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Effect of mineral admixtures on formwork pressure of self-consolidating concrete

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ABSTRACT

Owing to enhanced filling ability, self-consolidating concrete offers accelerated casting and superior quality control during construction. However, its high fluidity and high placement rate increase the lateral pressure on the formwork, necessitating an extensive supporting system to retain fresh mixtures in a desired shape. Current recommendations of formwork design for self-consolidating concrete adopt the concept of hydrostatic pressure, even though the measured pressure could be less than the recommended level. This study shows that mineral admixtures such as processed clays can appreciably lessen the formwork lateral pressure. In addition, the correlation between the formwork pressure response and the loss of slump flow is derived, providing an approximate method to estimate the reduction in formwork pressure.

1. Introduction

Self-consolidating concrete (SCC) is a new type of concrete developed to address durability issues associated with inadequate consolidation of ordinary concrete [1,2]. SCC flows into the furthest reaches of intricate formwork without additional vibrating consolidation, and it can mitigate air voids around congested reinforcing bars that lead to durability problems. However, because of the high flowability and the higher placement rate when using SCC, the lateral pressure on the formwork is substantially greater than that of ordinary concrete. ACI Committees 237 [3] suggests relatively heavier formwork for this material be designed for the hydrostatic head of plastic concrete on the basis of the following equation: $p = wh$, where p is the lateral pressure, w is the unit weight of concrete, and h is the depth of plastic concrete.

While the stiffening properties of SCC are not well understood, it was observed that the maximum lateral pressure measurements of SCC formwork are below the hydrostatic pressure [4–6]. The formwork pressure is affected by chemical admixtures such as high-range water-reducing admixture (HRWRA) and viscosity modifying admixture (VMA) [7–9]. In this study, the effect of mineral admixtures on the formwork pressure is investigated: incorporating mineral admixtures can reduce the formwork pressure of SCC. Three types of mineral admixtures were investigated: (1) silica fume; (2) calcined kaolin clay; and (3) wet-processed attapulgite clays. The formwork pressure of SCC mixtures incorporating these mineral admixtures was characterized in tandem with recording the loss of slump flow. A correlation between the aforementioned variables was also proposed to estimate the formwork lateral pressure in the field.

2. Experimental investigation

2.1. Materials preparation

In order to analyze the effects of mineral admixtures, other factors affecting the formwork pressure such as water–cementitious materials ratio [7] were kept constant. Table 1 shows the basic mix proportion used for all mixtures. Type I Portland cement and Class F fly ash were used in this study. Pea gravel having a size range between 4.75 mm and 12.5 mm was used except for mixtures indicated with an asterisk in Table 2. The asterisked mixes were produced with river gravel having a maximum size of 19 mm. All aggregates were used in an oven-dried condition. Chemical admixtures to control the slump flow within a narrow range were adjusted as shown in Table 2. HRWRA is a polycarboxylate-based admixture with a solid content of 30% by weight and 1.04 specific gravity. VMA is synthetic with a solid content of 3% and 1.002 specific gravity.

Groups D, E, and F are mixtures containing silica fume, calcined kaolin clay, and wet-processed attapulgite clay, respectively. Silica fume (SF) is a byproduct pozzolanic material. Purified calcined kaolin clay, generally called metakaolin (MK), also provides a pozzolanic reaction, and it is usually used for the production of high-strength concrete. The purified wet-processed attapulgite

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Table 1
Mix proportions.

Ingredient	Water	Cement	Fly ash	Sand	Gravel
Amount[a]	182	338	154	879	824

[a] The composition is expressed in kg for producing 1 m^3 concrete, where the fresh mixture density was assumed as 2400 kg/m^3.

clay is composed of magnesium alumino-silicate (MA). The oxide compositions of the mineral admixtures are listed in Table 3, including those of cement and fly ash. In addition, it should be noted that the particle sizes of these mineral admixtures are generally finer than those of cement and fly ash when they are well-dispersed in an aqueous solution. The average particle sizes are approximately 0.2 μm for SF, 1.20 μm for MK, and 1.75 μm for MA. The particle size distribution reportedly affects the rheological properties of fresh mixtures [10,11].

The mixtures were prepared after approximately 20 min mixing. A 40 L capacity and 26 rpm drum mixer was used to prepare 30 L batch of each mixture proportion. The initial slump flow (d_f) immediately after the mixing was measured following ASTM C 1611 [12], and the time to obtain the slump flow (stoppage time, t_f) was also measured. The results are reported in Table 2.

2.2. Formwork pressure test

2.2.1. Test methods

A formwork pressure device developed in a previous study [13] to simulate the lateral formwork pressure when vertical pressure is applied to concrete mixtures was employed. The pressure vessel is a 1 cm thick, 15 cm inner diameter, 30 cm tall steel cylinder that can be divided into two halves, as shown in Fig. 1. Vertical pressure is applied to the concrete mixture using a steel piston loaded by a closed-loop hydraulic testing machine, and a 22 kN load cell is fitted to measure the applied load. The lateral pressure was measured from direct contact with 345 kPa (50 psi) capacity transducers. The pore water pressure could also be measured with a filter and a water chamber connected to the pressure vessel, but in this study only the total pressure was measured.

Basically, the formwork pressure test measures the intrinsic pressure response of the mixture, without considering extrinsic factors such as formwork friction and flexibility. The intrinsic pressure response, the lateral-to-vertical pressure ratio, is a sort of material property, and the effect of mineral admixtures on the pressure response will be investigated.

Table 3
Oxide composition of mineral admixtures.

Oxide composition (%)	Cement	Fly ash	SF	MK	MA
Lime (CaO)	63.8	5.4	0.94	0.02	2.09
Silica (SiO_2)	20.1	47.5	95.5	53	55.1
Alumina (Al_2O_3)	4.8	26.4	0.41	43.8	10.5
Magnesia (MgO)	2.5	0.9	0.24	0.03	9.79
Ferric oxide (Fe_2O_3)	2.7	12.2	0.28	0.43	3.68
Sulfur trioxide (SO_3)	2.5	1.1	–	0.03	–
Titanium dioxide (TiO_2)	–	–	–	1.7	0.47
Loss of ignition (%)	1.42		2.04	0.46	14.6

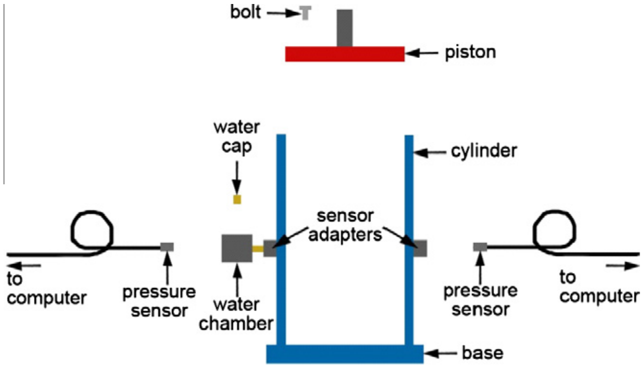

Fig. 1. Formwork pressure testing device.

The measured lateral pressure in relation to the applied vertical pressure showed loading-time dependency, and can be analyzed with the two-function model introduced by Kwon et al. [14]. Fig. 2a shows an example of three time-variant lateral pressures: $\sigma_L(t, t' = 0)$, $\sigma_L(t, t' = 1)$, and $\sigma_L(t, t' = 2)$, where t is the current time and t' is the time of loading. The corresponding vertical pressure $\sigma_V(t \geqslant 0,\ t' = 0) = 258$ kPa, $\sigma_V(t \geqslant 1,\ t' = 1) = 258$ kPa, or $\sigma_V(t \geqslant 2,\ t' = 2) = 258$ kPa is applied to each of three samples having the same mix proportion. Only $\sigma_V(t, t' = 0)$ is shown in Fig. 2a for simplicity. The decreasing lateral pressures induced by applying the same amount of vertical pressure vary according to the loading time (t').

Table 2
Amount of admixtures used and initial slump flow size.

Label	Admixtures			Slump flow		Formwork pressure	
	HRWRA [%][a]	VMA [%][a]	Mineral[b]	d_f [cm]	t_f [sec]	a [h^{-1}]	b [h^{-1}]
C1	0.575	0.40	–	61.6	46.8	0.216	0.346
C2	0.650	0.40	–	59.1	40.0	0.219	0.284
C3	0.700	0.40	–	68.6	45.0	0.206	0.055
D1	1.253	0.40	20% SF	69.3	70.0	0.114	0.119
D2	0.885	0.40	10% SF	66.0	59.0	0.197	0.269
D3	0.650	0.40	5% SF	70.5	60.0	0.149	0.266
E1	0.716	0.40	10% MK	71.1	61.0	0.083	0.472
E2	0.474	0.40	5% MK	62.2	24.2	0.139	0.589
E3	0.575	0.40	2% MK	61.6	46.4	0.203	0.262
E4	0.575	0.40	1% MK	57.8	37.9	0.124	0.347
E5[c]	0.476	0.30	1% MK	66.0	31.4	0.113	0.330
F1	0.981	0.40	1% MA	56.5	31.0	0.158	0.242
F2	0.899	–	0.66% MA	70.5	66.0	0.144	0.165
F3	0.600	–	0.33% MA	59.7	37.0	0.145	0.455
F4[c]	0.552	0.30	0.33% MA	62.9	18.0	0.168	0.467

[a] Dosages are expressed in the chemical admixture–powder ratio by weight.

[b] Mineral admixture replaces the cement-fly ash binder, and the replacement ratio is calculated by weight.

[c] The asterisked mixes were produced with river gravel having a maximum size of 19 mm, but the others used pea gravel having a size range between 4.75 mm and 12.5 mm.

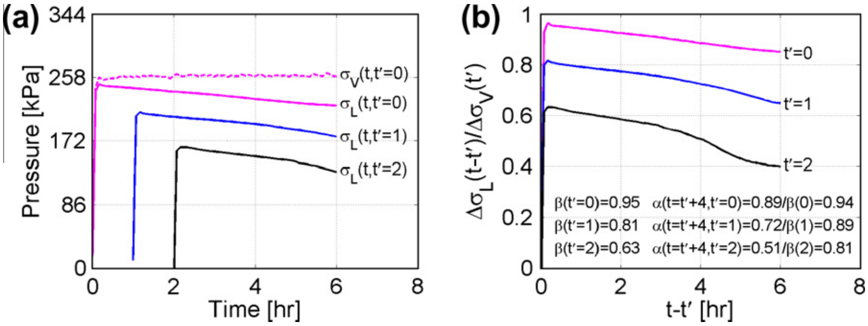

Fig. 2. Formwork pressure test results: (a) applied and measured pressures; and (b) lateral-to-vertical pressure ratio.

Two functions were introduced to describe the loading-time dependency. The first instantaneous lateral-to-vertical pressure ratio is defined as Eq. (1), and the second ratio in Eq. (2) is the delayed response of the lateral pressure:

$$\beta(t') = \frac{\sigma_L(t = t', t')}{\sigma_V(t = t', t')} \tag{1}$$

$$\alpha(t, t') = \frac{\sigma_L(t = t, t')}{\sigma_L(t = t', t')} = \frac{\sigma_L(t, t')}{\beta(t')\sigma_V(t = t', t')} \tag{2}$$

The trend of the functions over the loading duration $(t - t')$ is shown in Fig. 2b, where the y-intercepts become $\beta(t')$ because the sustained ratio is defined as 1.0 at the initial state: $\alpha(t = t', t') = 1$. The two-function model can be expressed as the following incremental form:

$$\Delta\sigma_L(t, t') = \alpha(t, t')\beta(t')\Delta\sigma_V(t') \tag{3}$$

If casting is finished before the final setting time of concrete, the two functions in Eqs. (2) and (3) decrease over time, and each of them can be simplified as a linear function [15]. The instantaneous and delayed responses were assumed to be $\beta(t') = 1 - bt'$ and $\alpha(t, t') = 1 - a^2t'(t - t')$, respectively. Therefore, the formwork pressure of SCC could be fully expressed with two coefficients: instantaneous coefficient b and delayed coefficient a.

A specific loading protocol was used to obtain both coefficients. Fundamentally, as shown in Fig. 2, several specimens were required to complete a series of pressure measurements at different loading times. The use of stepwise loading made it possible to use only one specimen instead of a series of specimens (see Figs. 3 and 4). A certain amount of vertical pressure at each loading time (0 h, 0.5 h, 1.0 h, and 1.5 h) was sequentially applied, where the increment of each step was 86 kPa for 2 min. The points in Figs. 3b and 4b are the instantaneous lateral-to-vertical pressure ratio $\beta(t')$ at each increment, and the decreasing slopes become the instantaneous coefficient, b. The points in Figs. 3c and 4c are the decreasing lateral pressure ratio $\alpha(t, t')$ for the duration of $t - t'$, and their slopes become the square of the delayed coefficient, a^2. Both coefficients were determined by least-squares fitting with a constrained condition. Details can be found elsewhere [15]. Finally, the determined coefficients are reported in Table 2.

2.2.2. Test results

The measured lateral pressures of Groups C and F are shown in Figs. 3a and 4a, respectively. While the applied vertical pressure

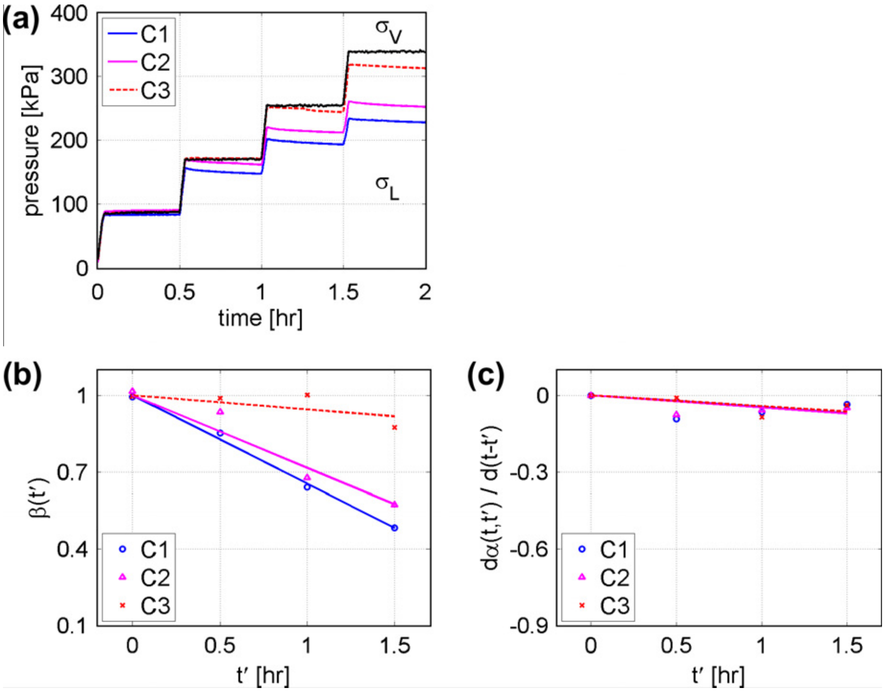

Fig. 3. Group C: (a) pressure measurement; (b) instantaneous; and (c) delayed response.

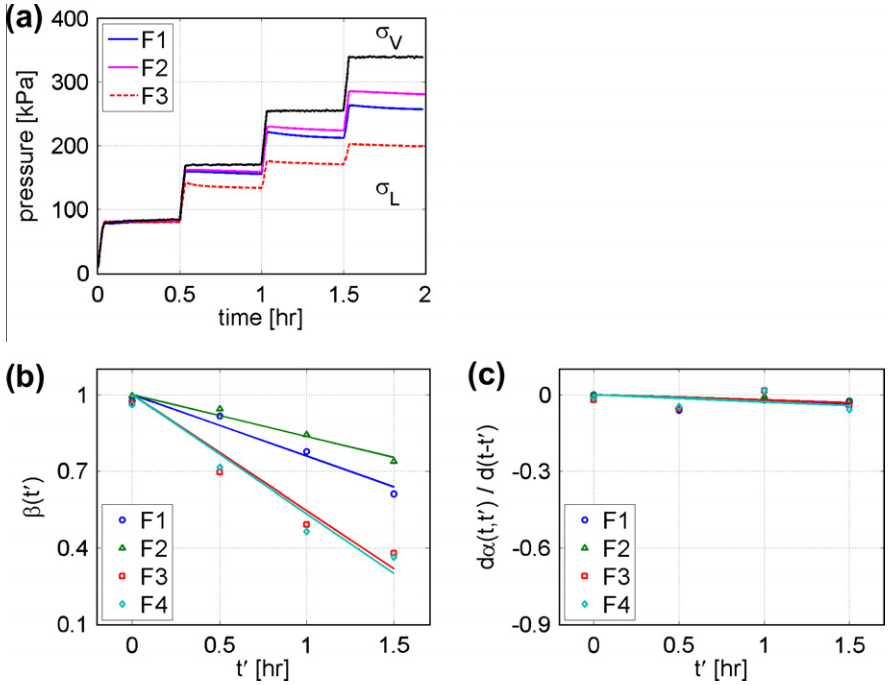

Fig. 4. Group F: (a) pressure measurement; (b) instantaneous; and (c) delayed response.

(σ_V), the solid black line, was being applied, the lateral pressure (σ_L) of each mix was measured, and its amount is clearly less than the amount of applied vertical pressure. The instantaneous responses, $\beta(t')$, are significantly different from each other, but the delayed responses, $\alpha(t, t')$, fluctuate within a narrow range. This can be seen in Table 2: the values of a range from 0.1 to 0.2. All results of the other groups also show that $\beta(t')$ is more sensitive than $\alpha(t, t')$. In addition, the contribution of $\alpha(t, t')$ to reduction of formwork pressure is less significant than that of $\beta(t')$, as reported in a previous study [15]. Therefore, the instantaneous coefficient, b, for $\beta(t')$ will be discussed as a major variable describing decrease in lateral formwork pressure.

The effect of chemical admixtures is reproduced from [15], in order to provide a reference for comparison. Fig. 5 presents a comparison for Mixes C1, C2, and C3, which have different amounts of HRWRA, where the used amounts are presented at the top of the figure. Increasing the amount of HRWRA decreases the instantaneous coefficient, which implies that the use of more HRWRA causes higher lateral pressure. This observation corresponds to results by other researchers [7], where a mixture having a lower water–cement ratio needs a larger amount of HRWRA and shows a slower drop in lateral pressure.

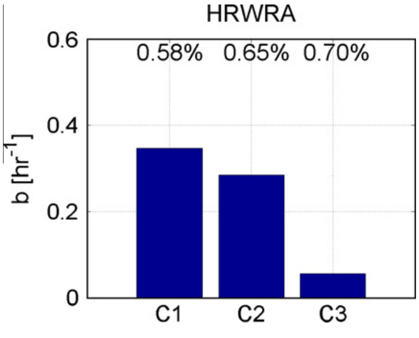

Fig. 5. Effect of chemical admixtures on the reduction slope.

The influence of mineral admixtures can be ascertained via an examination of Groups D, E, and F. It should be noted that the amount of HRWRA to maintain the desired slump flow was also adjusted. The measured formwork pressure depends on both the HRWRA dosage and the amount of mineral admixtures incorporated. This makes it difficult to extract the isolated influence of the mineral admixtures on the formwork pressure response. Nevertheless, a qualitative comparison was conducted as follows.

Fig. 6 shows three comparison plots, where each group has mixtures using a similar amount of HRWRA. First, in Fig. 6a, incorporating 0.33% MA contributes to a formwork pressure reduction compared to C1 and C2. However, the effects of 5% SF and 2% MK were not substantial. If the amount of MK was increased, as shown in Fig. 6b, an appreciable effect could be observed: 10% MK enhanced the formwork pressure reduction. Increasing the amount of SF was also effective for reduction of formwork pressure. Note that the effect of the mineral admixtures is likely to be greater than that shown in Fig. 6c, because the amount of HRWRA used was much larger than that of the reference (Mix C3). One of the more interesting findings is that 1% MA gave a similar effect with the case of 10% SF: the processed clay is more beneficial for reducing formwork pressure than silica fume.

2.3. Loss of slump flow

Due to the difficulties in applying a rheometer test for concrete mixtures, researchers have tried to adopt the slump flow test as a simplified rheological test [16–18]. The important finding was that the slump flow (d_f) is linked to the yield stress of concrete, and various correlating formula between these two variables have been reported. In addition, viscosity can be related to the time to spread, and hence the stoppage time (t_f) is expected to be a good indicator for concrete viscosity. A previous study [18] supports the use of the stoppage time, where the yield stress over the plastic viscosity (τ_y/η_p) showed a good correlation with the stoppage time. In the present study, the average spreading rate (the slump flow over the stoppage time, d_f/t_f) was adopted as an indicator to describe evolution of the plastic viscosity. A fluid having higher plastic viscosity

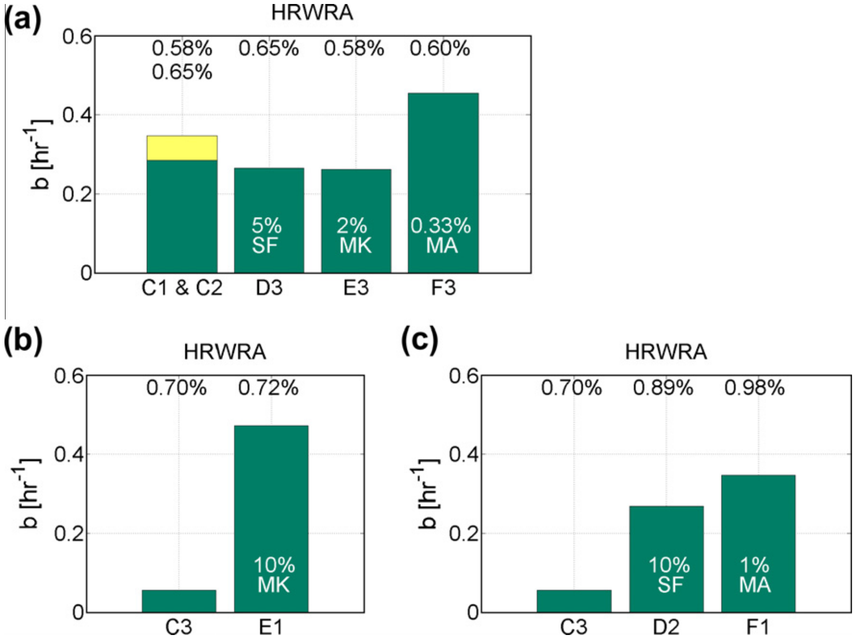

Fig. 6. Effect of mineral admixtures on the reduction slope of formwork pressure.

flows with a lower shear strain rate for a given stress, which results in an increase of the stoppage time. Therefore, loss of the spreading rate implies plastic viscosity gain in addition to the fact that the loss of slump flow equates with yield stress gain.

The slump flow test was conducted at intervals of 20 min. The test began after the initial slump flow of the SCC was deemed satisfactory with target flowability. The SCC was then filled into four Abrams cones, as defined in ASTM C 1611 [12], resting on similar polycarbonate plates. To prevent adhesion, form oil was sprayed inside the cones. Twenty-minutes after the initial slump flow test, one slump cone was lifted. After another 20 min, another cone was lifted, and so on. The slump flow (d_f) and the stoppage time (t_f) were recorded for five cones for each mixture.

The timed slump flow test was conducted with all mixtures in Table 3 except Group D. Fig. 7 shows the loss of slump flow and change of the spreading rate. The slump flow decreased over time, as expected. Some mixtures then ceased to flow (this was recorded with a cone size of 20 cm): Mixes C1, E1, E2, E3, and F2 at 80 min after casting and Mixes F1 and F3 at 40 min after casting. By this time, the mixtures were stiff enough to take on the shape of the slump cone after it was removed, thus marking the apparent setting time.

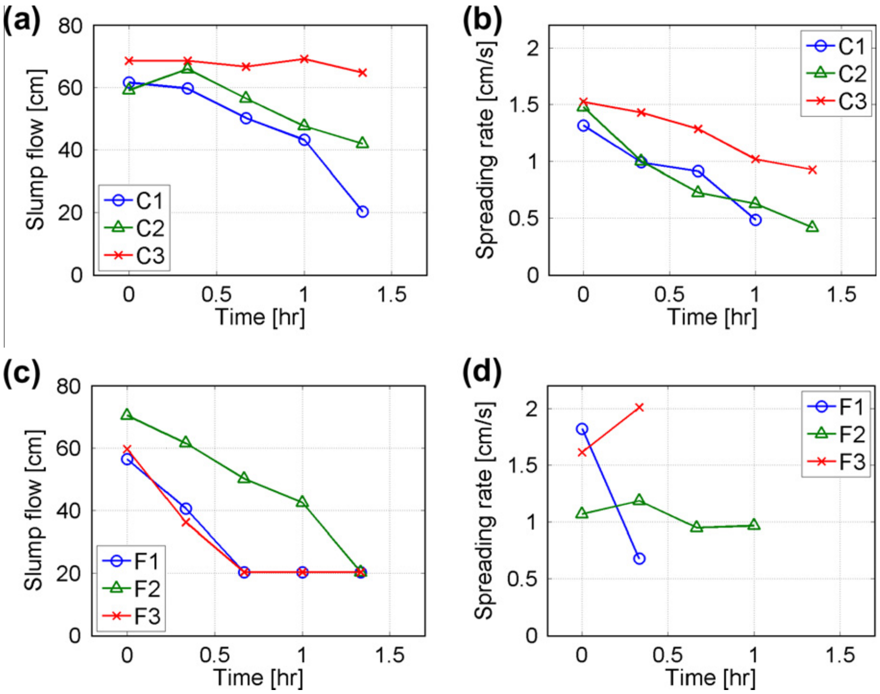

Fig. 7. Rheological evolution of SCC: (a) slump flow and (b) spreading rate of Group C; (c) slump flow and (d) spreading rate of Group F.

In Fig. 7a, it is observed that the slump flow rapidly decreased when a small amount of HRWRA was used (C1). The spreading rate also decreased over time, as shown in Fig. 7b, which presumably reflects a gain of plastic viscosity. Mix C3, having the highest dosage of HRWRA, showed almost no yield stress increase and the slowest gain of plastic viscosity. As shown in Fig. 7c and d, Group F, incorporating MA, showed quicker loss of the slump flow than Group C, thus indicating that the mineral admixture accelerates the stiffening process and enhances the yield stress evolution. However, it is difficult draw conclusions on a trend of the spreading rate.

3. Correlation and estimation of formwork pressure

It is evident that a small amount of mineral admixtures can significantly reduce the formwork pressure. The precise mechanism underlying the influence of clay on the fresh-state properties is complex and may entail consideration of thixotropy [7–9], structural buildup [19], particle packing [20], and capillary suction [21,22], change in diffusion coefficient of water [23], among other factors. Those considerations are beyond the scope of this paper. However, an attempt was made to correlate the reduction in formwork pressure with the field-friendly slump flow test.

In the following, an empirical correlation between the loss of slump flow and the reduction in formwork pressure is derived. Applying a linear fit to slump flow, $d_f(t)$ in the unit of centimeter, versus an instantaneous function, $\beta(t)$, the following equation is obtained with a coefficient of determination (R^2) of 0.92:

$$\beta(t) = 0.010 d_f(t) + 0.31 \tag{4}$$

The above equation, shown in Fig. 8, is valid when $d_f(t)$ is less than 73.5 cm and more than 20 cm. In addition to Eq. (4), many other empirical relationships including the spreading rate (d_f/t_f) were tested with the goal of discovering a better correlation. Among the attempts for correlation, the strongest ($R^2 = 0.92$) was the above equation, and was consistent for mixes with different compositions.

If casting proceeds under a constant placement rate R, the vertical pressure increment at the bottom of the formwork is calculated as $wR\Delta t$, where w is the unit weight of concrete and Δt is the time increment. As previously described, the contribution of the delayed response $\alpha(t, t')$ is not dominant. Simply and conservatively, the delayed response can be neglected in the two-function model: $\alpha(t, t')$ is assumed as 1.0. The corresponding lateral pressure is calculated with the following integration over the casting time t:

$$\sigma_L(t) = \int_0^t \alpha(t,t')\beta(t')\Delta\sigma_V(t') \leqslant wR\int_0^t \beta(\tau)d\tau \cong wRt\frac{\beta(0)+\beta(t)}{2} \tag{5}$$

In the above equation, the vertical pressure of wRt is considered as the design load (hydrostatic pressure) following the ACI 237 recommendation [1]. Therefore, the lateral pressure for SCC formwork design can be reduced up to a ratio of $1 - (\beta(0) + \beta(t))/2$ of the hydrostatic pressure. Furthermore, if the correlation in Eq. (4) is applied, the pressure reduction ratio can be estimated as $0.69-0.005\ (d_f(0) + d_f(t))$ using the initial slump flow, $d_f(0)$, and the slump flow measured at the end of placement, $d_f(t)$. For example, if we obtain 60 cm initial slump flow and 40 cm timed slump flow diameter after 1 h casting, the lateral pressure will be 19% less than the hydrostatic pressure.

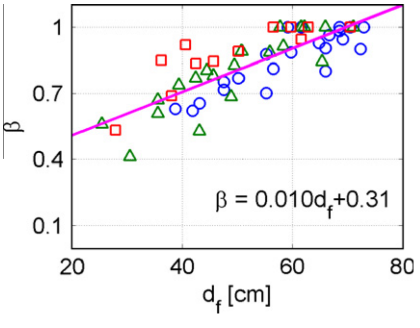

Fig. 8. Correlation between the slump flow loss and the formwork pressure response.

4. Conclusions

This study is motivated by the economical disadvantages of current SCC formwork systems due to the high formwork pressure. The primary goal was to reduce the formwork lateral pressure via incorporation of mineral admixtures. The mineral admixtures decrease the lateral pressure developed immediately after vertical pressure is applied (instantaneous response), but their effect is not dominant on the decrease of the lateral pressure when the vertical pressure is maintained (delayed response). The most interesting finding is that a small amount of processed clay, MK and MA, effectively enhances the shear resistance, leading to reduced formwork pressure. The loss of slump flow of the mixture at rest shows a good correlation with the instantaneous response, but the spreading rate does not. The loss of slump flow was found to be linked to the formwork pressure response, and accordingly a linear regression curve was derived in order to provide a parameter to estimate the lateral formwork pressure.

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References

[1] Okamura H, Ouchi M. Self-compacting concrete, development, present use and future. Proceedings of the 1st international RILEM symposium on self-compacting concrete, Stockholm, Sweden; 1999. p. 3–14.

[2] Okamura H, Ouchi M. Self-compacting concrete. J Adv Concr Technol 2003;1(1):5–15.

[3] ACI Committee 237. Self-consolidating concrete, ACI 237R-07. Farmington Hills: American Concrete Institute; 2007.

[4] Vanhove Y, Djelal C, Magnin A. Prediction of the lateral pressure exerted by self-compacting concrete on formwork. Mag Concr Res 2004;56(1):55–62.

[5] Billberg P, Silwerbrand J, Osterberg T. Form pressures generated by self-consolidating concrete. Concr Int 2005(October):35–42.

[6] Tejeda-Dominguez F, Lange DA, D'Ambrosia MD. Formwork pressure of self-consolidating concrete in tall wall field applications. Transport Res Rec: J Transport Res Board 2005;1914:1–7.

[7] Khayat KH, Assaad JJ. Effect of w/cm and high-range water-reducing admixture on formwork pressure and thixotropy of self-consolidating concrete. ACI Mater J 2006;103(3):186–93.

[8] Assaad JJ, Khayat KH. Effect of viscosity-enhancing admixtures on formwork pressure and thixotropy of self-consolidating concrete. ACI Mater J 2006;103(4):280–7.

[9] Khayat KH, Assaad JJ. Use of thixotropy-enhancing agent to reduce formwork pressure exerted by self-consolidating concrete. ACI Mater J 2008;105(1):88–96.

[10] Ferraris CF, Obla KH, Hill R. The influence of mineral admixtures on the rheology of cement paste and concrete. Cem Concr Res 2010;31:245–55.

[11] Tregger NA, Pakula ME, Shah SP. Influence of clays on the rheology of cement pastes. Cem Concr Res 2010;40:384–91.

[12] ASTM C 1611-05. Standard test method for slump flow of self-consolidating concrete. West Conshohocken: ASTM International; 2005.

[13] Gregori A, Ferron RP, Sun Z, Shah SP. Experimental simulation of self-consolidating concrete formwork pressure. ACI Mater J 2008;105(1):97–104.

[14] Kwon SH, Shah SP, Phung QT, Kim JH, Lee Y. Intrinsic model to predict formwork pressure. ACI Mater J 2010;107(1):20–6.

[15] Kim JH, Beacraft MW, Kwon SH, Shah SP. Simple analytical model for formwork design of self-consolidating concrete. ACI Mater J, accepted for publication.
[16] Roussel N. Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results. Mater Struct 2006;39(4):501–9.
[17] Wallevik JE. Relationship between the bingham parameters and slump. Cem Concr Res 2006;36(7):1214–21.
[18] Tregger N, Ferrara L, Shah SP. Identifying viscosity of cement paste from mini-slump-flow test. ACI Mater J 2008;105(6):558–66.
[19] Ferron RP, Gregori A, Sun Z, Shah SP. Rheological method to evaluate structural buildup in self-consolidating concrete cement pastes. ACI Mater J 2007;104(3):242–50.
[20] Santamarina JC, Klein KA, Fam MA. Solis and waves: particulate materials behavior, characterization and process monitoring. Chichester: John Wiley & Sons Ltd.; 2001.
[21] Bentz DP, Jensen OM, Hansen KK, Olesen JF, Stang H, Haecker CJ. Influence of cement particle size distribution on early age autogeneous strains and stresses in cement-based materials. J Am Ceram Soc 2001;84:129–35.
[22] Amziane S. Setting time determination of cementitious materials based on measurements of the hydraulic pressure variations. Cem Concr Res 2006;36:295–304.
[23] Amziane S, Andriamanantsilavo N. Prediction of cement paste pore water pressure variations during setting period. Adv Cem Res 2004;16(1):23–8.