Pressure of Self-Consolidating Concrete on Formwork

A new model for lateral pressure determination

by N.J. Gardner

The increasing use of self-consolidating concrete (SCC), a mixture that can flow into every corner of reinforcement congested formwork without vibration, is a concern for formwork designers and suppliers because they need to be able to predict lateral pressures. Published research on formwork pressures is inconsistent. While some researchers conclude that forms should be designed for full hydrostatic pressure, others suggest that the pressure exerted against the formwork could be less than hydrostatic, even for high rates of placement.

The lateral pressures generated during the placing and consolidation of conventional concrete are dominated by vibration, whereas for SCC, consolidation is by self-weight. The formulas developed to calculate the lateral pressure of internally vibrated concrete are not applicable for SCC and the use of SCC necessitates development of new lateral pressure equations.

Because of the interest in the magnitude of the form pressures exerted by SCC, and to reconcile the differences among recently developed measurement approaches, Peter Billberg, Chair of RILEM Technical Committee TC 233-FPC, organized a field test program of SCC form pressure determination in Stockholm, Sweden, during which the various prediction methods could be compared.[1] I was one of many researchers that participated in the program.

This article describes the rheological (flow) behavior of SCC, identifies the differences in the various form pressure models, and presents recommendations for determination of the lateral pressure of formwork exerted by SCC. Data from the Stockholm study and others are used to check the recommendations.

Research Significance

Designing and fabricating formwork to cast vertical elements are significant parts of the construction process of reinforced concrete structures. Because formwork reliability can have financial and safety implications, the increasing use of SCC necessitates development of new lateral pressure equations.

A number of models for predicting SCC-induced pressures have been developed, and all require some measure of the structural buildup (stiffening behavior over time) for the specific SCC mixture. Unfortunately, while lateral pressure measurements for SCC mixtures have been reported in the literature, the reports do not include sufficient characterization of the concrete to enable verification of many of those models.

Mechanical Properties of Fresh Concrete

Rheology is the study of flow and deformation of fluids and semi-solid materials, based on the response of the materials when subjected to shear strain. While being placed, under a high shear rate, the SCC flows; after placing, without further agitation, concrete begins to gain shear strength. This increase in shear strength with time is due to the development of the easily destroyed, at-rest (thixotropic) structure of SCC. For formwork pressure, the at-rest concrete properties are of interest.

Fresh SCC requires the applied shear stress to exceed a limiting value before flow occurs. With increasing strain rate, the material's resistance to shear stress increases linearly, behaving as a Bingham fluid (Fig. 1).

Evaluation of flow characteristics

The flow characteristics illustrated in Fig. 1 are measured by devices called rheometers. Rheometers designed for concrete use rotational motion imposed on a concrete sample using a revolving cylinder, a revolving plate or disk, or an axial or planetary motion impeller.

While the torque and rotational speed can be measured by all the devices, the stress in the material is a calculated quantity and the evaluation of stress requires assumptions regarding the area of the material affected by the cylinder, disk, or impeller.

Figure 2 shows a commercially available rheometer. Concrete is placed in the container, the vane is rotated at a chosen speed (angular velocity), and the applied torque is measured. The velocity is increased in steps to a predetermined, but arbitrary, maximum and then reduced in steps to zero. The torque measured at each step is recorded.

The results obtained for a trial mixture are shown in Fig. 3(a) and (b).[2] Figure 3(a) illustrates the torque required to maintain flow at various speeds, measured at various times after completion of mixing. The upper curve for each measurement time is obtained as the angular velocity of the impeller is incrementally increased, and the lower curve for each measurement time is obtained as the velocity is incrementally decreased. The decreasing (lower) velocity curves can be approximated by a straight line and the two Bingham constants of slope and "y (lower) intercept" can be calculated.

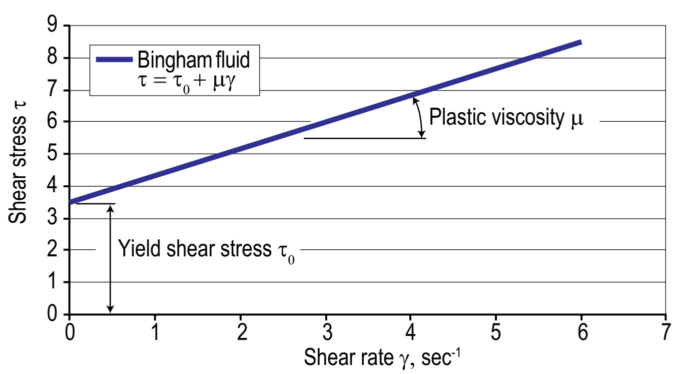

Fig. 1: A Bingham fluid is capable of resisting a statically applied shear strain up to a limiting (yield) stress. With increasing strain rate, the material's resistance to shear stress increases in proportion to its plastic viscosity

Fig. 2: Typical, commercially available portable rheometer

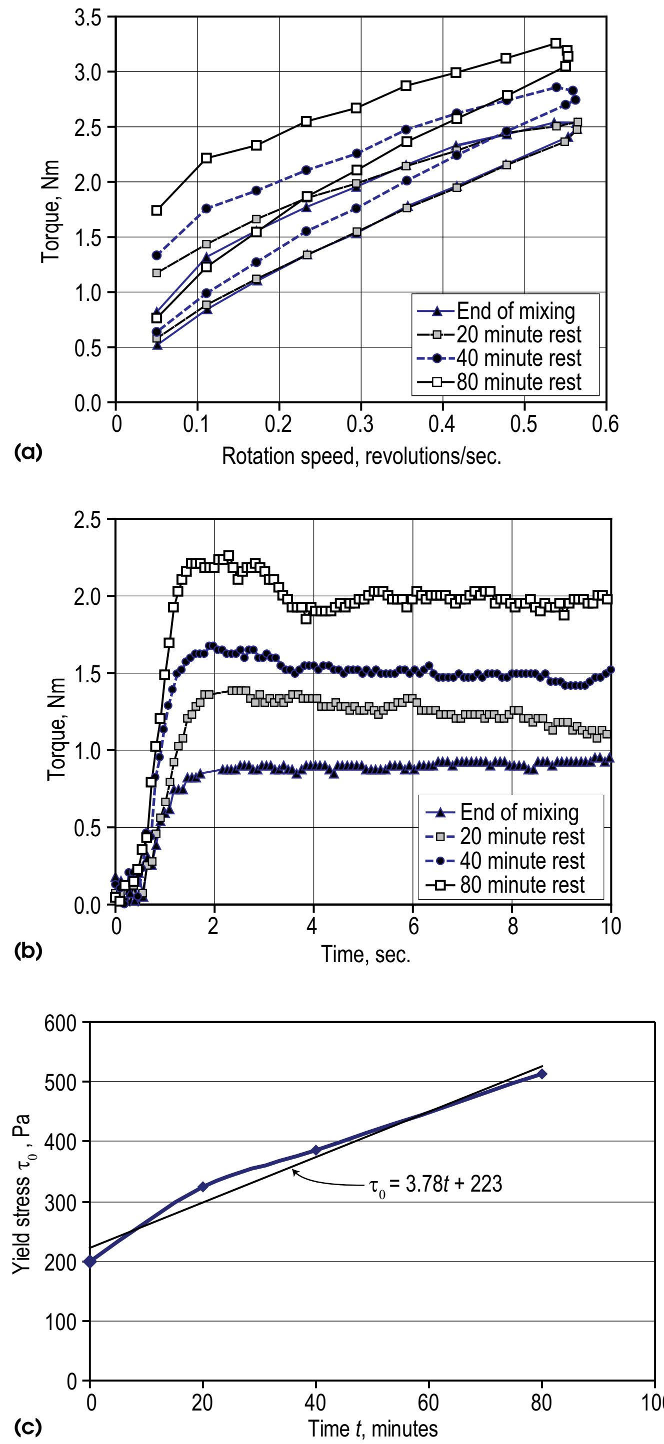

Fig. 3: Results that can be obtained using a typical rotary rheometer with non-agitated samples[2]: (a) flow curves; (b) stress growth; and (c) development of increasing yield strength with resting time

The static yield stress is the stress needed to initiate flow in an at-rest material. Static yield stress can be measured directly in a rheometer with a stress growth test capability, during which a very low shear strain rate is applied to the concrete and the stress (strength) required to initiate flow is monitored (Fig. 3(b)). The state (condition) of the concrete before the start of the test has a significant impact on the measured values, which may account for differences in reported data obtained by different rheometers. Figure 3(c) shows the development of yield strength with time corresponding to results in Fig. 3(b). The slope of the straight line is termed the structuration/thixotropy coefficient.

Because an SCC mixture's static yield stress (rather than its dynamic characteristics) is important for predicting formwork pressure, alternatives to using rheometers (References 3 and 4) have been proposed to measure the structural buildup (increase in static yield stress with time) of fresh SCC.

Calculation of Lateral Pressures

DIN 18218:2010-01

DIN 18218:2010-01[5] is the only code that has provisions to calculate the lateral pressures of SCC on vertical formwork. The early-age structural buildup of concrete is measured by the setting time, t_E, of the concrete determined using the flow table test according to DIN EN 12350-5.[6] An alternative measurement procedure for determining the setting time is the DIN 18218:2010-01 knead-bag test, which defines the setting time of the concrete, $t_{E,KB}$, as the age when penetration under an applied thumb force of 10 lbf (50 N) into a concrete specimen in a sealed plastic bag decreases to 0.04 in. (1 mm) or less. The value of t_E used to calculate lateral pressures is conservatively set at $1.25t_{E,KB}$. The formwork company MEVA[7] has recently marketed an electronic device to measure the setting time of fresh concrete, which would replace both the flow table test and the knead-bag test.

The design equations are based on work by Graubner et al.[8] using simulation tests on concrete block specimens 10 x 10 x 10 in. (250 x 250 x 250 mm), theoretical studies, and large-scale tests conducted in conjunction with a number of independent research facilities.

For SCC slump flow greater than 25 in. (630 mm), DIN 18212:2010-01[5] indicates that the limiting lateral pressure envelopes can be calculated from Eq. (1)

$$p_{\max} = (3.28 + 0.26Rt_E)w_c \geq 630 \leq p_{hydrostatic} \text{ (in.-lb units)}$$

or (1)

$$p_{\max} = (1.0 + 0.26Rt_E)w_c \geq 30 \leq p_{hydrostatic} \text{ (SI units)}$$

where R is the rate of placement in ft/h (or m/h); t_E is the setting time in hours; $p_{\max}$ is the limiting lateral pressure in lbf/ft² (or kPa); and w_c is the unit weight of concrete, lbf/ft³ (or kN/m³).

Lateral Pressure Prediction Models

A number of prediction models have been developed to characterize formwork pressures induced by SCC. The phenomenological models of Vanhove et al.[9]; Ovarlez and Roussel[10]; Proske and Graubner[11]; Perrot et al.[3]; and Beitzel[12] are based on Janssen's Silo Theory.[13] The lateral pressure model of Khayat and Omran[4] is a regression curve fitting based on extensive laboratory characterization of the material behavior and simulated lateral pressures. Lange et al.[14] characterized the concrete behavior at rest by the pressure decay after casting in a transducer-instrumented control column. The Gardner et al.[15] model used results obtained from field measurements and the projected time t_0, in hours, for the slump flow of the SCC mixture to reach zero. A short description of these models is given in Billberg et al.[1]

Proposed Model

The results of the TC 233-FPC test program in Stockholm[1] showed that the DIN 18212 equation provides reasonable predictions of formwork pressure and is based on a straightforward measurement. It's also evident that slump flow will approach zero when the concrete reaches initial set. Based on these observations, the equations developed by Gardner et al. [15] can be modified by using the setting time t_E

$$p = w_c R\left(t - \frac{t^2}{t_E}\right) \quad (2)$$

Equation (2) is valid in cases where the time is less than half t_E ($t < t_E/2$). For t greater than $t_E/2$, the pressure is assumed to remain constant at

$$p_{max} = w_c R t_E/4 \quad (3)$$

It can be noted that Eq. (3) is very similar to Eq. (1) in DIN 18218:2010-01.[5] If the time, $t_H = H/R$, required to fill a form to height H is less than $t_E/2$ a limiting later pressure will not be achieved. Substituting t_H for t in Eq. (2), the lateral pressure p_H at head H, (kPa), is given by

$$p_H = w_c R\left(t_H - \frac{t_H^2}{t_E}\right) = wH\left(1 - \frac{t_H}{t_E}\right) \quad (4)$$

Comparison with experimental data

Table 1 presents a reduced set of the data from the 2012 Stockholm field test program[1] with the results calculated using Eq. (4). Figure 4 shows the comparison of the pressures calculated using Eq. (4) with the maximum measured pressures given in Table 1. Due to the modest height of the walls and the relatively high rates of concrete placement, none of the test placements reached a limiting pressure. All of the predictive models[3,4,9-12,14] calculated near hydrostatic pressure. There is little agreement between the values obtained from the various proposals to measure the structuration/ thixotropy coefficient.

Few experimental results can be found for forms more than 13 ft (4 m) tall.[9,16-18] Limiting pressures were reported only in References 17 and 18, and initial setting time was reported only in Reference 16 (5.9 hours).

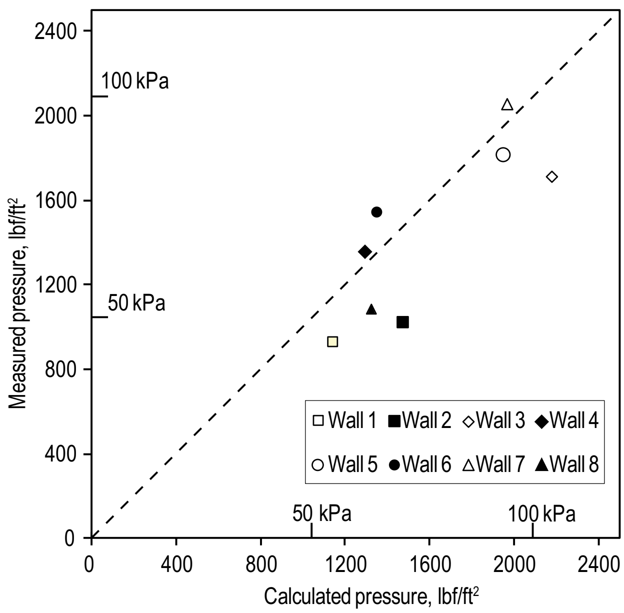

Fig. 4: Comparison of the maximum pressures measured in TC 233-FPC test program in Stockholm with maximum pressures predicted by Eq. (4)

However, Fig. A6 in Reference 17 shows a test specimen that had been removed from its form 4 hours after placement—this indicates that it would be reasonable and conservative to assign a setting time of 5 hours to the evaluated SCC. Reference 18 provides pressure decay curves that indicate that a setting time of 6 hours can be assigned to the subject SCC.

Figure 5 shows the comparison between the Table 2 reported pressures and those calculated using Eq. (4) and Eq. (1). As evident from the equations, the DIN 18218

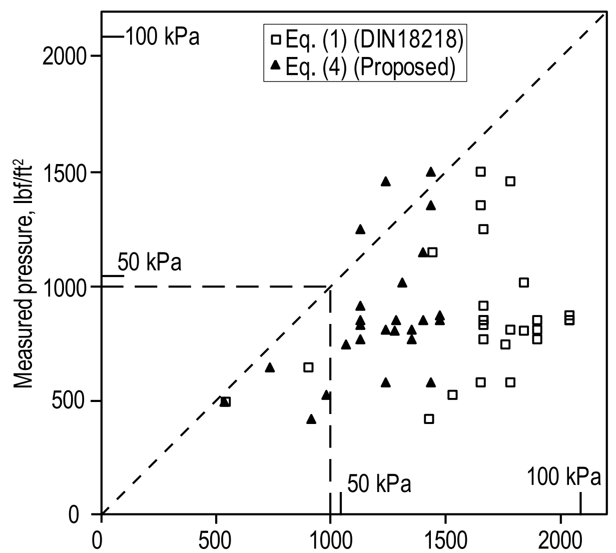

Fig. 5: Comparison of values calculated using Eq. (1) and Eq. (4) with pressures measured on tall forms

Table 1:
Stockholm round-robin SCC results (*courtesy of Peter Billberg*)

Wall	Head above gauge *H*, ft (m)	Wall thickness, in. (mm)	Concrete unit weight w_c, lbf/ft³ (kN/m³)	DIN* t_E, hours	Casting rate *R*, ft/h (m/h)	Measured pressure, lbf/ft² (kPa)	% Hydro-static	Eq. (4) calculated pressure p_H, lbf/ft² (kPa)
1	10.7 (3.26)	8.0 (203)	140.0 (2238)	3.8	11.9 (3.63)	932 (45)	62	1141 (55)
2	11.8 (3.61)	8.0 (201)	142.5 (2264)	5.8	16.9 (5.13)	1024 (49)	61	1470 (71)
3	20.0 (6.01)	8.0 (198)	143.3 (2261)	5.3	16.6 (5.06)	1712 (82)	59	2180 (104)
4	12.0 (3.66)	8.0 (203)	146.0 (2334)	5.2	8.9 (2.71)	1357 (65)	78	1290 (62)
5	16.4 (5.02)	8.0 (200)	140.0 (2238)	5.1	21.1 (6.44)	1817 (87)	79	1950 (93)
6	12.2 (3.71)	8.0 (202)	141.0 (2261)	5.3	10.7 (3.27)	1546 (74)	90	1350 (65)
7	16.4 (5.02)	8.0 (203)	146.0 (2343)	5.4	16.7 (5.09)	2056 (98)	86	1970 (94)
8	12.0 (3.65)	16.0 (400)	144.0 (2311)	4.9	10.5 (3.19)	1086 (52)	63	1320 (63)

*DIN setting times t_E courtesy of T. Proske

Table 2:
Tall form SCC lateral pressure results[16-18]

SCC placement	Rate of placement *R*, ft/h (m/h)	Head above gauge *H*, ft (m)	Measured pressure, lbf/ft² (kPa)	% Hydrostatic	Eq. (4) calculated pressure, lbf/ft² (kPa)	DIN 18212: 2010-01, lbf/ft² (kPa)	Setting time
2005 TRB Wall 1	5.5 (1.7)	22 (6.7)	720 (36)	22	1070 (51)	1760 (84)	Reference 16 Initial setting time of 5.9 hours given in report
		6 (1.83)	650 (31)	72	730 (35)	900 (43)	
Column	60 (18.3)	9.6 (2.9)	1152 (55)	80	1400 (67)	1440 (69)	
		3.6 (1.1)	500 (24)	90	530 (26)	540 (26)	
Wall 2	4.5 (1.4)	11.7 (3.7)	530 (25)	30	980 (47)	1530 (73)	
		9.5 (2.9)	425 (20)	30	910 (44)	1425 (68)	
Wall 3	6.3 (1.9)	20.2 (6.2)	1020 (49)	36	1310 (63)	1840 (88)	
		15.2 (4.6)	810 (39)	38	1280 (61)	1840 (88)	
2007-11-28 OFC Healthcare Peoria, IL	7.2 (2.2)	39 (11.8)	820 (39)	15	1350 (65)	1900 (91)	Reference 17 Estimated t_E of 5 hours
		32 (9.80)	780 (37)	26	1350 (65)		
		14 (4.3)	860 (41)	40	1280 (61)		
2008-01-04 OFS SFMC FDN 8/9	6.3 (1.9)	15 (4.60)	1510 (72)	95	1430 (69)	1650 (79)	Reference 18 Estimated t_E of 6 hours based on pressure decay curves
		15 (4.60)	1350 (65)	85			
		15 (4.60)	580 (28)	36			
2008-01-17 FDN 11	6.6 (2.01)	43.3 (13.2)	880 (42)	14	1470 (71)	2040 (98)	
		29.3 (8.94)	850 (41)	20	1470 (71)		
		15.3 (4.67)	850 (41)	38	1400 (67)		
2008-02-14 FDN 12	5.5 (1.68)	40.5 12.4)	1460 (70)	25	1240 (59)	1780 (85)	
		35.5(10.8)	810 (39)	16			
		22.5 (6.86)	590 (28)	18			
2008-02-22 FDN 19	5.0 (1.53)	19.3 (5.90)	860 (41)	31	1130 (54)	1660 (80)	
		19.3 (5.90)	770 (37)	27			
		19.3 (5.90)	840 (40)	30			
2008-02-28 FDN 13	5.0 (1.53)	42.2 (12.9)	1250 (60)	20	1130 (54)	1660 (80)	
		42.2 (12.9)	920 (44)	15			
		37.2 (11.9)	860 (41)	16			

values (Eq. (1)) are more conservative than those obtained using Eq. (4).

Table 3 gives the maximum pressures calculated using Eq. (4) for t_E of 7 hours. The values in this table approach hydrostatic pressures at high placement rates, perhaps showing why some researchers reported hydrostatic pressures while others did not. It should be noted that a standard modular form designed for 2000 lbf/ft² (100 kPa) can be used for all walls placed at 7 ft/h (2 m/h) and walls up to 20 ft (6 m) high placed at 10 ft/h (3 m/h).

Table 3:
Maximum pressures calculated using Eq. (4) for $t_0 = t_E = 7$ hours

Placement height *H*, ft (m)	Maximum lateral pressure, lbf/ft² (kPa)				
	Rate of placement *R*, ft/h (m/h)				
	7 (2)	10 (3)	15 (4.5)	23 (7)	33 (10)
13 (4)	1360 (65)	1550 (74)	1670 (80)	1775 (85)	1800 (86)
20 (6)	1650 (79)	2050 (98)	2290 (110)	2530 (121)	2630 (126)
29 (9)	1670 (80)	2450 (118)	3070 (147)	3530 (169)	3760 (180)
44 (13.5)	1670 (80)	2530 (121)	3700 (177)	4680 (224)	5260 (252)

Recommendations

While distortion of formwork is inconvenient, the consequences of a structural failure of a form (blowout) are dangerous for tall or elevated constructions. However, prediction of formwork pressures generated by SCC is difficult on multiple levels. First, determining the structuration/thixotropy coefficient for a mixture requires equipment and expertise that are not widely available. Second, the variability of concrete means that the results obtained in a series of tests in the laboratory may not be representative of the concrete produced in the field. Third, ensuring that production batches made on different days are consistent with qualification mixtures will compound the difficulties. Fourth, controlling the rate of placement R is difficult. Finally, even after an SCC mixture has built up a structure, an unintended shock can destroy that structure and increase the form pressure.

Provided a reasonable estimate of t_E can be determined for a specified mixture, the proposed method is easy to use and is conservative. It's even possible to estimate the setting time. DIN 18218[5] suggests that t_E would be 5 to 7 hours for a rapidly stiffening mixture and 7 to 10 hours for a typical mixture. DIN 18218 cautions, however, that a reliable estimate of t_E cannot be made for lower concrete temperatures or when retarding admixtures are used. It also notes that high-range water-reducing admixtures can retard mixtures.

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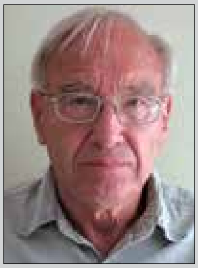

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