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Effect of wall friction on variation of formwork pressure over time in self-consolidating concrete

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ABSTRACT

In order to accurately predict the varying of formwork pressure over time, it is necessary to consider various factors influencing the development of formwork pressure. A prediction model has been previously proposed, but that model has some limitations in that only intrinsic material characteristics are taken into account. Extrinsic effects such as wall friction, formwork flexibility, and external temperature are excluded in the model. This study focuses on the wall friction effect as one of the extrinsic factors. First, by incorporating the intrinsic model and friction stress acting on the interface, a method of calculating formwork pressure considering the wall friction effect is suggested. To find out how much friction stress is acting on the interface and how it varies over time, formwork pressure tests were performed with circular column formworks having three different diameters. In these columns, the vertical pressure at the bottom and the lateral pressures were measured. To calibrate parameters of the intrinsic model for the same material as that used in the formwork pressure tests, additional tests were conducted with a specially designed apparatus that can exclude effects of extrinsic factors. From tests and analysis results, it was found that wall friction greatly affects the variation of formwork pressure over time. The newly suggested calculation method can give a good prediction of real formwork pressure.

1. Introduction

Self-consolidating concrete (SCC) was first developed in Japan and has become popular in construction all over the world because it offers a lot of advantages. SCC can flow easily into complex shapes; it improves strength and durability; it reduces labor; and it shortens the placing and finishing time. However, the formwork pressure of SCC is higher than that of normal concrete [1–3] mainly due to SCC's rheological feature, that is, lower yield stress [4–6]. Therefore, it is necessary to build more expensive and stronger formworks. In addition, the cancellation time of formwork pressure may be longer than that of ordinary concrete, which results in delay of the removal time of the formwork. In order to reduce the maximum lateral pressure and the cancellation time, it is necessary first to understand and predict the variation of formwork pressure over time.

There was pioneering research to find out the mechanism for SCC formwork pressure, where thixotropic behavior (or structural buildup at rest) was turned out to be the origin of the variation or decrease of the pressure during and after casting [6–8]. This current study focuses on suggesting a methodology to quantitatively predict the formwork pressure, rather than investigating the mechanisms related to the variation of formwork pressure.

Formwork pressure is influenced by many factors such as mix proportions, placing temperature, admixture, external temperature, casting rate, and friction at the interface between the concrete and the formwork. These factors can be classified into two categories, intrinsic and extrinsic factors. The intrinsic factors are related only to the material itself, while the extrinsic factors are related to the external environment and the formwork conditions. Most of the existing prediction models do not separately consider the intrinsic and extrinsic factors. Some empirical models [9–14] are primarily used to estimate the peak pressure, and do not provide information on the formwork pressure's varying over time. Another prediction model [15] was developed based on the rheological properties such as viscosity, yield stress, and thixotropy of the material. A model describing the intrinsic pressure response was previously developed by the authors [16]. This model only considers the intrinsic characteristics of materials. The applicability of the proposed model to cement-based materials for the prediction of formwork pressure, excluding extrinsic factors, was verified. Nevertheless, in order to

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predict real formwork pressure, it is necessary to consider the extrinsic factors. In this study, the effect of wall friction is investigated as one of the major extrinsic factors.

There have been several studies on the effect of friction on formwork pressure. In Graubner and Proske's model to predict SCC formwork pressure [17], friction was considered as a function of friction coefficient depending on the normalized time based on the final setting time of concrete. The studies of Djelal, Vanhove and Magnin [18–20] determined the correlation between friction coefficient and lateral pressure. Friction between mixture and the wall was determined by means of a tribometer specially designed for a complex medium such as fresh concrete. The friction coefficient was obtained from the ratio between friction force and normal force. These studies showed that there was no difference between static and dynamic friction and that friction coefficient depended on the roughness of the formwork surface. It was also pointed out that the maximum formwork pressure exerted by SCC was smaller than the hydrostatic pressure, and then the smaller formwork pressure was attributable to the wall friction. Roussel and co-workers [21] performed laboratory experiments with cement pastes to validate the formwork prediction model proposed by Ovarlez and Roussel [22]. The wall stress, that is, the average shear stress acting on the surface of a plate or column, was calculated based on the difference between the actual weight of the paste and the force acting on the bottom. These researchers also found that the wall friction depended on the roughness of the interface.

The existing studies have limitations in quantitatively estimating the effect of friction in real formworks and in determining the time-varying friction stress from the beginning of casting to the cancellation time for formwork pressure. In this study, column formwork tests were performed. The columns had circular cross-sections with three different diameters. Mixtures were poured into the columns at two different casting rates. The variation of vertical pressure over time was measured at the bottom, and the variation of lateral pressure was measured at three different positions over the lateral side of the columns. It was possible to calculate the friction stress acting over the interface between the mixture and formwork using the self-weight of mixtures and the vertical pressure measured at the bottom of the formwork. The measured friction stresses are compared according to the diameter pouring rate and type of mixtures.

By combining the effects of the intrinsic pressure responses and wall friction, a method to calculate the varying of formwork pressure over time is suggested. In order to obtain the parameters of the two-function model [16,24,25] for intrinsic pressure responses, the formwork pressure test was performed. In addition to the intrinsic parameters, application of measured friction stress to the model makes it possible accurately to predict the formwork lateral pressures of the columns.

2. Calculation of formwork pressure

2.1. Intrinsic model for non-friction cases

The intrinsic two-function model has been developed under the condition of excluding extrinsic factors [16]. Two pressure response functions, $\beta(t)$ for instantaneous response and $\alpha(t,t')$ for delayed response, were introduced to describe the time evolution of the formwork lateral pressure. The function $\beta(t)$ is defined as the ratio of the lateral pressure response to the vertical pressure increment at time t, as described in the following equations:

$$\beta(t) = \begin{cases} 1 - s_1 t & \text{for } t \le t_b \\ \beta_s - s_2(t - t_b) & \text{for } t > t_b \end{cases} \quad (1)$$

where t_b is the time at which the slope of $\beta(t)$ is changed, β_s is the value of $\beta(t)$ at time t_b, and s_1 and s_2 are the initial slope and the slope after t_b, respectively. The function $\alpha(t,t')$ represents a gradual change of the lateral pressure under a constantly sustained vertical pressure that is applied at time t', as described as follows:

$$\alpha(t,t') = \begin{cases} 1 - U_{pc}\left(\dfrac{t - t'}{t_c - t'}\right)^n & \text{for } t \le t_c \\ U_{pc} + \dfrac{t - t_c}{t_e - t_c}\alpha(t,t_c) & \text{for } t > t_c \end{cases} \quad (2)$$

where t_e is the cancellation time of the lateral pressure, t' is the time when a vertical pressure is applied, t_c is the time when the decreasing rate of $\alpha(t,t')$ is changed, and the value of U_{pc} and the exponent of n represent the nonlinearity of the initial branch.

The linear superposition method can be applied to the calculation of the lateral pressure for a general casting condition in which the vertical pressure is gradually increasing during casting and is sustained over time after casting. The lateral pressure according to the increment of vertical pressure $\Delta\sigma_V(z,t')$ can be calculated with the following recursive form:

$$\sigma_L(z,t) = \{\sigma_L(z,t') + \beta(t')\Delta\sigma_V(z,t')\} \cdot \alpha(t,t') \quad (3)$$

where $\sigma_L(z,t)$ is the lateral pressure at position z and time t. The calculation method for the lateral pressure of the incremental vertical pressure is shown in Fig. 1.

The two functions of the intrinsic model, $\beta(t)$ and $\alpha(t,t')$, are representing the lateral pressure decrease over time, which is due to the thixotropy and structural buildup at rest of fresh mixture as turned out through the existing studies [6–8].

2.2. Consideration of friction effect

The time evolution of the formwork pressure, excluding the friction effect, can be simulated with the model explained above. Given that the material properties $\alpha(t,t')$ and $\beta(t)$ for the intrinsic pressure response and the friction stress developed at the interface between mixtures and formwork are known, the formwork lateral pressure can be estimated by considering the friction effect in the model.

In the derivation, the friction stress is assumed to depend only on time. The background for this assumption will be explained later with experimental results. The friction stress plays a role in reducing vertical pressure. If the average friction stress τ_{FA} is known, the vertical pressure $\sigma_V(z,t)$ at an arbitrary position z and time t can be expressed by the following equations based on the force equilibrium.

$$\sigma_V(z,t) = \left(w - \frac{P}{A}\tau_{FA}(t)\right) \cdot (h(t) - z) \quad (4)$$

where w is the unit weight of the mixture, A is the cross-section area, and P is the perimeter of the specimen. The mixture height $h(t)$ considers the casting situation, as shown in Fig. 2(a). The height increases during casting and remains constant as the final height H since the end of placement. Fig. 2(b) gives a schematic description of the stress state inside the formwork. The formwork lateral pressure can be predicted with the superposition method of Eq. (3). The vertical pressure increment $\Delta\sigma_V(z,t')$ considering the friction effect is obtained with the height increment $\Delta h(t')$:

$$\Delta\sigma_V(z,t') = \left(w - \frac{P}{A}\tau_{FA}(t')\right) \cdot \Delta(h(t') - z) \quad \text{for } z \le h(t'). \quad (5)$$

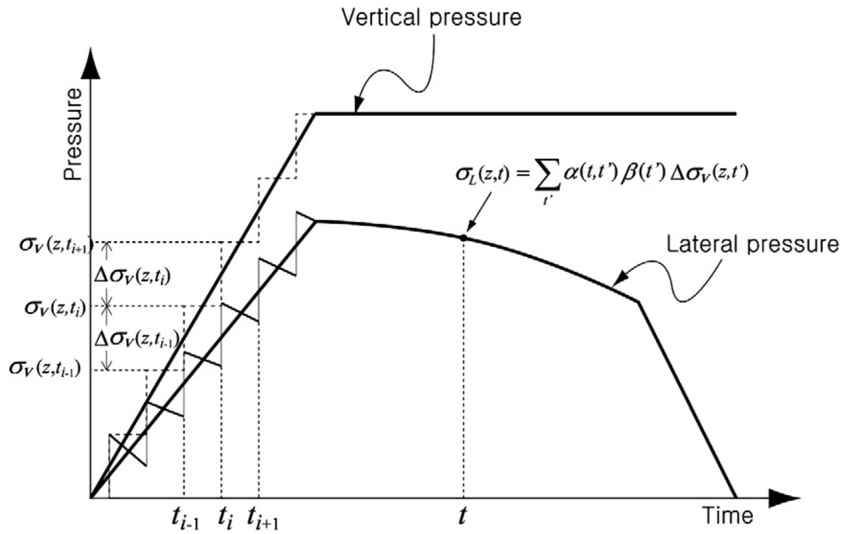

Fig. 1. Calculation method of lateral pressure.

3. Experiments

3.1. Materials preparation

Tests were performed with mortar and SCC mixes, the mix proportions of which are shown in Table 1. Type I Portland cement was used. The maximum coarse aggregate size was 10 mm in SCC mix. In the case of SCC, the water-to-binder ratio was 0.41, in which C-class fly ash substitutes for cement with a weight ratio of 25%. A polycarboxylate-based superplasticizer (SP) with a specific gravity of 1.08 g/cm^3 was used. The specific gravity of the viscosity-modifying admixture (VMA) was 1.12 g/cm^3. The slump flow of the SCC mix was 680 mm, and the time to reach the flow diameter of 500 mm was 4 s. The proportion of ingredients of the mortar mix is the same as that of the SCC mix, but to prevent segregation the mortar mix with no coarse aggregate had lower amounts of VMA and SP. All ingredients of the mixtures were kept in a room of constant temperature of 20 °C before mixing, and all tests to be described later were performed at the same temperature.

3.2. Test program and apparatus

An apparatus to measure the intrinsic pressure responses $\alpha(t,t')$ and $\beta(t)$, the so called formwork pressure test, was manufactured in the previous study [16]. Fig. 3 shows detailed dimensions of the apparatus and the test setup. The apparatus was made of steel, and was stiff enough that we could ignore the deformation of formwork. The apparatus had the shape of a cylinder with a diameter of 150 mm, a thickness of 20 mm and a height of 350 mm. To minimize the friction between mixtures and formwork, calcium-based grease was

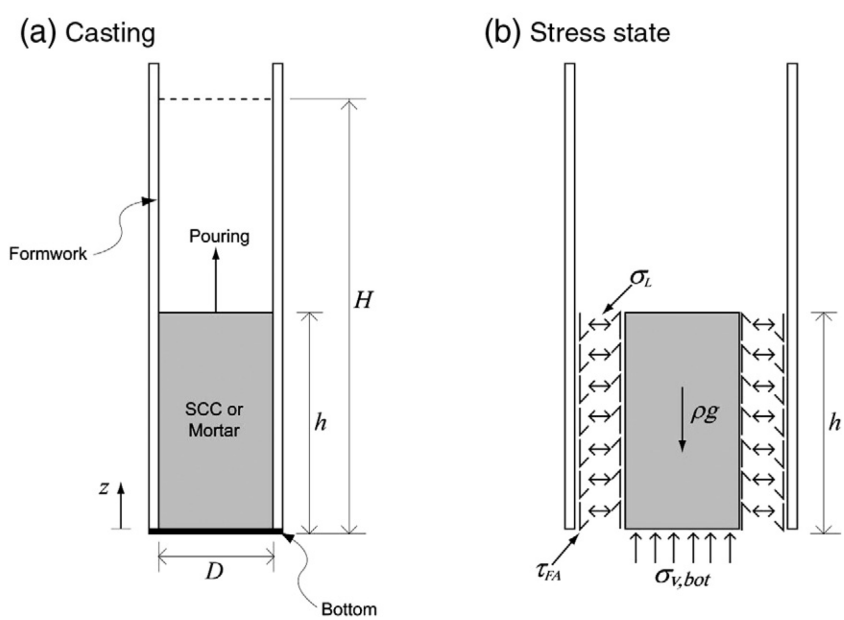

Fig. 2. Schematic representation of stress state in the specimen.

Table 1
Mix proportions.

Materials	Unit mass (kg/m^3)						
	Water	Cement	Fly ash	Sand	Gravel	VMA	SP
Mortar	263	479	160	1182	–	0.38	0.49
SCC	182	332	111	819	875	1.35	1.05

applied over the entire inside surface. The consistency of this grease is characterized as NLGL (National Lubricating Grease Institute) Grade No. 1. During the test, concrete was filled to a height of 300 mm. An air compressor was connected at the top plate of the apparatus, and the air vertical pressure was controlled with a mechanical pressure gauge. In order to prevent air infiltration into the mixture, the top and bottom surfaces were covered with plastic film. Two pressure cells of 175 kPa capacity were attached at the middle of the column to measure the lateral pressure.

In this study, to measure vertical pressure to confirm that the formwork pressure test excludes the friction effect, an additional pressure cell was positioned at the bottom of the apparatus. Fig. 4 shows externally applied vertical air pressures and vertical pressures measured at the bottom, where both vertical pressures are almost the same for both SCC and mortar mixes. The results indicate that friction stress does not develop during the formwork pressure test shown in Fig. 3, where no discrepancy was found between two measurement. Therefore, the intrinsic pressure responses $\alpha(t,t')$ and $\beta(t)$ in Eqs. (1) and (2) can be obtained from the measured lateral pressure regardless of the friction effect.

In order to obtain the material properties $\alpha(t,t')$ and $\beta(t)$, elapsed-step loading was applied: a constant vertical pressure was instantly applied at different times after pouring and then constantly sustained over time. A vertical pressure of 80 kPa was applied at times 0, 6, 12 and 18 h (see Table 2). It was possible to calibrate the parameters

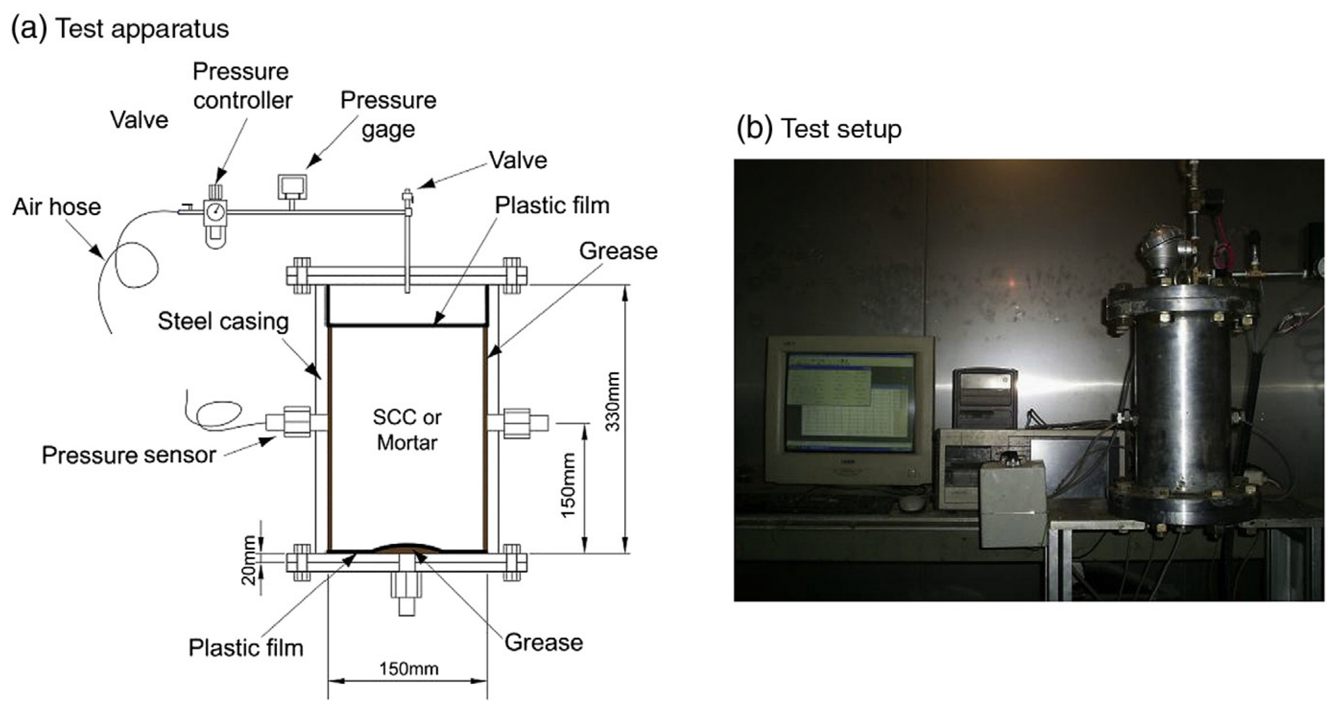

Fig. 3. Formwork pressure test under non-friction.

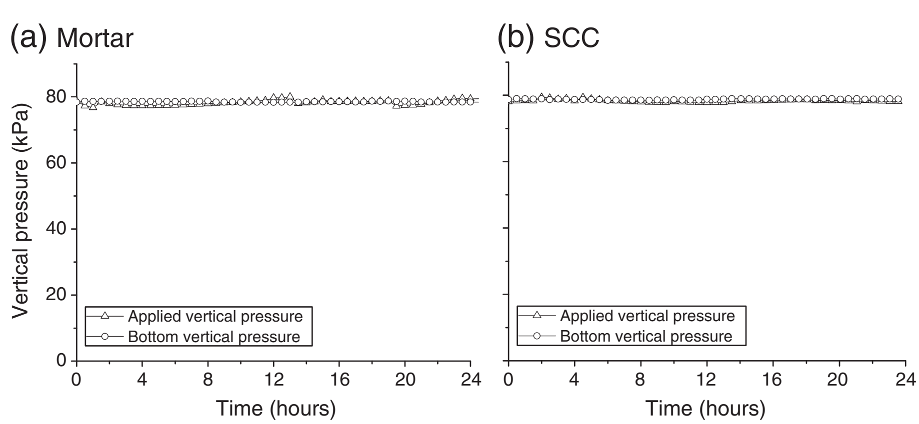

Fig. 4. Applied vertical pressure vs. bottom pressure.

Table 2
Test variables for non-friction tests.

Protocol	Vertical pressure	Applied time
Elapsed-step loading	$\sigma_V = 80$ kPa	$t = 0$ h
		$t = 6$ h
		$t = 12$ h
		$t = 18$ h
Ramp loading	$\sigma_V \leq 36.5$ kPa for mortar mix	R1 increasing for 1.65 h
	$\sigma_V \leq 38$ kPa for SCC mix	R2 increasing for 0.825 h

Table 3
Test variables for column tests.

Materials	Labels	Diameter (mm)	Casting rate (m/h)
Mortar	M-D1-R1	130	1
	M-D2-R1	180	1
	M-D3-R1	280	1
	M-D1-R2	130	2
	M-D2-R2	180	2
	M-D3-R2	280	2
SCC	S-D1-R1	130	1
	S-D2-R1	180	1
	S-D3-R1	280	1
	S-D1-R2	130	2
	S-D2-R2	180	2
	S-D3-R2	280	2

used in the intrinsic model from the results of the elapsed-step loading. The instantaneous lateral-to-vertical pressure ratios for the four elapsed-step loadings directly determine the value of $\beta(t)$, and the sustained portion of the lateral pressure becomes $\alpha(t,t')$. Details can be found in the literature [16,24,25].

In addition to the elapsed-step loading, ramp loading until a certain time was also considered to simulate a casting situation: the vertical pressure for mortar mix was gradually increased up to 36.5 kPa for 1.65 h and 0.825 h, and that for SCC mix was gradually increased up to 38 kPa for 1.65 h and 0.825 h. The developed lateral pressure under non-friction conditions could be experimentally simulated with this loading protocol [3]. The different increasing rates R1 ((36.5 or 38) kPa for 1.65 h = 1 m/h placement rate) and R2 ((36.5 or 38) kPa for 0.85 h = 2 m/h placement rate) correspond to the casting situations of the following column formwork test.

The friction effect on formwork pressure is investigated with the circular column formworks manufactured in this study. Fig. 5 shows the three column formworks made of 10 mm thick polyvinyl chloride (PVC). They have the same height of 1.8 m, but diameters of 130 mm, 180 mm, and 280 mm. The inner surface of the column was covered with a mineral-based form oil having a kinematic viscosity of 130 cSt at 40 °C. The lateral pressure was measured using three pressure cells located at 0.55 m (PL3), 1.15 m (PL2), and 1.65 m (PL1) from the top. Also, an additional pressure cell was attached at the bottom (PB1) of the column to measure vertical pressure. Mixtures were cast up to 1.7 m in height, poured from the top with placement rates of 1 m/h and 2 m/h. Table 3 shows the test variables for the column formwork tests.

4. Results and discussion

4.1. Measured friction stress

Fig. 6 shows the vertical pressures measured at the bottom and the formwork lateral pressure profile measured at the lateral surface in the 280 mm diameter specimen (S-D3-R1). Without friction, the vertical pressure measured at the bottom could be expected to be identical to the stress induced by the self-weight of the mixture. The straight line in Fig. 6(a) is the pressure calculated with the mixture weight assuming non-friction conditions. The difference between the calculated and the measured vertical pressures is mainly due to the fiction stress; so, it was observed that the friction effect increases with time.

On the other hand, the friction stress is represented by the Coulomb friction model, as follows:

$$\tau_F = \mu \cdot \sigma_N + C \tag{6}$$

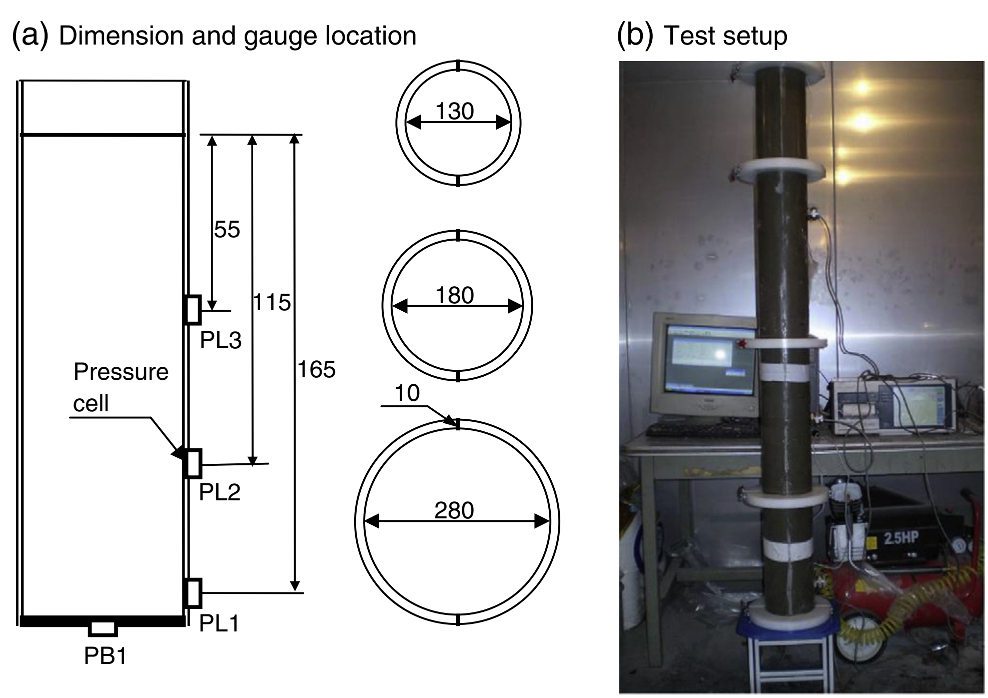

Fig. 5. Column formwork test.

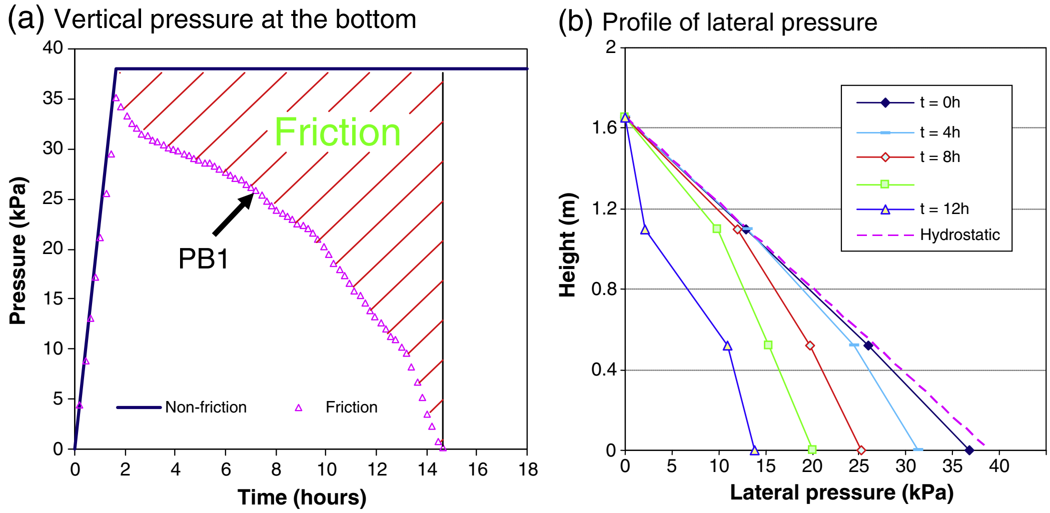

Fig. 6. Measured pressure of specimen S-D3-R1.

where τ_F is the friction stress, μ is the friction coefficient, σ_N is the normal stress applied to the frictional surface, and C is friction stress due to cohesion. In the case of the formwork pressure problem, the formwork lateral pressure is considered as the normal stress, and then the Coulomb friction stress decreases with the decrease of the lateral pressure. The lateral pressure on the formwork is decreasing, as shown in Fig. 6(b), so the first term in Eq. (6) is expected to decrease even though the slight increase of friction coefficient, reported in the literature [17,20], is considered. However, the measured friction stress does not decrease but increases with time, as already described, which indicates that the cohesion C is dominant in the developed friction stress. The Coulomb friction stress depends on both time and location because the lateral pressure varies with height, but the cohesion-induced friction stress depends only on time. Therefore, the assumption, in Eq. (4), of time-dependent friction stress, is valid.

In the same way, Fig. 7 shows the vertical pressures measured at the bottom (PB1) of the mortar and SCC mixes for casting rates 1 m/h and 2 m/h. The results showed that the vertical pressure reached a peak right after casting, and then this peak was larger with a faster placement rate. In the case of the mortar mix, the pressure steeply decreased after the peak until around 5 h, then gently changed from 5 h to 11 h, and, finally, the decreasing rate of the pressure accelerated again until it canceled out. The bottom pressure of the SCC mix gradually decreased compared to the mortar mix. Based on the vertical pressures measured at the bottom, the average friction stress in Eq. (5) can be evaluated with the vertical pressure measured at the bottom as the following equation, where $\sigma_{v,bot}(t) = \sigma_v(t,0)$:

$$\tau_{FA}(t) = \frac{D}{4}\left\{\rho g - \frac{\sigma_{v,bot}(t)}{h(t)}\right\}. \tag{7}$$

In Fig. 8, the average friction stresses developed on the columns with different diameters are compared. The friction stresses during casting are almost identical for the different diameters. Afterward, the stress for the bigger diameter is larger than that for the smaller diameter. It is also shown that the increasing rate of stress over time suddenly changes at the end of casting. The mixture inside the form was not completely at rest during casting because it was disturbed, especially at the interface between the form and the mixture, by falling the fresh mix from the top of the column. After finishing placement, the mixture was strictly at rest. The abrupt change of the increasing rate right after casting may be caused by the different state of the mixture.

Fig. 9 shows the friction stresses divided by the corresponding diameters. The friction stress-to-diameter ratios are almost identical even though small deviation is found in the mortar sample after 10 h

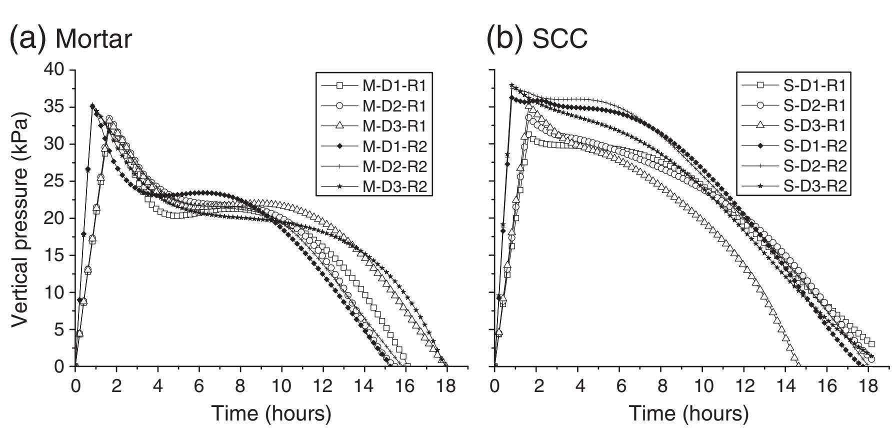

Fig. 7. Vertical pressure measured at position PB1.

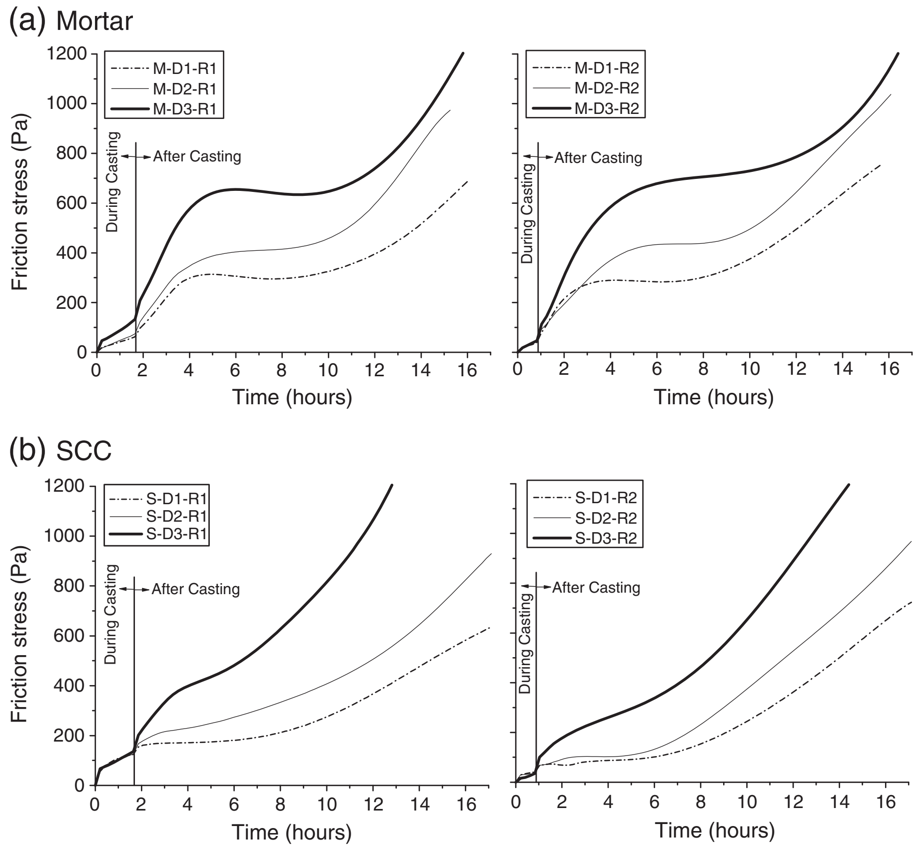

Fig. 8. Variation of friction stress over time.

and SCC sample up to 9 h. There is no trend in the divided values according to the size of diameter, and so the deviations are thought to be experimental error. Therefore, it is can be seen that the friction stress is proportional to the diameter size after casting. As mentioned in the above, the friction is mainly induced by the cohesion, which may be related to the structural buildup at rest [6–8] at the interface. However, it does not mean that the structural buildup at the interface is faster or stronger in a formwork having larger diameter. The friction strength developed by the structural buildup is higher than the friction stresses measured in the specimens. In Eq. (7), after casting, $h(t)$ is constant as the final height H, and only the vertical pressure at the bottom, $\sigma_{v,bot}(t)$, is varying over time. The proportionality of the friction stress to the diameter indicates that the vertical pressures at the bottom are identical for the different diameters. If the diameter of column is so large that the friction stress overcomes the friction strength, the vertical pressure at the bottom would not cancel differently from the test results of this study.

The effect of placement rate is also compared in Fig. 10. Even though there is little deviation according to the different pouring rates (R1 and R2), the evolution trend of the friction stress is very similar.

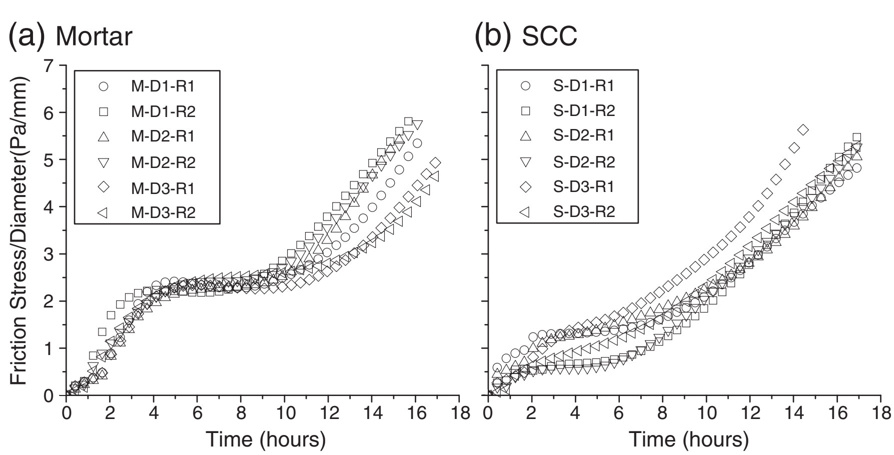

Fig. 9. Friction stress divided by the column diameter.

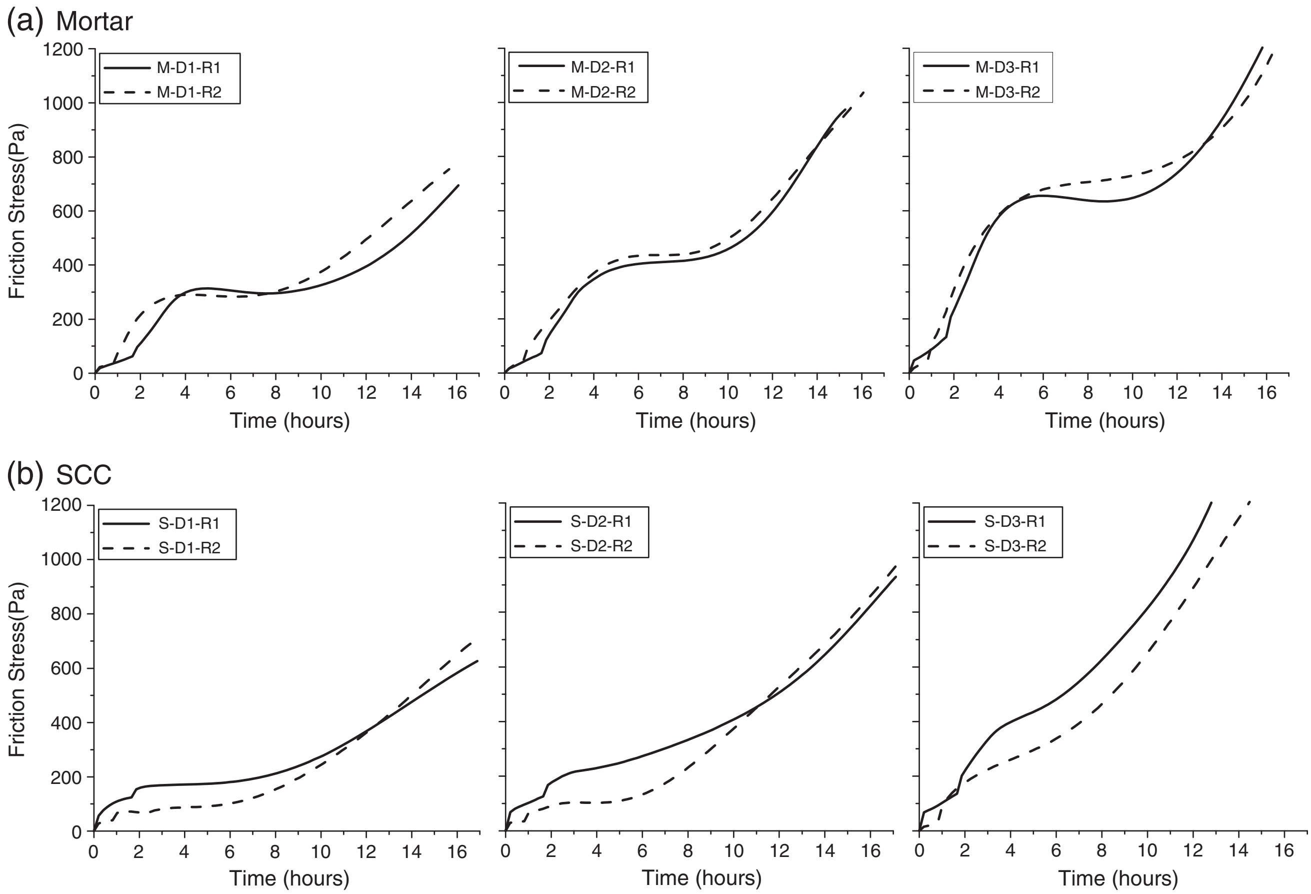

Fig. 10. Friction stress of different casting rates.

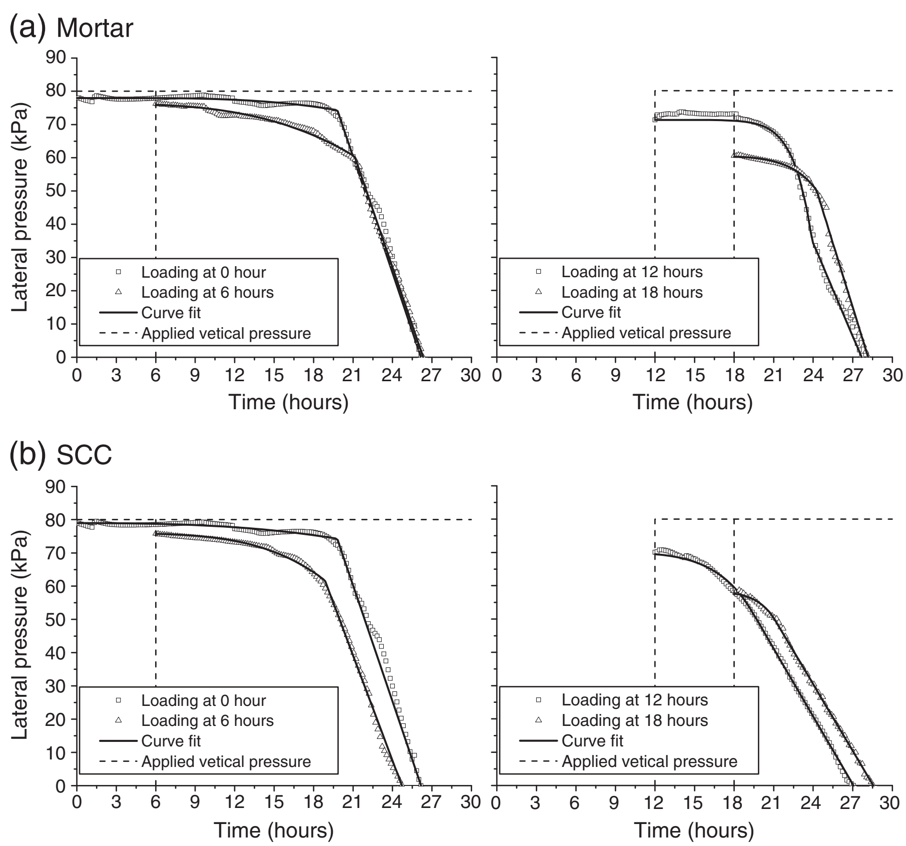

Fig. 11. Elapsed-step loading results for the formwork pressure test.

Table 4
Calibrated parameters for intrinsic model.

Materials	Parameters		Calibration results
Mortar	$U_p(t,t')$	t_c	$17+0.27\ t$
		U_{pc}	$0.014+0.061t$
		t_e	$26+0.12\ t$
	$\beta(t)$	t_b	12
		s_1	0.0071
		s_2	0.022
SCC	$U_p(t,t')$	t_c	$16+0.079\ t$
		U_{pc}	$0.0060+0.11\ t$
		t_e	$25+0.16\ t$
	$\beta(t)$	t_b	12
		s_1	0.0093
		s_2	0.024

Fig. 9 also shows that the fiction stress does not depend on the placement rate within the range of interests.

4.2. Results of the formwork pressure test

The material properties $\alpha(t,t')$ and $\beta(t)$ for intrinsic pressure response of mixtures can be determined via the formwork pressure test in Fig. 3, as already described. Fig. 11 shows the elapsed-step loading results of the formwork pressure test shown in Fig. 3. The hollow dotted line is the measured lateral pressure; the solid line is the optimal fit with the functions $\alpha(t,t')$ and $\beta(t)$. The parameters calibrated from the test results are listed in Table 4, in which for simplicity the exponent n in Eq. (3) is assumed to be 1.0.

Fig. 12 shows the responses of formwork pressure to the ramp loading (gradually increasing vertical pressure). The solid line is the predicted pressure using the material properties previously determined and given in Table 4. The measured and calculated pressures had acceptable agreement even though there were small errors. Considering the unit weight of mortar and SCC mixes, the measured lateral pressure in Fig. 12 correspond to that measured at the bottom of the column formwork test (PL1 in Fig. 5). Both lateral pressures are compared in Fig. 13, which figure confirms two important findings, as follows: (1) the friction effect decreases the formwork lateral pressure including the peak pressure; and (2) the friction effect also decreases the cancellation time of the formwork pressure.

The peak lateral pressure of the column in Fig. 13 is summarized in Fig. 14, where all results are normalized by the hydrostatic pressure. It was observed that the peak lateral pressures increase with the increase of the column diameter and the increase of the placement rate. Because the friction stress increases with the age of mixture, lower placement rate gives higher friction stress at the peak formwork pressure. In other words, the more amount of the applied vertical pressure is sustained by the higher friction stress. In addition, low placement rate extend the time period for thixotropy (structural buildup) of mixture, and then considerable shear resistance bears the applied vertical pressure.

4.3. Formwork pressure estimation considering the friction effect

It was possible to estimate the decrease of the formwork pressure due to the friction effect with the two-function model given in Eq. (3), in which the friction effect is implemented with Eq. (5). Based on the measured pressure responses in Table 4 and the measured average friction stress in Fig. 7, the formwork lateral pressure was estimated

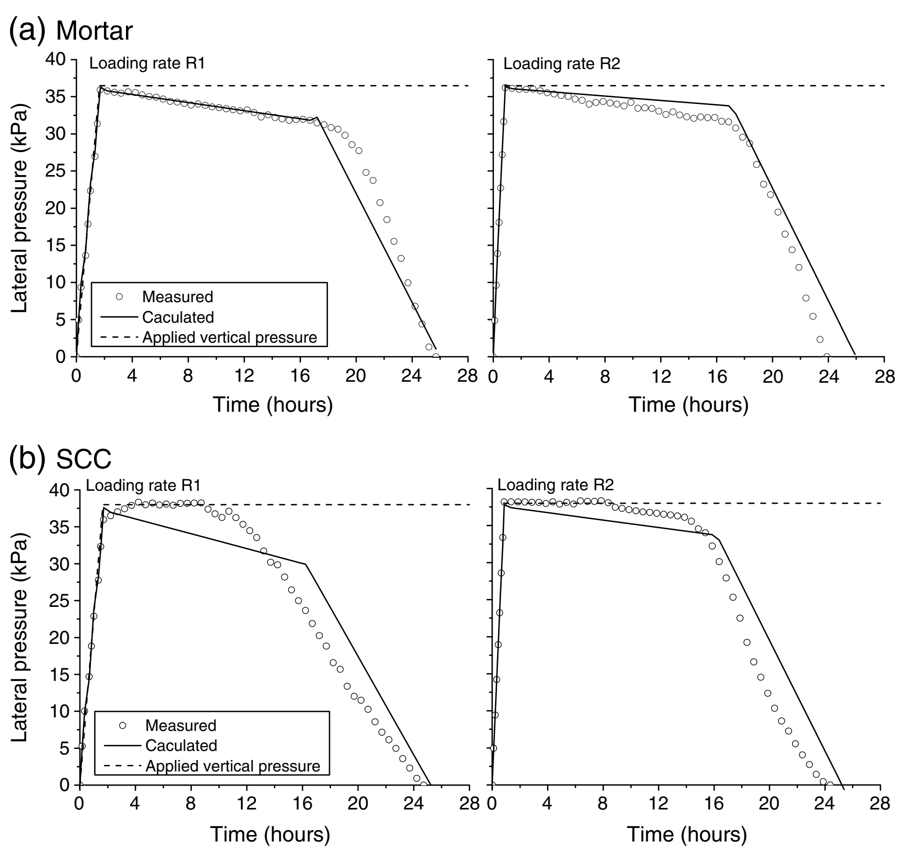

Fig. 12. Verification of intrinsic model.

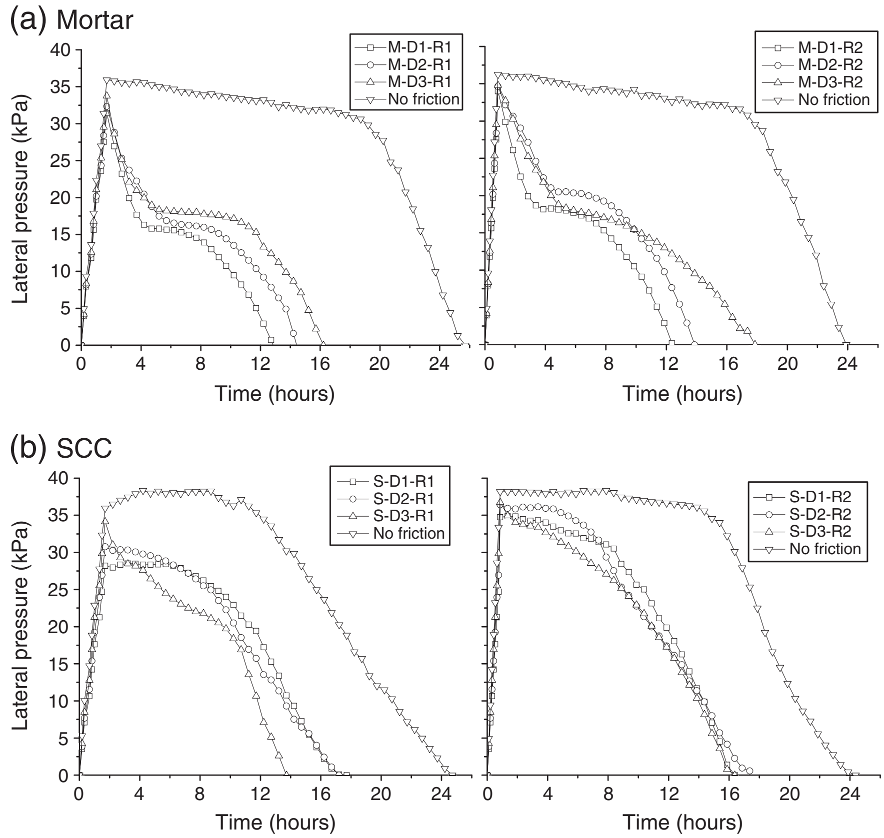

Fig. 13. Measured lateral pressure with and without friction.

for the heights of 55 cm, 115 cm and 165 cm from the top of the mixtures. Fig. 15 shows a comparison between the estimated and measured pressures plotted with the solid and hollow dotted lines, respectively. Even though there are small differences in several cases, both pressures had acceptable agreement, especially for the peak pressure and the cancellation time. The difference is thought to be attributable to other factors that were not considered in this study, such as the formwork flexibility, temperature, expansion and shrinkage of mixtures.

Formwork is basically a deformable structure. The deformation is the largest at the peak of the formwork pressure, and the formwork tends to return to the original position as the formwork pressure decrease over time. However, the recovery of the formwork may be delayed due to the viscosity of the concrete inside the form, which can be considered as a phenomenon like creep in a hardened state of concrete. At the very beginning, the delayed time of the formwork recovery is very short because the viscosity is relatively low. As hydration progresses, the concrete starts to stiffen, and the time delay becomes longer. More flexible formwork shows larger deformation and longer recovery time. Therefore, the stiffness or the flexibility of the formwork also affects the evolution of the formwork pressure, and the pressure is expected to cancel earlier in the stiffer formwork because the deformation to recover is relatively small.

Hydration is an exothermal reaction. As the hydration proceeds, temperature of inner concrete is rising, and so does the formwork. Even though it is hard to find out the amount of thermal expansion of

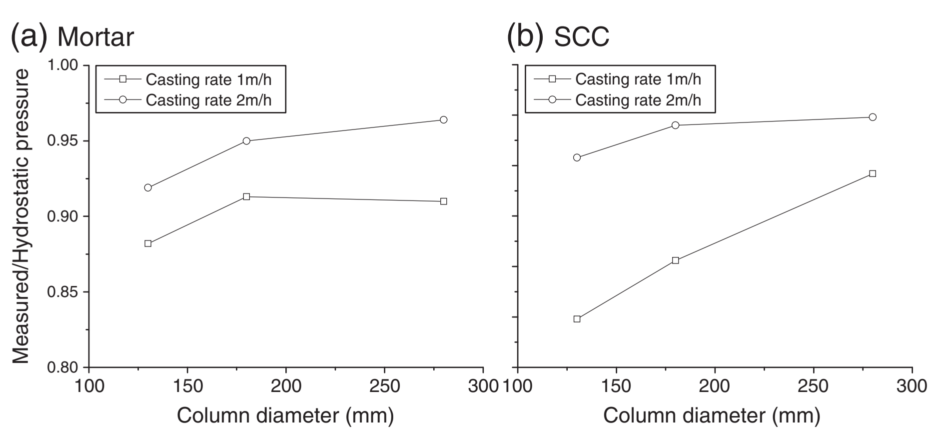

Fig. 14. Relationship between peak lateral pressure and column diameter.

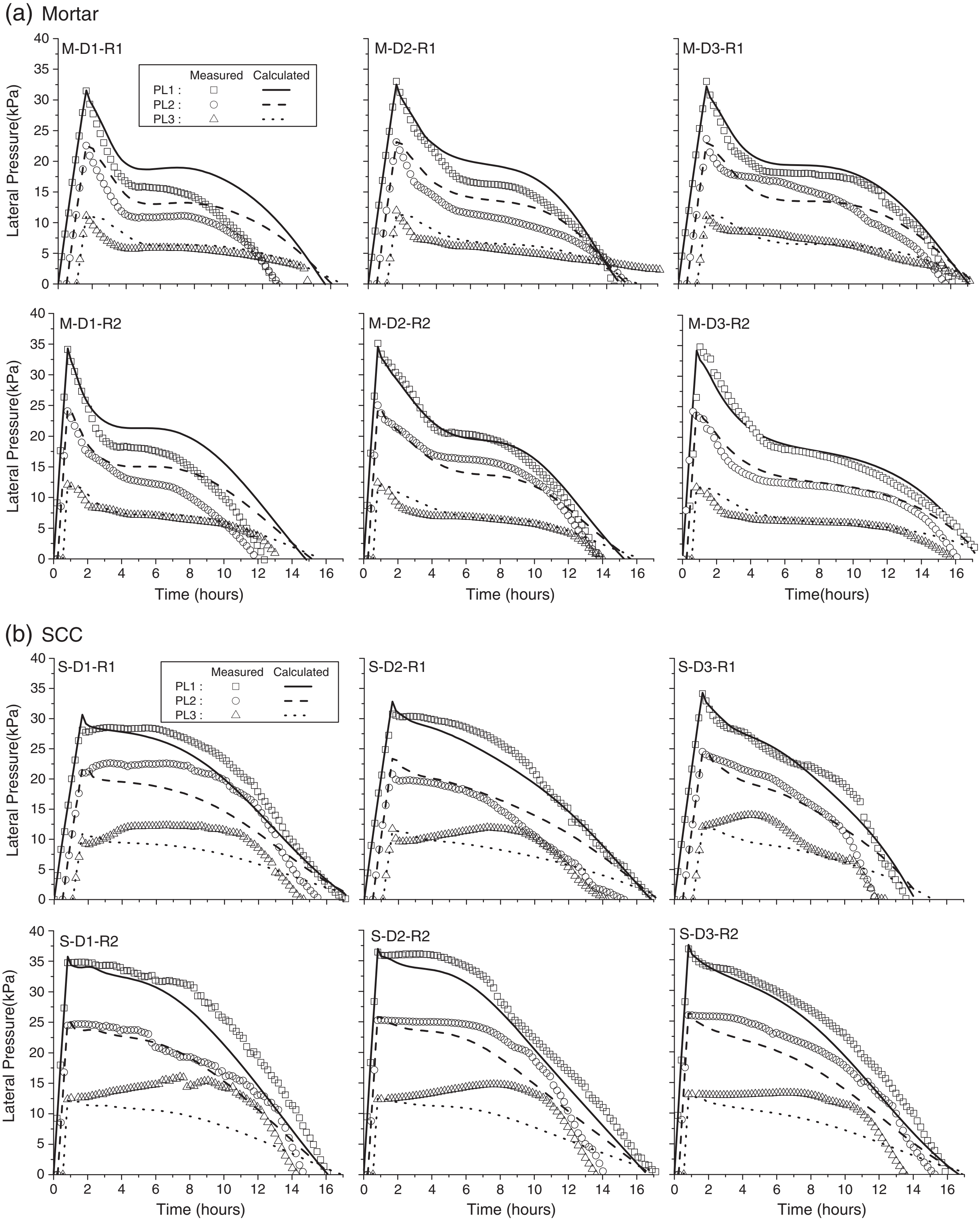

Fig. 15. Measured and predicted formwork pressures.

mixture, it is obvious that the temperature variation can influence the formwork pressure. In addition, mixture may contract due to autogenous shrinkage [23]. In reality, the effect of flexibility of formwork, thermal expansion and contraction, autogenous shrinkage on the pressure are coupled. However, the investigation of those factors is beyond the scope of this study.

5. Conclusions

The friction between mixtures and formwork affects the formwork lateral pressure. In order to quantitatively investigate the friction effect, a column formwork test apparatus was devised to measure the total or average friction stress. Column formworks having three different cross-sectional diameters were prepared to measure the vertical pressure at the bottom as well as the lateral pressure. The friction stresses were evaluated from the vertical pressures measured at the bottom. In addition, the lateral pressures were predicted by incorporating the intrinsic two-function model and the friction stress acting on the interface. The newly suggested prediction method was verified by a comparison between the estimated and measured formwork pressures. From the analytical and experimental results, the following features related to the friction effect were found: (1) the effect of the friction coefficient was not dominant in the measured friction stress, but a significant amount of cohesion developed over time; (2) the friction stress is mainly due to the cohesion and generally depends only on time; (3) the friction stress is independent of the placement rate; (4) a wider cross-section formwork induces greater friction stress; and, finally, (5) the friction stress decreases the extent and the cancellation time of the formwork pressure.

Experiments were performed in restricted conditions for materials, dimension and shape of column specimen, pouring rate, external temperature, etc. There is limitation to generalize the findings of this study to all SCC mixes. However, it is plausible to validate the suggested method to predict the formwork pressure considering friction effect. In a further study, experiments including other influencing factors for plenty of SCC mixes need to be performed to develop a generalized prediction method for SCC formwork pressure.

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