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Effect of *w/cm* and High-Range Water-Reducing Admixture on Formwork Pressure and Thixotropy of Self-Consolidating Concrete

by Kamal H. Khayat and Joseph J. Assaad

*An experimental program was undertaken to evaluate the effect of water-cementitious material ratio (*w/cm*) and type of high-range water-reducing admixture (HRWRA) on the development of formwork pressure that can be exerted when using self-consolidating concrete (SCC). Pressure variation was monitored using an experimental column measuring 2800 mm in height. The tested mixtures were proportioned with a similar initial slump flow consistency of 650 ± 15 mm. Three *w/cm* of 0.36, 0.40, and 0.46 and three types of HRWRA (polycarboxylate, polynaphthalene sulphonate, and polymelamine sulphonate) were investigated. Variations in lateral pressure were related to the thixotropy of the concrete.*

*Test results show that the variations in lateral pressure and thixotropy of SCC are significantly affected by the *w/cm*. Irrespective of the HRWRA type, mixtures proportioned with 0.46 *w/cm* exhibited greater initial pressure and lower thixotropy compared with mixtures made with a *w/cm* of 0.40 and 0.36. This is related to the higher water content and lower coarse aggregate volume in concrete proportioned with the higher *w/cm*, which can lead to a reduction in shear strength properties of the plastic concrete. The rate of pressure drop and increase in thixotropy with time, however, were greater in mixtures made with a higher *w/cm*. This is attributed to the lower HRWRA demand that can lead to sharper fluidity loss with time.*

*For any given *w/cm*, the type of HRWRA appears to have a limited effect on initial lateral pressure. Compared with naphthalene- and melamine-based HRWRA, the use of polycarboxylate-based HRWRA in SCC resulted in lower rate of pressure drop with time. This is reflected by the greater fluidity retention of the mixtures containing the polycarboxylate-based HRWRA. The incorporation of a water-reducing agent in mixtures made with polynaphthalene sulphonate-based HRWRA is shown to increase lateral pressure development of the plastic concrete over time.*

Keywords: admixtures; self-consolidating concrete; thixotropy; water-to-cementitious material ratio.

INTRODUCTION

The design of vertical formwork systems is governed by the lateral pressure that can be developed by the plastic concrete. Savings in the cost of formwork stemming from the reduction in lateral pressure exerted by the concrete can be of special interest.

Numerous laboratory and field studies have been carried out to determine the major parameters affecting lateral pressure of fresh concrete with normal consistency.[1-3] In general, formwork pressure is affected by the shear strength properties of plastic concrete which include: 1) frictional resistance and interlocking between solid particles, and 2) bond development between these particles following cement hydration.[4] The former component of shear strength is referred to as internal friction; it requires some deformation for such friction development to be mobilized. The latter component is termed "cohesion," which results from cement hydration (chemical effect). Cohesion therefore depends on the elapsed time after the initial contact of cement with water. Cohesion is affected by the incorporation of chemical admixtures (physical effect) such as the viscosity-enhancing admixture (VEA) and high-range water-reducing admixture (HRWRA).[5] Generally speaking, the use of polysaccharide-based VEA can lead to the formation of a gel structure and inter-particle links among adjacent polymer molecules that can increase the cohesiveness of the plastic mixture. On the other hand, the incorporation of HRWRA tends to decrease cohesion given the better degree of dispersion of flocculated cement particles.[5]

Given the high fluidity of self-consolidating concrete (SCC), such concrete can result in hydrostatic pressure on the formwork, especially when the casting rate is high. In recent studies, the authors[6-8] evaluated the effect of the rate of increase in shear strength characteristics on lateral pressure variations of SCC by assessing the degree of thixotropy of concrete. Thixotropy is defined as a decrease in viscosity with time when the material is subjected to a constant shearing stress, and can be used to quantify the degree of restructuring of the concrete.[9] At rest, the cement paste undergoes some restructuring due to the internal friction and attractive forces among solid particles as well as the development of physical and chemical bonds among the various phases during cement hydration.

The authors[6-8] evaluated the effect of mixture parameters on the thixotropy and variations of formwork pressure of SCC. The investigated SCC mixtures had a slump flow consistency of 650 ± 15 mm and were prepared with different coarse aggregate volumes, admixture combinations, binder type, and content. Experimental columns measuring 2100 or 2800 mm in height were used to monitor lateral pressure variations during the plastic stage of cement hydration. The authors reported that initial pressure measured right after the end of casting can decrease for SCC made with relatively high volumes of coarse aggregate and/or relatively low binder content; low binder content corresponds to low paste volume because the water-to-cementitious material ratio (*w/cm*) values were held constant.[6,7] This can be related to the increase in degree of internal friction resulting from the increase in coarse aggregate volume, thus leading to lower

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lateral pressure. The results also showed that SCC can exhibit a greater degree of thixotropy arising from the incorporation of a set-accelerating admixture and/or higher binder content, which promote a faster development of cohesion, thus leading to a sharper rate of lateral pressure drop with time.[7,8] The use of CSA Type GU (Type 10) cement resulted in higher initial pressure and a lower rate of pressure drop with time compared to mixtures made with blended cements containing various replacement values of cement by supplementary cementitious materials.[7]

Limited information exists regarding the effect of *w/cm* and HRWRA type on lateral pressure developed by SCC. Roby[10] evaluated the formwork pressure of concrete made with a high *w/cm* of 0.86 to 0.91. The slump consistency varied from 80 to 180 mm, and the cement:sand:coarse aggregate ratio was set at 1:2:3.5. Roby[10] reported that concrete made with greater water content can develop 20 to 25% greater initial lateral pressure than that of dry concrete. This is attributed to the increased lubrication of the cement paste that decreases the degree of internal friction among aggregate particles. On the other hand, Gardner[3] found that adding HRWRA to enhance fluidity leads to higher formwork pressure. Mixtures incorporating HRWRA to reduce the *w/cm* for a given slump consistency, however, can develop similar pressure compared with concrete made without any HRWRA of similar slump consistency.[3]

The main objective of the study reported herein is to evaluate the influence of *w/cm* and HRWRA type on lateral pressure exerted by SCC during the plastic stage of cement hydration. Eleven SCC mixtures made with *w/cm* varying from 0.36 to 0.46 were evaluated. The concrete incorporated polycarboxylate acid-based (PC), polynaphthalene sulphonate (PNS), and polymelamine sulphonate (PMS) HRWRA. The effect of a water-reducing agent was also tested for mixtures with PNS. Rheological measurements were carried out to assess the degree of thixotropy and its influence on lateral pressure development.

RESEARCH SIGNIFICANCE

Appropriate determination of lateral pressure exerted by freshly cast concrete is essential to ensure safe and economic formwork systems. With the growing use of SCC, it is important to develop an understanding of key factors affecting formwork pressure and its variation with time. This paper aims to assess the effect of *w/cm* and HRWRA type on the variations in lateral pressure of SCC. The results can be of special interest to concrete technologists and contractors using highly flowable concrete.

EXPERIMENTAL PROGRAM

Materials

Commercially available blended cement containing approximately 6% silica fume, 22% Class F fly ash, and 72% Type 10 (GU) portland cement was used. The cement has 60% C_3S, 6.4% C_3A, and 0.74% Na_2O equivalent. The Blaine specific surface of the cement and fly ash are 325 and 410 m^2/kg, respectively, and the B.E.T. surface area of the silica fume is 20,250 m^2/kg. Crushed limestone aggregate with 10-mm nominal size and well-graded siliceous sand were employed. Their particle-size distributions were within the CSA A23.1 recommendations. The coarse aggregate and sand had fineness moduli of 6.4 and 2.5, respectively. Their bulk specific gravities were 2.71 and 2.69, and their absorption values were 0.4% and 1.2%, respectively.

As mentioned previously, three types of HRWRA were incorporated: PNS, PMS, and PC. The PNS- and PMS-based HRWRA conform to CSA3-A266.6-M85 and have solid contents of 42% and 40% with specific gravities of 1.21 and 1.20, respectively. The PC-based HRWRA had a specific gravity of 1.1 and solid content of 27%. A lignosulfonic acid-based water-reducing agent was used in some mixtures.

Polysaccharide-based VEA (welan gum) was used to enhance the stability of mixtures made with PNS- and PMS-based HRWRA. The powder gum was mixed in 1% solution of the mixing water to prehydrate the polymer prior to its addition into concrete. A cellulose-based VEA was employed in the case of mixtures incorporating the PC-based HRWRA, given that such HRWRA present some incompatibilities with the polysaccharide-based VEA.[5] The liquid-based cellulosic VEA had a solid content of 39% and specific gravity of 1.12. It was diluted in 1/3 of the mixing water before introduction into the mixer. A synthetic detergent-based air-entraining agent (AEA) was used in all tested mixtures.

Mixture proportions

The investigated mixtures were prepared with three different *w/cm* of 0.36, 0.40, and 0.46. An increase in *w/cm* resulted in an increase in paste volume because the binder content was held fixed at 450 kg/m^3 (Table 1). Depending on the *w/cm*, the dosage of VEA was adjusted to eliminate bleeding and reduce the risk of segregation. No VEA was needed in SCC made with a low *w/cm* of 0.36. The cellulose-based VEA dosage was incorporated at concentrations of 260 and 370 mL/100 kg of binder for the mixtures proportioned with *w/cm* of 0.40 and 0.46, respectively. In the case of SCC containing PNS- or PMS-based HRWRA, the dosage of polysaccharide-based VEA was set at 0.03% and 0.04% of the binder mass for mixtures made with *w/cm* of 0.40 and 0.46, respectively. This corresponds to VEA concentrations of 0.075% and 0.087%, by mass of water.

As shown in Table 1, in the case of concrete made with 0.40 *w/cm* and PNS-based HRWRA, various concentrations of water-reducing agent were incorporated to determine the effect of such admixtures on formwork pressure. These concentrations corresponded to null, low, and medium contents. It is important to note that water-reducing admixtures are often used in mixtures made with PNS-based HRWRA, even in the case of SCC, to reduce the unit cost of concrete.

The sand-to-total aggregate ratio remained fixed at 0.46 for all of the tested mixtures. The HRWRA and AEA were adjusted to secure initial slump flow values and fresh air contents of 650 ± 15 mm and 6 ± 2%, respectively.

Test methods

All mixtures were prepared in an open-pan mixer of 125 L capacity. The mixing sequence consisted of homogenizing the coarse aggregate and sand for 1 minute before introducing part of the mixing water. The AEA was then added along with the cementitious materials, followed by the HRWRA and remaining part of the water. After 3 minutes of mixing,

Table 1—Mixture proportions of evaluated concretes

w/cm	0.36			0.40					0.46		
Mixture codification	0.36-PC	0.36-PNS	0.36-PMS	0.40-PC	0.40-PNS	0.40-PNS-low	0.40-PNS-med	0.40-PMS	0.46-PC	0.46-PNS	0.46-PMS
Ternary cement, kg/m^3	450	450	450	450	450	450	450	450	450	450	450
Water, kg/m^3	162	162	162	180	180	180	180	180	207	207	207
Sand (0 to 5 mm), kg/m^3	760	760	760	740	740	740	740	740	700	700	700
Coarse aggregate (5 to 10 mm), kg/m^3	900	900	900	870	870	870	870	870	820	820	820
Cellulose VEA, mL/100 kg of cement	—	—	—	260	—	—	—	—	370	—	—
Powder polysaccharide VEA, % of cement	—	—	—	—	0.03	0.03	0.03	0.03	—	0.04	0.04
Polycarboxylate-based HRWRA, L/m^3	4.2	—	—	3.8	—	—	—	—	2.1	—	—
Naphthalene-based HRWRA, L/m^3	—	10.1	—	—	7.3	7.2	6.9	—	—	4.9	—
Water-reducing agent, mL/100 kg of cement	—	—	—	—	—	100	200	—	—	—	—
Melamine-based HRWRA, L/m^3	—	—	12.6	—	—	—	—	11.9	—	—	6.5
Air-entraining admixture, mL/100 kg of cement	65	70	110	120	150	150	150	170	130	180	220

the VEA was introduced, and the concrete was mixed for two additional minutes. The ambient temperature during mixing and testing was fixed to 20 ± 2 °C.

Slump flow, temperature, unit weight, air volume, L-box flow characteristics, surface settlement, and time-dependent properties (thixotropy) were determined shortly after the end of mixing. The L-box test is an L-shaped apparatus with a gate separating the vertical and horizontal compartments.[11] The vertical part of the box is filled with concrete and left at rest for 1 minute before opening the gate separating the two compartments. The concrete flows out through reinforcing bars of 12-mm diameter at the bottom that are spaced 35 mm apart. The ratio of the height of concrete remaining in the leading edge h_2 and that in the vertical section h_1 is determined to evaluate the self-levelling and passing ability characteristics of the concrete. The surface settlement used to evaluate static stability was assessed by casting concrete in a polyvinyl chloride (PVC) column measuring 200 mm in diameter and 800 mm in height.[12] The settlement was monitored using a linear dial gauge fixed on top of a thin plate positioned and anchored at the concrete surface.

The protocols adopted for the evaluation of the degree of thixotropy were determined using a modified concrete rheometer.[13] Four structural breakdown curves evaluated at rotational velocities of 0.3, 0.5, 0.7, and 0.9 rps were used for determining the breakdown area A_b of concrete. For each rotational speed and immediately after the vane drive mechanism is started, readings of the torque were noted as a function of time without any delay. The first reading is considered as the initial shear stress necessary to break down the structure after a given period of rest that leads to structural build-up of the concrete matrix. On the other hand, the mean of the five smallest measurements over 25-second test duration at a given rotational speed is taken as the equilibrium shear stress value. This latter value is obtained after destruction of the material caused by the shearing action. The time required to perform each of the structural breakdown tests at a given rotational speed was approximately 7.5 minutes, of which 5 minutes correspond to a rest period of the concrete in the bowl of the rheometer and 2.5 minutes correspond to conducting the rheological testing and rehomogenizing the material for subsequent measurements. In total, 30 minutes were required to determine the initial and equilibrium shear stresses for the four rotational speeds needed to calculate the breakdown area. To determine the variations of thixotropy with time and their influence on changes in lateral pressure, two additional series of measurements corresponding to time intervals of 60 to 90 minutes and 120 to 150 minutes were performed.

An experimental PVC column measuring 2800 mm in height and 200 mm in diameter was used to monitor the lateral pressure distribution exerted by fresh concrete. The column had a smooth inner face to minimize friction. The lateral pressure was determined using five pressure sensors of 100 kPa capacity each mounted at 50, 250, 450, 850, and 1550 mm from the base. The face of each sensor was set flush with the inside of the formwork, and the sensors were properly calibrated prior to use.

The general procedure of concrete placement consisted of continuously discharging the concrete from the top, without vibration, at a rate of rise of 10 m/h. The PVC column had to be emptied prior to concrete stiffening; therefore, pressure monitoring was terminated when the slump consistency of the concrete reached approximately 150 mm.

TEST RESULTS AND DISCUSSION

Fresh concrete properties

Fresh properties of the tested SCC are summarized in Table 2. All mixtures exhibited proper passing ability, particularly in the case of SCC made with the higher values of *w/cm*. The L-box h_2/h_1 blocking ratios ranged from 0.81 to 0.95 (0.83 and 0.94 for the 0.36-PNS and 0.46-PNS mixtures, respectively). An increase in *w/cm*, or paste volume, resulting in lower coarse aggregate volume, can reduce the degree of internal friction, thus increasing the ability of concrete to flow through restricted bars.

Generally speaking, mixtures prepared with a moderate *w/cm* of 0.40 exhibited the lowest surface settlement. The maximum surface settlement increased from 0.34% to 0.45% when the *w/cm* was decreased from 0.40 to 0.36, respectively, for

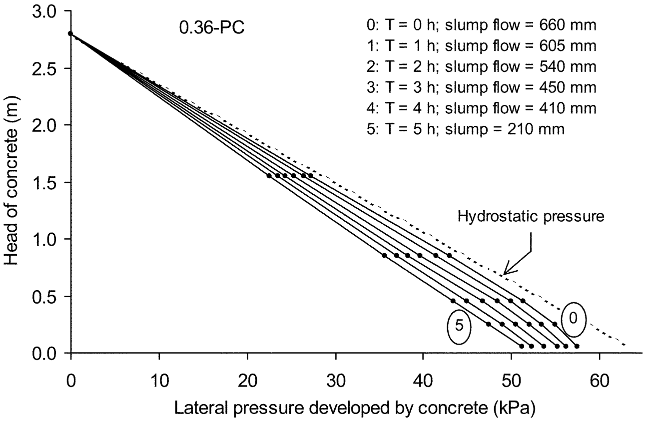

Fig. 1—Variations of lateral pressure envelope with time for 0.36-PC mixture.

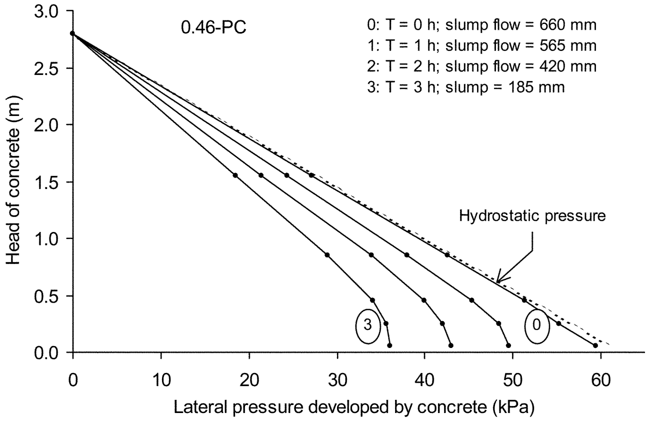

Fig. 2—Variations of lateral pressure envelope with time for 0.46-PC mixture.

Table 2—Fresh properties of evaluated concretes

	Initial slump, mm	Air content, %	Temperature, °C	Unit weight, kg/m^3	h_2/h_1 of L-box test	Maximum surface settlement, %
0.36-PC	660	4.7	19.6	2350	0.90	0.45
0.36-PNS	655	7.6	20.5	2245	0.83	0.40
0.36-PMS	650	7.9	21.1	2195	0.85	0.39
0.40-PC	665	4.3	21.7	2265	0.81	0.34
0.40-PNS	640	5.1	21.8	2310	0.87	0.44
0.40-PNS-low	650	5.9	19.7	2250	0.85	0.41
0.40-PNS-med	645	8.2	21.9	2165	0.89	0.52
0.40-PMS	660	4.9	20.2	2290	0.83	0.38
0.46-PC	660	5.0	21.3	2240	0.95	0.48
0.46-PNS	650	5.5	18.9	2285	0.94	0.55
0.46-PMS	655	4.9	20.6	2360	0.95	0.53

mixtures incorporating PC-based HRWRA. Such value was 0.48% for the 0.46-PC mixture. In the case of SCC made with 0.36 *w/cm*, the increase in surface settlement can be due to the relatively higher HRWRA demand, resulting in longer dormant periods. In the case of SCC made with 0.46 *w/cm*, the increase in surface settlement can be attributed to increased water content that can decrease cohesiveness and viscosity. Concrete made with water-reducing agent exhibited an increase in surface settlement, given its effect on prolonging the dormant period of cement hydration.

Lateral pressure development

Two diagrams showing the variations of lateral pressure envelop for the 0.36-PC and 0.46-PC mixtures are plotted in Fig. 1 and 2, respectively. Right after casting, the lateral pressure exerted by the 0.36-PC mixture is shown to correspond to 91% of hydrostatic pressure. The pressure envelope was linear, and no significant change was noted with time. In the case of the 0.46-PC mixture, the initial lateral pressure corresponded to 97% of the hydrostatic pressure. However, a sharp reduction in the pressure envelope occurred soon after casting with the residual pressure reaching 60% of hydrostatic pressure after 3 hours.

Table 3 summarizes the relative pressure values *P*(maximum)/*P*(hydrostatic) measured initially and 100 and 200 minutes thereafter near the bottom of the 2800 mm-high column. The elapsed time periods required to reduce the initial lateral pressures by 10, 25, and 40% are also reported. Such a drop in pressure is of special interest for scheduling subsequent concrete placements.

Table 3—Rates of lateral pressure drop with time

	P(maximum)/ P(hydrostatic), %			Elapsed time necessary to decrease relative pressure, minute		
	at 0 minutes	at 100 minutes	at 200 minutes	by 10%	by 25%*	by 40%*
0.36-PC	91	89	85	335	—	—
0.36-PNS	91	80	70	96	240	385
0.36-PMS	93	69	55	60	150	240
0.40-PC	90	76	69	100	250	400
0.40-PNS	93	70	56	57	140	230
0.40-PNS-low	94	73	62	80	200	320
0.40-PNS-med	94	76	65	98	245	390
0.40-PMS	92	74	64	81	200	325
0.46-PC	97	74	58	51	125	205
0.46-PNS	96	67	—	28	70	110
0.46-PMS	96	65	—	27	65	110

*Indicates lateral pressure measurements were extrapolated to determine corresponding elapsed time. Some values are not indicated as they exceeded initial setting time.

Effect of w/cm *on variations in lateral pressure*—Variations of the relative pressure with respect to time for the mixtures incorporating PC- and PNS-based HRWRA are plotted in Fig. 3 and 4, respectively. The slump consistencies measured at the end of the pressure monitoring periods are noted. The SCC made with 0.46 *w/cm* and either PC- or PNS-based HRWRA developed the highest initial relative pressure of 97%. This decreased to 91% for SCC made with 0.36 *w/cm*. Greater water, and paste, contents resulting from higher *w/cm*

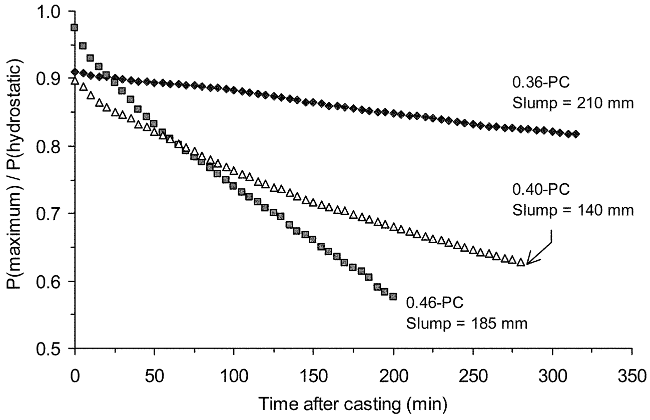

Fig. 3—Effect of w/cm *on relative pressure variations of SCC made with PC-based high-range water-reducing admixture.*

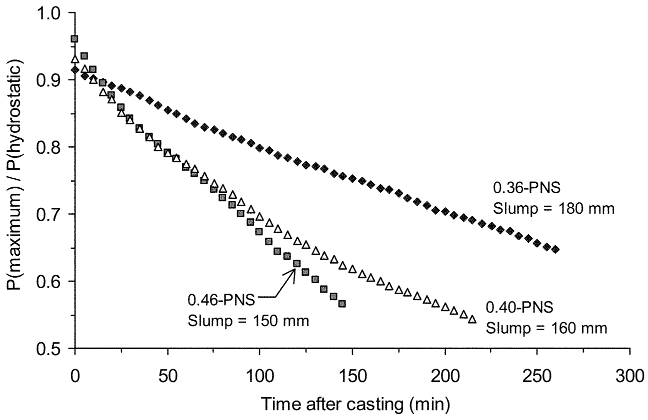

Fig. 4—Effect of w/cm *on relative pressure variations of SCC made with PNS-based high-range water-reducing admixture.*

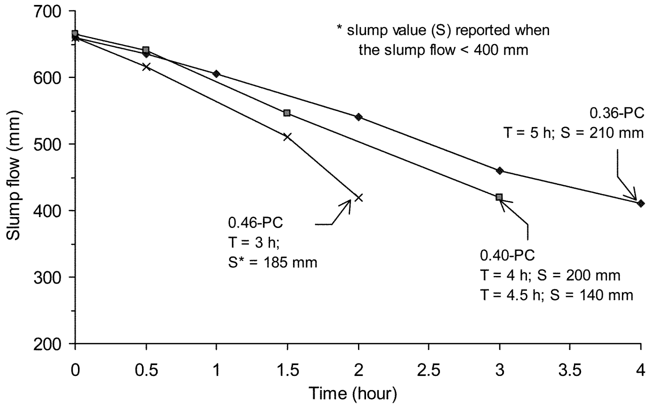

Fig. 5—Slump flow loss of SCC mixtures made with PC-based high-range water-reducing admixtures.

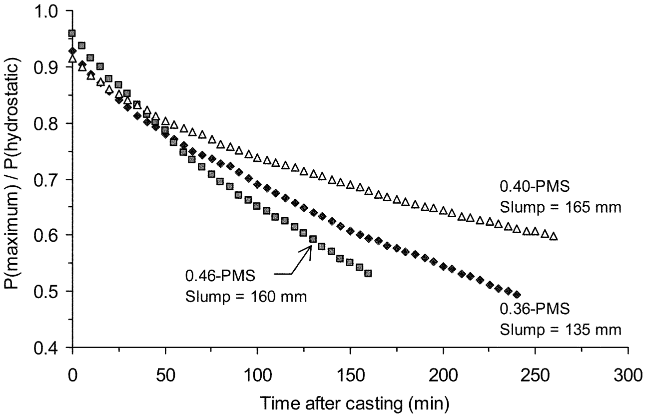

Fig. 6—Effect of w/cm *on pressure variations of mixtures incorporating PMS-based high-range water-reducing admixtures.*

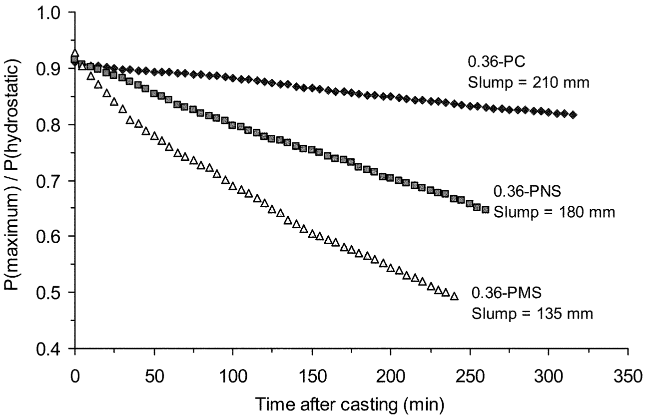

Fig. 7—Effect of high-range water-reducing admixture type on pressure variations of SCC made with 0.36 w/cm*.*

can increase the lubrication of the cement paste, thus decreasing the cohesiveness of the mixture.[10] Furthermore, mixtures proportioned with higher *w/cm* incorporated relatively lower coarse aggregate volumes (Table 1). This can reduce the degree of internal friction and increase the mobility of the concrete, thus resulting in greater initial lateral pressure.[6]

Despite the higher initial pressure, the rate of pressure drop with time is shown to increase in mixtures prepared with higher *w/cm* (Fig. 3 and 4). For example, the time required to reduce the relative pressure by 10% increased from 51 to 100 and 335 minutes for the SCC mixtures made with *w/cm* of 0.46, 0.40, and 0.36, respectively, and PC-based HRWRA. As noted in Table 1, the HRWRA demand decreased with the increase in *w/cm*; this resulted in a lower degree of fluidity retention. Such concrete can then develop its cohesiveness at a faster rate. This is illustrated in Fig. 5 where the time necessary to reach slump flow consistency of 400 mm decreased from 4 to 3 and 2 hours after casting for the 0.36-PC, 0.40-PC, and 0.46-PC mixtures, respectively; these mixtures are made with successively lower HRWRA dosages of 4.2, 3.8, and 2.1 L/m^3, respectively. It is to be noted that SCC made with higher *w/cm* necessitated greater VEA concentration to provide enough stability, thus increasing the cohesiveness and contributing in limiting the pressure developed in time.[14]

As in the case of mixtures containing PC- or PNS-based HRWRA, proportioning the SCC with *w/cm* of 0.46 and PMS-based HRWRA resulted in an increase in the initial pressure and a sharper rate of pressure drop with time (Fig. 6). SCC prepared with 0.36 *w/cm* had faster drop in pressure compared with the mixture made with 0.40 *w/cm*. The elapsed time to reduce the relative pressure by 25% decreased from 200 to 150 minutes with the decrease in *w/cm* from 0.40 to 0.36 for SCC made with PMS-based HRWRA.

Effect of HRWRA type on variations in lateral pressure—Variations of the relative pressure for SCC made with 0.36 and 0.46 *w/cm* are plotted in Fig. 7 and 8, respectively. For

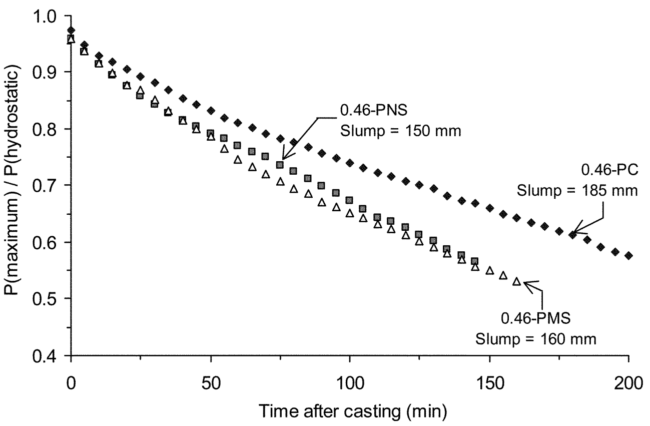

Fig. 8—Effect of high-range water-reducing admixture type on pressure variations of SCC made with 0.46 w/cm.

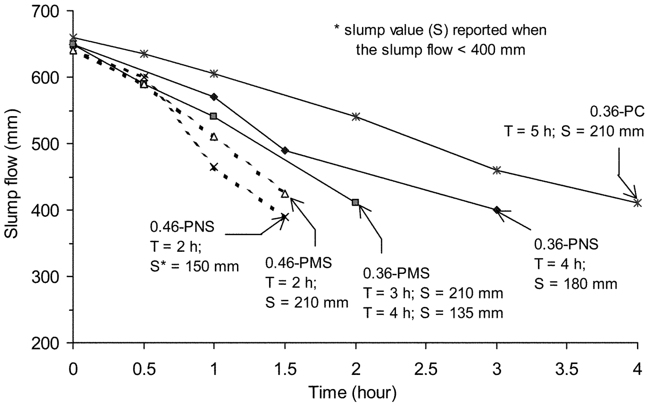

Fig. 9—Slump flow loss for mixtures made with various HRWRA types and w/cm.

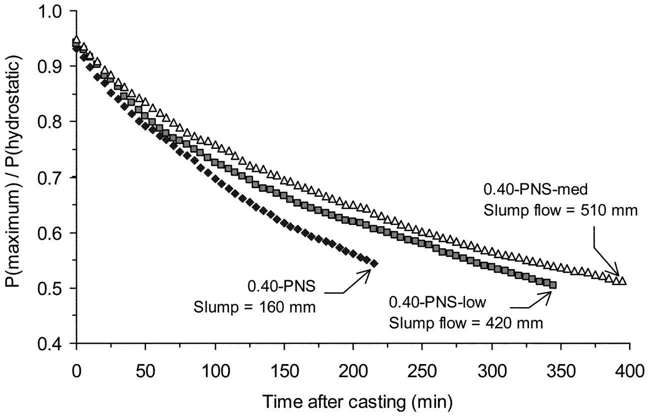

Fig. 10—Effect of water-reducing agent on pressure variations for SCC made with 0.40 w/cm.

any given *w/cm*, the initial relative pressures were quite similar, regardless of the HRWRA type. The type of HRWRA appears to have limited effect on the initial pressure, which is affected rather by the degree of internal friction of the concrete (*w/cm*, volume of aggregate).[6,7] On the other hand, the rate of pressure drop with time, which is influenced by the increase in cohesiveness, is significantly affected by the type of HRWRA. For example, SCC made with polycarboxylate exhibited the lowest rate of pressure drop with time, particularly when used in SCC proportioned with 0.36 *w/cm*. The time required to reduce the relative pressure by 10% from initial pressure decreased from 335 to 96 and 60 minutes for the 0.36-PC, 0.36-PNS, and 0.36-PMS mixtures, respectively (Table 3). This can be attributed to the greater fluidity retention associated with the use of the PC-based HRWRA compared with the PNS- or PMS-based HRWRA.[15] As can be seen in Fig. 9, the time required to attain 400-mm slump flow increased from 2 to 3 and then to 4 hours for the 0.36-PMS, 0.36-PNS, and 0.36-PC mixtures, respectively. The limited loss in flowability after casting reduces the rate of gain in shear strength properties, and hence the rate of drop in lateral pressure over time.

At a low *w/cm* of 0.36, SCC incorporating PMS-based HRWRA exhibited a higher rate of pressure drop compared to similar SCC containing PNS-based HRWRA (Fig. 7). For the SCC mixtures proportioned with 0.40 *w/cm*, however, this tendency was reversed because the mixture containing PNS-based HRWRA exhibited higher rate of pressure drop. The elapsed time needed to achieve 25% reduction from initial pressure decreased from 200 to 140 minutes for the 0.40-PMS and 0.40-PNS mixtures, respectively (Table 3). For SCC made with 0.46 *w/cm*, both sulphonate-based HRWRA exhibited similar rates in pressure drop with approximately 67 minutes required to achieve 25% decrease in lateral pressure (Fig. 8).

Effect of water-reducing agent on variations in lateral pressure—The variations of the relative pressure of mixtures made with or without a water-reducing agent and with PNS-based HRWRA are plotted in Fig. 10. Initially, the three mixtures developed almost similar relative pressures corresponding to 94% of hydrostatic pressure (Table 3). As expected, however, the rate of pressure drop after placement is slowed down with the incorporation of water-reducing agent. The time necessary to achieve 25% reduction in pressure increased from 140 to 200 and 245 minutes for the 0.40-PNS, 0.40-PNS-low, and 0.40-PNS-med mixtures, respectively, which incorporate increasingly higher dosages of a water-reducing agent. As shown in Fig. 10, a slump flow of 510 mm was measured 6.5 hours from casting for the 0.40-PNS-med mixture. This can decrease the development of cohesion and lead to higher lateral pressure.

Effect of thixotropy on lateral pressure development

When tested at constant rotational speed ($N = 0.3$, 0.5, 0.7, or 0.9 rps), all mixtures exhibited the same pattern of shear-time transient behavior. This was characterized by an initial yield stress τ_i that decays with time toward a minimum equilibrium value τ_e. This later value corresponds to a state where a balance between particle flocculation and deflocculation is reached under constant shearing rate.[13] The degree of thixotropy was quantified through the determination of the breakdown area A_b; this area comprised between the initial flow curve (τ_i versus N) and equilibrium flow curve (τ_e versus N),[13] as indicated in Fig. 11. Table 4 summarizes the A_b values calculated during the three time intervals of measurement (T_1, T_2, and T_3).

Effect of *w/cm*, HRWRA type, and use of water-reducing agent on thixotropy

Generally speaking, two different magnitudes of thixotropy can be distinguished for the A_b values determined at T_1. Relatively high A_b values of 320 ± 20 J/m^3·s were obtained for SCC made with 0.36 or 0.40 *w/cm*. This suggests that similar thixotropy can be obtained for SCC made with either

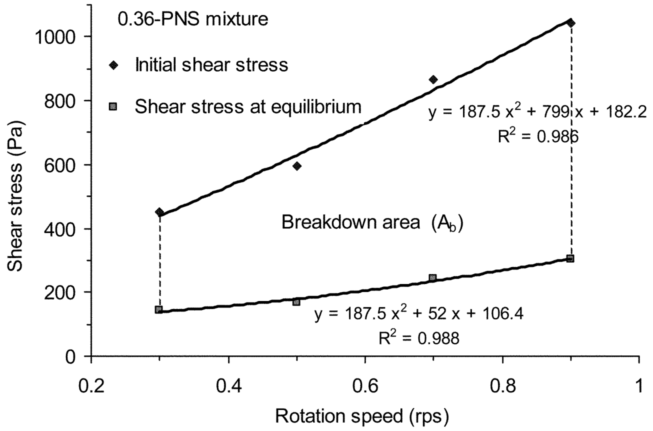

Fig. 11—Breakdown area calculated at T_1 *for 0.36-PNS mixture.*

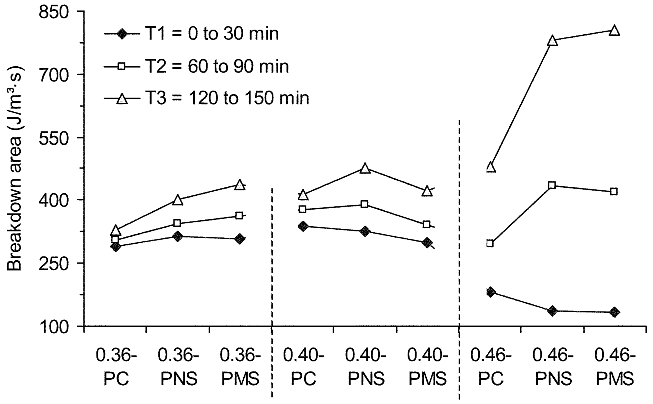

Fig. 12—Variations of breakdown area determined during three time intervals.

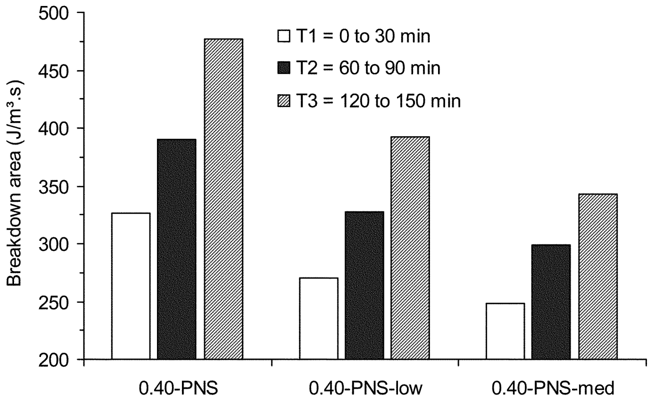

Fig. 13—Effect of water-reducing agent on variations of breakdown area.

low *w/cm* and no VEA or moderate *w/cm* and VEA. On the other hand, mixtures made with 0.46 *w/cm* exhibited lower A_b values of 155 ± 20 J/m^3·s. This indicates that higher water content and relatively lower coarse aggregate volume have predominant influence on lowering the degree of thixotropy, despite the greater demand of VEA necessary to ensure proper stability (Table 1).

For mixtures prepared with 0.36 *w/cm*, SCC made with PC-based HRWRA had the lowest initial A_b value of 290 J/m^3·s compared with mixtures incorporating PNS- or PMS-based HRWRA (Table 4). With the increase in *w/cm* to 0.40 and 0.46,

Table 4—Magnitude of breakdown area determined during three tested time intervals

	Breakdown area A_b, J/m^3·s		
	T_1 = 0 to 30 minutes	T_2 = 60 to 90 minutes	T_3 = 120 to 150 minutes
0.36-PC	290	306	330
0.36-PNS	314	344	402
0.36-PMS	309	362	437
0.40-PC	339	377	412
0.40-PNS	326	390	477
0.40-PNS-low	270	327	392
0.40-PNS-med	248	299	343
0.40-PMS	298	340	421
0.46-PC	181	295	480
0.46-PNS	135	433	781
0.46-PMS	133	419	804

this tendency was reversed because the mixtures incorporating PC-based HRWRA exhibiting the highest degree of thixotropy. For example, the A_b values at T_1 time interval increased from 298 and 326 J/m^3·s for the 0.40-PMS and 0.40-PNS mixtures, respectively, to 339 J/m^3·s for the 0.40-PC mixture. This can be attributed to the increased shear thinning behavior resulting from the use of cellulose-based VEA used in SCC made with the PC-based HRWRA.[14] Irrespective of the *w/cm*, it is to be noted that mixtures incorporating PNS-based HRWRA exhibited slightly higher thixotropy compared with those made with PMS-based HRWRA.

The variations of A_b values determined during the three time intervals of rheological measurements are illustrated in Fig. 12 for mixtures made various *w/cm* and HRWRA types. As expected, thixotropy increases when measurements are conducted at longer elapsed times (T_2 and T_3) due to cement hydration and increase in cohesiveness. Such an increase was particularly important for mixtures proportioned with 0.46 *w/cm*. For example, the A_b value increased from 133 J/m^3·s at T_1 to 804 J/m^3·s at T_3 for the 0.46-PMS mixture. As mentioned previously, mixtures prepared with 0.46 *w/cm* necessitated significantly lower HRWRA demand compared with those prepared with 0.36 or 0.40 *w/cm*. This can result in sharper loss in slump flow consistency (Fig. 5 and 9), thus causing the material to increase its shear strength characteristics, and therefore its thixotropy over longer elapsed time intervals.

The variations of A_b values determined during the three time intervals (T_1, T_2, and T_3) for SCC made with 0.40 *w/cm* and various concentrations of water-reducing agent are illustrated in Fig. 13. The incorporation of a low or medium dosage of water-reducing agent is shown to successively decrease thixotropy compared with the 0.40-PNS mixture made without any water-reducing agent.

Relationship between thixotropy and lateral pressure—The relationship between A_b evaluated during the first 30-minute time interval of rheological measurements and relative pressure determined right after the filling of the experimental columns is shown in Fig. 14. The figure also illustrates the relationships between the A_b values evaluated during the T_2 and T_3 intervals with respect to the relative pressure calculated 100 and 200 minutes after casting. Despite moderate correlation coefficients R^2 of 0.66 to 0.77, the relative pressure is shown to decrease for mixtures with greater A_b values. Such a trend becomes clearly more

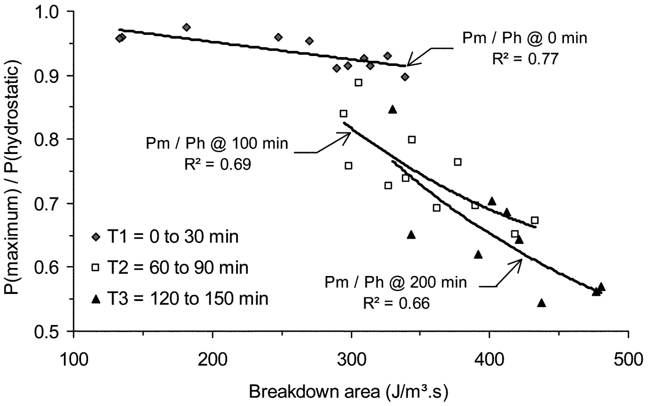

Fig. 14—Relationship between breakdown area and lateral pressure.

pronounced with time. For example, for the 0.36-PC and 0.46-PC mixtures having initial A_b values of 290 and 181 J/m^3·s, respectively, the relative pressure decreased by four-fold after 200 minutes in the case of the latter mixture, which exhibited higher thixotropy at T_3.

Lateral pressure exerted by plastic concrete depends largely on shear strength development.[4] On the other hand, thixotropy is a reversible phenomenon that begins as soon as the material is left at rest. The onset of the structural build-up phase causes the structure to flocculate, hence increasing the cohesiveness.[13] For SCC with greater thixotropy, increased kinetics of the build-up phase can lead to a faster gain in shear strength properties, thus limiting the transformation of vertical stresses into lateral pressure.[6-8] For example, SCC made with 0.40 *w/cm* exhibited higher initial thixotropy compared with similar mixtures with a *w/cm* of 0.46; this resulted in lower lateral pressure measured right after casting.

CONCLUSIONS

Based on the previous results, the following conclusions can be drawn:

1. The development of formwork pressure exerted by SCC can be related to thixotropy. An increase in thixotropy can lead to lower lateral pressure and a faster rate of pressure drop with time;

2. Both lateral pressure and thixotropy of SCC are significantly affected by the *w/cm*. Mixtures proportioned with 0.46 *w/cm*, which have relatively high paste volume, exhibited lower thixotropy and greater initial pressure compared with SCC made with *w/cm* of 0.40 or 0.36. This can be related to the increased water and paste contents and reduction in coarse aggregate volume that lead to lower shear strength properties of the plastic concrete;

3. The rate of drop in lateral pressure and gain in thixotropy with time are greater for mixtures proportioned with 0.46 *w/cm* compared with those made with a *w/cm* of 0.40 or 0.36. This can be due to the greater HRWRA demand of the latter mixtures which can reduce fluidity loss with time and build-up in cohesiveness;

4. For any given *w/cm*, the HRWRA type appears to have a limited effect on the maximum initial pressure. Compared with PNS- or PMS-based HRWRA, the use of PC-based HRWRA exhibits better fluidity retention, which leads to lower gain in thixotropy and a drop in lateral pressure with time; and

5. The incorporation of a water-reducing agent reduces the rate of build-up in shear strength properties and, hence, the drop in lateral pressure with time.

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