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Kinetics of formwork pressure drop of self-consolidating concrete containing various types and contents of binder

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Abstract

A comprehensive research study was carried out to determine the effect of binder type and content on the variations in lateral and pore water pressures that can be exerted by self-consolidating concrete after casting and up to early stages of hardening. Test results show that both physical and chemical phenomena can influence the kinetics of the decrease in lateral pressure until cancellation. The former phenomenon occurs mainly during the dormant period of cement hydration, and is significantly affected by the binder type and content. Regardless of the binder type, the effect of increasing the binder content resulted in sharper drops in pressure. The cancellation of lateral pressure depends on a chemical effect and occurs after the end of the dormant period when the rate of cement hydration is accelerated. Beyond the dormant period, the progressive formation of hydration products leads to the creation of a structural network, and the pore water pressure begins to drop abruptly towards negative values.

Keywords: Binder; Lateral pressure; Pore water pressure; Self-consolidating concrete

1. Introduction

Self-consolidating concrete (SCC) is a new type of high-performance concrete characterized by its ability to flow under its own weight and achieve good consolidation without any mechanical vibration. Appropriate estimates of the maximum lateral pressure exerted on formwork and its rate of drop with time until cancellation are important to reduce formwork costs and facilitate scheduling of concrete placement.

The type and content of the binder are key parameters affecting formwork lateral pressure of concrete. Roby [1] investigated a series of relatively rich, normal, and lean mixtures made with different cement/sand/coarse aggregate ratios of 1:1.25:2.25, 1:2:3.5, and 1:2.5:5, respectively. An ordinary portland cement was used for concrete mixtures with slump values varying between 50 and 150 mm. Cement content was found to have significant effect on lateral pressure since the rich mixtures developed 40% greater pressure than the normal mixtures, which in their turn, developed about 15% greater pressure than that of the lean mixtures. Similar findings were reported by Ritchie [2] who stated that, independently of the consistency and method of placement, concrete made with higher cement content can develop greater formwork pressure. Roby [1] and Ritchie [2] concluded that this can be indirectly related to the lower volume of coarse aggregate of mixtures proportioned with greater cement content. A lower degree of aggregate-to-aggregate contact can lead to lower internal friction, thus increasing the mobility of the concrete and leading to higher transformation of vertical load in lateral pressure.

Limited information exists regarding the effect of supplementary cementitious materials (SCM) on the development and variation in formwork pressure, especially in the case of SCC that is typically proportioned with SCM. Gardner [3] investigated the influence of cement replacement by fly ash for concrete mixtures with slump values ranging between 65 and 115 mm. Fly ash substitutions of up

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to 50% were used. Concrete containing fly ash was found to develop higher lateral pressure than similar mixture prepared with only Type 10 cement. The incorporation of fly ash increases the mobility of fresh concrete and reduces the rate of shear strength gain at early age, thus resulting in higher lateral pressure [3]. Shear strength properties of fresh concrete are functions of the frictional resistance and interlocking between aggregate and cement particles as well as the development of bond among solid particles during cement hydration [4]. The former component of shear strength is termed internal friction and requires strain to be mobilized, while the latter component is referred to as cohesion. The cohesion results from cement hydration and depends on the elapsed time after the initial contact of water with cement [4].

In recent studies, Assaad et al. [5,6] evaluated the effect of the rate of increase in shear strength on lateral and pore water pressure variations through the assessment of the degree of restructuring of fresh concrete which is assessed by determining the thixotropy of the concrete. Thixotropy is defined as a decrease in viscosity with time when a material is submitted to a constant shearing stress [7]. Various SCC mixtures with slump flow consistency of 650±15 mm were investigated. The mixtures were prepared with different coarse aggregate concentrations and set-modifying admixtures. Experimental columns measuring 200 mm in diameter and either 2100 or 2800 mm in height were used to monitor lateral pressure variations of the plastic concrete. Test results showed that the maximum initial pressure measured right after casting decreases with the increase in coarse aggregate volume. This was attributed to the increase in the degree of internal friction that reduces the mobility of the concrete, thus resulting in lower pressure right after casting [5]. On the other hand, the rate of pressure drop with time was found to increase with the use of a set-accelerating admixture, given the higher development of cohesion [6]. Considering that the lateral pressure (σ) is the sum of the pressure obtained from the pore water (u) and solid particles (σ'), it was found that both σ and u are equal (σ'=0) during the plastic stage [5].

Limited information is available regarding the kinetics of the drop in lateral and pore water pressures at early stages of hardening. The time period corresponding to the cancellation of such pressures is of special interest as well. Amziane et al. [8] evaluated the drop in lateral and pore water pressures of cement paste made with 0.30 to 0.45 water-to-cement ratio (w/c). An experimental column measuring 1000 mm in height and 110 mm in diameter equipped with two pressure transducers was used. The authors reported that lateral and pore water pressures are strongly affected by the w/c and the applied stress level. Both pressures were found to be equal to the theoretical hydrostatic pressure exerted by the mixture, and their rates of drop were perfectly identical. After the cancellation of lateral pressure, depressions of tens of kPa were recorded for the pore water pressure before stabilization at zero [8].

The assessment of the kinetics of lateral pressure drop until cancellation at early stages of hardening is important for scheduling formwork removal. Harrison [9,10] found that the key parameter for assessing the time required for formwork removal is the characteristic in-situ strength of the concrete. The increase in early strength of the in-situ concrete for equal maturity and/or the increase of concrete maturity for equal real time can reduce the time before formwork removal. Early strength can be increased by using set-accelerating admixtures, cements with rapid strength development, or concrete mixture of higher characteristics strength. On the other hand, the maturity can be increased, for any real time, by specifying a higher placing concrete temperature, increasing the insulating effectiveness of the formwork, or accelerating the curing process [9,10].

The study reported in this paper is the second phase of a comprehensive research program undertaken to evaluate the formwork lateral pressure developed by SCC mixtures made with various binder types and contents. The first part of this study aimed at evaluating the effect of thixotropy on the development of lateral pressure; this later being determined on an experimental column measuring 2800 mm in height during the plastic stage of cement hydration [11]. Ten mixtures with 650±15 mm slump flow and 0.40 w/c were tested in order to evaluate the kinetics of the drop in lateral and pore water pressure up to early stages of hardening. The influence of binder type and content on the time necessary for lateral pressure cancellation is determined and interpreted with respect to concrete temperature rise. Standard setting times of the tested mixtures are evaluated and correlated to pressure cancellation.

2. Experimental program

2.1. Materials

A Type 10 (T10) and Type 30 (T30) CSA Canadian cements, similar to ASTM C 150 Type I and Type III cements, respectively, were used along with three other blended cements. The blended cements included a binary cement (BIN) containing 8% silica fume (SF) and 92% T10 cement, a ternary cement (TER) made with 6% SF, 22% Class F fly ash (FA), and 72% T10 cement, and finally a quaternary cement (QUA) containing 6% SF, 28% FA, 16% granulated blast-furnace slag (BFS), and 50% T10 cement. The binary and ternary cements are commercially available, whereas the quaternary cement was prepared for this investigation in the laboratory. All replacement values of the T10 cement by SCM are expressed on total mass basis of the binder.

The chemical and physical characteristics of the T10, T30, and SCM are summarized in Table 1. The packing densities of the T10 and T30 portland cements were determined to be 59% and 64%, respectively. Such values were calculated using a gyratory compacting machine that

Table 1
Chemical and physical properties of T10 and T30 cements and SCM

	T10	T30	SF	FA	BFS
SiO_2, %	21.0	19.5	93.6	50.0	36.1
Al_2O_3, %	4.2	4.7	0.3	29.4	10.0
Fe_2O_3, %	3.1	2.0	0.5	13.5	0.5
CaO, %	62.0	63.8	0.3	1.7	33.9
MgO, %	2.9	2.0	0.5	0.7	15.4
Na_2O eq., %	0.74	0.83	1.4	0.4	0.7
C_3S, %	59.6	66.7	–	–	–
C_2S, %	14.5	10.3	–	–	–
C_3A, %	6.4	9.1	–	–	–
C_4AF, %	7.9	5.4	–	–	–
Blaine specific surface, m^2/kg	325	600	–	410	445
Surface area B.E.T., m^2/kg	–	–	20,250	–	–
Mean apparent diameter, μm	17	11	0.1	13	10
Specific gravity	3.14	3.15	2.22	2.53	2.88
Percent passing 45 μm	92	99	100	95	100
Bulk unit weight, kg/m^3	3150	3160	280	2160	–
Loss on ignition, %	2.5	1.5	2.8	2.2	0

T10: Type 10 cement, T30: Type 30 cement, SF: silica fume, FA: fly ash, and BFS: granulated blast furnace slag.

enables the determination of the void ratio by compressing the tested powder sample. The packing densities of the binary, ternary, and quaternary cements are 63%, 67%, and 68%, respectively.

Continuously graded crushed limestone aggregate with nominal size of 10 mm and a well-graded siliceous sand were employed. Their particle size distributions were in compliance with 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.

A polycarboxylate-based high-range water-reducing admixture (HRWRA) with specific gravity of 1.1 and solid content of 27% was used. A liquid cellulosic-based viscosity-modifying admixture (VMA) was employed to enhance stability. It had a specific gravity of 1.12 and a solid content of 39%. A synthetic detergent-based air-entraining agent (AEA) was used to secure the required air content.

2.2. Mixture proportions

As summarized in Table 2, various contents of binary, ternary, or quaternary cement varying between 400 and 550 kg/m^3 were used. These mixtures reflect typical SCC with limited to high volume of cement paste used in commercial applications with different degrees of congested reinforcing bars. A binder content of 450 kg/m^3 was employed for the mixtures made with T10 and T30 cements. The *w/c* (or water-to-binder ratio) and sand-to-total aggregate ratio were fixed at 0.40 and 0.46, respectively.

The dosage of the liquid-based VMA was set at 260 mL/100 kg of binder for all mixtures. The HRWRA and AEA dosages were adjusted to secure an initial slump flow and fresh air content of 650±15 mm and 6±2%, respectively.

2.3. Instrumented formwork for measuring lateral stresses

Variations in lateral pressure exerted by fresh concrete were determined using an experimental column measuring 1100 mm in height and 200 mm in diameter [12]. The inside face of the form was coated with a formwork release oil prior to each use. The lateral pressure was measured using three pressure sensors of 100-kPa capacity mounted at 50, 250, and 450 mm from the base. At the same heights, three pore water pressure sensors usually employed in soil mechanics

Table 2
Mixture composition of evaluated concrete

Binder type	Type 10 cement	Type 30 cement	Binary cement: 8% SF+92% Type 10		Ternary cement: 6% SF+22% FA+72% Type 10				Quaternary cement: 6% SF+26% FA+18% BFS+50% T10	
Mixture codification	450-T10	450-T30	450-BIN	550-BIN	400-TER	450-TER	500-TER	550-TER	450-QUA	550-QUA
Type 10 cement, kg/m^3	450	–	–	–	–	–	–	–	–	–
Type 30 cement, kg/m^3	–	450	–	–	–	–	–	–	–	–
Binary cement, kg/m^3	–	–	450	550	–	–	–	–	–	–
Ternary cement, kg/m^3	–	–	–	–	400	450	500	550	–	–
Quaternary cement, kg/m^3	–	–	–	–	–	–	–	–	450	550
Water, kg/m^3 (w/c=0.40)	180	180	180	220	160	180	200	220	180	220
Sand (0–5), kg/m^3	770	770	760	670	800	750	710	660	750	650
Coarse aggregate (5–10), kg/m^3	900	900	890	790	940	880	830	780	880	770
V sand/V paste	0.89	0.89	0.86	0.62	1.0	0.83	0.71	0.6	0.82	0.58
V coarse aggregate, L/m^3	332	332	328	291	347	325	306	288	325	284
HRWRA, L/m^3	3.3	3.2	3.9	2.75	4.6	3.8	3.2	2.7	4.6	3.5
VMA, mL/100 kg of cement	260	260	260	260	260	260	260	260	260	260
AEA, mL/100 kg of cement	160	170	200	150	135	120	110	90	65	50

Table 3
Fresh properties of evaluated SCC mixtures

	Initial slump flow, mm	Air content, %	Temperature, °C	Unit weight, kg/m^3	h_2/h_1 of L-box test	Surface settlement, %
450-T10	650	4.3	22.9	2360	0.81	0.41
450-T30	640	6.2	21.7	2335	0.85	0.15
450-BIN	660	5.0	22.2	2320	0.83	0.29
550-BIN	655	4.8	21.6	2260	0.89	0.28
400-TER	650	4.4	20.8	2350	0.79	0.37
450-TER	655	4.7	20.6	2235	0.81	0.34
500-TER	640	5.2	19.6	2250	0.88	0.25
550-TER	635	5.0	22.0	2230	0.91	0.22
450-QUA	640	8.2	21.6	2210	0.85	0.37
550-QUA	635	5.5	21.2	2160	0.92	0.26

were placed to determine the pressure resulting from the fluid phase. The sensors contain a water filtering device made of compacted fiber to prevent the infiltration of cement paste into the pore water measurement system [5]. All sensor faces were set flush with the inside of the formwork, and were frequently calibrated using water prior to use.

2.4. Fabrication and testing program

Each mixture of 100-L batch volume was prepared in an open-pan mixer. The mixing sequence consisted of homogenizing the coarse aggregate and sand for one minute before introducing one third of the mixing water along with the AEA. The cementitious materials were then added and followed by the HRWRA and one third of the water. After 3 min of mixing, the VMA diluted with the remaining water was introduced, and the concrete was mixed for 2 additional minutes. Concrete temperature during mixing and sampling varied between 20±2 °C.

The slump flow, temperature, unit weight, air volume, L-box flow characteristics, and surface settlement were determined (Table 3). Descriptions of the L-box and surface settlement test methods are reported in Refs. [13,14], respectively. The initial and final setting times were evaluated in compliance with ASTM C 403, Penetration Resistance Test Method, on a mortar sample obtained by sieving fresh concrete. Temperature rise was determined by measuring temperature changes using two thermocouples placed in the center of the 200-mm diameter column that was used to monitor lateral pressure variations.

For casting the SCC in the instrumented column, the concrete was continuously discharged from the top at a rate of 10 m/h without any mechanical vibration. Pressure monitoring was conducted for 24 h following casting. The ambient temperature was maintained at 20±2 °C.

3. Results and discussion

3.1. HRWRA demand

For any given binder type, mixtures containing lower binder content are shown to increase the HRWRA demand compared to those made with higher binder content. As can be seen in Table 2, this can be attributed to the relative increase in coarse aggregate that increases internal friction during the flow, thus requiring additional HRWRA to secure the targeted deformability.

The incorporation of greater content of SCM in the binary, ternary, and quaternary cements necessitated greater HRWRA demand compared to mixture made with only T10 cement. For example, additional HRWRA dosages of 0.6 and 1.2 L/m^3 were necessary for the 450-TER and 450-QUA mixtures compared to the 450-T10 mixture, respectively. This can be due to changes in morphology, grain-size distribution, packing density, and water adsorption of the SCM particles.

3.2. Fresh concrete properties

Fresh properties of the tested mixtures are summarized in Table 3. As expected, the increase in binder content enhanced the passing ability of the SCC. For example, the h_2/h_1 blocking ratio increased from 0.85 to 0.92 when the binder content was increased from 450 to 550 kg/m^3, respectively, for SCC made with quaternary cement. The increase in binder content decreases the relative coarse aggregate concentration, thus reducing the degree of internal friction among solid particles and enhancing the passing ability of the concrete. The h_2/h_1 value was not much affected by the binder type.

The surface settlement is shown to increase with the decrease in binder content (or the increase in coarse aggregate volume). For example, the surface settlement increased from 0.22% to 0.37% for the 550-TER and 400-TER mixtures, respectively. Greater volume of coarse aggregate results in greater HRWRA demand that can increase the free water content and lead to longer dormant period, thus increasing the risk of consolidation and bleeding.

3.3. Kinetics of lateral pressure drop at early age

3.3.1. Effect of binder type

The variations of the relative pressure measured along the 1100-mm experimental column (P(maximum)/P(hydrostatic)) are plotted in Figs. 1 and 2 for SCC mixtures made

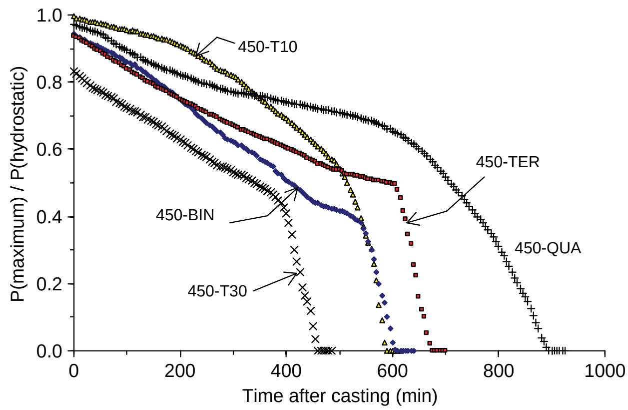

Fig. 1. Variations in lateral pressure for SCC mixtures made with 450 kg/m^3 of various types of binder.

with 450 or 550 kg/m^3 of binder, respectively. In general, maximum relative pressures varying from 83% (450-T30 mixture) to 100% are measured. Lower pressure values ranging from 78% (450-T30 mixture) to 98% were obtained when using the 2800-mm-high experimental column [11]. The time necessary to fill the higher column is longer than that of the 1100-mm column for a given casting rate, hence leading to greater increase in shear strength properties and reduction in lateral pressure right after casting. However, the rates of pressure drop with time were quite similar for both experimental columns.

Partial substitutions of Type 10 cement by SF, FA, or BFS of lower specific gravity and higher surface area can increase solid volume content and degree of particle interlock [11]. Given that fresh concrete behaves in a dilatant fashion and expands when subjected to vertical load [15], the partial substitutions of Type 10 cement by SF, FA, or BFS can reduce the expanding response. This can then decrease the extent by which the vertical stresses can transform into lateral stresses.

3.3.2. Effect of binder content

The variations of the P(maximum)/P(hydrostatic) values with respect to elapsed time after casting for mixtures made with various contents of ternary cement are plotted in Fig. 3. The same pressure variations for mixtures prepared with binary or quaternary cement are given in Fig. 4. Irrespective of the type of binder, SCC made with higher binder content can result in increased initial lateral pressure. This is mainly due to the lower coarse aggregate volume in mixtures made with higher binder content (Table 2) that reduces the degree of internal friction [5,11].

Unlike the effect of binder content on the initial pressure, the rate of drop in lateral pressure is shown to increase with the binder content. Alexandridis and Gardner [4] reported that internal friction is an inherent property of concrete that remains constant with time and temperature change. For longer elapsed periods after casting, it is the increase in cohesion that allows plastic concrete to develop higher shear strength through the formation of a gel structure capable of carrying an increasing fraction of the vertical load [4]. In consequence, mixtures made with higher binder contents can result in increased degree of cohesiveness, thus leading to sharper reduction in lateral pressure after placement. It is important to note that SCC made with higher binder content necessitated lower HRWRA demand compared to concrete prepared with lower binder content (Table 2). This can increase the rate

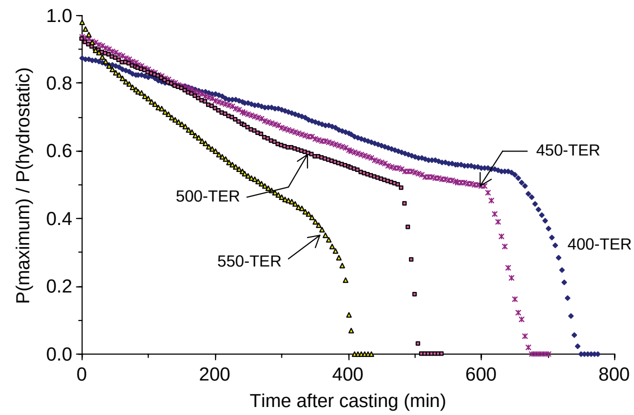

Fig. 3. Variations in lateral pressure for SCC mixtures made with various contents of ternary cement.

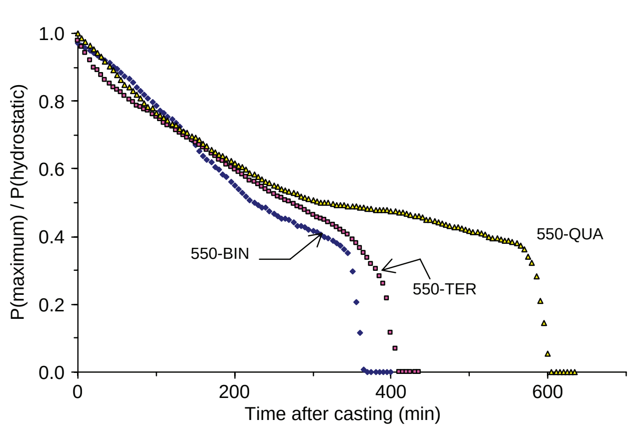

Fig. 2. Variations in lateral pressure for SCC mixtures made with 550 kg/m^3 of various types of binder.

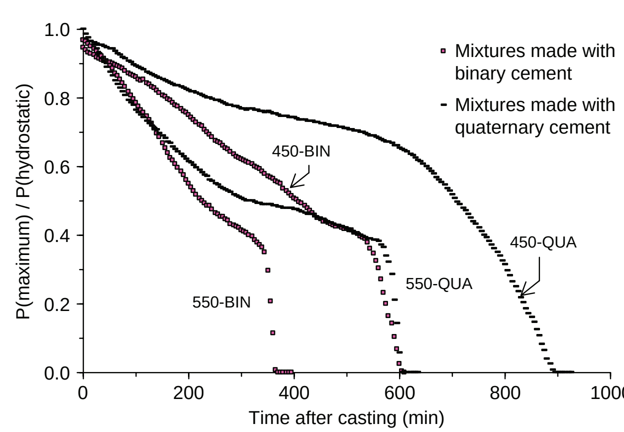

Fig. 4. Variations in lateral pressure for SCC mixtures made with various contents of binary or quaternary cement.

of slump flow loss with time, thus increasing the development of cohesion and enabling the concrete to further resist the applied vertical load [11].

3.3.3. Phenomena responsible for pressure drop until cancellation

Both physical and chemical phenomena take place after placement and contribute to the drop in lateral pressure until cancellation. This is illustrated in Figs. 5 and 6 for the 450-QUA and 450-T10 mixtures, respectively (symbols in Fig. 6 will be defined latter). The physical effect refers here to as the reverse of thixotropy (physical restructuring) which is in part due to a reorganization of solid particles and increase in the internal friction. This is coupled with a chemical effect that takes place predominantly after the end of the dormant period due to rapid formation of hydration products and absorption of water onto the hydrates. Therefore, the so-called physical/chemical effect occurring during the dormant period of cement hydration is directly affected by the binder type and content as well as the HRWRA dosage. For example, higher binder content associated with a lower HRWRA demand can increase the rate of pressure drop and reduce the length of this effect. Conversely, longer dormant period resulting in prolonged physical/chemical effect can occur in the case of mixtures necessitating higher HRWRA demand.

As shown in Figs. 5 and 6, some residual pressure can still be exerted at the end of the dormant period. Pressure cancellation is shown to take place well into the accelerated stage of cement hydration. This was also observed by Ore and Straughan [16] who reported that the cancellation of lateral pressure would coincide with the initial setting time of the paste. In consequence, it can be stipulated that the cancellation of pressure depends mostly on the so-called chemical effect whereby cohesion increases rapidly due to cement hydration. The acceleration in the formation of hydrates enables the material to be self-bearing, thus leading to an abrupt drop in lateral pressure towards zero.

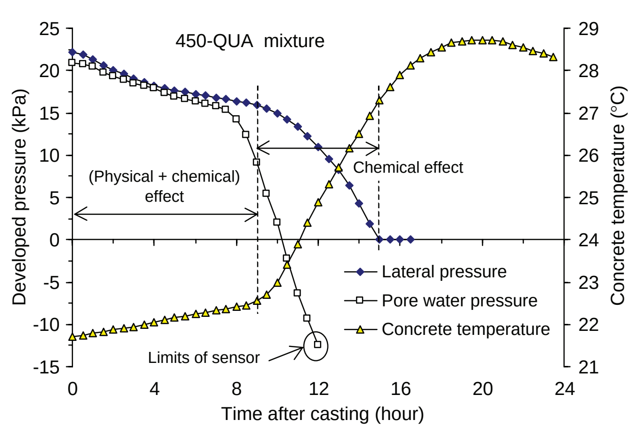

Fig. 5. Variations of concrete temperature and developed stresses with time for the 450-QUA mixture.

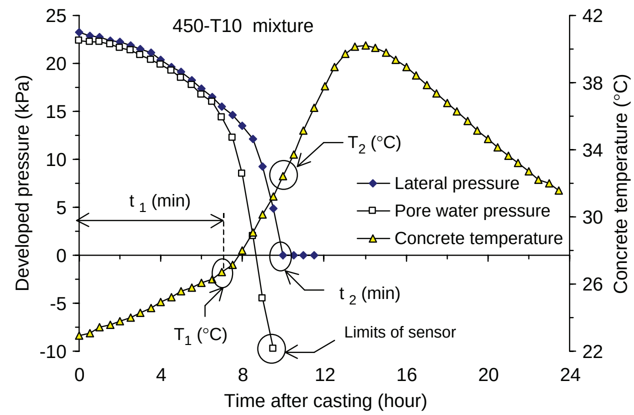

Fig. 6. Variations of concrete temperature and developed stresses with time for the 450-T10 mixture.

3.4. Pore water pressure developments

The kinetics of pore water pressure and lateral pressure drop determined at the base of the experimental column are plotted in Figs. 5 and 6 for the 450-QUA and 450-T10 mixtures, respectively. The figures also show concrete temperature variations with time measured in the center of the column. Irrespective of the binder type or content, the pore water pressure is shown to follow exactly the variations of lateral pressure during the plastic stage of cement hydration. Such behaviors were also found for SCC mixtures made with various sand-to-total aggregate ratios [5]. Assuming that soil mechanics principles apply to plastic concrete, the lateral pressure (σ) can be considered as the sum of the pressure obtained from the pore water (pore water pressure: u) and the solid particles (effective pressure: σ'). According to Clear and Bonner [17], when stress is applied to a saturated material from which there is no water drainage, the total stress (σ) becomes equal to u and $\sigma'=0$. The applied lateral pressure is then totally due to the pore water pressure during the plastic stage of cement hydration.

By the end of the plastic stage when the concrete skeleton becomes relatively rigid, the pore water pressure decreases abruptly towards zero. This corresponds roughly to the time when the concrete temperature starts to increase at a faster rate (Figs. 5 and 6). The mechanism of pore water pressure drop is governed by chemical shrinkage caused by cement hydration that starts as soon as the cement begins to react with water [18]. However, it is after the end of the plastic stage that progressive formation of hydration products can cause the creation of a network connection and development of empty capillary pores. The largest capillary pores will begin gradually to dry, and gel pores formed during the hydration will start to drain water from the coarsest capillary pores, as free water is held by forces that are inversely proportional to the apparent diameter (self-desiccation process) [19]. The consequence of such process is the formation of meniscus at the interface water/vapour, resulting in decrease in relative humidity and drop in pore water pressure towards negative values.

Table 4
Results of setting time, dT/dt, and elapsed periods corresponding to the cancellation of lateral pressure

	Initial set, min	Final set, min	Values when dT/dt starts to increase		Values when lateral pressure is canceled		Spread in temperature (T_2-T_1), °C	Spread in time (t_2-t_1), min
			T_1, °C	t_1[a], min	T_2, °C	t_2[a], min		
450-T10	510	570	27.1	450	32.8	610	5.7	160
450-T30	425	470	27.2	420	29.6	490	2.4	70
450-BIN	620	730	25.9	500	27.4	630	1.5	130
550-BIN	450	535	24.7	390	24.9	400	0.2	10
400-TER	660	750	23.8	550	28.5	780	4.7	230
450-TER	610	705	22.3	530	25.2	715	2.9	185
500-TER	530	610	25.3	460	27.1	535	1.8	75
550-TER	470	550	25.0	405	25.3	430	0.3	25
450-QUA	690	780	22.7	560	27.3	930	4.6	370
550-QUA	605	685	23.1	440	25.9	650	2.8	210

[a] Elapsed time considered from initial contact of cement with water.

As indicated in Figs. 5 and 6, a maximum depression of approximately—10 kPa was measured from the pore water pressure sensors. It is important to note that this negative pressure corresponds to the limit of the sensors used to determine the pore water pressure. As noted earlier, the hardening process of concrete causes the reduction in water content in the capillary pores. This can eventually lead to interruption of further measurements, as the pressure sensors necessitate continuous waster saturation to function [12].

3.5. Effect of binder type and content on elapsed time before pressure cancellation

Initial and final setting times can be considered as suitable references to indicate the time at which the concrete starts to stiffen, and therefore cease to exert lateral pressure. The determined setting times of the tested SCC mixtures are given in Table 4. In general, the increase in HRWRA dosage led to delayed setting, as illustrated in Fig. 7. For example, the initial setting time increased from 470 to 660 min when the dosage of the polycarboxylate-based HRWRA increased from 2.7 to 4.6 L/m^3 for the 550-TER and 400-TER mixtures, respectively.

The rise in concrete temperature beyond the dormant period affects lateral pressure development due to the acceleration of the formation of hydrates and onset of stiffening. In the case of the 450-QUA mixture, the drop in lateral pressure towards zero occurred approximately towards the middle of concrete temperature rise period (Fig. 5). This happened earlier in the case of the 450-T10 mixture where the elapsed time for lateral pressure cancellation was closer to the beginning of the onset of temperature rise (Fig. 6). In order to better determine the effect of binder type and content on the time for cancellation of pressure, temperature data measured at the center of the 200-mm diameter experimental column were derived as a function of time. The general shape of the $d_{Temperature}/d_{time}$ (dT/dt) curve is given in Fig. 8 for the 450-BIN mixture. The concrete temperature and elapsed time corresponding to the location when dT/dt starts to increase at a faster rate are determined and referred to as T_1 and t_1, respectively. The sharp increase in dT/dt can reflect the end of the dormant period and beginning of the acceleration of formation of hydrates. Furthermore, elapsed time (t_2) corresponding to the cancellation of lateral pressure is noted along with the temperature of the concrete at that instance (T_2), as can be seen in Fig. 6. The results obtained are summarized in Table 4. The table also gives the spread between concrete

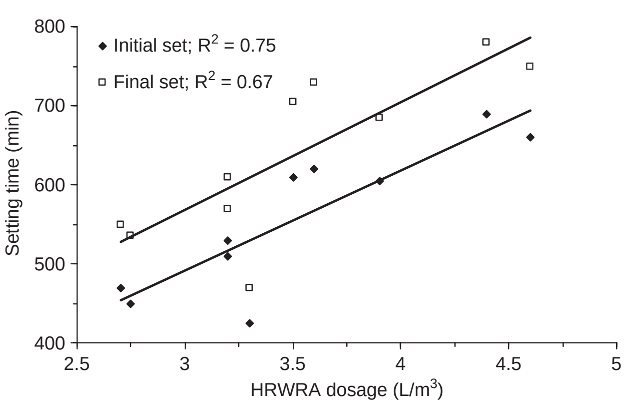

Fig. 7. Relationship between setting time and dosage of the polycarboxylate-based HRWRA.

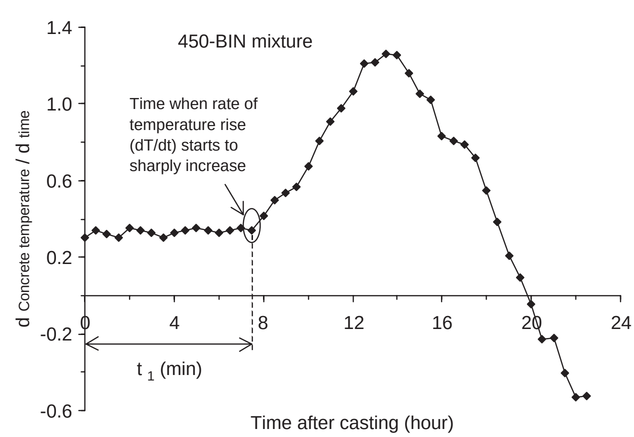

Fig. 8. Concrete temperature data derived as a function of time for the 450-BIN mixture.

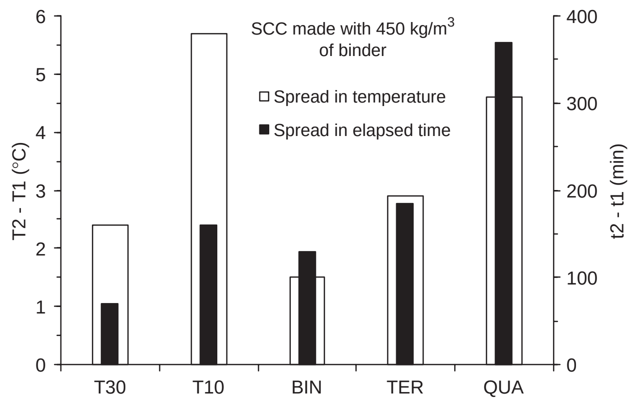

Fig. 9. Values of spread in concrete temperature rise and elapsed time before pressure cancellation for mixtures made with 450 kg/m^3 of binder.

temperature and elapsed time determined at the two specified periods of t_1 and t_2.

The spreads in concrete temperature rise (T_2-T_1) and elapsed time before pressure cancellation (t_2-t_1) are plotted in Fig. 9 for all mixtures proportioned with 450 kg/m^3 of binder. Generally speaking, mixtures containing higher volumes of SCM necessitated greater elapsed times before pressure cancellation. For example, such increase was from 80 to 210 min and then to 410 min for mixtures made with T30, ternary, and quaternary cements, respectively. The corresponding spread in concrete temperature increased from 2.4 to 3.0 °C and then to 3.3 °C, respectively. This may be due to the increased volume of SCM that reduces the rate of strength increase. The concrete then requires further formation of hydrates in order to be self-bearing, hence canceling the lateral pressure exerted on the formwork. In the case of the mixture made with T10 cement and no SCM, a relatively higher spread in concrete temperature (T_2-T_1) of 5.7 °C was obtained. This may be due to the significant release of heat resulting from cement hydration that occurred after the end of the dormant period before the cancellation of pressure, as illustrated in Fig. 6.

The spreads in concrete temperature rise (T_2-T_1) and elapsed time before pressure cancellation (t_2-t_1) are plotted in Fig. 10 for all SCC mixtures containing SCM. Irrespective of the binder type, the increase in binder content led to a reduction in both the spread in temperature rise and elapsed time required for pressure cancellation. For example, the (T_2-T_1) value decreased from 4.7 to 0.3 °C for the mixtures made with 400 and 550 kg/m^3 of ternary cement, respectively. This can be due to greater rate of formation of hydrates when higher binder content is employed, thus requiring lower rise in concrete temperature before pressure cancellation.

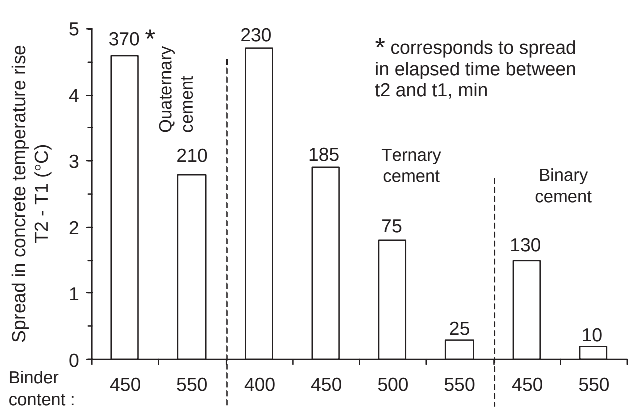

Fig. 10. Values of spread in concrete temperature rise before pressure cancellation for mixtures made with different types and contents of binder.

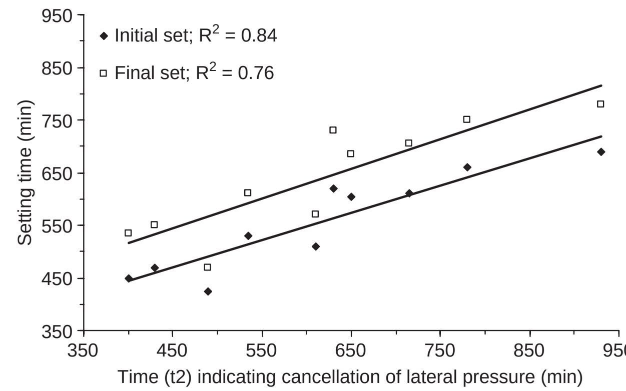

Fig. 11. Relationship between setting times and cancellation of lateral pressure.

Relationships between the elapsed time (t_2) corresponding to the cancellation of pressure and the initial and final setting times of all tested mixtures are plotted in Fig. 11. As expected, mixtures exhibiting greater setting times necessitated longer periods after concrete placement before pressure cancellation. It is to be noted that better correlation is obtained in the case of the initial setting time.

4. Conclusions

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

1. The kinetics of drop in lateral pressure of SCC mixtures can be related to both physical and chemical phenomena. The former has predominant influence during the early stages of cement hydration and depends on the rate of development of internal friction and cohesion of the plastic concrete. The chemical effect occurs after the end of the dormant period of cement hydration as the formation of hydrates is accelerated.
2. For a given binder content, the initial lateral pressure and its rate of drop with time are significantly affected by the binder type. Concrete made with Type 10 cement and no SCM exhibited the highest initial pressure and the lowest rate of pressure drop with time. Mixtures made with ternary cement or Type 30 cement exhibited lower initial pressures and higher rates of pressure drop.
3. For a given binder type, the initial lateral pressure is shown to increase when the binder content is increased (or, when the coarse aggregate content is decreased).

However, mixtures proportioned with higher binder contents exhibited faster rate of pressure drop with time.

4. After the end of the plastic stage, pore water pressure drops sharply towards negative values as a result of the self-desiccation process.
5. Mixtures containing higher volumes of SCM and/or lower contents of binder necessitate greater temperature gain prior to full cancellation of lateral pressure. This may be attributed to the lower degree of formation of hydrates that prolongs setting.
6. The time necessary for pressure cancellation can be correlated to the setting time determined from the Standard Penetration Method.

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