

# Use of Thixotropy-Enhancing Agent to Reduce Formwork Pressure Exerted by Self-Consolidating Concrete

by Kamal H. Khayat and Joseph J. Assaad

*This paper seeks to evaluate the impact of a thixotropy-enhancing agent (TEA) on the variations in thixotropy and formwork lateral pressure of self-consolidating concrete (SCC) with  $650 \pm 15$  mm ( $24.3 \pm 0.6$  in.) slump flow consistency. Six mixtures containing various TEA concentrations along with either a melamine- or polycarboxylate-based high-range water-reducing admixture (HRWRA) were tested. The results are compared with similar SCC mixtures made with conventional viscosity-enhancing admixtures (VEAs), including a liquid polysaccharide, powder polysaccharide, and cellulose-based.*

*Test results show that the use of TEA can significantly increase the degree of thixotropy and reduce the formwork pressure compared with similar mixtures containing conventional VEAs. This is attributed to the thixotropic nature of this agent that enables the material to rapidly recover its cohesiveness following some time at rest. The combination of TEA with either powder polysaccharide or cellulose-based VEA at low concentration was found to reduce the maximum initial pressure and increase the rate of pressure drop with time compared with SCC containing only conventional VEA at similar concentration. The TEA/VEA combinations resulted in better fluidity retention with time.*

*A good relationship exists between the lateral pressure and thixotropy determined from SCC mixtures containing various concentrations of TEA and/or low concentrations of conventional VEA. The higher the degree of thixotropy, the less the mixture develops lateral pressure. This is attributed to the reversible effect of thixotropy that enables the material to increase its shear strength properties after some resting time.*

**Keywords:** formwork pressure; self-consolidating concrete; thixotropy; viscosity-enhancing admixture.

## INTRODUCTION

Viscosity-enhancing admixtures (VEAs) are often incorporated in self-consolidating concrete (SCC) to enhance viscosity of the material, thus reducing any risk of bleeding, segregation, and surface settlement.<sup>1</sup> Commonly used VEAs are water-soluble polysaccharides of microbial sources such as welan gum and cellulose-based polymers such as hydroxypropyl methyl cellulose and hydroxyethyl cellulose. The mode of action of a VEA depends on the type and concentration of the polymer in use. Welan gum and cellulose derivatives, for instance, are categorized by long-chain polymers of complex forms. When diluted in water, these polymers can adhere to the periphery of water molecules, thus adsorbing and fixing part of the mixing water. With hydration of the polymer, the VEA continues to aggregate and begins to expand as it imbibes water. Molecules in adjacent polymer chains can intertwine and develop attractive forces through hydrogen bond and polymer entanglement, thus resulting in increased cohesiveness of the mixture.<sup>1</sup>

It is important to note that an increased degree of viscosity of cement-based materials can also be ensured by using thixotropy-enhancing agents (TEAs). For example, Maeder et

al.<sup>2</sup> evaluated the effect of two types of TEA, including an organic carbonate and sulphonated ester of fatty acids, on the variations in apparent viscosity of cement paste mixtures. The water-to-cementitious materials ratio ( $w/cm$ ) ranged from 0.40 to 0.50, and the TEAs were incorporated at a dosage varying from 1 to 5% of the cementitious materials. With the addition of the various TEAs, a dramatic increase in the apparent viscosity was found at low shear rates. At higher speeds, the viscosity decreases significantly and is practically the same as the reference cement pastes made without any TEA. The authors reported that such admixtures can undergo hydrolysis in the basic medium by the formation of alcohols in an exothermic reaction.<sup>2</sup> The increased heat development and precipitation of Ca-carbonate can result in higher thixotropy and accelerate the setting of the cement paste.<sup>2</sup>

Another investigation was carried out by Khayat et al.<sup>3</sup> to evaluate the effect of a propylene carbonate-based TEA on the variations of cohesiveness of concrete mixtures having  $220 \pm 10$  mm ( $8.6 \pm 0.4$  in.) slump values and  $0.41 w/cm$ . Combinations of 0.5% of propylene carbonate with powder cellulose-based VEA at a low or medium concentration of 0.15% and 0.3% by mass of water, respectively, were found to result in highly flowable yet cohesive concrete with proper resistance to washout, bleeding, and surface settlement. Unlike conventional VEAs, the authors suggested that the TEAs function by inducing a network structure in the liquid phase through increased interactions of the solid particles.<sup>3</sup> Therefore, the actual mechanism could be the combination of several effects, including the development of hydrogen bonds and interaction of the carbonate with the cement particles, thus modifying the early hydration reactions.<sup>3</sup>

Limited information exists regarding the effect of the increased degree of thixotropy resulting from the use of TEAs on the formwork lateral pressure developed by SCC. In recent studies, Assaad and Khayat<sup>4</sup> and Assaad et al.<sup>5</sup> evaluated the variations in formwork pressure exerted by SCC mixtures having various degrees of thixotropy resulting from different coarse aggregate volumes and set-modifying admixtures. The tested mixtures had  $650 \pm 15$  mm ( $25.3 \pm 0.6$  in.) slump flow consistency and were prepared with a  $w/cm$  varying between 0.40 and 0.42. Experimental columns measuring 200 mm (7.8 in.) in diameter and either 2100 or 2800 mm (81.9 or 109.2 in.) in height were used to determine lateral pressure. The authors reported that the decrease in

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initial lateral pressure as well as the increase in the rate of pressure drop with time can be well correlated to thixotropy. This was attributed to the reversible effect of thixotropy that enables the material to increase its shear strength, namely, internal friction and cohesion, and develop lower lateral pressure after casting.<sup>4,5</sup>

A comprehensive research study was undertaken to evaluate the effect of type and concentration of conventional VEAs and/or TEAs on the variations in thixotropy and formwork lateral pressure of SCC. The study is divided into two parts. The first one involving the evaluation of three conventional VEAs, including a liquid polysaccharide, powder polysaccharide, and cellulose-based is reported elsewhere.<sup>6</sup> Therefore, the results presented in this paper seek to evaluate the impact of using TEA on the variations in thixotropy and lateral pressure. The comparison of the TEA with respect to the three conventional VEAs is of great interest herein. In total, 17 SCC mixtures with  $650 \pm 15$  mm ( $25.3 \pm 0.6$  in.) slump flow consistency were evaluated.

## RESEARCH SIGNIFICANCE

Thixotropy-enhancing agents are usually incorporated in cementitious materials to enhance stability and thixotropy. Limited studies exist, however, regarding their effects on the

formwork lateral pressure that can be developed by SCC mixtures. Seventeen mixtures prepared with combinations of TEA and/or conventional VEAs with various types of high-range water-reducing admixtures (HRWRAs) are evaluated and compared. Data presented in this paper are intended to provide test results for the use of TEA in SCC applications to ensure safe and cost-effective formwork systems.

## EXPERIMENTAL PROGRAM

### Materials

A commercially available ternary cement containing 6% silica fume, 22% Class F fly ash, and 72% Type 10 portland cement was used. The Type 10 cement had  $C_3S$ ,  $C_3A$ , and  $Na_2O_{eq}$  characteristics of 60%, 6.4%, and 0.74%, respectively. The Blaine specific surface of the Type 10 cement and fly ash was 325 and 410  $m^2/kg$  (1580 and 2000  $ft^2/lbm$ ), respectively. The silica fume had a BET surface area of 20,250  $m^2/kg$  (98,800  $ft^2/lbm$ ). Crushed limestone aggregate with a nominal size of 10 mm (0.4 in.) and a well-graded siliceous sand were employed. Their particle size distributions were within the CSA Standards 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 absorptions were 0.4% and 1.2%, respectively.

As summarized in Table 1, two kinds of polysaccharide-based VEAs were employed. The first was in a liquid form with 42.5% of solid content and 1.21 specific gravity. This VEA was diluted in 1/3 of the mixing water before its introduction to concrete. The second kind was in a powder form and was vigorously mixed in 1% solution of the mixing water to prehydrate the polymer before addition to the concrete. A high molecular-weight cellulose-based VEA with a solid content of 39% and a specific gravity of 1.12 was also used. This VEA was in a liquid form and was diluted in

**Table 1—Mixture composition of evaluated SCC**

	Mixture codification*	Ternary cement, $kg/m^3$	Water, $kg/m^3$	$w/cm$	Sand (0 to 5 mm), $kg/m^3$	Coarse aggregate (5 to 10 mm), $kg/m^3$	Dosage of TEA or VEA	Naphthalene-based HRWRA, $L/m^3$	Melamine-based HRWRA, $L/m^3$	Polycarboxylate-based HRWRA, $L/m^3$	AEA, mL/100 kg of cement
Reference mixtures without VEA	C-noVEA	450	162	0.36	760	900	0	—	—	4.2	65
	M-noVEA	450	162	0.36	760	900	0	—	12.6	—	110
	N-noVEA	450	162	0.36	760	900	0	10.1	—	—	70
Thixotropy-enhancing agent, % of water	C-TEA-L	450	180	0.40	740	870	0.2	—	—	2.8	55
	C-TEA+Cell-L	450	180	0.40	740	870	TEA = 0.2 Cell = 260	—	—	3.9	130
	C-TEA-H	450	180	0.40	740	870	1.1	—	—	2.9	65
	M-TEA-L	450	180	0.40	740	870	0.2	—	7.9	—	150
	M-TEA+Pow-L	450	180	0.40	740	870	TEA = 0.2 Pow = 0.03	—	11.8	—	155
	M-TEA-H	450	180	0.40	740	870	1.1	—	8.3	—	160
Liquid polysaccharide-based VEA, mL/100 kg of water	N-Poly-L	450	180	0.40	740	870	1100	7.8	—	—	110
	N-Poly-M	450	180	0.40	740	870	1550	11.3	—	—	140
	N-Poly-H	450	180	0.40	740	870	1900	15.4	—	—	150
Powder polysaccharide-based VEA, % of cement	N-Pow-L	450	180	0.40	740	870	0.03	7.3	—	—	150
	N-Pow-H	450	180	0.40	740	870	0.075	18.5	—	—	190
Cellulose-based VEA, mL/100 kg of cement	C-Cell-L	450	180	0.40	740	870	260	—	—	3.8	120
	C-Cell-M	450	180	0.40	740	870	500	—	—	4.7	155
	C-Cell-H	450	180	0.40	740	870	730	—	—	8.1	210

\*Mixture codification refers to type of HRWRA (C: polycarboxylate, M: melamine, and N: naphthalene), type of VEA (TEA: thixotropy-enhancing agent, Cell: cellulose, Pow: powder polysaccharide, and Poly: liquid polysaccharide), and dosage of TEA or VEA (L: low, M: medium, and H: high).

Note:  $1 kg/m^3 = 0.06 lbm/ft^3$ ;  $1 L/m^3 = 1 oz/ft^3$ ; and  $1 L/100 kg = 15.8 oz/100 lbm$ .

1/3 of the mixing water before use in concrete. The liquid polysaccharide, powder polysaccharide, and cellulose-based VEAs are referred in this paper to as Poly, Pow, and Cell, respectively. Finally, a new propylene carbonate-based TEA was employed as a thixotropic admixture. It was diluted in 5% solution of the mixing water before its addition to concrete.

A naphthalene-based HRWRA conforming to CSA3-A266.6-M85 was used. Its solid content and specific gravity were 42% and 1.21, respectively. This HRWRA was used in mixtures containing the liquid and powder polysaccharide-based VEAs, as well as in the reference mixture made without any VEA. A melamine-based HRWRA with a solid content of 40% and specific gravity of 1.20 conforming to CSA3-A266.6-M85 was incorporated in a reference mixture and those containing the TEA. It is important to note that this HRWRA was employed with the TEA because it exhibits better fluidity retention compared with a combination of the TEA with naphthalene-based HRWRA.<sup>2</sup>

A polycarboxylate-based HRWRA with 1.1 specific gravity and 27% solid content was also employed. This HRWRA was used in a reference mixture and those containing the TEA. Mixtures containing cellulose-based VEA also incorporated this type of HRWRA because of their incompatibilities with naphthalene-based HRWRA.<sup>1</sup> The letters N, M, and C are used in this paper to refer to naphthalene, melamine, and polycarboxylate-based HRWRAs, respectively. A synthetic detergent-based air-entraining agent (AEA) was used in all tested SCC mixtures.

### Mixture proportions

The SCC mixtures were prepared with 450 kg/m<sup>3</sup> (27 lbf/ft<sup>3</sup>) of cementitious materials (Table 1). The *w/cm* was set at 0.40 for all mixtures incorporating TEA and/or conventional VEAs. The *w/cm* was reduced to 0.36 for the reference mixtures made without any VEA to enhance stability of the plastic concrete. The sand-to-total aggregate ratio was fixed at 0.46 for all mixtures.

Each VEA type was incorporated at a relatively low (L), medium (M), and high (H) concentration (Table 1). Low concentrations are based on the specifications recommended by the admixture producers. For example, the dosage recommended for the cellulose-based VEA can vary typically between 260 and 1300 mL/100 kg (4.1 to 20.5 oz/100 lbf) of cementitious materials. This value can range from 1100 to 2700 mL/100 kg (17.4 to 42.7 oz/100 lbf) of water for the liquid polysaccharide-based VEA. With the increase in VEA to medium and high, an increase in HRWRA demand was necessary, though this was kept to a minimum in selecting the VEA dosages. Mixtures containing powder polysaccharide-based VEA or TEA were tested at low and high polymer concentrations. The two mixtures prepared by combining the TEA with either cellulose or powder polysaccharide-based VEA were tested only at a low concentration.

In all mixtures, the HRWRA and AEA dosages were adjusted to secure initial slump flow and fresh air content of 650 ± 15 mm (25.3 ± 0.6 in.) and 6 ± 2%, respectively.

### Instrumented column for measuring lateral pressure

An experimental PVC column measuring 2800 mm (109.2 in.) in height and 200 mm (7.8 in.) in diameter was used to determine the lateral pressure distribution exerted by fresh concrete. The column had a smooth inner face to minimize friction during and after concrete placement. The lateral

pressure was determined using five pressure sensors of 100 kPa (145 × 10<sup>-4</sup> ksi) capacity mounted at 50, 250, 450, 850, and 1550 mm (1.9, 9.7, 17.5, 33.1, and 60.4 in.) from the base. All sensor faces were flush with the inside of the formwork and were frequently calibrated using a free head of water before use.

### Fabrication and testing program

All mixtures were prepared in an open-pan mixer of 125 L (33 gal.) capacity. The mixing sequence consisted of homogenizing the coarse aggregate and sand for 1 minute before introducing 1/3 of the mixing water. The AEA was then added along with the cementitious materials and followed by the HRWRA and remaining part of water. After 3 minutes of mixing, the TEA or VEA diluted as specified earlier was introduced, and the concrete was mixed for an additional 2 minutes. The ambient temperature during mixing and testing was maintained at 20 ± 2 °C (68 ± 35.6 °F).

The slump flow, temperature, unit weight, air volume, L-box flow characteristics, surface settlement, time-dependent properties (or thixotropy), and formwork lateral pressure were determined. The description of the L-box and surface settlement tests is given in References 7 and 8, respectively. The protocols adopted for evaluating thixotropy of SCC mixtures were based on a previous study.<sup>9</sup> Four structural breakdown curves determined at four different rotational speeds *N* of 0.3, 0.5, 0.7, and 0.9 rps were determined. Immediately after the vane drive mechanism is started, readings of the torque were noted as a function of time without delay. The first reading is considered as the initial maximum torque value necessary to breakdown the structure. The mean of the five smallest measurements over the 25-second duration at each *N* is taken as the equilibrium torque value. The time required to perform each of the structural breakdown tests at a given rotational speed was 7.5 minutes: 5 minutes when the concrete is at rest in the rheometer bowl and 2.5 minutes for testing and rehomogenizing the concrete for subsequent measurements. In total, 30 minutes were necessary to determine the four structural breakdown curves during the first time interval *T*<sub>1</sub>. To determine the variations of thixotropy with time and its influence on changes in lateral pressure, two additional series of measurements referred to as *T*<sub>2</sub> and *T*<sub>3</sub> were performed corresponding to time intervals of 60 to 90 minutes and 120 to 150 minutes, respectively. The concrete in the rheometer bowl was covered with wet burlap during the resting period to prevent evaporation of water. A complete discussion pertaining to the fundamental mechanisms of thixotropy, as well as its assessment, is proposed in Reference 9.

The general procedure of filling the experimental column consisted of continuously discharging the concrete from the top at a rate of rise of 10 m/hour (32.8 ft/hour) without any mechanical vibration. The monitoring of lateral pressure distributions was stopped once the concrete had a slump consistency of approximately 150 mm (5.8 in.) to enable the emptying of the column before hardening. It is to be noted that the consistency of each mixture was evaluated every 1 hour interval until the end of the pressure monitoring. The concrete was vigorously mixed in a bucket before conducting each of the slump tests.

## TEST RESULTS AND DISCUSSION

### Fresh concrete properties

The results obtained from the L-box and surface settlement tests for all of the tested mixtures are summarized in Table 2.

Generally speaking, mixtures made with a low concentration of TEA (as well as conventional VEA) exhibited  $h_2/h_1$  values greater than 0.80, indicating good passing ability. This was also the case for mixtures prepared without any VEA. The increase in TEA concentration led, however, to a decrease in the  $h_2/h_1$  value. For example, such a decrease was from 0.80 to 0.62 for the M-TEA-L and M-TEA-H mixtures, respectively. Given that viscosity increases with the incorporation of higher TEA or conventional VEA, this can slow down the flow velocity of the plastic concrete and lead to greater degree of blockage around the reinforcing bars in the L-box apparatus.

The SCC mixtures made with the TEA, particularly at a high concentration of the polymer, exhibited the lowest surface settlement values compared with those containing conventional VEAs. For example, settlement values of 0.05% and 0.08% were obtained for mixtures containing high dosage of TEA with either polycarboxylate or melamine-based HRWRA, respectively. This can be due to the thixotropic nature of the TEA that can result in a fast build-up of viscosity soon after casting, thus reducing any risk of bleeding, segregation, and surface settlement.

### Assessment of thixotropy of tested mixtures

When tested at constant rotational speed ( $N = 0.3, 0.5, 0.7,$  or  $0.9$  rps), all of the tested mixtures exhibited the same pattern of shear-time transient behavior, that is, a peak yield stress  $\tau_i$ , which corresponds to the initial structural condition, and thereafter a shear stress decay with time toward a minimum value  $\tau_e$ . The degree of thixotropy was then quantified through the determination of the breakdown area  $A_b$  that comprise the initial flow curve ( $\tau_i$  versus  $N$ ) and equilibrium flow curve ( $\tau_e$  versus  $N$ ),<sup>9</sup> as shown in Fig. 1 for the C-TEA-H mixture. Table 2 summarizes the  $A_b$  values calculated during the three time intervals of measurements for all of the tested mixtures.

The amplitude of the time-dependent phenomenon can also be assessed by determining the drop of apparent viscosity  $[\Delta\eta_{app} = (\tau_i - \tau_e)/\dot{\gamma}]$ , where  $\dot{\gamma}$  is the shear rate at a

given rotational speed.<sup>10</sup> This takes into account the extreme conditions of the structural modification during shearing, that is, the initial shear stress necessary to break down the structure and the one obtained at equilibrium. The relationships between  $A_b$  with respect to  $\Delta\eta_{app}$  values determined at 0.3

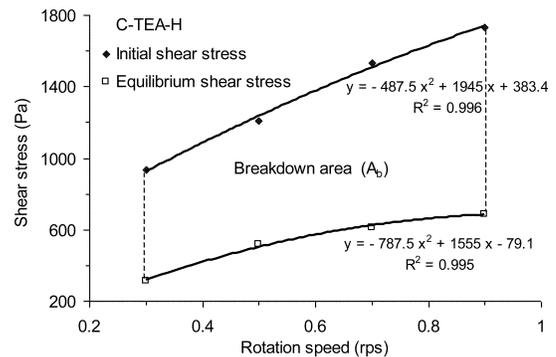


Fig. 1—Breakdown area representing degree of thixotropy for C-TEA-H mixture. (Note:  $1 \text{ Pa} = 145 \times 10^{-6} \text{ psi}$ .)

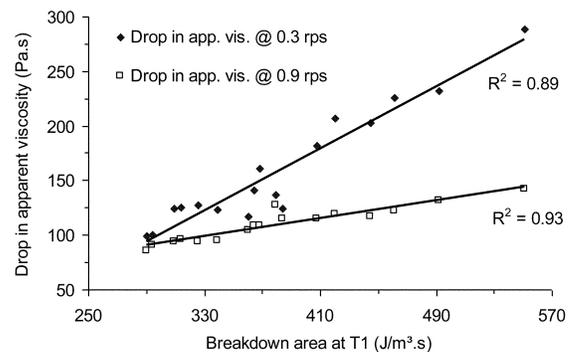


Fig. 2—Relationships between  $A_b$  and  $\Delta\eta_{app}$  values determined during  $T_1$  time interval for all of four tested mixtures. (Note:  $1 \text{ J/m}^2 \cdot \text{s} = 0.02 \text{ lb}\cdot\text{ft}/\text{ft}^3 \cdot \text{s}$ .)

Table 2—Fresh properties and thixotropic indexes of evaluated SCC

	Initial slump flow, mm	Air content, %	Temperature, °C	Unit weight, kg/m <sup>3</sup>	$h_2/h_1$ (L-box test)	Surface settlement, %	Breakdown area, J/m <sup>2</sup> ·s		
							$T_1 = 0$ to 30 minutes	$T_2 = 60$ to 90 minutes	$T_3 = 120$ to 150 minutes
C-noVEA	660	4.7	19.6	2350	0.90	0.45	290	306	330
M-noVEA	650	7.9	21.1	2195	0.85	0.39	309	362	437
N-noVEA	655	7.6	20.1	2245	0.83	0.40	314	344	402
C-TEA-L	665	8.3	20.8	2225	0.88	0.35	360	412	475
C-TEA+Cell-L	640	5.2	21.4	2290	0.83	0.31	364	405	441
C-TEA-H	650	8.7	19.0	2150	0.67	0.05	492	646	840
M-TEA-L	660	6.5	20.7	2270	0.80	0.29	384	437	502
M-TEA+Pow-L	650	5.3	20.3	2290	0.84	0.27	379	421	464
M-TEA-H	660	7.5	20.9	2250	0.62	0.08	551	730	983
N-Poly-L	640	5.3	20.2	2310	0.84	0.39	294	354	436
N-Poly-M	635	8.2	19.6	2175	0.82	0.35	368	412	457
N-Poly-H	650	8.0	22.1	2170	0.71	0.27	420	436	460
N-Pow-L	640	5.1	21.0	2310	0.87	0.44	326	390	477
N-Pow-H	635	8.3	21.9	2200	0.73	0.28	445	471	510
C-Cell-L	665	4.3	21.7	2265	0.81	0.34	339	377	412
C-Cell-M	655	4.0	20.4	2330	0.78	0.29	408	434	465
C-Cell-H	655	5.1	19.2	2315	0.67	0.22	461	480	503

Note: °F = 1.8 °C + 32; 1 kg/m<sup>3</sup> = 0.06 lbm/ft<sup>3</sup>; and 1 J/m<sup>2</sup>·s = 0.02 lb·ft/ft<sup>3</sup>·s.

and 0.9 rps during the  $T_1$  time interval are plotted in Fig. 2 for all of the 17 tested mixtures. The  $A_b$  and  $\Delta\eta_{app}$  values are shown to be well correlated, with a coefficient of correlation  $R^2$  greater than 0.89. Similar correlations were also obtained at rotational speeds of 0.5 and 0.7 rps used in the testing protocol. This indicates that both the structural breakdown method determined using four rotational speeds or the drop in apparent viscosity at a given rotational speed can be used to assess thixotropy of SCC. From a statistical point of view, however, it is to be noted that the breakdown area can be more precise in evaluating thixotropy as it requires four measurements, thus reducing the resulting relative error of the testing protocol.

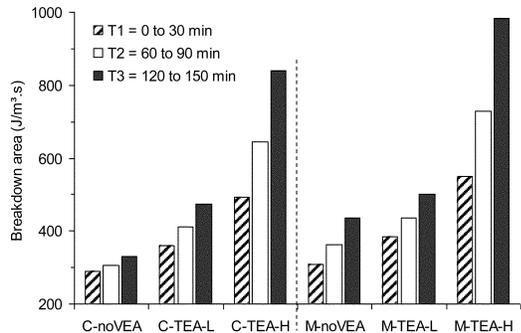


Fig. 3—Variations of thixotropy for mixtures containing various concentrations of TEA with either polycarboxylate or melamine-based HRWRA. (Note:  $1 \text{ J/m}^3 \cdot \text{s} = 0.02 \text{ lb}\cdot\text{ft}/\text{ft}^3 \cdot \text{s}$ .)

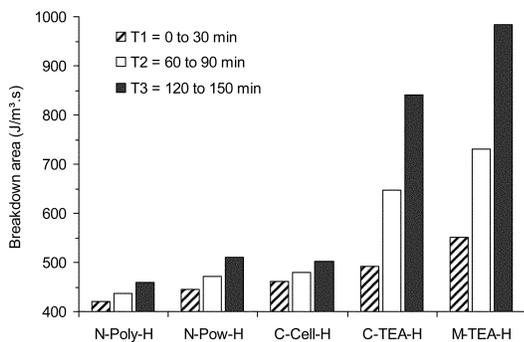


Fig. 4—Variations of thixotropy for mixtures containing high concentration of TEA or conventional VEA. (Note:  $1 \text{ J/m}^3 \cdot \text{s} = 0.02 \text{ lb}\cdot\text{ft}/\text{ft}^3 \cdot \text{s}$ .)

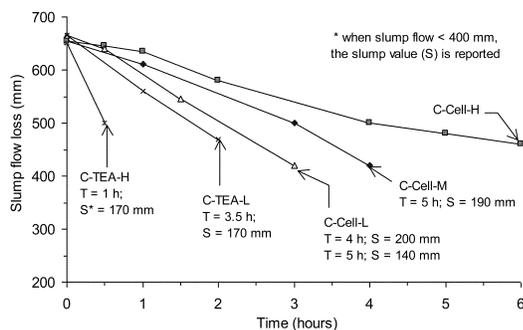


Fig. 5—Variations of slump flow loss for mixtures containing various concentrations of TEA or cellulose-based VEA. (Note:  $100 \text{ mm} = 3.9 \text{ in.}$ )

## Variations of thixotropy with TEA and/or conventional VEAs

A detailed discussion pertaining to the variations of thixotropy with conventional VEAs is given in Reference 6. In general, the test results show that the incorporation of cellulose-based VEA with polycarboxylate-based HRWRA exhibits higher thixotropy compared with similar concrete prepared with liquid or powder polysaccharide-based VEA and naphthalene-based HRWRA. The SCC with cellulose-based VEA, however, had a lower rate of increase in thixotropy with time. On the other hand, the use of conventional VEA at high concentrations of the polymer was shown to increase thixotropy compared with the reference mixtures made without any VEA as well as those containing a lower VEA concentration.

The variations of  $A_b$  values for mixtures containing various concentrations of TEA along with either polycarboxylate or melamine-based HRWRA are plotted in Fig. 3. Irrespective of the HRWRA type and time interval of rheological measurement, mixtures incorporating TEA at low or high concentration exhibited greater  $A_b$  values compared with the reference mixtures. For example, an increase in the  $A_b$  value from 309 to 384 and 551  $\text{J/m}^3 \cdot \text{s}$  ( $6.2$  to  $7.7$  and  $11 \text{ lb}\cdot\text{ft}/\text{ft}^3 \cdot \text{s}$ ) was obtained for the M-noVEA, M-TEA-L, and M-TEA-H mixtures, respectively. This is due to the thixotropic nature of the TEA that enables higher recovery of viscosity after some resting period.<sup>2,3</sup> It is to be noted that the mixtures incorporating the polycarboxylate-based HRWRA resulted in relatively lower  $A_b$  values compared with those made with melamine-based HRWRA, given the greater fluidity retention associated with the former HRWRA.<sup>11</sup>

The comparison of the effect of incorporating TEA with respect to conventional VEAs at high concentration on the variations in  $A_b$  values is plotted in Fig. 4. Mixtures containing TEA are shown to exhibit significantly higher  $A_b$  values compared with those made with conventional VEAs, particularly at  $T_2$  and  $T_3$  time intervals. For example, the increment between the  $A_b$  values determined at  $T_1$  and  $T_3$  increased from 42 to 348  $\text{J/m}^3 \cdot \text{s}$  ( $0.84$  to  $6.9 \text{ lb}\cdot\text{ft}/\text{ft}^3 \cdot \text{s}$ ) for the C-Cell-H and C-TEA-H mixtures, respectively. Mixtures containing a low or high concentration of TEA necessitated similar HRWRA demand to achieve the targeted slump flow. For example, the increase from a low to high concentration of TEA necessitated a limited increase of  $0.1 \text{ L/m}^3$  ( $0.1 \text{ oz}/\text{ft}^3$ ) of the polycarboxylate-based HRWRA (C-TEA-L and C-TEA-H mixtures). Such an increase was  $4.3 \text{ L/m}^3$  ( $4.3 \text{ oz}/\text{ft}^3$ ) for the C-Cell-L and C-Cell-H mixtures containing the cellulose-based VEA (Table 1). This can affect the rate of build-up of cohesion over time as well as the loss in slump flow, as illustrated in Fig. 5 for mixtures made with various concentrations of TEA or cellulose-based VEA. A slump flow of 170 mm (6.6 in.) was obtained for the C-TEA-H mixture 1 hour after casting, whereas a slump flow of 450 mm (17.5 in.) was still measured after 6 hours for the C-Cell-H mixture. Therefore, higher TEA concentration associated with similar HRWRA demand can result in increased degree of cohesiveness and thixotropy. It is to be noted that similar tendencies are obtained when comparing mixtures made with low concentrations of TEA or conventional VEAs.

The variations in  $A_b$  values for mixtures incorporating TEA alone or in combination with cellulose or powder polysaccharide-based VEA are plotted in Fig. 6. Irrespective of the HRWRA type (either polycarboxylate or melamine-

based), such combinations did not result in any significant change in the  $A_b$  values determined at  $T_1$ . For example, approximate  $A_b$  values of  $362 \text{ J/m}^3 \cdot \text{s}$  ( $7.24 \text{ lb} \cdot \text{ft}/\text{ft}^3 \cdot \text{s}$ ) were obtained for the C-TEA-L and C-TEA+Cell-L mixtures (Table 2). This indicates that the rate of build-up of viscosity is predominantly affected by the TEA. For measurements conducted at longer elapsed times ( $T_2$  and  $T_3$ ), combinations of TEA with conventional VEA appear to reduce the spread of increment in thixotropy. This can be due to the increased HRWRA dosage used in mixtures containing such combinations (Table 1), thus reducing the rate of increase in thixotropy.

### Variations of formwork lateral pressure

A typical diagram showing the variations of pressure envelope for the C-TEA-H mixture is plotted in Fig. 7. Right after casting, the maximum pressure was measured at 250 mm (9.7 in.) from the base of the experimental column. A significant and rapid change in the pressure envelope took place following casting. After 110 minutes, the maximum pressure was approximately 40% of hydrostatic.

Ratios of maximum measured pressure to the corresponding hydrostatic pressure ( $P(\text{maximum})/P(\text{hydrostatic})$ ) are compared to evaluate the effect of TEA or VEA type and concentration on lateral pressure development. The hydrostatic pressure is calculated as  $P_{hyd} = \rho \times g \times h$ ; where  $\rho$ ,  $g$ , and  $h$  refer to the concrete unit weight, gravity, and height of the formwork, respectively. Table 3 summarizes the relative pressure values determined right after filling of the experimental column and then after 100 and 200 minutes of elapsed time for all of the tested mixtures. The table also gives the rates of pressure drop that correspond to the time required to reduce the maximum lateral pressure by 10, 25, and 40%. Such elapsed time periods can be of special interest for contractors and engineers for better scheduling of deep concrete placements.

*Effect of conventional VEAs on lateral pressure variations—* The discussion regarding the effect of conventional VEAs on the variations in lateral pressure is given in Reference 6. In general, the SCC made with the lowest VEA concentration exhibited lower lateral pressure development compared with reference mixtures made without any VEA and 0.36 w/cm as well as those containing medium or high concentrations of conventional VEA. This was attributed to the coupled effect of VEA and HRWRA demand. The use of VEA can display increased build-up of cohesiveness, though it should be kept to a minimum to reduce the HRWRA demand. Mixtures with higher VEA and HRWRA contents can exhibit better fluidity retention, thus causing the material to behave like a fluid for longer elapsed times and continue to exert high lateral pressure despite the considerable increase in viscosity of the matrix.<sup>6</sup>

*Variations of pressure with TEA and/or conventional VEAs—* The variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing various concentrations of TEA with either polycarboxylate or melamine-based HRWRA are plotted in Fig. 8 and 9, respectively. The reference mixtures made with 0.36 w/cm and no TEA are also included. Irrespective of the type of HRWRA, the use of TEA at low or high concentration resulted in a considerable reduction in initial pressure compared with the reference mixtures. For example, the M-noVEA, M-TEA-L, and M-TEA-H mixtures developed maximum relative pressures of 93%, 84%, and 78%, respectively. Furthermore, the rate of pressure drop increased significantly with the incorporation of the TEA, especially when used at high concentration. The time for

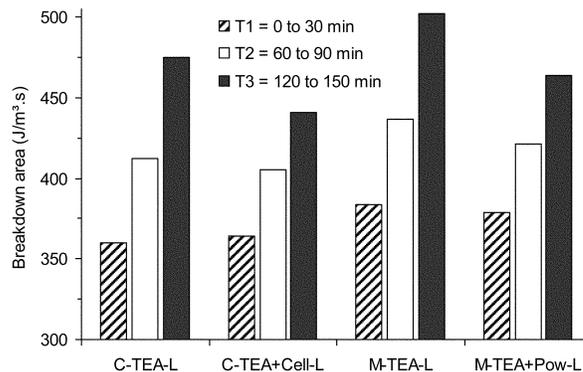


Fig. 6—Variations of thixotropy for mixtures containing combinations of TEA with conventional VEA. (Note:  $1 \text{ J/m}^3 \cdot \text{s} = 0.02 \text{ lb} \cdot \text{ft}/\text{ft}^3 \cdot \text{s}$ .)

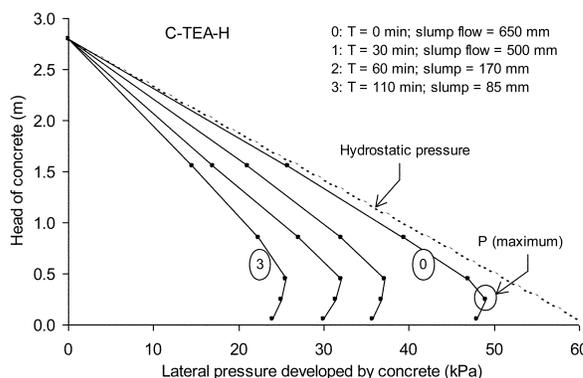


Fig. 7—Variations of lateral pressure envelope with time for C-TEA-H mixture. (Note:  $1 \text{ m} = 3.28 \text{ ft}$ .)

Table 3—Rates of lateral pressure drop with time for evaluated SCC

	$P(\text{maximum})/P(\text{hydrostatic})$ , %			Elapsed time necessary to decrease initial pressure, minutes		
	At 0 minutes	At 100 minutes	At 200 minutes	By 10%	By 25%*	By 40%*
C-noVEA	91.0	88.7	84.7	335	—	—
M-noVEA	92.7	69.1	54.5	60	150	240
N-noVEA	91.4	79.8	70.4	95	240	380
C-TEA-L	88.1	70.9	62.5	82	205	—
C-TEA+Cell-L	88.6	70.9	61.2	79	200	340
C-TEA-H	81.9	44.1	—	26	65	100
M-TEA-L	84.4	51.1	39.0	44	110	220
M-TEA+Pow-L	85.8	54.2	42.6	46	115	190
M-TEA-H	77.8	30.9	—	21	55	85
N-Poly-L	93.1	75.3	63.8	70	175	280
N-Poly-M	93.3	81.8	72.9	100	250	400
N-Poly-H	95.4	88.8	82.6	155	390	620
N-Pow-L	93.0	69.6	56.2	55	140	220
N-Pow-H	96.4	92.5	87.4	225	560	—
C-Cell-L	89.8	76.3	68.7	100	250	400
C-Cell-M	91.6	89.2	86.9	425	—	—
C-Cell-H	94.5	91.9	90.9	645	—	—

\*Indicates that lateral pressure measurements were extrapolated to determine corresponding elapsed time. Some values were not given as they exceeded initial setting time of mortar extracted from SCC.

25% decrease from initial pressure dropped from 750 to 205 and 65 minutes for the C-noVEA, C-TEA-L, and C-TEA-H mixtures, respectively. As already noted, this can be related to the thixotropic nature of the TEA that enables the material to rapidly recover its cohesiveness and increase its shear strength resistance when left at rest.

The effect of combining powder polysaccharide or cellulose-based VEA with low content of the TEA is shown to lead to similar initial maximum relative pressure and rate of pressure drop with time compared with mixtures containing the TEA alone at low concentration (Fig. 8 and 9). For example, the

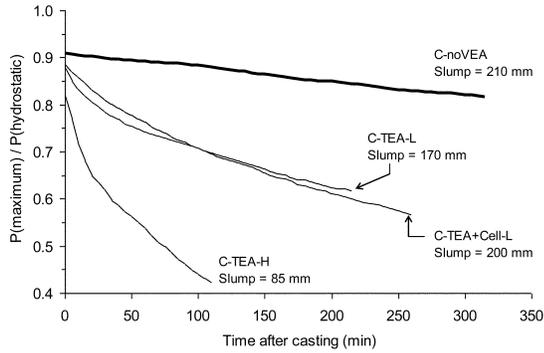


Fig. 8—Variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing various concentrations of TEA and polycarboxylate-based HRWRA. (Note: 100 mm = 3.9 in.)

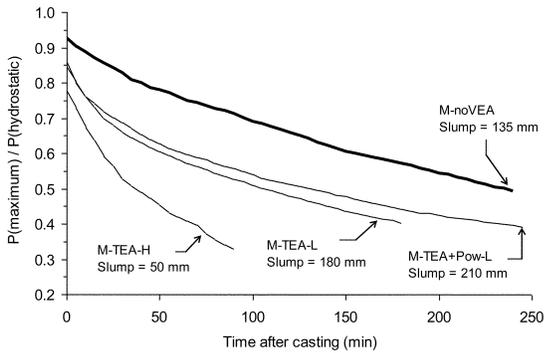


Fig. 9—Variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing various concentrations of TEA and melamine-based HRWRA. (Note: 100 mm = 3.9 in.)

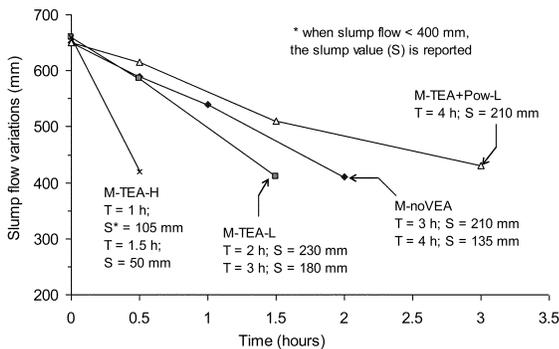


Fig. 10—Variations of slump flow loss for mixtures containing melamine-based HRWRA and various concentrations of TEA. (Note: 100 mm = 3.9 in.)

initial relative pressure remained at 88% for the C-TEA-L and C-TEA+Cell-L mixtures, and their rates of pressure drop corresponded to approximately 200 minutes for 25% decrease from initial pressure (Table 4). This suggests that the rate of build-up of viscosity soon after casting, and thereby lateral pressure development, is predominantly affected by the TEA. The effect of combining the conventional VEA with TEA, however, can enhance the retention in concrete consistency, given the higher HRWRA demand (Table 2). As shown in Fig. 10, a slump of 210 mm (8.2 in.) can be obtained after 4 hours from casting for the M-TEA+Pow-L mixture compared with 180 mm (7 in.) after 3 hours in the case of the M-TEA-L mixture.

The comparison of the  $P(\text{maximum})/P(\text{hydrostatic})$  values resulting from mixtures containing a low concentration of TEA or various conventional VEAs is plotted in Fig. 11. Mixtures prepared with powder or liquid polysaccharide-based VEA (N-Pow-L or N-Poly-L, respectively) developed the highest initial residual pressures of 93%. Lower relative values of 88% and 84% were obtained for the C-TEA-L and M-TEA-L mixtures, respectively. On the other hand, the SCC made with TEA and melamine-based HRWRA exhibited the highest rate of pressure drop with time. For example, the time periods necessary for a 25% decrease from initial pressure dropped from 250 and 175 to 110 minutes for the C-Cell-L, N-Poly-L, and M-TEA-L mixtures, respectively (Table 3). It is to be noted that the C-TEA-L mixture containing polycarboxylate-based HRWRA had a lower rate of pressure

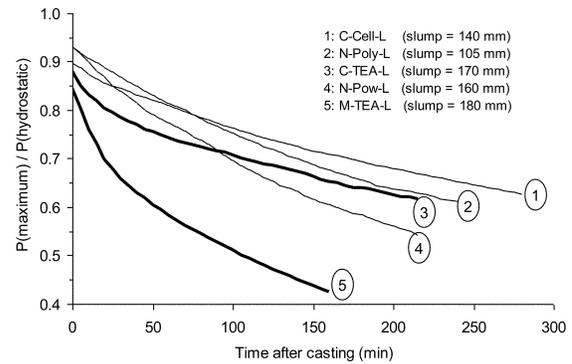


Fig. 11—Variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing low concentration of TEA or conventional VEAs. (Note: 100 mm = 3.9 in.)

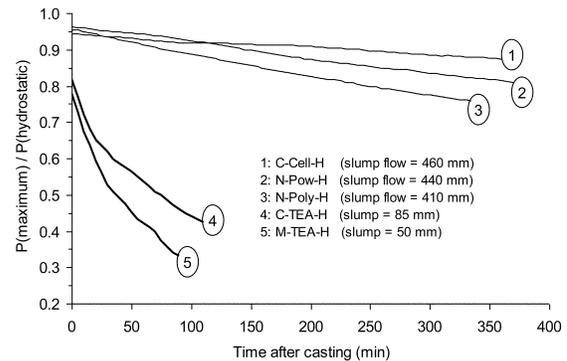


Fig. 12—Variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing high concentration of TEA or conventional VEAs. (Note: 100 mm = 3.9 in.)

drop, given the increased fluidity retention associated with such HRWRA.

Similar trends, yet much sharper, are obtained when comparing the TEA with conventional VEAs at a high concentration (Fig. 12). Initial residual pressures of 78% and 82% were registered for the M-TEA-H and C-TEA-H mixtures, respectively, compared with residual pressure values greater than 95% for the mixtures made with conventional VEAs. A significant and sharp drop in pressure with time occurred for both mixtures incorporating the TEA. Higher TEA concentration with relatively low HRWRA demand can increase the loss in slump flow, thus resulting in lower lateral pressure development. For example, slump values of approximately 70 mm (2.7 in.) were measured for the M-TEA-H and C-TEA-H mixtures (Fig. 12). In contrast, slump flow values of approximately 440 mm (17.2 in.) were obtained after 6 hours from casting in the case of the mixtures made with a high concentration of conventional VEAs, given their higher HRWRA demand.

The variations of  $P(\text{maximum})/P(\text{hydrostatic})$  values for mixtures containing combinations of TEA with conventional VEA at a low concentration with respect to those made with only conventional VEA are plotted in Fig. 13. Despite the relatively lower loss in slump flow, mixtures made with TEA and VEA are shown to reduce the initial maximum pressure and increase the rate of pressure drop. For example, the time

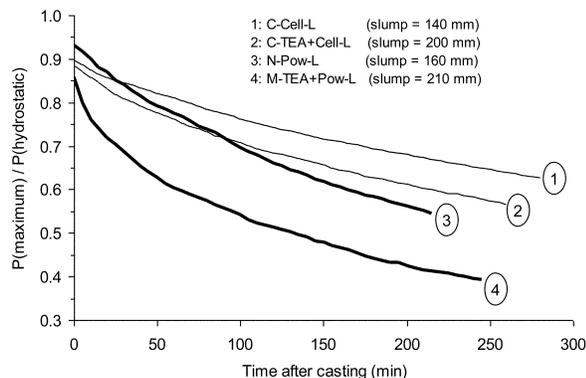


Fig. 13—Effect of combining TEA with conventional VEAs at low concentration on variations in  $P(\text{maximum})/P(\text{hydrostatic})$  values. (Note: 100 mm = 3.9 in.)

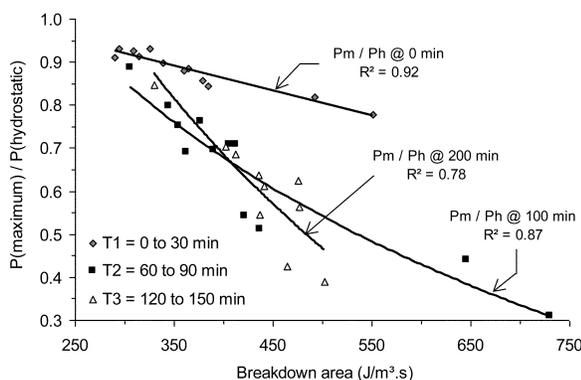


Fig. 14—Relationship between thixotropy and lateral pressure for mixtures containing various concentrations of TEA and/or low concentration of conventional VEAs. (Note:  $1 \text{ J/m}^2 \cdot \text{s} = 0.02 \text{ lb}\cdot\text{ft}/\text{ft}^2 \cdot \text{s}$ .)

for 25% decrease from initial pressure reduced from 250 to 200 minutes for the C-Cell-L and C-TEA+Cell-L mixtures, whereas the slump consistency measured at the end of pressure monitoring was 140 and 200 mm (5.4 and 7.8 in.), respectively. Such TEA and VEA combinations can result in increased shear thinning behavior whereby higher viscosity at rest can reduce the lateral pressure. Given that the concrete was mixed before conducting the slump test, however, a considerable drop in viscosity can occur leading to higher slump consistency. Therefore, concrete containing such combinations can be of special interest at the job site as it develops lower pressure while maintaining the flowability for longer elapsed times.

### Relationships between lateral pressure and thixotropy

As indicated in Reference 6, no correlation can be established between thixotropy and lateral pressure resulting from SCC mixtures containing various concentrations of a given type of conventional VEA. This was attributed to the HRWRA demand that increases significantly with the incorporation of greater VEA concentration, thus leading to higher lateral pressure development despite the considerable increase in thixotropy.

The relationship between the  $A_b$  values evaluated during the first 30-minute time interval of rheological measurements and the corresponding  $P(\text{maximum})/P(\text{hydrostatic})$  determined right after filling the formwork is illustrated in Fig. 14 for mixtures containing various concentrations of TEA and/or low concentrations of conventional VEAs. The reference mixtures made without any VEA are also included. This figure also illustrates the relationships between the  $A_b$  values evaluated during the  $T_2$  and  $T_3$  intervals and the  $P(\text{maximum})/P(\text{hydrostatic})$  calculated at 100 and 200 minutes after casting, respectively. For the three correlations, the  $P(\text{maximum})/P(\text{hydrostatic})$  value decreases for the mixtures having greater  $A_b$  values. Such a decrease becomes more pronounced with time as indicated by the sharper slope obtained at 100 and 200 minutes after casting.

Lateral pressure developed by plastic concrete is highly affected by the development of shear strength properties, namely internal friction and cohesion.<sup>12</sup> On the other hand, it is well established that thixotropy is a reversible phenomenon that takes place as soon as the material is left standing at rest.<sup>9</sup> The onset of the structural build-up phase causes the structure to flocculate and display increased cohesiveness. For mixtures having a greater degree of thixotropy, the increased kinetics of the build-up phase can cause a faster increase in the shear strength properties, thus reducing the development of higher lateral pressure.<sup>4,5</sup>

### CONCLUSIONS

Based on the results presented in this paper, the following conclusions can be made:

1. The incorporation of TEA with either a melamine- or polycarboxylate-based HRWRA can exhibit a higher degree of thixotropy compared with mixtures made with conventional VEAs, such as liquid polysaccharide, powder polysaccharide, or cellulose-based;

2. The SCC made with the lowest conventional VEA concentration is shown to exhibit lower lateral pressure development compared with reference mixtures made without any VEA and 0.36 w/cm as well as those containing medium or high concentration of conventional VEA. This was attributed to the coupled effect of VEA and HRWRA demand;

3. Unlike conventional VEAs, the effect of increasing the TEA concentration from low to high is shown to reduce the initial residual pressure and increase the rate of pressure drop. This is due to the thixotropic nature of the TEA accompanied with similar HRWRA demand that enable fast and significant recovery of viscosity following casting;

4. The effect of combining a conventional VEA with TEA at low concentrations is beneficial in reducing the residual pressure and increasing the rate of pressure drop compared with mixtures containing only conventional VEA at similar concentration. Such combinations can maintain flowability for longer elapsed times;

5. Mixtures containing combinations of powder polysaccharide or cellulose-based VEA with the TEA at a low concentration exhibited similar lateral pressure development compared with those made only with TEA. This suggests that the rate of build-up of viscosity is predominately affected by the TEA; and

6. Thixotropy determined from SCC mixtures containing various concentrations of TEA and/or a low concentration of conventional VEAs can be used to evaluate the initial lateral pressure exerted on the formwork and its rate of drop with time. The more the degree of thixotropy is higher, the less the mixture develops lateral pressure.

## REFERENCES

1. Khayat, K. H., "Viscosity-Enhancing Admixtures for Cement-Based Materials—An Overview," *Cement and Concrete Composites*, V. 20, 1998, pp. 171-188.

2. Maeder, U.; Wombacher, F.; and Lichtsteiner, F., "Thixotropic Agents for Cementitious Materials," *Superplasticizers and Other Chemical Admixtures in Concrete*, Proceedings of the Fifth CANMET/ACI International Conference, Supplementary Papers, Rome Italy, V. M. Malhotra, ed., 1997, pp. 185-198.

3. Khayat, K. H.; Saric-Coric, M.; and Liotta, F., "Influence of Thixotropy on Stability Characteristics of Cement Grout and Concrete," *ACI Materials Journal*, V. 99, No. 3, May-June 2002, pp. 234-241.

4. Assaad, J., and Khayat, K. H., "Effect of Coarse Aggregate Characteristics on Lateral Pressure Exerted by Self-Consolidating Concrete," *ACI Materials Journal*, V. 102, No. 3, May-June 2005, pp. 145-153.

5. Assaad, J.; Khayat, K. H.; and Mesbah, H., "Variations of Formwork Pressure with Thixotropy of Self-Consolidating Concrete," *ACI Materials Journal*, V. 100, No. 1, Jan.-Feb. 2003, pp. 29-37.

6. Assaad, J., and Khayat, K. H., "Effect of Viscosity-Enhancing Admixtures on Formwork Pressure and Thixotropy of Self-Consolidating Concrete," *ACI Materials Journal*, V. 103, No. 4, July-Aug. 2006, pp. 280-287.

7. Petersson, Ö.; Billberg, P.; and Van, B. K., "A Model for Self-Compacting Concrete," *Proceedings of the International RILEM Conference on Production Methods and Workability of Concrete*, P. J. M. Bartos, D. L. Marris, and D. J. Cleland, eds., Chapman & Hall, Paisley, 1996, pp. 483-490.

8. Manai, K., "Evaluation of the Effect of Chemical and Mineral Admixtures on the Workability, Stability, and Performance of Self-Compacting Concrete," Master's thesis, Université de Sherbrooke, Sherbrooke, QC, Canada, 1995, 182 pp.

9. Assaad, J.; Khayat, K. H.; and Mesbah, H., "Assessment of Thixotropy of Flowable and Self-Consolidating Concrete," *ACI Materials Journal*, V. 100, No. 2, Mar.-Apr. 2003, pp. 99-107.

10. Legrand, C., "Contribution to Study of the Rheology of Fresh Concrete," Doctoral thesis, Université Paul Sabatier de Toulouse, France, 1971, 150 pp. (in French)

11. Ramachandran, V. S.; Malhotra, V. M.; Jolicoeur, C.; and Spiratos, N., "Superplasticizers: Properties and Applications in Concrete," CANMET, MTL 97-14 (TR), 1998, 400 pp.

12. Gardner, N. J., and Ho, P. T.-J., "Lateral Pressure of Fresh Concrete," *ACI JOURNAL, Proceedings* V. 76, No. 7, July 1979, pp. 809-820.

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