SCC Evolution of Formwork Hydraulic Pressure and Rheological Properties

by S. Amziane and C.F. Ferraris

Synopsis: An experimental investigation was performed to determine the hydraulic pressure variation of cementitious based materials (cement paste, limestone paste, concrete, Self compacting concrete (SCC), etc.) during the plastic phase. A method based on measurements of both total lateral pressure and hydraulic pressure, using a novel device, has been investigated. Just after mixing, a simultaneous drop of both the hydraulic and the total lateral pressures was recorded, followed by a cancellation of total lateral pressure and a negative value of hydraulic pressure. Compared to other standard methods (Vicat, calorimetry, ultrasonic pulse-echo, etc …), the device was able to give simple and direct information about the mechanical state of the material, in situ. The kinetic variation of the hydraulic pressure occurring during the plastic phase of cement pastes using two portland cement fractions and a limestone filler was investigated. To relate the hydraulic pressure measurements with workability, a study on the evolution of the rheology of the cement paste was conducted. The experiments on standard concretes, which had the same free water content as an equivalent cement paste, show a similar hydraulic pressure variation as long as the pressure is positive. This is not the case for SCC where the observed hydraulic pressure variation is slower and the time of zero pressure is delayed compared to the equivalent cement paste. The presence of limestone and the HRWRA is the main reason for this retardation effect. In addition, as soon as the pressure becomes negative, due to the presence of aggregates, a delaying effect on the pressure variation was observed. In the end, field test show that the hydraulic pressure device could be used to monitor the field schedule of successive pouring, setting and demolding.

Keywords: field testing; mixture proportioning; rheology; self-consolidating concrete (SCC); slump flow; stability; workability

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INTRODUCTION

The pressure that self Compacting Concrete (SCC) creates on formwork is a real concern in the construction process (1, 2) since it is usually higher than for conventional concrete since SCC has no yield stress (or very high slump). The more serious problems are due to unpredicted high pressure resulting from a high casting rate. Another subject for pressure investigation of SCC concerns the prediction of setting time and the time for formwork removal. These two subjects are in fact closely connected due to the relationship between the age of the concrete and the hydraulic pressure exerted against the formwork. The hydraulic pressure is defined as the pressure exerted by the water contained in the concrete on the formwork. It has been experimentally found (3, 4, 5, 6) that there is equivalence between total lateral pressure and hydraulic pressure during the plastic phase of the material. However, other factors could affect the evolution of the form pressure that will result in a lateral pressure being higher or lower than the hydraulic pressure. For instance, a high rate of casting could induce a lateral pressure higher than the hydrostatic pressure due to the inability of the interparticle friction forces to sustain the load of the concrete falling into the form (7). On the other hand, the lateral pressure could be lower when the concrete is cast in layers: the bottom lateral pressure is significantly reduced by each subsequent layer as the concrete has had the time to settle and the yield stress to increase due to hydration (8).

Therefore, the determination of the hydraulic pressure and its relationship with setting time and workability is more complex than can be explored in this short paper.

The main scope of the present paper is: first, to establish a relation between the hydraulic pressure in concrete and the equivalent cement paste; and second, to understand the relationship between the rheological parameters (shear yield stress) and the hydraulic pressure.

RESEARCH SIGNIFICANCE

Despite the long tradition of characterizing cement paste structural evolution by the initial and final setting time, these values are not sufficient to answer some of the more practical questions related to materials science and constructability, such as:

- Obtaining information about the maturation and the evolution of setting of the cement-based material just after mixing.
- Following the setting of a cement-based material containing aggregate such as concrete
- Applying the setting measurement directly in the field with the goal to have a precise indication about the time for safe removal of formwork.

The proposed investigation was performed based on the idea that it would be possible to monitor the setting through the variation of hydraulic pressure and rheological properties.

BACKGROUND

Some of the most important fresh state properties of SCC or any concrete are the setting time, the rheological properties (e.g., workability) and pressure on the formwork. The evolution of these properties is related to the hydration of the cement paste, therefore the hypothesis of this research work is that some relationship between them should exist.

Cement paste, just after mixing, is a suspension with a very high concentration of solid material, composed of water, air and cement, which undergoes three successive phases. The cement paste, initially, is in a disorganized state. Solid particles are suspended in the liquid phase, which bears all applied load including the material's own weight. The water pressure U_0 is equal to the total lateral pressure ($U_0 = \rho g z$), where ρ is the density, g the gravitational constant and z the height of the material. Thereafter, the initial development of the physical and chemical properties of the cement, which usually occurs within the first 3 h to 4 h after mixing, induces a drop of the hydraulic[1] pressure on the formwork, since the material becomes a solid that can sustain itself.

The rheological behavior, or flow, of a fluid such as cement paste (10), mortar, or concrete is often characterized by two parameters, yield stress, τ_0, and plastic viscosity, μ, as defined by the Bingham equation. Relating rheological parameters with setting time is not new. For instance, Ish-Shalom et al. (11) used a coaxial rotational rheometer to characterize cement paste at various times and for a range of water/cement ratios and showed that plastic viscosity and yield stress increase significantly during the setting period.

[1] In the literature the measurements discussed here are often referred to as "pore water pressure". In this paper, we will use "hydraulic pressure" because we think that the device used provides a value of water pressure at a macroscopic scale, and not at the pore scale.

This result may be explained by several closely connected physico-chemical and mechanical phenomena that occur when the water and cement are in contact (12). The work described by Helmuth (13) shows that the stiffening of the cement paste is related to the interaction of the liquid and solid phases. Nonat et al. (14) explain that early hydration reactions of the cement affect the specific surface area, free water content and, therefore, the water-film thickness around particles during the dormant period. The water thickness is a strong contributor to the fluidity of the cement paste. The hydraulic pressure as well as the rheological properties, depends on the water thickness because the water is the lubricant that keeps the particles separated. Therefore, the measurement of the variation of hydraulic pressure and variation of the rheological properties should monitor the evolution of setting. Other factors should be considered to explain why there is a negative hydraulic pressure after initial setting such as chemical shrinkage and self-desiccation (15).

HYDRAULIC PRESSURE MEASUREMENT

To measure the pressure on formwork, a novel device and method was designed (3, 4). Briefly, this device consists of a tubular glass column measuring 1.3 m in height, and 110 mm in diameter with a wall 5.3 mm thick, fitted with two special transducers (Figure 1.a) that are able to measure the total lateral and hydraulic pressure exerted by the material. In the case of cement paste, the equality of the evolution between hydraulic pressure and lateral pressure until cancellation of the lateral pressure has been shown previously (3). For this reason, this paper presents only the hydraulic pressure data.

The system of the hydraulic pressure transducer is positioned 1 m under the free surface (Figure 1), and consists of a pressure transducer mounted on the formwork through the "de-aerator block" that is filled with oil. To separate the cement paste from the measurement system, a water-filtration device (compacted cotton fibers) is used. The balance of the pressures of both the water repellent oil in the chamber and the water found in the paste is achieved by the transfer of pressure through the filter.

TESTING PROGRAM

Materials

The portland cement (CEM II/B-LL-32.5 R) used contains =70.5 % clinker, 4.5 % gypsum, 24 % limestone, and 1 % filler by mass fraction. The particle size distributions of the cement and limestone are shown in Figure 2. The two aggregates for the concrete tests were a natural sand denoted “Pliocène” and coarse aggregate denoted “Gneiss”. The sand and coarse aggregate had minimum/maximum sizes of 0 mm to 3.15 mm and 4 mm to 10 mm, respectively. The sand and coarse aggregate had absorption capacities of 0.9%

and 2.64% by mass, respectively. The high-range water-reducing admixture (HRWRA) was a polycarboxylate-based admixture.

The mix compositions of the cement pastes (P_{36} and P_{45}) and of the limestone filler paste (LP_{36}) are presented in Table 1, and of the concretes (NC and SCC) in Table 2. The main difference among these cement pastes is their water/cement ratio (w/c). Taking into account the absorption of water by the aggregates, the calculated (free water/cement) ratio of concrete NC is the same as the P_{45} cement paste. In the same way, SCC has the same free water/cement ratio as the P_{36} paste. Therefore, P_{45} and P_{36} are considered to be the equivalent pastes for NC and SCC concrete, respectively.

Mixing and placement methods

All mixtures for the hydraulic pressure test were prepared in a 20 L mixer according to the standard EN 196-1 (16). The cement paste for the rheological measurements was prepared using the methodology developed by the Portland Cement Association (PCA) (17). The PCA methodology consists of using a blender with a capacity of 1 L connected to a speed controller and to a temperature controlled water bath. The speed controller allows the speed of the blades in the mixer to be held at a preset speed regardless of the load. The controlled temperature bath is set to 15 ºC in this study. This temperature allows the paste temperature to be about 20 ºC to 22 ºC at the end of the mixing cycle, which is the temperature that is usually measured in concrete just after mixing. Without the temperature controller, the temperature of the cement paste would be much higher and this would affect the hydration of the paste as well as its rheological behavior. The cooled base of the mixer plays the role of the aggregates, which are a heat sink

The mixing procedure adopted for the cement paste was: the cement was introduced in 30 s into the water while mixing at a speed of about 419 rad/s (4000 rpm). Then, the cement paste was mixed at 1047 rad/s (10000 rpm) for another 30 s. After 2.5 min of rest, the cement paste was mixed at a speed of 1047 rad/s for 30 s. The temperature of the mixture was recorded at the end of the mixing cycle (18,19).

The placement of the mixtures in the hydraulic pressure test is made by pouring the material in the column and then submitting it to vibration. The depth of immersion of the vibrator was standardized at 0.5 m and the duration of vibration at 1 min per 0.5 m lift.

Rheological testing

A parallel-plate rheometer with 35 mm diameter serrated test plates was used (Figure 1.b). To limit as much as possible the evaporation of the water from the cement paste during the test, the sample was enclosed in a chamber containing a wet sponge. The first test could only begin 6 min after the first contact of water with cement due to the time needed for mixing and placing the cement paste in the rheometer. Between rheological measurements, the mixture was stored in a hermetically sealed vacuum bottle. Before each measurement, the cement paste was mixed for 30 s, then a rheological measurement

was performed using a gap of 1 mm (18) between the plates at a temperature of 23 °C ± 0.2 °C. The rheological measurements consist of two types of procedure, one for the "Stress growth test", and the second for the "Bingham test". More details on the procedures and results can be found in Ref. (9, 21). Only the results obtained with the stress growth test will be presented and discussed here.

The stress growth test is characterized by the material being sheared at a very low shear rate (0.01 s^{-1} in our case) while the stress induced by the material is measured. This shear rate was selected as the minimum shear rate possible with the available rheometer. The stress is recorded versus time for 5 min. The yield stress is defined as the peak stress of the stress versus time curve (9, 21).

RESULTS AND DISCUSSIONS

Cement paste hydraulic pressure and rheological properties variations

The experimental results of the time evolution of the hydraulic pressure are shown in Figure 3. The hydraulic pressure in this paper will be represented in the graphs as a relative hydraulic pressure defined as the ratio of the hydraulic pressure (measured) to the hydrostatic pressure recorded initially for each mixture.

The typical curve obtained with the device shows that the hydraulic pressure decreases from hydrostatic pressure to zero (regime [AB] in figure 3), becomes negative (regime [BC] and then abruptly returns to zero (regime [CD], figure 3). As the w/c ratio increased, the time to obtain a null pressure was delayed. One reason for the pressure decrease before the setting of the cement paste, as defined by the Vicat test, is related to the relative humidity decrease due to the dissolution of alkaline hydroxides from cement particles into the aqueous phase. According to Kelvin's law, the relative humidity (RH) affects the level of the suction and thus the decrease of hydraulic pressure. In addition to these capillary forces, the action of gravity, attractive forces such as Van der Waals forces and the electrostatic forces cause the solid cement particles to approach one another, so that the pore radii decreases. Simultaneously with the decrease of the water pressure during the setting period, some physical phenomena are induced, such as bleeding (23), and plastic shrinkage (24), and rheological properties (25), such as thixotropy (26, 27) evolve. In the last [CD] regime, the subsequent increase to zero of the hydraulic pressure could be linked to the separation of the device from the concrete due to shrinkage of the cement paste. Further discussions of this phenomenon are described in Refs. (3, 6), and some analyses are done in Ref (5, 6, 9).

In reading the literature, it could be inferred that the drop and the negative values of the hydraulic pressure measured is attributed to either of the following phenomena: 1) increase in chemical reactions of the cement due to hydration or 2) appearance of attractive capillary forces by the formation of menisci due to the reduction in RH during hydration. These two phenomena are not unrelated in cement paste, as the increase in hydration degree reduces the available free water leading to an increase in capillary forces. It would be interesting to determine which phenomenon is predominant. Another

aspect that also needs to be addressed is to determine whether the drop of the hydraulic pressure is linked to the progressive setting of the cement paste or it is observed with any powder due to other unknown causes.

To start addressing this issue, an experiment with a non-hydraulic material was performed. A paste using a limestone filler with a granular size distribution (Figure 2) similar to the cement was prepared. The mixture composition of the limestone filler paste LP_{36} was made to be identical on a mass basis with the P_{36} cement paste by replacing the cement with the limestone filler. In LP_{36} there is no hydration evolution and no water was lost due to evaporation or other causes, therefore, there is no free water reduction during the measurement period. The comparisons of hydraulic pressure variation (Figure 3) of paste P_{36} and the mixture of limestone paste LP_{36}, show that while, hydraulic pressure decreases quickly for the P_{36} paste, the hydraulic pressure of LP_{36} remains almost constant and stable. The negligible hydraulic pressure decrease in the case of the limestone filler paste is certainly generated by sedimentation and bleeding. Consequently, the hydration phenomenon and the progressive setting of the cement paste are the leading causes of the hydraulic pressure drop observed.

Furthermore, to describe the variation of the lateral pressure of SCC on formwork, Roussel et al. (22) have proposed a model based on the yield stress variation during the setting time. From a theoretical point of view, the model was justified by the assumption that the shear yield stress is fully mobilized at the wall. During the resting time, the yield stress increases, inducing a drop of the lateral pressure. The presented model is very promising and has shown good simulation results. However, the physical relation between the increase of yield stress and the drop of pressure request an experimental justification. This is why the measurement of the variation of the rheological properties is proposed below.

The discussion in this paper is limited to the P_{45} cement paste rheology testing as an example of the type of measurements obtained. Similar data were obtained for cement paste at other w/c ratios (9) and more complete results about the rheology experiments are presented in Refs. (9).

The stress growth test (9) was conducted to monitor the evolution of the yield stress with time. Figure 4 shows a typical stress response obtained for P_{45}. The stress growth curve contains three phases: the pre-peak phase, the peak phase and the post-peak phase. In the pre-peak phase, the cement paste displays an elastic behavior as shown by the linear increase of the shear stress vs. time at constant shear rate. The cement paste is still acting as a solid, thus the elastic behavior. A non-linear behavior follows leading to the peak stress. The end of the linear behavior defines the real yield stress but it is not possible to measure this point with our rheometer since too few points were recorded before the peak value.

In the post-peak phase, the stress is reduced to an equilibrium value. At a later age (> 7 h for P_{45}) a stable equilibrium value is not reached, as shown by Figure 4. The particles of cement are partially agglomerated at this point, and the layer of water between

particles is reduced due to hydration. The shear action imposed by the rheometer can cause some of the agglomerates to break or overcome the solid-solid frictional force, forcing particles to move. The occasional breakage of one of the agglomerates may allow the paste to suddenly flow easily, leading to a reduction of the measured shear stress, followed by an increase as soon as the agglomerates or the friction prevents further flow. This zigzag aspect of the post-peak phase in the curves appears after about 7 h of hydration in the cement paste studied here.

Figure 5 shows the evolution of the hydration versus time using three types of measurements: yield stress (defined as the peak value), Vicat penetration and hydraulic pressure. In the yield stress curve, the key points (Figure 5) are points A, B and C. The point A is the initial yield stress, Point B is where the curve sharply increases, and Point C is the last measured point. Usually, C denotes the highest stress that our rheometer is able to measure. These points can be used, for cement paste curves in Figure 5, to define two specific sections:

- Section AB (from point A to B): A slow steady increase of the yield stress with time.
- Section BC (from point B to C): A dramatic increase of the yield stress occurs indicating the change of the cement paste from a fluid to a solid state.

In Figure 5, the hydraulic pressure, and the Vicat penetration value are represented as dimensionless ratios: the ratio of the hydraulic pressure (measured) to the hydrostatic pressure recorded initially, and the measured Vicat needle penetration divided by the measured penetration distance of 40 mm, the initial value. These two methods show the same sharp increase (or decrease) as the yield stress curve at about the same hydration time. Therefore, any of these methods proposed could be used to determine setting time but only the hydraulic pressure could be used to monitor the hydration process before initial set. This information could be used to better link material composition with concrete flow behavior.

Finally there is a close relation between the yield stress kinetics and the hydraulic pressure variations. Then, in order to model the initial pressure against formwork and the evolution at rest of cement based material pressure, following the method proposed in ref. (22), it should be relevant to introduce the hydraulic pressure kinetics as a physical parameter of the model.

Concrete and SCC pressure variation

The next part of this study was to determine the correlation between the hydraulic pressure measurements in concrete and its cement paste. A comparison of concrete NC and its equivalent cement paste P_{45} (Table 1) shows that NC has almost similar behavior during the plastic stage (Figure 6). This result can be explained by the fact that the hydration process of the cement paste governs the hydraulic pressure variation of the concrete. The aggregates present do not affect, at this stage, the decrease of hydraulic pressure. In the second step, when the medium is in negative pressure, the relative hydraulic pressure is more important for cement paste. This is probably due to two

competing facts that would prevent further reduction on the hydraulic pressure: 1) the aggregates could be settling and form a solid skeleton; 2) the cement paste content in concrete is lower than in neat cement paste due to the presence of the aggregates.

Comparing the SCC with P_{36} paste pressure variation (Figure 7), it can be noticed that SCC hydraulic pressure is zeroed at about 5 h, while in the cement paste, zero pressure is obtained in only about 3 h, a reduction of 2 h. One possible explanation is that the SCC mixture contains limestone (and less cement) that, as shown earlier, does not reduce the hydraulic pressure (Figure 3). The presence of HRWRA in the concrete mixture is the other possible cause of the delay, due to its possible retardation effect and dispersion on the cement particles. Also, in the same way with the normal concrete, the presence of aggregate have a delaying effect on the pressure variation.

Further experiments, using different aggregates, HRWRA and limestone concentration and size distributions are needed to further explain the influence of these parameters on the kinetics of pressure variation. Nevertheless, these results are encouraging in that the same trends were observed in concrete and in cement paste when the concrete is prepared with the same cement with no addition of chemical admixtures and limestone fillers (NC and P_{45}). It is conceivable that the correlation between SCC and an equivalent paste could be improved if the cement paste were prepared with the same HRWRA and filler as those used in the concrete.

Field testing

The technique to monitor setting time in concrete by measuring the changes in hydraulic pressure becomes especially interesting if it can be used in the field on a construction site. It would allow a better determination of time for form removal. Therefore, a field test was also conducted to demonstrate the portability of the hydraulic pressure device. As shown in Figure 8, the formwork (Figure 8a) has been directly fitted with a hydraulic pressure measurement device (Figure 8b) placed 200 mm above the base of the formwork. The formwork geometry had a height of 6 m, a length of 30 m and a width of 0.28 m. The concrete was pumped and then dropped from around 1m height after being transported by truck for an hour. It took an hour to fill the formwork in two layers. This correlates with an average climbing rate of less than 6m/h.

For confidential reasons requested by the owner of the wall, it is not possible to give in this paper the exact concrete mixture used in the field. However, the concrete used was a traditional concrete, with mixture proportions similar to the NC concrete mixture given in Table 2.

As the formwork was filled to ¾ of the total height (4.5 m), the hydraulic pressure immediately increased and reached the first peak (*Peak 1* in Figure 8c) in 20 min, i.e., a filling rate of 13.5 m/h. After the first filling phase (4.5 m of concrete), the maximum pressure measured was about 47 % of the hydrostatic pressure (Figure 8c). This reduction of the hydraulic pressure from the hydrostatic pressure is expected and it is due to the

internal friction resulting from the granular phase and wall/material friction. After the filling of the form in this first phase, a rapid decrease of the hydraulic pressure was then observed during about 25 min (Figure 8c).

Concrete of a height of 1.5 m was added as a second layer, at a loading speed of 8.3 m/h. Again, it could be observed in Figure 8c that the hydraulic pressure increases (*Peak 2* in Figure 8c) and then decreases with this second concrete addition. The same decrease of almost 50 % of the relative hydraulic pressure after the first and second stages in 25 min was observed. This property is very interesting from a safety point of view because the loading rate could be monitored using this device. The pressure on the formwork could be reduced by filling the mold in stages instead of one lift.

The cancellation of pressure was recorded after about 9 h. A partial formwork removal, consisting of separating the forms from the concrete without complete removal, was done after 11 hours. This can be seen by an immediate increase in the pressure measured (Figure 8c). The pressure measuring device was no longer in contact with the concrete.

This preliminary field test shows that the hydraulic pressure device could be used to monitor the field schedule of successive pouring, setting and demolding. Although, further tests are needed, it seems that the device provided meaningful information in a construction site environment.

CONCLUSIONS

The main scope of the paper was to compare concrete and cement paste behavior using hydraulic pressure and rheology measurements to monitor plastic behavior of cement pastes, concrete and SCC, start investigating the underlining reasons for the hydraulic pressure drop during setting of cement paste, and determine the practicality of using the new hydraulic pressure test device on a construction site.

Two testing methods were used: 1) monitoring of the hydraulic pressure using a novel device in paste and concrete; 2) rheological measurements on cement paste by stress growth.

The major conclusions that can be drawn are:

- For the cement paste in the column device, the hydraulic pressure decreases starting from the hydrostatic pressure and becomes null at the same time as the initial set detected by the Vicat test. The final set and the increase of the hydraulic pressure (becoming zero starting from the negative values) is correlated with a change in the flow behavior of the material as shown by a sharp increase in the yield stress measured by stress growth. This sharp change can be attributed to an increase in contact points between the particles due to hydration and the transformation of the material from a free flowing fluid to a fluid with high frictional forces between the particles.

- For traditional concrete (non-SCC), it was found that for a paste with the same free water content as the concrete, similar hydraulic pressure variations during the setting period were observed. On the other hand, probably due to a different composition of the cement paste fraction in SCC (presence of limestone and HRWRA) the hydraulic pressure cancellation is delayed in SCC compared with the "equivalent" pure cement paste.

- The hydraulic pressure device was successfully used on a construction site to monitor the schedule of the concrete pouring, the setting time, and the formwork removal.

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Table 1: Cement paste mixture

Mix	W [L/m^3]	C [kg/m^3]	LF	W/S	ϕ_0	ρ [kg/m^3]
P_{36}	523	1454	0	0.36	0.48	1977
P_{45}	579	1285	0	0.45	0.42	1864
LP_{36}	523	0	1454	0.36	0.51	1980

W: water, C: cement, LF : limestone filler, ϕ_0 : solid volume fraction, LP : Limestone Paste, S : Solid (Cement or Limestone)

Table 2: Traditional concrete (NC) and SCC mixture

Mixture		NC	SCC
Gravel 4/10 (Oven Dry)	*kg/m^3*	1031	891
Sand 0/3.15 (Oven Dry)	*kg/m^3*	795	735
Total water (Free and Absorbed)	*kg/m^3*	228	218
HRWRA	*L/m^3*	0	2.6
Cement	*kg/m^3*	350	280
Limestone filler	*kg/m^3*	0	170
W/C		0.65	0.47
(W_{free}/C)		0.45	0.36
Total Volumic mass	*kg/m^3*	2404	2404
Slump	*mm*	90	*
Slump flow	*mm*	*	510

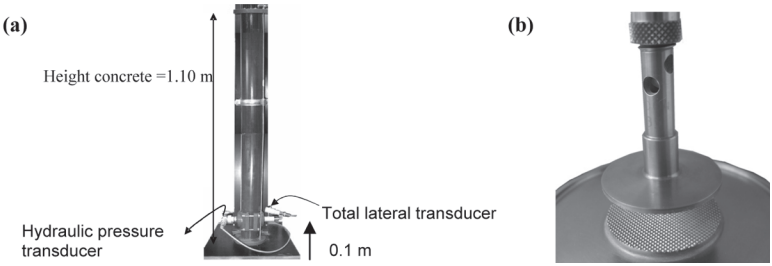

Figure 1: Total and hydraulic pressure device; Serrated parallel plate rheometer

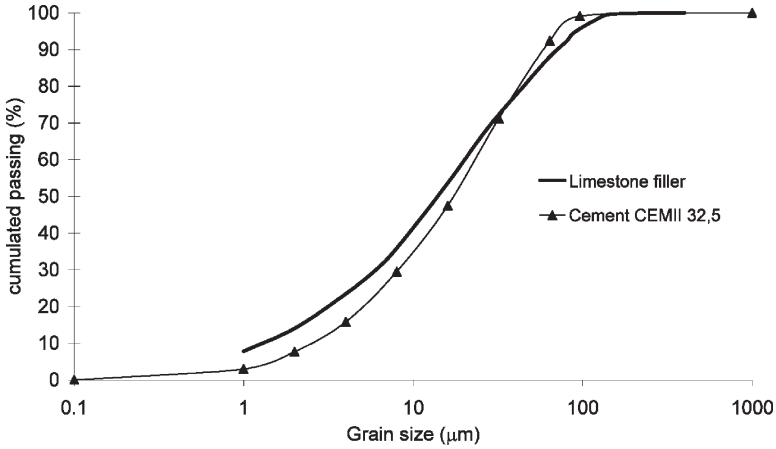

Figure 2: Particle size distribution of limestone filler and cement

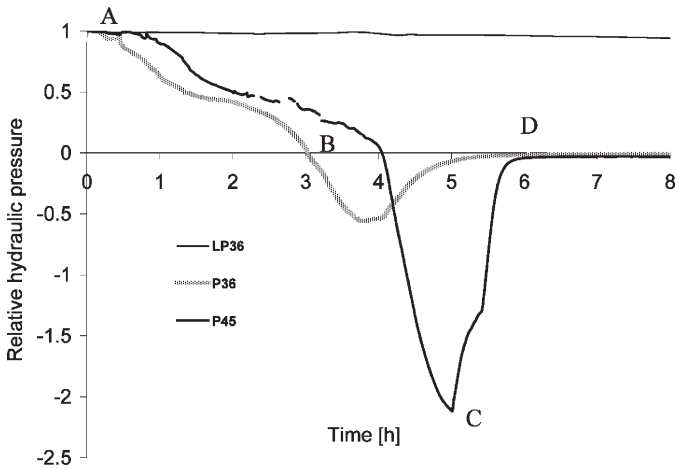

Figure 3: Relative Hydraulic pressure variation (ratio of the hydraulic pressure (measured) to the hydrostatic pressure recorded initially) for cement and filler pastes

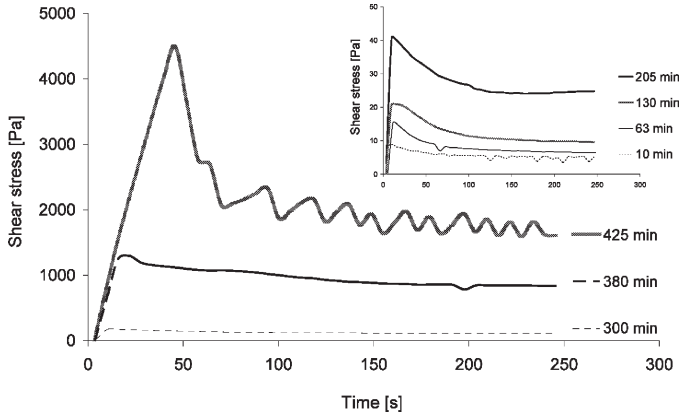

Figure 4: Shear stress response obtained with stress growth experiment (P45 sample) from 10 min to 425 min

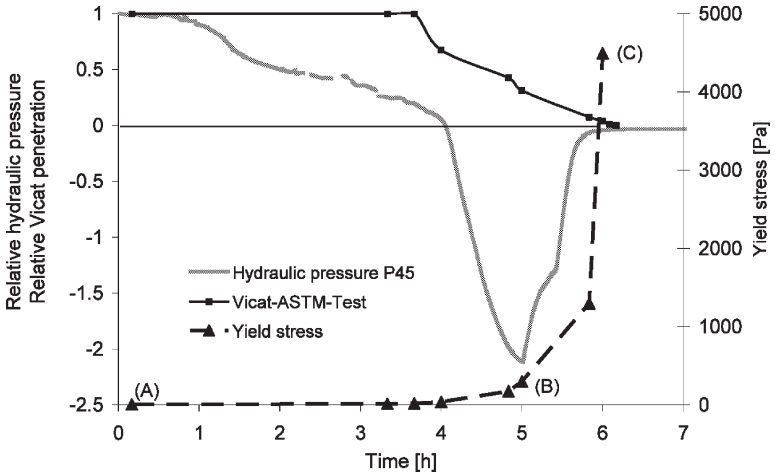

Figure 5: Hydraulic pressures, yield stress and needle penetration variation versus time of P45 cement paste.
(Relative hydraulic pressure = measured hydraulic pressure / hydrostatic pressure; Relative Vicat penetration = penetration of Vicat needle / 40)

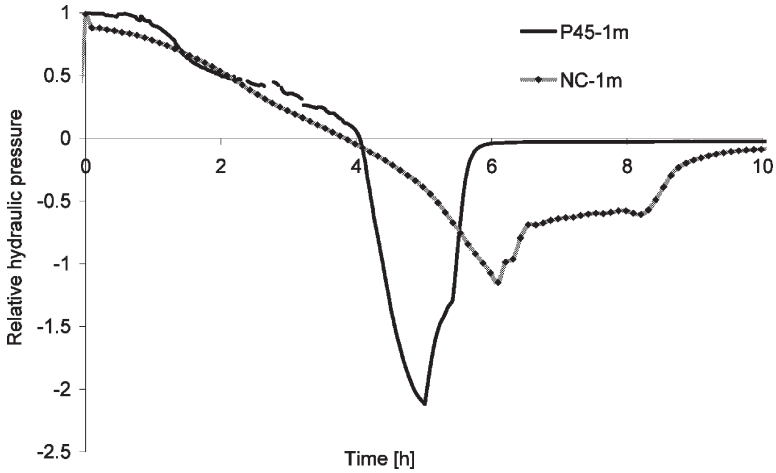

Figure 6: Comparison of relative hydraulic pressure variation (ratio of the hydraulic pressure (measured) to the hydrostatic pressure recorded initially) for P45, and NC

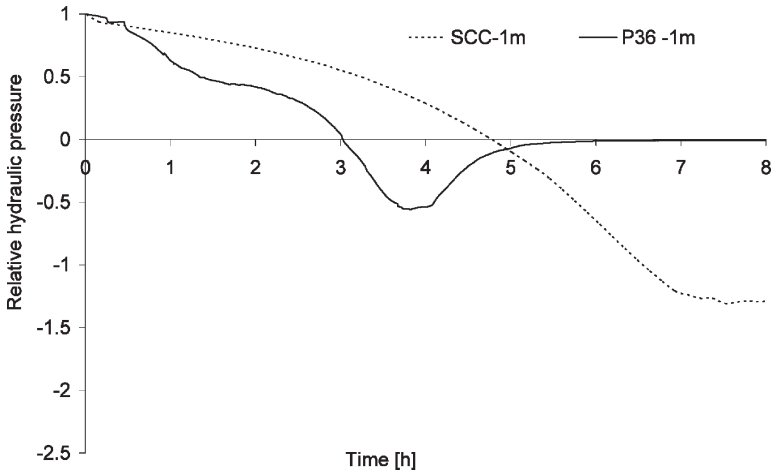

Figure 7: Comparison of relative hydraulic pressure variation for P_{36}, and SCC

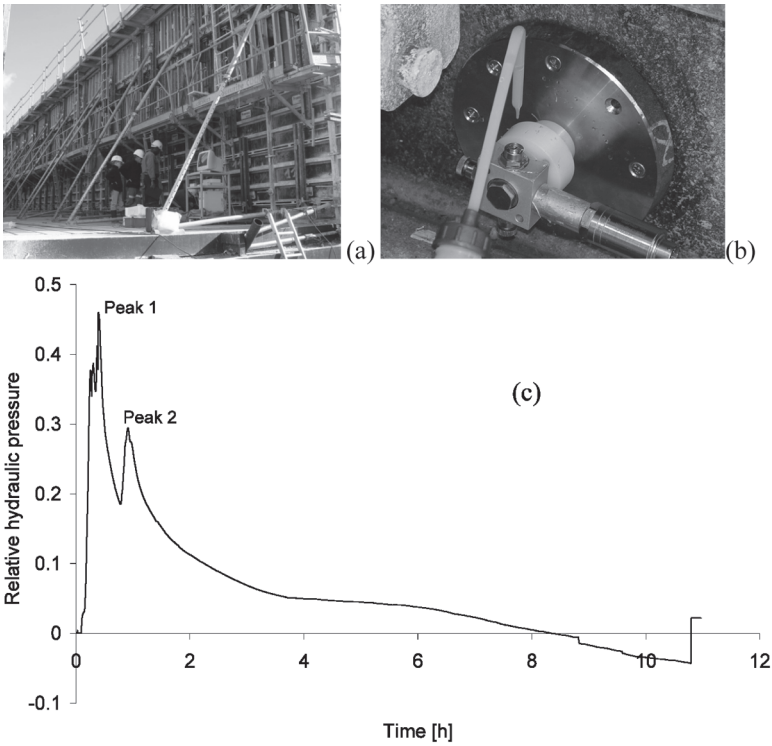

Figure 8: Field testing (a): 5.50 m height formwork fitted with a hydraulic pressure transducer (b); (c): hydraulic pressure versus time diagram