposed design equations to predict formwork pressure of SCC on column and wall elements are also presented.

PORTABLE DEVICE TO MEASURE SCC FORMWORK PRESSURE

A portable pressure device, referred to as UofS2 pressure column, was developed following a former device (UofS1 pressure column) [1] that was successfully used by the researchers to evaluate lateral pressure exerted by plastic concrete. The UofS2 pressure column shown in Fig. 1 has a circular in cross-section measuring 0.2 m in internal diameter and 0.7 m in total height with a wall thickness of 10 mm. The tube is initially filled to a height of 0.5 m with SCC at the required rate from the top without any vibration. The top of the pressure column is then firmly closed, and air pressure is gradually introduced from the top to simulate pressure increase up to 13 m at a given placement rate. A pressure sensor is set flush with the fresh concrete surface at 63 mm from the base of the column to record the exerted lateral pressure during casting and to monitor the pressure decomposition during the plastic stage of the concrete. Another transducer is fixed above the concrete

surface at 625 mm from the column base to determine the net overhead pressure inside the column.

The sensor is AB-high-performance pressure transducer supplied by Honeywell and is extremely accurate down to 0.25% over a wide compensated temperature range. It works using semiconductor gages on bending beams isolated by stainless steel media and has a capacity of 1380 kPa (200 psi). The sensor is 19 mm in diameter and can operate over a temperature range varying from -54 to $+93^{\circ}\text{C}$. The sensors are connected to data acquisition system to monitor pressure variation at 90-s intervals. The sensor is excited using 5 V dc current. Numerical dial-gauge (manometer) was set on a controlling chamber attached to the UofS2 pressure column to manage the air-pressure flow on the top surface of the concrete to simulate further concrete heights.

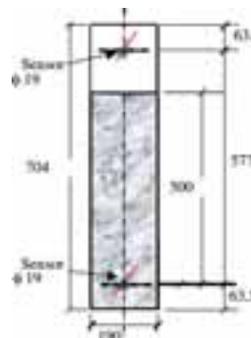


Fig. 1 - Schematic of UofS2 portable pressure column to evaluate formwork pressure



Fig. 2 - Photo of UofS2 portable pressure column to evaluate formwork pressure

The tested SCC had initial slump flow of 660 ± 15 mm, paste volume of 370 l/m^3 , w/cm of 0.42, and polycaroxylate-based high-range water-reducing agent (HRWRA) and viscosity-modifying agent (VMA) dosages of 3.6 and 2.8 l/m^3 , respectively. The casting rate was set at 10 m/hr. The column was then sealed, and air pressure was applied in steps equivalent to one-meter of concrete head at the same casting rate of 10 m/hr until a concrete head corresponding to 13 m was reached. The corresponding lateral pressure exerted on the column wall was recorded using the sensor at the base of the UofS2 pressure column. Between each consecutive increment, a decrease in lateral pressure profile was obtained reflecting the restructuring (or structural build-up at rest) of the concrete. This was more apparent at the end of casting where pressure decay is observed. The pressure device is usually demolded before concrete hardening. The maximum lateral pres-

pressure (P_{max}) recorded at each increase of simulated concrete height is plotted, indicating that the SCC developed 40% lower relative lateral pressure (K_0) than the equivalent hydrostatic pressure at concrete height of 13 m. K_0 refers to the ratio between P_{max} and equivalent hydrostatic pressure (P_{hyd}) and is plotted against concrete height.

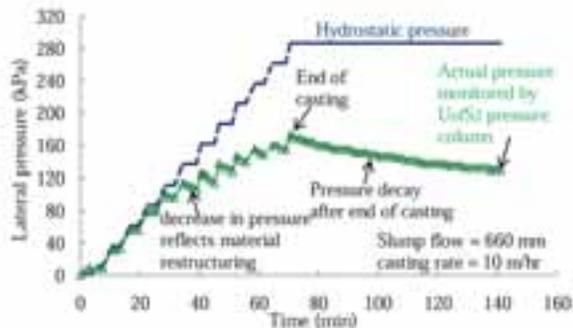


Fig. 3 - Variations of lateral pressure with time for typical SCC mixtures

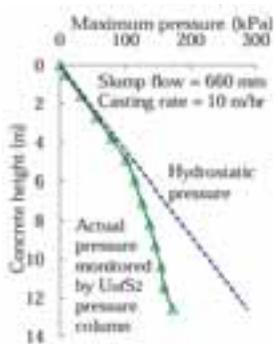


Fig. 4 - Decrease in maximum lateral pressure of SCC with height

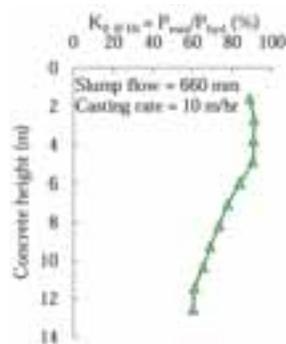


Fig. 5 - Variations of relative lateral pressure (K_0) of SCC

In order to determine the repeatability of the UofS2 pressure column, an SCC mixture was prepared and tested four times. The results of the relative errors of K_0 at various heights are given in Table 1 and indicate high precision of pressure measurements.

The lateral pressure characteristics of three different SCC mixtures determined using the UofS2 device were also compared to measurements obtained from a PVC column measuring 0.2 m in diameter and 3 m in height. Good agreement was obtained between both systems in terms of initial lateral pressure and pressure drop in time [2]. Further validation of the UofS2 pressure device clearly demonstrated that the device is capable of adequately reflecting the effect of placement rate, initial slump flow, and mix design (including paste volume, w/cm, maximum size aggregate (MSA) and VMA dosage) on lateral pressure characteristics [2].

Table 1 - Relative error in predicting relative lateral pressure value (K_0)

Concrete height, H (m)	Relative error (%)
1	± 0.7
4	± 2.4
8	± 2.3
12	± 4.0

EMPIRICAL TESTS TO EVALUATE STRUCTURAL BUILD-UP AT REST

A total of six field-oriented test methods were developed and used to evaluate the structural build up at rest of concrete-equivalent mortar (CEM) and SCC mixtures. The portable vane, inclined plane, and undisturbed spread test methods showed good repeatability and low relative error [2]. The response obtained with the portable vane and inclined plane were compared to rheological measurements obtained using a modified Tattersall-Type MK-III concrete rheometer [3] using 22 SCC mixtures prepared with various mix designs and material constituents. The comparison clearly indicates that the empirical methods can capture the structural build up of SCC at rest in terms of static yield stress and its rate of gain in time [2].

Portable vane test

The portable vane test is inspired from a field test for in-situ measurement of shear strength of soil (in particular clay soils). Four-blade vanes of different sizes (Table 2) were manufactured from stainless steel to enable the use of one torque-meter to capture shear strength of the plastic concrete after various times of rest. The largest vane is used for the weakest structure, i.e., shortest resting time, and vice versa. A torque-meter measuring with high precision was employed to capture the torque values.

Table 2 - Vane dimensions

	Time at rest (min)	Vane dimensions (mm)		
		R	H	h
Vane # 1 (largest)	15	37.5	250	Vary according to the filling height of up to total height (H)
Vane # 2	30	37.0	200	
Vane # 3	45	37.5	149	
Vane # 4 (smallest)	60	37.5	100	



Fig. 6 - Four buckets and four vanes used in the portable vane test

minimum formwork dimension. The UofS2 pressure column and the empirical test methods were employed to evaluate the lateral pressure characteristics and relate them to relevant SCC rheological properties.

Table 4 - Investigated parameters affecting SCC formwork pressure

Parameter		Range
Mix design and material constituents	Initial slump flow	Can be replaced by one of structural build-up indices determined using concrete rheometer or empirical test
	Dosage of VMA	
	Volume of coarse aggregate (Vca)	
	Paste volume (Vp)	
	Sand-to-total aggregate volume ratio (S/A)	
	Maximum size aggregate (MSA)	10, 14, and 20 mm
Concrete height (H)		1 - 13 m
Casting rate (R)		2, 5, 10, 17, 24, and 30 m/hr
Concrete temperature (T)		12, 22, and 32 ± 2°C
Waiting period between consecutive lifts (WT)		<ul style="list-style-type: none"> o Continuous o WT of 30 min at middle of casting o Two WT's of 30 min each at middle of casting
Minimum formwork dimension (Dmin)		200, 250, 300, and 350 mm

Analytical models for relative lateral pressure prediction

The results obtained from approximately 780 data points were used to establish analytical models to predict form pressure of SCC. Two analytical models enabling the predicting of relative lateral pressure (K0) are discussed. The first model was derived to predict K0 as function of concrete height (H in m), casting rate (R in m/hr), concrete temperature (T in °C), and structural build up (Eq. 4). The structural build up is expressed in terms of static yield stress at rest after 15 min of rest determined using the portable vane test (PV τ0 rest @15 min in Pa). Similar models were developed using the inclined plane test method. The influence of maximum size aggregate (MSA) is incorporated in the model (fMSA) when using MSA other than 14 mm. The effect of different waiting times between successive lifts (fWT) is also taken into consideration. PV τ0 rest @15 min measurements in Eq. 4 are measured at 22 ± 2 °C. Thus, a separate factor expressing the influence of concrete temperature is introduced.

$$K_0 = [112 - 3.8H + 0.63R - 0.6T + 0.01D_{min} - 0.021 PV \tau_{0 \text{ rest @15 min}}] \times f_{MSA} \times f_{WT} \quad (4)$$

where
 f_{MSA} is a correction factor for MSA other than 14 mm.

> For relatively low thixotropic SCC [PV τ0 rest @15 min ≤ 700 Pa] and

$$H < 4 \text{ m} \quad f_{MSA} = 1$$

$$H = 4 - 12 \text{ m} \quad f_{MSA} = 1$$

when MSA = 20 mm

$$f_{MSA} = 1 + 1.26 H - 5.04/100$$

when MSA = 10 mm

> For high thixotropic SCC [PV τ0 rest @15 min > 700 Pa], $f_{MSA} = 1$

f_{WT} is a correction factor reflecting the effect of waiting time (WT) between successive lifts and ranges between 0.85 and 1.0 for a waiting time of 30 min, depending on the thixotropy of the concrete.

A second prediction model for K0 values is shown in Eq. 5 in which the structural build up varies with the temperature of the SCC at casting. The fMSA and fWT factors are the same as those defined for Eq. 4.

A comprehensive testing program was undertaken to evaluate key mixture parameters affecting formwork pressure exerted by SCC.

$$K_0 = [98 - 3.82H + 0.63R + 0.011D_{min} - 0.021 PV \tau_{0 \text{ rest @15 min}}] \times f_{MSA} \times f_{WT} \quad (5)$$

Correlations between measured and predicted K0 values are shown in Figs. 12 and 13. Figure 14 compares the predicting of K0 from the models given in Eqs. 4 and 5. The 1:1 relationship with coefficients of correlation (R²) in Fig. 14 indicates excellent agreement between both prediction models for K0.

It is imperative noting down that the two prediction models are valid only for the ranges of tested parameters shown in Table 4 in terms of mix design, casting conditions, and formwork geometry. These limitations are as follows:

H: Concrete height (1 – 13 m)

R: Casting rate (2 – 30 m/hr)

T: Concrete temperature (12 – 32 °C)

Dmin: Minimum formwork dimension (200 – 400 mm)

PVτ0rest@15min: Static yield stress at rest from portable vane test (up to 2000 Pa)

An example of abacuses resulting from Eq. 4 or 5 is shown in Fig. 15 where K0 at a given concrete height can be estimated given the structural build up index obtained

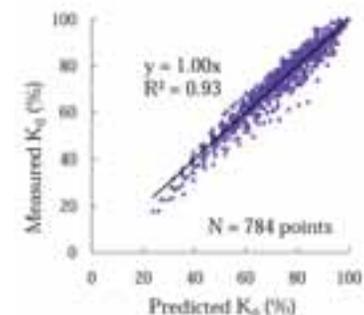


Fig. 12 - Measured to predicted K0 from analytical model Eq. 4

Back to School with NRMCA



Register now for these important classes. Be part of the NRMCA education experience, where knowledge is shared, networking is everywhere and you remain agile by building diverse professional skills for greater job security to support a rewarding career.

Class Schedule August – December 2009

August 11-14, Charlotte, NC

NRMCA Plant Manager Certification Course

Technical, operational, safety, environmental, business and HR practices that plant operators and managers need to master.

September 15, Phoenix, AZ

NEW – Handling Concrete Specifications, Low Strength Problems and Mixture Submittals

Dealing with Concrete Specifications, Low Strength Problems and Mixture Submittals can be expensive and time consuming. This one-day course will get into potential conflicts in concrete specifications and ways to address them before the project starts. The course will also suggest ways to effectively troubleshoot low strength problems and conduct mixture submittals.

September 15-17, Silver Spring, MD

NEW – The Effective RMC Supervisor Hands-on people management processes and communication skills for driver supervisors, operations, fleet, QC supervisors to increase daily operations productivity, efficiency and reduce front line employee liabilities and claims.

September 22-25, Silver Spring, MD

NRMCA CCSP Module I - "Concrete 101" - Technical/Product Knowledge Overview of technical concepts and operations for industry sales and non-QC staff.

September 28-30, Silver Spring, MD

NEW – NRMCA Concrete Durability Course: Concrete Technologist Level IV Certification Covers the fundamental factors impacting concrete's durability, symptoms, tests, code and specification criteria. Taught by subject matter consultant experts.

September 30-October 1, Silver Spring, MD

Sales Manager Workshop Certification Extensive industry-specific territory management and supervision skills. Classroom plus 5 follow-up, extensive internet training and support sessions.

November 2-6, Silver Spring, MD

Concrete Technologist Training & Certification (Short Course)

Intense workshop on materials, standards, codes, specifications, mix design calculations for industry technical service reps, QC personnel, and materials suppliers.

November 10-12, Silver Spring, MD

Dispatcher Training Forum Technical, operational, and customer service applied skills and best practices specifically for RM schedulers, shippers, dispatchers, and dispatch managers.

November 17-19, Silver Spring, MD

NRMCA CCSP Module II "Understanding the Concrete Contractor's Business" - Customer Business Knowledge Overview of contractor's business to help sales reps, sales managers, and area managers produce better bids.

December 2-4, Silver Spring, MD

Environmental Certification for the Ready Mixed Concrete Industry Tools and best practices for concrete plant managers, environmental managers, compliance managers or anyone with fiscal and/or environmental responsibilities who must implement to meet EPA, Clean Water Act and Resource Conservation and Recovery Act compliance and regulations.

December 8-11, Silver Spring, MD

NRMCA Plant Manager Certification Course

Technical, operational, safety, environmental, business and HR practices that plant operators and managers need to master.

NRMCA offers a wide variety of education and training programs for concrete industry professionals. Detailed content information, printable registration forms, and online registration are available at www.nrmca.org. The seminars and workshops listed qualify for credit toward NRMCA's new Certified Concrete Professional (CCPf) STEPS® program.



CERTIFIED CONCRETE PROFESSIONAL

The highest professional designation in the industry. This seminar is part of NRMCA's Seminars, Training and Education Programs, STEPS®, and earns you credit towards becoming a CCPf.



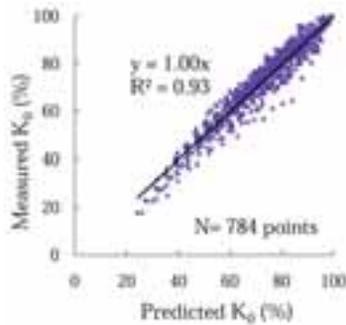


Fig. 13 - Measured to predicted K_0 from analytical model Eq. 5

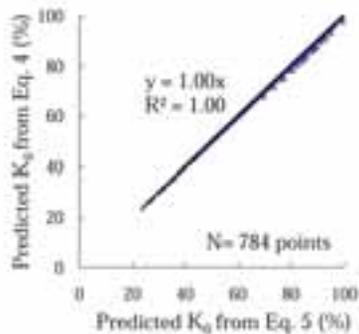


Fig. 14 - Predicted K_0 from Eqs. 4 versus 5

after 15 min of rest using the portable vane device. This relationship was constructed for a constant casting rate of 10 m/hr, concrete temperature of 22 °C, a minimum formwork dimension of 200 mm, and no waiting time between successive lifts.

CONCLUSIONS

A portable device (UofS2 pressure column) is developed to monitor lateral pressure exerted by SCC. The pressure column is filled with 0.5 m of concrete subjected to overhead air pressure to simulate free concrete head of up to 13 m in height. Empirical field test methods (portable vane, inclined plane, and undisturbed spread) are proposed to evaluate the structural build up of SCC at rest. The initial static yield stress after a rest period of 15 min, rate of change in static yield stress with rest time, and the couple effect of these parameters can be considered to describe the degree of structural build-up of the concrete. These indices are shown to correlate well to the lateral formwork pressure determined from the UofS2 device when using SCC. The analytical models (Eqs. 4 and 5) expressing the major influencing parameters on formwork pressure are established to predict formwork pressure exerted by SCC. ■

References

1. Khayat, K.H., and Asaad, J., "Measurement Systems for Determining Formwork Pressure of Highly Flowable Concrete," *Materials and Structures*, 41, 2008, pp. 37-46.
2. Khayat, K.H., Omran, A., Neji, S., Billberg, P., and Yabia, A., "Test Methods to Evaluate Form Pressure of SCC," *Proceedings of the international conference of ACBM on SCC (SCC 2008)*, Chicago, USA, Nov. 2008.
3. Yabia, A., Khayat, K.H., "Modification of the Concrete Rheometer to Determine Rheological Parameters of SCC – Vane Device," *Proc. 2nd Int. RILEM Symp. on Advances in Concrete through Science and Engineering*, Sept. 2006, pp. 375-380.
4. Coussot, P., Boyer, S., "Determination of Yield Stress Fluid Behaviour from Inclined Plane Test," *Rheol Acta*, 34, 1995, pp. 534-543.
5. NCSS: statistical & power analysis software, <http://www.ncss.com/>.

beck
concrete mixers

**A family company committed to
Innovative toughness and reliability**

- New Mixers
- Replacement Parts
- Replacement Drums
- Mixer Refurbishment
- Batch Plants

beck industrial
concrete mixers

www.beckindustrial.com **toll free: 877-777-BECK**