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Formwork lateral pressure of precast normal-concrete composite shear walls infilled with self-compacting concrete *

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Abstract: Wall cracking and mold expanding due to concrete vibrations can be effectively solved through the application of precast normal-concrete composite shear walls infilled with self-compacting concrete (SCC). However, the high liquidity of SCC will induce a higher lateral pressure. Therefore, it is important to obtain a better understanding of the template lateral pressure. In this work, nine composite shear walls were experimentally investigated, focusing on the effects of two parameters, i.e., the casting rate and the section width of the formwork. The time-varying pressure was monitored during the SCC pouring. It is found that the increase of casting rate from 3.2 m/h to 10.3 m/h resulted in a higher maximum lateral pressure. The higher casting rate led to a longer time required for the lateral pressure to drop to a steady value. There was no correlation between the section width and the rate of decrease in the initial formwork pressure and stable value. Based on the test results, a formula considering the effect of casting speed for the calculation of SCC formwork pressure was established to fill the gap in the current standards and for engineering applications.

Keywords: formwork lateral pressure; self-compacting concrete (SCC); composite shear wall; casting rate

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1 Introduction

The design of formwork systems is to determine the lateral pressure exerted by the fresh concrete during casting. It is well accepted that the casting rate, mixture proportion, concrete consistency, consolidation, and placement method, concrete temperature, cement type, maximum aggregate size, pore water pressure, and shape and size of the formwork have marked effects on the development of lateral pressure [1-2]. The lateral pressure was evaluated on 4 500 mm high and 700 mm^2 columns by Roby [3], with the rate of filling varied between 0.05 m/h and 1.00 m/h. Roby concluded that the maximum pressure increases with the rate of casting. Ritchie [4] performed an experimental study on the effect of the rate of casting in 1962, in which two series of concrete compositions having cement-to-total aggregate ratios of 1:3 and 1:6 were prepared. For both series, the maximum pressure was reported to increase with the increase of the rate of

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casting. The influences of the casting process of the wall or column elements on the distribution of lateral pressure envelope developed by plastic concrete were reviewed by Gardner [5]. Self-compacting concrete (SCC) was developed in Japan during the 1980s as a special category of highly flowable concretes [6]. Formworks for SCC are currently dimensioned according to the assumption that the pressure exerted by the concrete is equal to the hydrostatic pressure exerted by a fluid having the same density of the concrete [7]. Studies have shown, however, that SCC does not always achieve a hydrostatic pressure. Assaad et al. showed that variations in lateral pressure of SCC can be closely related to thixotropy [8-9], and they determined the effects of binder type and content on the variations of pressures that can be exerted by SCC after casting and up to early stages of hardening [10]. Kim et al. studied the effects of limestone filler or fly ash replacement on the formwork pressure and workability retention of a SCC mixture [11], and also showed the effects of mineral admixtures on SCC formwork pressure [12]. So far, several studies on the effects of casting rate of SCC have been carried out regarding material types and working performance [13-15].

In this study, the two precast reinforced concrete panels of a composite shear wall were connected by a steel bar truss, and were installed in construction site to form a cavity infilled with cast-in-place self-compacting concrete (SCC). The two wall panels were also used as formworks during casting [16]. The wall systems were first introduced by Germany, and currently are increasingly used in engineering construction for environmental protection and industrialization [17]. However, the cavity between two precast concrete shear walls is too narrow to allow the vibration of concrete, resulting in uncompacted concrete. SCC is used instead of normal concrete. SCC possesses high fluidity under self-weight and ensures good consolidation without any vibrations [18-19]. Mold expanding caused by formwork pressure would generate cracks in precast walls. Considering the uncertainty of formwork pressure, it is necessary to obtain a better understanding of the variation of formwork pressure of SCC. Because fresh SCC almost has no ability to support itself, the formwork pressure will reach a maximum value. Therefore, the formwork should be of high strength, stiffness and stability for safety concerns.

2 Experimental description

2.1 Materials

Ordinary Portland cement PO42.5 was used. Cementitious materials were made with approximately 24% Class F fly ash, 6% silica fume, and 70% cement. A high range carboxylic acid-based water-reducing admixture (HRWRA) was adopted. Ordinary medium river sand with fineness modulus of 2.5 and tap water were employed [20]. The mechanical properties of the SCC are listed in Table 1.

Table 1 Mix proportion of self-compacting concrete kg m^{-3}

Cement	Fly ash	Silica fume	Water	Sand	Stone	Water-reducing
360	125	30	186	834	873	5.6

The slump flow of SCC was 680 mm. In the J-ring test, the SCC spread value was 655 mm, while the height difference between the inside and outside rings was 10 mm. The ratio of the height of SCC at the leading edge in the horizontal section to that remaining in the vertical section in the L-box test was 0.85. All the test on SCC indicated relatively good self-leveling characteristics.

2.2 *Design of test specimens*

A total of nine wall specimens were designed, including six walls of the same size made with different casting rates, and three of different sizes, as shown in Table 2.

Reinforcement diagram and construction details of composite shear walls measuring 1 400 mm in width are given in Fig. 1. The concrete used in the normal concrete walls was of strength grade C30. It was poured with thicknesses of 40 mm and 50 mm for outer and inner walls, respectively. At first, two-way steel bars were installed and the cross bridging was welded. The cross bridging was used to connect the two pieces of wall. It ensured the precast normal-concrete wall and casting parts to form together. Four 30 mm diameter holes were reserved in the wall surface along the wall height for fixing the pressure sensor. Construction steps of composite shear walls are shown in Fig. 2.

2.3 *Test instrument*

The stress of SCC lateral pressure in the precast wall was measured with four BW-1 type pressure sensors mounted at 150 mm, 400 mm, 700 mm, and 970 mm from the bottom. The DH3817 dynamic-static strain instrument was used to collect data. Fig. 3 shows the arrangement of pressure sensors.

2.4 *Casting method*

There are two different methods of casting. One is casting from the bottom and the other is pouring from the top. In this experiment, the latter was used because of slightly lower lateral pressure caused [21]. The casting rate was controlled by the casting time. The casting details are summarized in Table 2.

Table 2 Sizes of composite shear walls and casting details

Wall No.	Size/mm	Design casting time/min	Actual casting time/min	Casting rate/(m h^{-1})
W-1-a	1 800×700×110	11.0	11.4	10.3
W-1-b	1 800×700×110	15.0	15.4	7.0
W-1-c	1 800×700×110	18.0	18.2	6.4
W-1-d	1 800×700×110	20.0	21.2	5.3
W-1-e	1 800×700×110	25.0	24.2	4.2
W-1-f	1 800×700×110	35.0	35.5	3.2
W-2	1 800×1 400×110	26.0	27.2	5.3
W-3	1 800×450×110	25.0	18.9	5.3
W-4	1 800×950×110	25.0	24.1	5.3

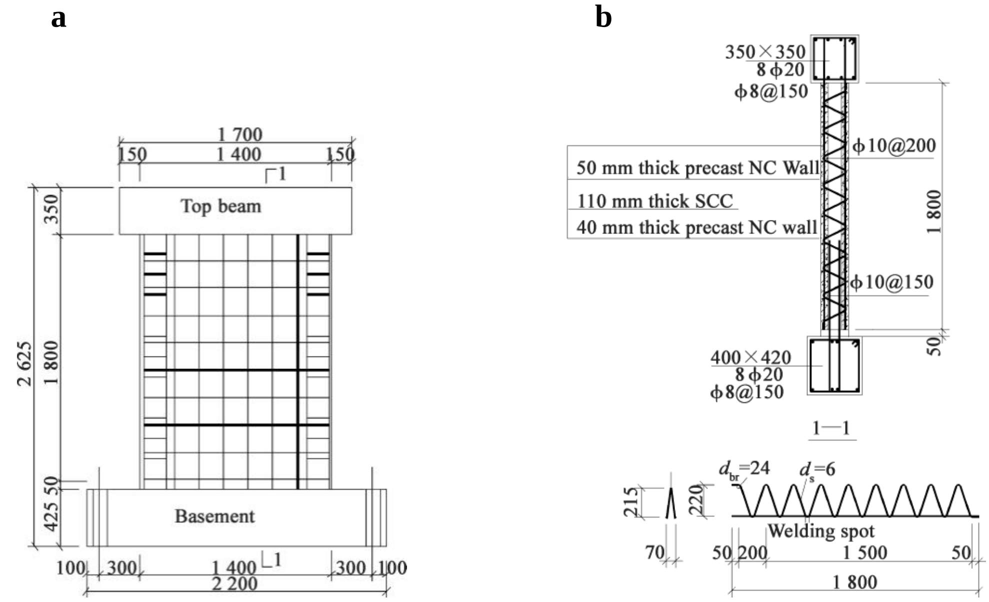

Fig. 1 Reinforcement details of composite shear walls: a) elevation of test specimen; and b) sketch of cross bridging

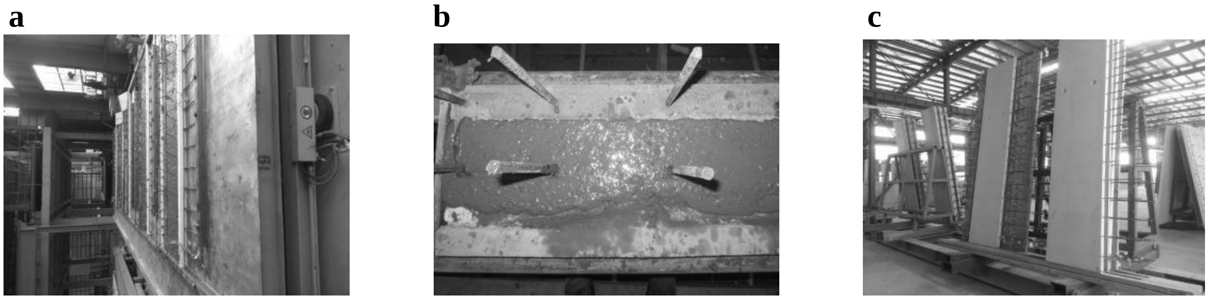

Fig. 2 Construction steps of composite shear walls: a) 50 mm thick precast normal-concrete wall; b) composite member installation; c) cavity infilling SCC

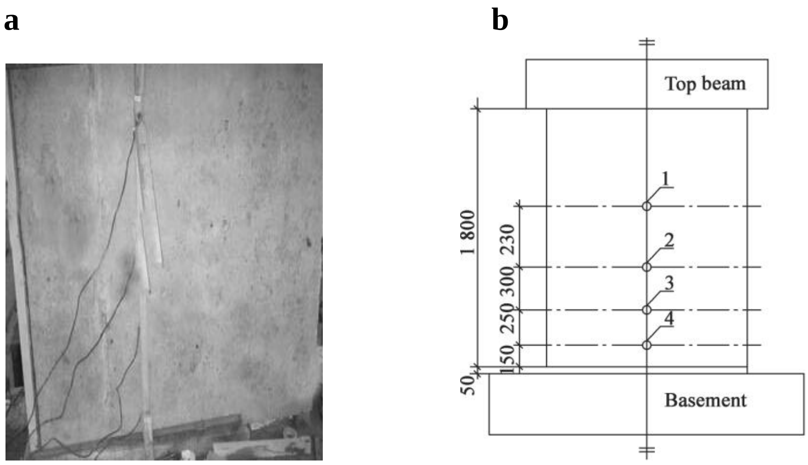

Fig. 3 Arrangement of pressure sensors

3 Analysis of test results and pressure formula

3.1 Influence of casting rate

In order to investigate the influence of casting rate (v) on maximum pressure with time, six casting rates (10.3 m/h, 7.0 m/h, 6.4 m/h, 5.3 m/h, 4.2 m/h and 3.2 m/h) were used. The lateral pressure developed on the formwork along the height during the first 3.5 h or 4.5 h after casting is shown in Fig. 4.

For example, in the case of v=7.0 m/h according to Fig. 4b, at the beginning t=0, the lateral pressure of the template at measuring points 1 to 4 reached the peak values of 17.7 kPa, 21.3kPa, 26.8 kPa and 30.3 kPa, which were 79.7%, 82.2%, 83.2%, and 84% of the hydrostatic pressure, respectively. The lateral pressure of the template decreased to 7.3 kPa, 8.5 kPa, 9.7 kPa, and 10.3 kPa, corresponding to reduction by 58.8%, 60.1%, 63.8%, and 66.0% respectively in 1.5 h after pouring SCC. It tended to reach a stable value after 4.5 h. The stable lateral pressures were 4.7 kPa, 5.8 kPa, 7.1 kPa, and 7.7 kPa, which were 20.3%, 22.1%, 22.9% and 24.6% of the hydrostatic pressure. Seen from the lateral pressure at the measuring point 4, a decline rate of pressure was 13.3 kPa/h after 1.5 h from casting. During the next 2.0 h, it dropped to 1.3 kPa/h. In comparison, the relative pressures determined initially at v=10.3 m/h and v=3.2 m/h were 84% and 76% of the hydrostatic pressure after casting, respectively. This indicates that a higher casting rate results in a greater maximum pressure. The maximum pressure is relevant to the flowability of mixture and thixotropy (shear recovery) that cause the increase of cohesiveness and rigidity. With a higher casting rate, the SCC has less time to build up cohesiveness and shear strength in the process of casting, which results in a high pressure. Moreover, the increase in the lateral pressure under impact loading was much greater.

Immediately after the SCC was infilled into the formwork, the SCC acted as a fluid exerting an almost hydrostatic head. It is noted from Fig. 5 that the maximum pressure was the highest at the rate of 10.3 m/h. However, the decrease trend in the lateral pressure was similar for different casting rates. Table 3 shows that the pressure tended to reach a stable value at t=3.5 h when v≤6.4 m/h. As for the case v=10.3 m/h or v=7.0 m/h, the pressure was not stable until t=4.5 h. In the same test conditions, building up some shear strength and cohesiveness can possess less time with a higher casting rate.

Table 3 Stable value of formwork pressure at different casting rate (v)

Height from the bottom /m	Formwork pressure/kPa											
	v=10.3 m/h		v=7.2 m/h		v=6.4 m/h		v=5.3 m/h		v=4.2 m/h		v=3.2 m/h	
	3.5 h	4.5 h	3.5 h	4.5 h	3.5 h	4.5 h	3.5 h	4.5 h	3.5 h	4.5 h	3.5 h	4.5 h
0.93	4.9	4.8	4.7	4.7	4.9	4.8	4.9	4.9	4.8	4.8	4.8	4.8
0.70	6.0	5.8	5.9	5.8	5.3	5.3	5.3	5.3	5.5	5.5	5.5	5.4
0.40	7.3	7.0	7.2	7.0	6.7	6.6	6.7	6.6	6.6	6.6	6.6	6.6
0.15	7.9	7.5	7.8	7.5	7.4	7.3	7.4	7.4	7.5	7.5	7.4	7.4

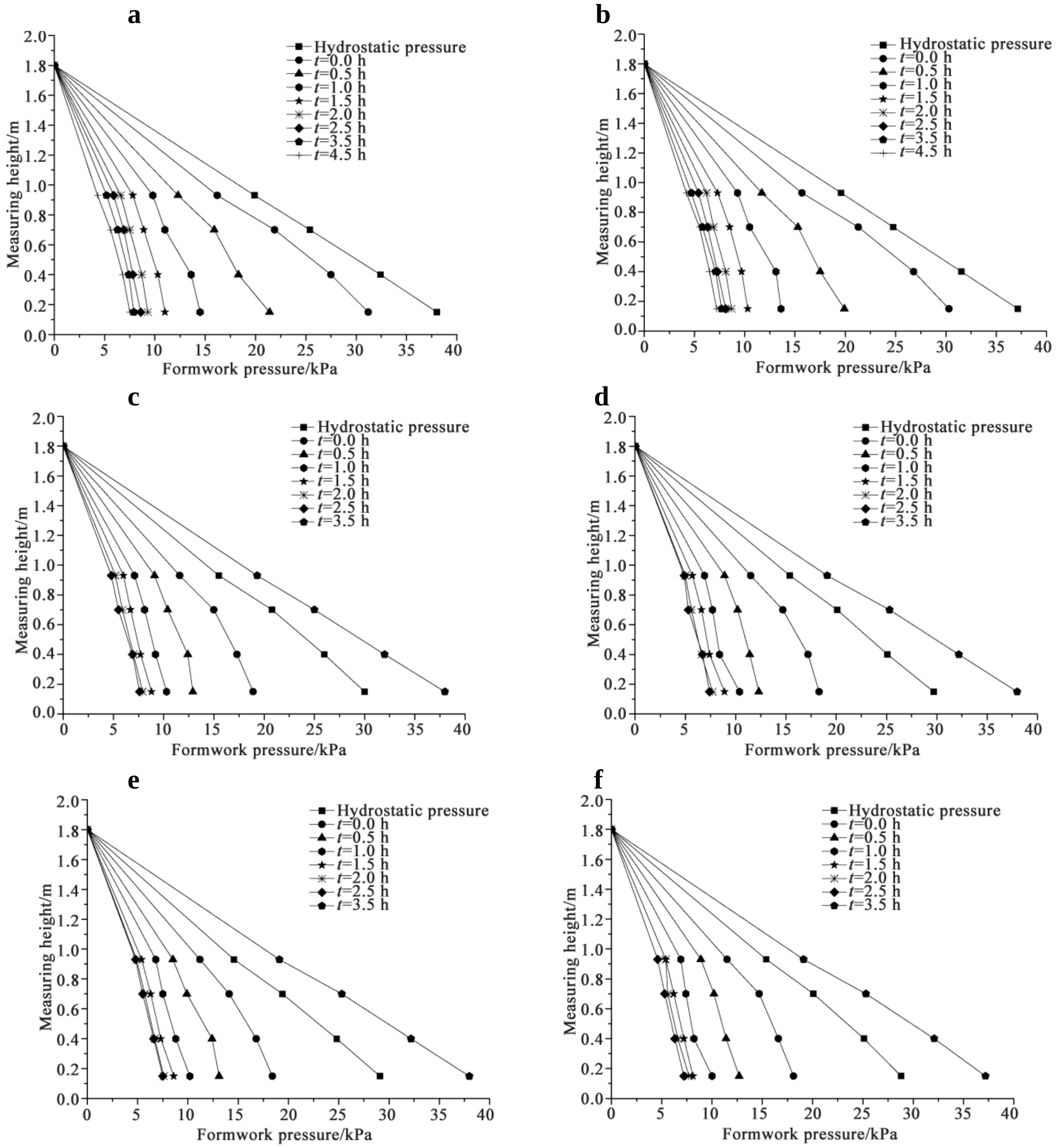

Fig. 4 Variations of lateral pressure after pouring with different casting rates: a) 10.3 m/h; b) 7.0 m/h; c) 6.4 m/h; d) 5.3 m/h; e) 4.2 m/h; and f) 3.2 m/h

As concluded above, six casting rates resulted in almost the same rate of lateral pressure drop. At a higher casting rate, a longer time is needed to achieve the stable pressure value, which suggests that casting rate has no relationship with the pressure dropping trend or the stable value of pressure. Variations of hydration and setting time are correlated to the rate of decrease in the formwork pressure. The development of pressure depends on the increase in the cohesiveness and shear strength of SCC.

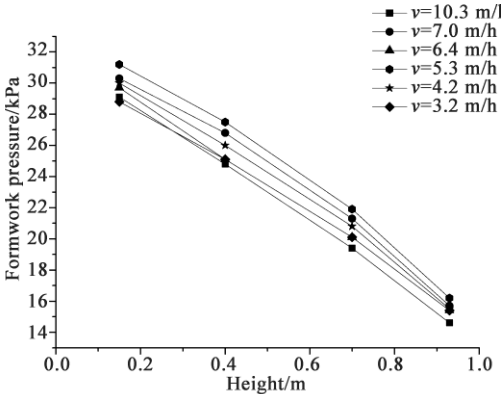

Fig. 5 Initial formwork pressure (*t*=0)

3.2 Influence of formwork width

To compare the effect of different width of formwork on the lateral pressure of SCC, three composite shear walls were cast at the same casting rate of 5.3 m/h and the whole casting time was controlled in 25 min. The variations of formwork pressure along with the height for different widths are shown in Fig. 6.

Compared with the template lateral pressure of width of 0.45 m, 0.95 m and 1.40 m, the maximum lateral pressure of the 0.45 m wide wall was the greatest. With a narrower width of the formwork, the pouring height of SCC increased faster, which caused a higher maximum lateral pressure in the formwork at the same discharging speed.

It is found that although the shapes of the formwork pressure curves were somehow different, the decreasing trend of the lateral pressure was similar with different width of template, and the stable values of the lateral pressure measured at the points were also similar. It can be concluded that the formwork width has no effect on the decreasing trend and stable value of formwork pressure. As mentioned above, the lateral pressure is related to the hydration process and the strength of formation process of the SCC.

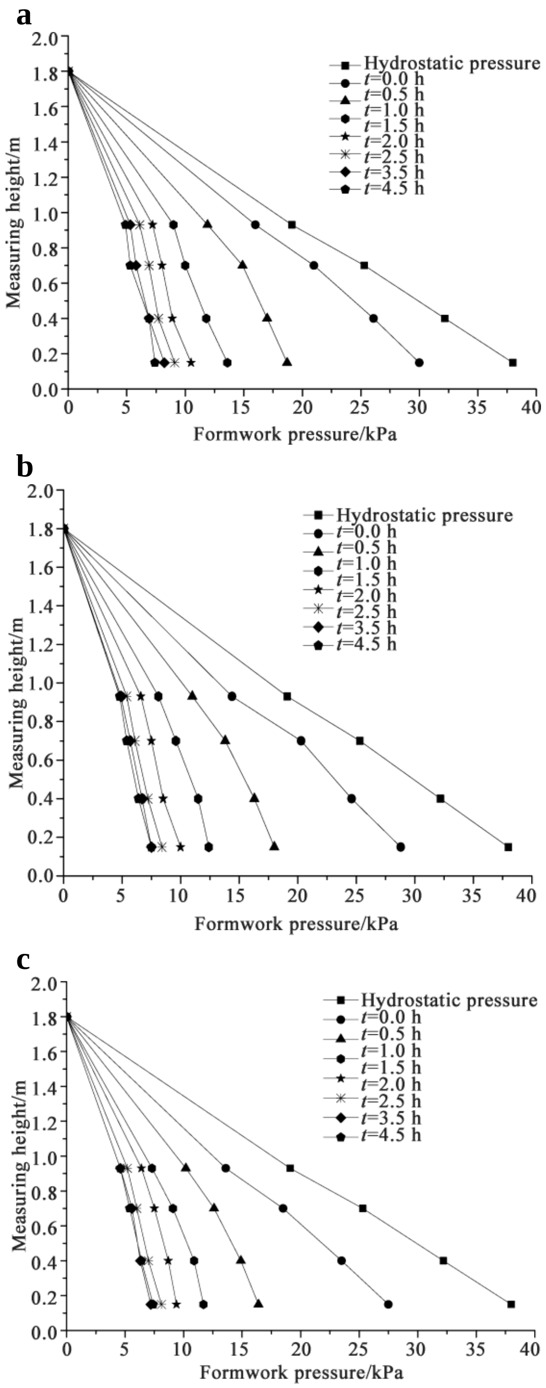

Fig. 6 Variations of formwork pressure with time for different widths of a) 0.45 m; b) 0.95 m; and c) 1.40 m

3.3 Formwork pressure formula

In accordance with Chinese code for acceptance of constructional quality of concrete structures (JB50666-2011), when using internal concrete vibrator, the maximum formwork pressure (F) of fresh concrete takes the smaller value between Eqs. (1) and (2):

$$F = 0.28\gamma_c t_0 \beta v^{1/2}, \tag{1}$$

$$F = \gamma_c H. \tag{2}$$

where γ_c is the concrete density; t_0 is the initial setting time; β is the modified coefficient of concrete slump; and H is the concrete pouring height. In Eq.(1), the formwork pressure is related to the weight, the initial setting time, admixtures, slump, and casting speed, respectively [22-23]. Results indicate that if SCC is poured in a fixed mix proportion, which means to have stable flow properties, SCC casting rate affects the initial pressure significantly. The admixtures and temperature are the major factors influencing the pressure decreasing trend. Considering the effect of the casting rate of SCC, a coefficient K of the formwork pressure is introduced, and it can be calculated by

$$K = av^b, \tag{3}$$

where a is the modified coefficient of the casting rate and b is the modified coefficient of the index.

As listed in Table 4, the pressure coefficients of four measuring points become much closer when v is 6.4 m/h and above. It is slightly higher on the upper section of template than on the lower section when the casting speed is 5.3 m/h, 4.2 m/h and 3.2 m/h, which is due to the lower casting speed and the longer casting time. When the solidifying cohesive strength continues to grow, the lower portion of the concrete pressure decreases. So the pressure on the upper region of the wall is higher than that on the lower region.

According to the wall pressure test results, the data of measuring point at the bottom of wall are fitted by the least square method at different casting rate. Considering the effect of casting speed, K can be calculated by

$$K = 0.704\,94v^{0.147\,82} \approx 0.7v^{0.15}. \tag{4}$$

Considering the high fluidity of SCC, Eq. (2) can be directly used [24].

The maximum formwork pressure of SCC (F) is expressed as

$$F = K\gamma_c H, \tag{5}$$

Table 4 Coefficient (K) of formwork pressure of a measuring point of different distance (H) from the bottom for different casting rate (v)

v/(m h^{-1})	$K1$	$K2$	$K3$	$K4$
	$H1$=970 mm	$H2$=700 mm	$H3$=400 mm	$H4$=150 mm
10.3	0.95	0.95	0.94	0.94
7.2	0.93	0.93	0.93	0.92
6.4	0.91	0.90	0.91	0.91
5.3	0.91	0.90	0.89	0.85
4.2	0.90	0.88	0.84	0.83
3.2	0.85	0.79	0.75	0.77

where $K = 0.7v^{0.15}$. When the casting rate is high, there is a calculation error induced by the influence of the solidifying cohesive strength. Therefore, the parameter ξ is introduced to correct the lateral pressure.

It can be seen from Table 4, when v≥6.4 m/h, $\xi = K1/K4 = 1.0$. Otherwise, when v<6.4 m/h, $\xi = K1/K4 = 1.1$.

Therefore, Eq. (5) can be modified as:

$$F = \xi K \gamma_c H. \tag{6}$$

4 Conclusions

1) The initial lateral pressures at different casting speeds indicate that, when the SCC casting rate is increased, a higher maximum formwork pressure will be exerted by SCC and it will take a longer time for the pressure to drop to a steady value. Nevertheless, the pressure dropping trend will not be affected by the change in the casting speed.

2) The effect of the section width on the maximum lateral pressure, decline trend and stability value can be neglected. However, at the same SCC discharging speed, the increase in the width of the formwork will result in the decrease of the SCC pouring speed, and the reduction of the maximum initial value of the template lateral pressure.

3) It is found that the casting rate will affect the maximum formwork pressure. When v≥6.4 m/h, the solidifying cohesive strength will lead to an insignificant pressure decrease. Based on this, it is feasible to use Eq. (6) to calculate the formwork pressure, and it can be applied to SCC construction.

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