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Effect of section width and casting rate on variations of formwork pressure of self-consolidating concrete

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ABSTRACT

The influence of formwork dimensions and rate of casting of self-consolidating concrete (SCC) on the development and variations of lateral pressure were evaluated using two types of experimental columns; the first measuring 2100 mm in height and 200 mm in diameter, and the second 3600 mm in height and 920 mm in diameter. Variations of heat of hydration and setting time were correlated to the rate of decrease in formwork pressure.

Test results show that the scale effect has an influence on the rate of drop in lateral pressure with time. Two distinctive rates of pressure drop were obtained during the plastic and setting stages of hydration. A rate of pressure decrease of 5.3 kPa/hr was obtained during the first 6 hours of time and is mostly associated with the increase in the restructuring process due to the reversible effect of thixotropy. A second distinctive slope of 2 kPa/hr was noted beyond 6 hours until the canceling of pressure, and is related to setting. The increase in the casting rate from 10 to 25 m/hr in the 200-mm diameter column resulted in slightly higher lateral pressure.

RÉSUMÉ

L'influence des dimensions du coffrage ainsi que la vitesse de coulage sur les pressions latérales développées par les bétons autoplaçants ont été évaluées sur deux tubes expérimentaux; l'un mesurant 2100 mm en hauteur et 200 mm en diamètre, et l'autre 3600 mm en hauteur et 920 mm en diamètre. Les variations de la cinétique d'hydratation et du temps de prise ont été également déterminées.

Les résultats obtenus montrent que la géométrie du coffrage a une influence sur la diminution des pressions avec le temps. Deux différentes pentes de diminution de pression ont été aperçues. La première de 5,3 kPa/h obtenue pendant la période dormante du ciment est essentiellement reliée à un phénomène de restructuration qui est due à l'effet réversible de la thixotropie. La seconde pente de 2 kPa/h attribuée à un effet de prise du ciment est ensuite apparue. L'augmentation de la vitesse de coulage de 10 et 25 m/h dans le tube ayant 200 mm de diamètre a induit une légère hausse des pressions latérales.

1. INTRODUCTION

The design of formwork systems for vertically cast elements is controlled by the lateral pressure developed by the fresh concrete. It is well established that concrete consistency, method of placement and consolidation, type of cement, temperature of concrete, maximum aggregate size, head of concrete, pore water pressure, rate of placement, and size and shape of the formwork have all marked effect on the development of lateral pressure [1-3]. Roby [4] evaluated the effect of the rate of placement on formwork pressure. Several mixtures with slump values varying between 50 and 100 mm were prepared with either low or high cement content. The lateral pressure was evaluated on 4500 mm high and 700 mm square columns; the rate of filling varied between 0.05 and 1 m/hr. Independently of the cement content, the author concluded that the maximum pressure increases with the rate of casting.

In 1962, Ritchie [5] attempted to determine the effect of the rate of casting, mode of consolidation, consistency level, and mixture composition on lateral pressure envelope. Two series of concrete compositions having cement-to-total aggregate ratios of 1:3 and 1:6 were prepared. The concrete was compacted either by hand or by internal vibration. The water-

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to-cement ratio varied between 0.39 and 0.65 corresponding to mixtures of low and high consistency levels, respectively. For both series, the maximum pressure was reported to increase with the increase in the rate of casting. The increase in lateral pressure due to mechanical vibration was much greater for the lean mixtures (1:6) than the rich ones (1:3) [5].

The influence of the casting process of wall or column elements on the distribution of lateral pressure envelope developed by plastic concrete was reviewed by Gardner [6]. When vibrated, fresh concrete was found to behave as a liquid with the pressure envelope tangential to the line of hydrostatic pressure. When the concrete head becomes sufficiently high (more than 2 meters), the effect of the vibrator becomes considerably reduced or even cancelled. Concrete in the lowest part of the formwork can no longer be fluidized by the consolidation effort. The concrete will then develop shear strength and wall friction, and the lateral pressure at the bottom will start to deviate from hydrostatic. When the concrete head is again increased, the shear strength magnitude becomes more significant, and the lateral pressure reaches a maximum value at some elevation above the base of the formwork. Even with further increase in concrete head, the lateral pressure remains constant at a maximum value that remains constant until the bottom of the formwork [6].

Rodin [2] stipulated that the maximum lateral pressure should be smaller in formworks of limited cross-sections. This is due in part to the arching action that precludes the transfer of higher lateral pressure. The author concluded that the presence and concentration of reinforcing bars can have beneficial effect on form pressure since the reinforcement can partially support the weight of the overhead concrete. However, such beneficial effect might be cancelled by the increased tamping consolidation necessary to distribute the concrete between the reinforcement [2].

Smith [7] reported from field tests that the maximum formwork pressure decreases slightly when concrete is cast through limited cross-sections. The presence of reinforcement inside the form tends to decrease the pressure to a limited extent; however, the author suggested that this effect could be neglected for determining the maximum pressure for design purposes.

The CIRIA [8] sponsored a large-scale field investigation into formwork pressure development and concluded that lateral pressure is governed by the rate of pour, concrete temperature, slump consistency, minimum formwork dimension, and continuity of vibration. In narrow sections, it was stated that wall friction limits significantly the maximum exerted pressure. The CIRIA [8] design recommendations consider that lateral pressure envelope is hydrostatic up to a maximum value limited by the lesser of concrete stiffening and arching effects, as follows:

Arching criterion:

$$P_{max} = 14.37 + 0.094\ d + 3.14\ R < 24\ h \text{ or } 143.7$$

Stiffening criterion:

$$P_{max} = \frac{\gamma R t}{1 + c\left(\dfrac{t}{t_{max}}\right)^4} + (4.6 - 1.89R) < 24\ h \text{ or } 143.7$$

where P_{max} : maximum lateral pressure, kPa
d : minimum formwork dimension, mm
R : rate of placing, m/hr
t : time after start of placing, hr
t_{max} : stiffening time, hr
c : vibration constant
γ : unit weight of concrete, kg/m^3
h : head of concrete, m

(c and t_{max} are defined in empirically derived charts)

Self-consolidating concrete (SCC) is a new type of highly flowable concrete that can spread under its own weight and achieve good consolidation without any mechanical vibration. Limited research has been conducted to determine lateral pressure exerted by such concrete and the factors affecting the pressure envelop and its variations with time. Assaad *et al.* [9] showed that variations in lateral pressure of SCC can be closely related to thixotropy. The tested SCC were proportioned with 0.42 water-to-cementitious materials ratio (*w/cm*) and had initial slump flow of 650 ± 15 mm. The protocols adopted for the evaluation of thixotropy consisted of fixing the rotational speed, N, of a concrete rheometer and recording the variations of the structural breakdown of the material with respect to time [10]. Each curve determined at a given rotational speed showed a peak yield stress, τ_i, which corresponds to the initial structural condition, and thereafter a shear stress decay with time towards a minimum value, τ_e. This latter value corresponds to an equilibrium condition that is independent of the shear history. The area comprised between the initial flow curve (τ_i - N) and the equilibrium flow curve (τ_e - N) is calculated to quantify the amplitude of the thixotropic phenomenon [10]. Mixtures with higher thixotropy developed lower initial lateral pressure and exhibited faster reduction in pressure with time [9]. This was attributed to the reversible effect of the thixotropy which enables the material to re-gain its shear strength, internal friction and cohesion, when left at rest without any shearing action. Immediately after casting, any decrease in lateral pressure was attributed to the increase in internal friction resulting from the use of ternary cement and greater concentration of coarse aggregate. The use of set-retarding admixture led to a slower rate of drop in lateral pressure. Conversely, the incorporation of a set-accelerating agent resulted in an increase in the rate of pressure drop [9].

To date, limited information exists regarding the effect of casting rate of SCC on the development of lateral pressure and its variation with time. Casting rates of SCC can vary with the size of the cast element and placement method. For example, the CEBTP [11] evaluated formwork pressure of SCC made with 0.46 *w/cm* and slump flow consistency of 700 mm on experimental columns measuring 12 m high, 2 m length, and 0.34 m width. The casting rate was either 25 m/hr for concrete pumped in the formwork from the bottom or 10 m/hr for concrete cast by bucket from the top. The maximum lateral pressures at the base of the walls were found to correspond to 70% and 65% of the hydrostatic pressure, respectively [11]. These casting rates are quite high and can be as low as 2-3 m/hr when SCC is employed for casting wall elements for residential or commercial type of construction [12]. In some repair operations when SCC is used to replace outer part of column or bridge pier abutment walls, high casting rates of approximately 10 m/hr can be experienced.

In addition to the effect of the casting rate of SCC, there is no information regarding the influence of the section width on lateral pressure development and variations with time. The "silo effect" that can mitigate some of the lateral pressure in relatively stiff concrete may not be applicable to SCC, given the relatively low cohesiveness of such concrete.

The objective of this paper is to evaluate the effect of formwork width and casting rate on variations in lateral pressure of SCC. The pressure was evaluated using two types of experimental columns; the first measured 2100 mm in height and 200 mm in diameter, and the second 3600 mm in height and 920 mm in diameter. The influence of the rate of casting on lateral pressure was evaluated with the 2100-mm high column with SCC cast at a relatively medium rate of 10 m/hr and high rate of 25 m/hr.

2. EXPERIMENTAL PROGRAM

2.1 Materials

A ternary cement made with approximately 6% silica fume, 22% Class F fly ash, and 72% Type 10 cement was used. A continuously graded crushed limestone aggregate with nominal size of 10 mm and well-graded siliceous sand were employed. The sand had a fineness modulus of 2.5. The bulk specific gravities of the aggregate and sand were 2.72 and 2.69, and their absorptions were 0.4% and 1.2%, respectively. A naphthalene-based high-range water reducer (HRWR) with solid content of 41% and specific gravity of 1.21 was used. A liquid-based polysaccharide was used for the viscosity-modifying admixture (VMA) to enhance stability of the plastic concrete. A synthetic detergent-based air-entraining admixture (AEA) and a carboxylic acid-based water-reducing admixture were incorporated.

2.2 Mixture proportion

For the SCC mixture used in this study, a proven mixture prepared using 490 kg/m^3 of binder, 0.38 *w/cm*, and 0.44 sand-to-coarse aggregate ratio was used. The VMA was incorporated at a dosage of 1325 mL/100 kg of water, and the HRWR dosage was adjusted at 6 L/m^3 to secure initial slump flow of 650 mm. A dosage of 150 mL/100 kg of cementitious materials of the AEA was used. The unit weight and air content were 2280 kg/m^3 and 6.1%, respectively.

2.3 Instrumented formworks

As already mentioned, two experimental formworks were used. The first measured 2100 mm in height and 200 mm in diameter. The PVC tube had a wall thickness of 10 mm and a smooth inner face to minimize friction during and after concrete placement. The stress in the diaphragm caused by concrete lateral pressure was determined using five pressure sensors mounted at 850, 1250, 1650, 1850, and 2050 mm from the top. The monitoring of pressure distribution was stopped once the concrete had an approximate slump consistency of 100 mm. The second column consisted of a sonotube of 3600 mm in height and 920 mm in diameter. The column was adequately braced and reinforced. The lateral pressure was determined using two pressure sensors located at 2050 and 2880 mm from the top. In this case, the lateral pressure was monitored until the hardening of the concrete.

The pressure sensors had 100-kPa capacities. They were carefully sealed into the forms to support the pressure exerted by the concrete without leakage. Each pressure cell was properly calibrated prior to use.

2.4 Fabrication and testing

Ready-mixed concrete was delivered to the experimental site. The ambient and concrete temperatures were 16 and 19°C, respectively. The slump flow, air content, JRing and L-box flow characteristics, and surface settlement were determined for the SCC. The JRing test shown in Fig. 1 consists of a co-centric ring placed at the base of the slump cone [13]. The measurement corresponds to the mean diameter of the spread concrete at the end of flow. The JRing spread value was 600 mm.

The L-box test consists of an L-shaped apparatus with the vertical part of the box being filled with 12.7 L of concrete, as shown in Fig. 2 [14]. The gate separating the vertical and horizontal compartments is then lifted, and the concrete flows out through closely spaced reinforcing bars of 12-mm diameter at the bottom. The ratio of the height of concrete at

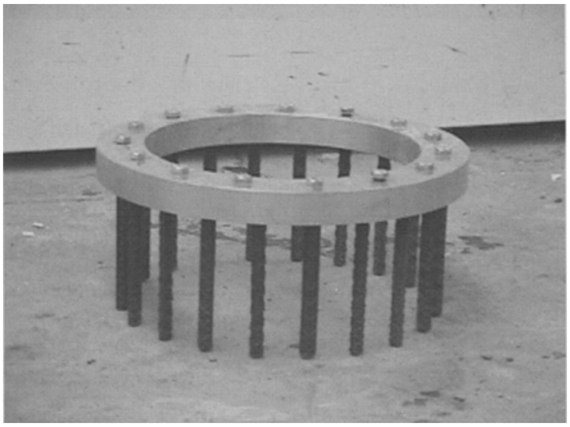

Fig. 1 - Photo of the JRing test.

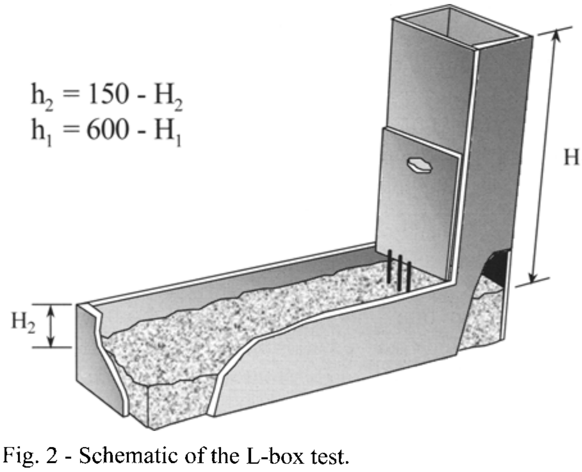

Fig. 2 - Schematic of the L-box test.

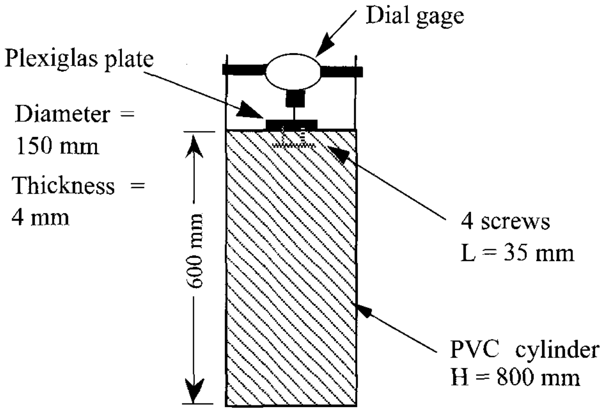

Fig. 3 - Schematic of the surface settlement test.

the leading edge in the horizontal section (h_2) and that remaining in the vertical section (h_1) is determined; this value was equal to 0.81 for the tested concrete indicating relatively good self-leveling characteristics.

The surface settlement was assessed by casting the concrete in a PVC column measuring 200 mm in diameter and 800 mm in height (Fig. 3) [15]. The settlement was monitored using a linear dial gage fixed on top of a thin plate positioned and anchored at the concrete surface. The maximum surface settlement was 0.34% which is considered as a low value.

The concrete was directly discharged from the mixing truck into the formwork from the top at the desired pouring rate without stoppage or vibration. In the case of the 3600-mm high column, the concrete was placed at a rate of rise of 10 m/hr. For the 2100-mm high column, the formwork pressure was evaluated twice; once using a rate of placement of 10 m/hr and then at 25 m/hr for a second column. The slump flow values determined upon the arrival on site of the concrete and after 1 and 2 hours were 650, 635, and 450 mm, respectively. After 3 and 3.5 hours, slump consistencies of 180 and 65 mm were measured, respectively.

The initial and final setting times were determined in the laboratory at 20°C in compliance with ASTM C403 and are given in Fig. 4. The adiabatic temperature was also evaluated in an adiabatic calorimeter on mortar obtained by sieving fresh concrete through a 4.75-mm sieve. The heat evolved was determined by deriving the temperature rise as a function of time. The time between the initial contact of cement with water and that corresponding to the beginning of the acceleration of temperature rise was 6 hours, as also shown in Fig. 4.

3. TEST RESULTS AND DISCUSSION

3.1 Lateral pressure variations

The variations of the lateral pressure envelope determined on the 2100-mm high column along with the consistency are plotted in Fig. 5.

Immediately after filling the formwork, the concrete is shown to act as a fluid exerting almost hydrostatic head. However, a gradual decrease in lateral pressure takes place with time. The relative pressures at the base of the column determined initially and after 1, 2 and 3 hours were 98%, 89%, 83% and 76% of hydrostatic pressure, respectively. This hydrostatic pressure (P_{hyd}) was calculated as: $P_{hyd} = \rho \times g \times h$; where ρ, g, and h refer to the concrete unit weight, gravity constant, and head of concrete in the formwork, respectively.

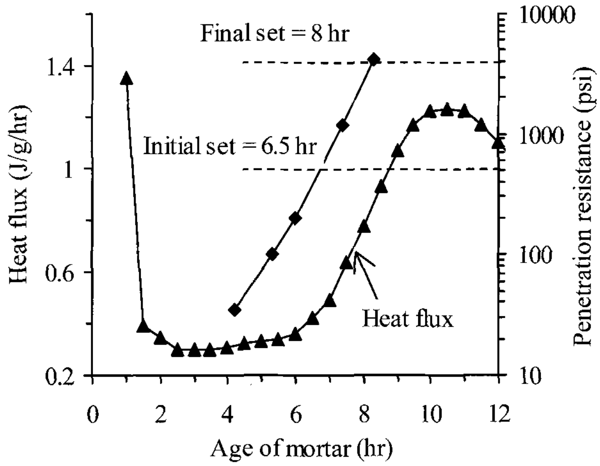

Fig. 4 - Variations of hydration and stiffening kinetics with time.

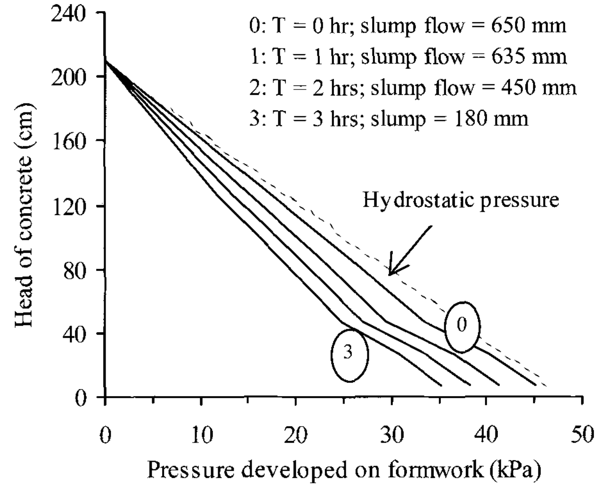

Fig. 5 - Lateral pressure variations for the 2100-mm high column.

3.2 Influence of casting rate

In order to determine the effect of casting rate on maximum pressure at the base of the instrumented column, the ratio of the stress determined from the bottom sensor to the corresponding hydrostatic pressure is plotted in Fig. 6 during the first two hours following casting. The reduction of the casting rate from 25 to 10 m/hr is shown to result in slight decrease in the maximum pressure obtained right after casting. Both casting rates then resulted in the same rate of pressure drop with time.

The development of lateral pressure is directly related to the increase in shear strength of the plastic concrete. With the lower casting rate, the concrete can possess more time to build up some cohesiveness and shear strength, thus enabling the development of relatively lower lateral pressure [16].

3.3 Influence of section width

The effect of column diameter (200 vs. 920 mm) on changes in lateral pressure is illustrated in Fig. 7 by plotting the variations of the P(measured)/P(hydrostatic) values calculated at 2050 mm from the top of the formworks as a function of time. It is important to mention that both columns were cast on the job site at the same casting rate of 10 m/hr. Initially, the mixture placed in the larger column exhibited slightly greater pressure of 99% of hydrostatic pressure compared to 96% for the 200-mm diameter column. However, the rate of drop in pressure was significantly different. In the case of the former concrete placed in the 920-mm diameter column, the time required to reduce lateral pressure by 5% of the hydrostatic value was 20 minutes, resulting in a slope of 5.3 kPa/hr. Conversely, for the 200-mm diameter column, this period was 38 minutes resulting in a slope of 3.3 kPa/hr.

In general, the rate of drop in lateral pressure of plastic concrete depends on the degree of thixotropy or shear recovery [9]. This phenomenon causes a build-up of the structure and an increase in cohesiveness soon after the material is left standing at rest without any shearing action. In the case of the 200-mm diameter column, the arching effect can be relatively more pronounced than that resulting from the 920-mm diameter column. This might then influence the rate of build-up of the structure after casting which can reduce the rate of pressure drop. More research is, however, required to further investigate the scale effect on pressure development of SCC.

3.4 Variations of lateral pressure drop with time

The variations of lateral pressure drop with time were monitored until the hardening of the concrete cast in the 3600-mm high column. The results obtained at 2880 and 2050 mm from the top are plotted in Fig. 8. It is to be noted that the pressure sensor located at the bottom (*i.e.* 2880 mm) of the column stopped after 6 hours. The lateral pressure increased initially progressively to attain a maximum value close to hydrostatic pressure. The initial increase before attaining the maximum value is due to the time necessary for filling the column that was proceeded at a rate of 10 m/hr. Beyond the peak pressure, the rate of decrease in pressure was similar at both sensors, as shown in Fig. 8.

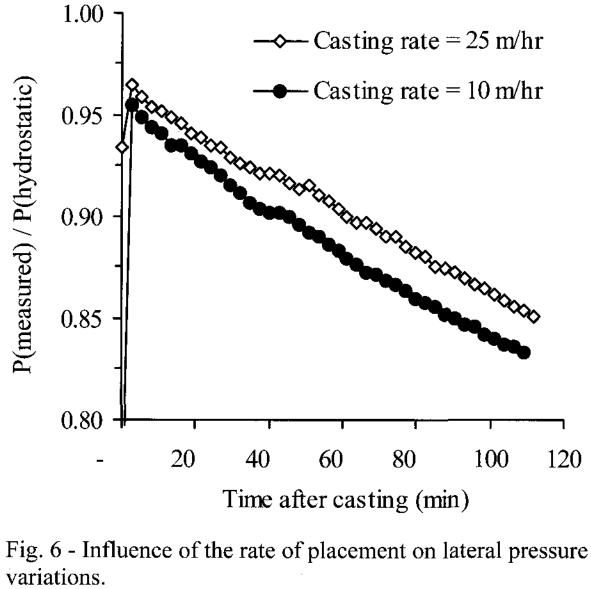

Fig. 6 - Influence of the rate of placement on lateral pressure variations.

For the pressure resulting from the sensor located at 2050 mm from the top of the formwork, two different slopes of the descending leg of the pressure drop can be distinguished. Such variations of the P(measured)/P(hydrostatic) values with time are illustrated in Fig. 9 until the canceling of the pressure. A first slope of 5.3 kPa/hr is observed between the maximum pressure and the residual value of 40% of the hydrostatic pressure that was attained after 6 hours from the beginning of the casting. It is important to note that the beginning of casting corresponds to approximately 45 minutes following the first contact between the water and cement. A lower rate of pressure drop of 2 kPa/hr is observed thereafter until the canceling of the pressure that took place after 17 hours from casting.

These slopes can be related to two different –physical and chemical– phenomena. Right after casting, the cement enters the dormant period of slow reactions that enables the concrete to be in a plastic stage. Any drop in lateral pressure can therefore be mainly attributed to the reversible effect of

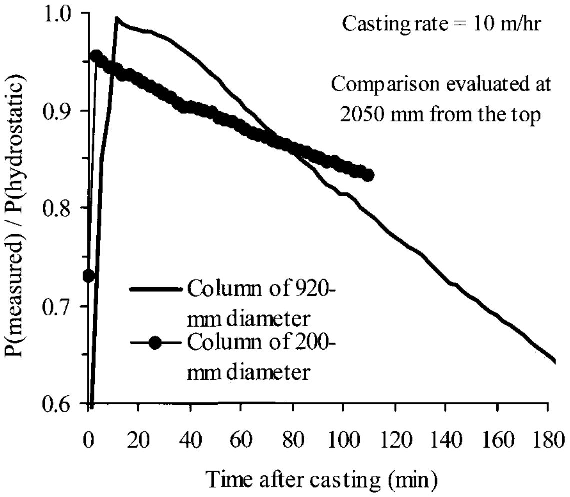

Fig. 7 - Effect of the section width on lateral pressure.

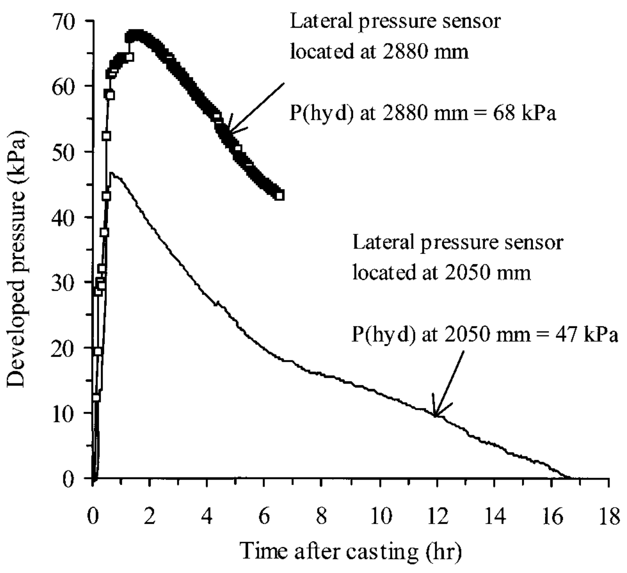

Fig. 8 - Variations of lateral pressure with time of SCC cast in the 3600-mm high column.

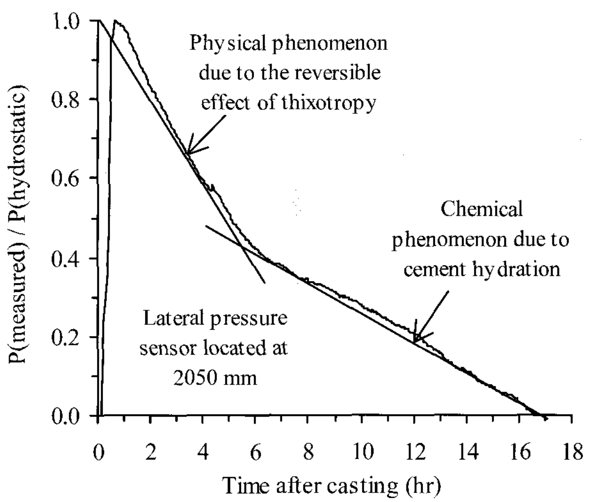

Fig. 9 - Two phenomena are responsible for lateral pressure drop until cancellation.

thixotropy (shear recovery) that causes the restructuring of the material and the increase of cohesiveness and rigidity. This effect can be considered as a physical phenomenon since it depends on the mixture proportioning and the ability of the material to restructure and gain cohesiveness soon after casting.

On the other hand, the chemical transformation of the anhydrous binder into hydrates takes place as soon as it is mixed with water. However, its notable effect on the hardening of the structure does not become evident before the end of the plastic stage and the acceleration of formation of hydrates [17]. Given the results of the heat flux obtained from the calorimeter test (Fig. 4), the time indicating the end of the dormant period corresponds to approximately 6 hours. This coincides roughly to the distinctive change between the two slopes and the initial setting time that took place at 6.5 hours of age (Fig. 4). The lower rate of drop in lateral pressure could be in part due to some deformation resulting from autogenous shrinkage of the paste during the hardening of concrete.

4. CONCLUSIONS

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

1. The scale effect had an influence on the rate of drop in lateral pressure of SCC with time; however, no appreciable difference in the maximum initial pressure was observed.
2. Immediately after casting, the SCC placed in the 200-mm diameter column was found to exert slightly less pressure than that cast in the 920-mm column. This can be due to an arching effect in the relatively restricted section.
3. The development of maximum lateral pressure exerted by the SCC was slightly affected by the increase in the casting rate from 10 to 25 m/hr for the column having 200 mm in diameter.
4. Leading up to the end of the dormant period, the physical restructuring of the concrete had predominant influence on reducing the lateral pressure exerted by the SCC. A reduction of 60% of initial pressure was obtained after 6 hours following the beginning of casting.
5. As the rate of hydration increased, further drop in lateral pressure took place at a slower rate. The remaining 40% residual pressure was eliminated in 11 hours which corresponds to 17 hours after casting.

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