Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cement and Concrete Research 34 (2004) 2141–2152
CEMENT AND CONCRETE RESEARCH
Pergamon

Maturation of fresh cement paste within 1- to 10-m-large formworks

Ny Riana Andriamanantsilavo, Sofiane Amziane*

LG2M, Université de Bretagne Sud, rue St Maudé, Lorient 56321, France

Received 18 December 2002; accepted 24 March 2004

Abstract

The objective of this research was to examine the maturation of early-aged cement paste through the survey of the evolutions of the total lateral pressure exerted by cement paste against formworks and of the pore water pressure. The experimental device was specially developed for this purpose. Three types of cement paste mixtures with a water/cement (W/C) ratio of 0.30, 0.36 and 0.45, respectively, have been tested. In addition, temperature and setting kinetics were also examined. The results have shown that the kinetics of the pore water pressure and the total lateral pressure were strongly affected by the W/C ratio, the vibration and the level of stress, to which the fresh cement paste is subjected. The confrontation of these results with the theory currently available as regards setting of cement makes it possible to identify the physicomechanical phenomena, which occur within formworks.

Keywords: Fresh concrete; Vibration; Kinetics; Pore water pressure; Shrinkage

1. Introduction

During the last couple of years, significant improvements have been carried out to both rheological and mechanical characteristics of cement-based materials, particularly of concrete. These improvements have been made, thanks to the addition of admixture and/or fines, like superplasticizers, air-entraining agents and fillers, to the ordinary water–cement–aggregates mixture. Several types of concrete, such as self-compacting concrete, fiber-reinforced concrete and high-strength concrete, are currently at the builders' disposal.

This new generation of concrete has been created to satisfy the needs of civil engineering companies to face new architectural requirements and the constraints of shorter deadlines.

From an architectural point of view, the builders are brought to build structures with ever more complex geometry and greater height. They also have to meet strict requirements on the quality of the facings, as well as on the color homogeneity or on the surface appearance.

Regarding time constraint, keeping the deadline implies a quick rotation of the formworks and, sometimes, the use of up to 20-m-high formworks filled in one pour only at a very high pouring rate.

All these constraints require a better knowledge of the various phenomena, which occur in the cement-based materials and at the interface of the formwork, in particular, under the conditions of high pressure related to the depth of poured material.

Within this context, the objective of this research is to characterize fresh cement paste in order to:

- Establish a relationship between the intrinsic properties of the cement-based mixtures and the fresh concrete pressure exerted on the surface of the formwork,
- Explain the process of maturation of cement-based materials between casting and striking phases of the form.

As far as these subjects are concerned, the research, conducted to examine cement-based materials before setting, mainly concerns three domains: the process of hydration of the cement [1], the rheology [2] and the characterization of the stress and strain of the cement pastes and the mortars [3–5].

These studies demonstrate that many parameters have a significant impact on hydration, rheology and shrinkage. The main parameters are the following: the test conditions (temperature, hygroscopy, air velocity, pouring method,

* Corresponding author. Tel.: +33-2-97874535; fax: +33-2-97874570.
E-mail addresses: ny.riana@univ-ubs.fr (N.R. Andriamanantsilavo), Sofiane.Amziane@univ-ubs.fr (S. Amziane).

0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2004.03.027

etc.), the physicochemical characteristics of the materials (fineness of cement and aggregate grains, admixture type, level of C3S in cement, etc.) and the mix design (water content, paste/aggregate volume ratio, etc.).

The level of the pressure exerted by the freshly mixed concrete just after casting depends on several parameters [6]. The height of concreting, the unit weight and the casting conditions are the main ones. The pouring rate and the method of vibration of the mixture (frequency, duration and depth penetration of the vibrating needle into the mixture), in particular, greatly affect the shape of the load diagram of the pressure exerted by concrete against a formwork. The friction between fresh concrete and formwork has also a significant influence and produces a decrease in the maximum total lateral pressure [7].

The process of maturation of cement-based materials is currently approached in a roundabout way through the evaluation of setting tests conducted on cement pastes. The setting times are assessed using either a Vicat (ASTM C191) or Gillmore (ASTM C266) needle [8]. Another convenient method for monitoring hydration kinetics is via the measurement of chemical shrinkage [9,12].

Therefore, to address the kinetics of evolution of the total lateral pressures exerted by a cement-based material on great height formworks, an experimental program has been developed here. To understand the influence of the various components on the concrete pressure better, the study conducted by the authors on water–cement mixtures is first described. The present work, thus, contributes to improve our understanding of the physicomechanical mechanism sequencing, which accompanies the setting of a cement-based material under constraint within a formwork.

2. Experimental method and materials

2.1. Experimental setup and measurements

All the phenomena occurring within formworks are reproduced using an experimental setup made up of a "tubular glass" column. The form is 1100 mm deep, 5.3 mm thick and has a diameter of 110 mm. The column is connected to two special pressure measuring (Fig. 1C and D) devices positioned at a height of 50 mm (Fig. 1).

To simulate the equivalent hydrostatic pressure of fresh cement paste at heights of 5 and 10 m, an equivalent pressure is applied on the surface of the material inside the column (Fig. 1A). This pressure is supplied by an air actuator. The force is controlled by a force transducer fixed between the air actuator and the surface of the material.

Temperature measurement, pore water pressure and total lateral pressure measurements are carried out 1 m deep under the top surface of the material. Three thermocouples are installed to measure the temperature in the heart of the mixture. Two types of pressure transducers,

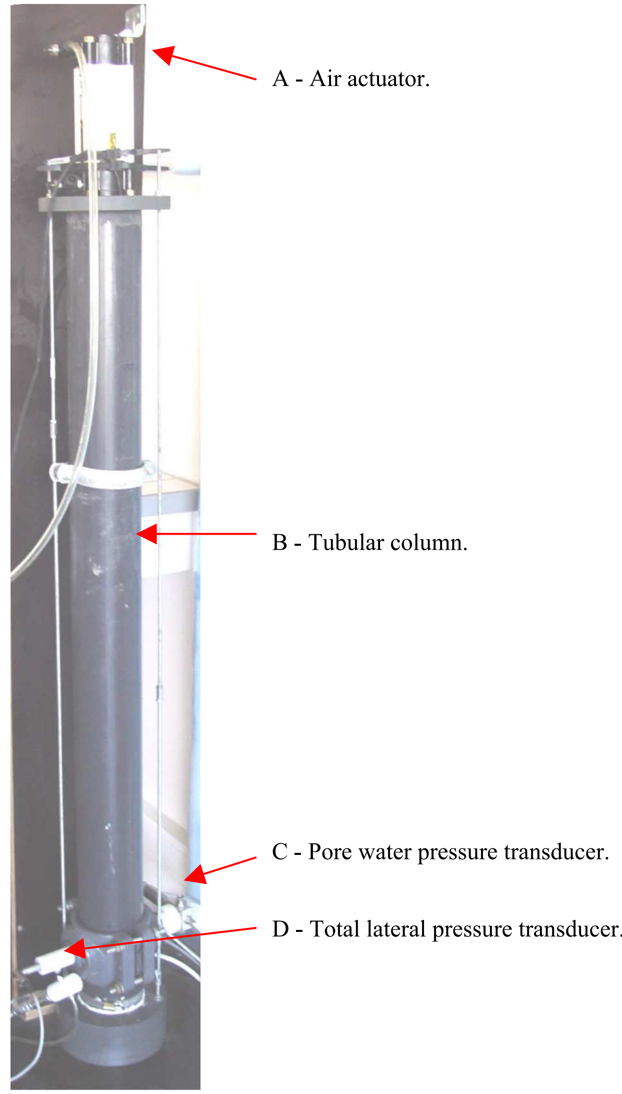

Fig. 1. View of the setup device.

specially designed for this study, make it possible to follow up pore water pressure and total lateral pressure variations. These transducers are connected to a data acquisition device. Simultaneously, a characterization of the setting of cement paste using the Vicat test method is performed.

2.1.1. The total lateral pressure transducer

The measurement of the lateral pressure is generally carried out using diaphragm pressure transducers touching the material. Under the pressure of the fluid or gas materials, the membrane deforms and produces a variation in both the sensor wire resistance and the output voltage. This measurement method does not suit hardening materials, like cement paste, in the setting process. When a material is setting, the deformation of the transducer diaphragm due to the flow of freshly mixed paste, indeed, is not reversible, although no pressure is applied by the transducer anymore. (Fig. 2a).

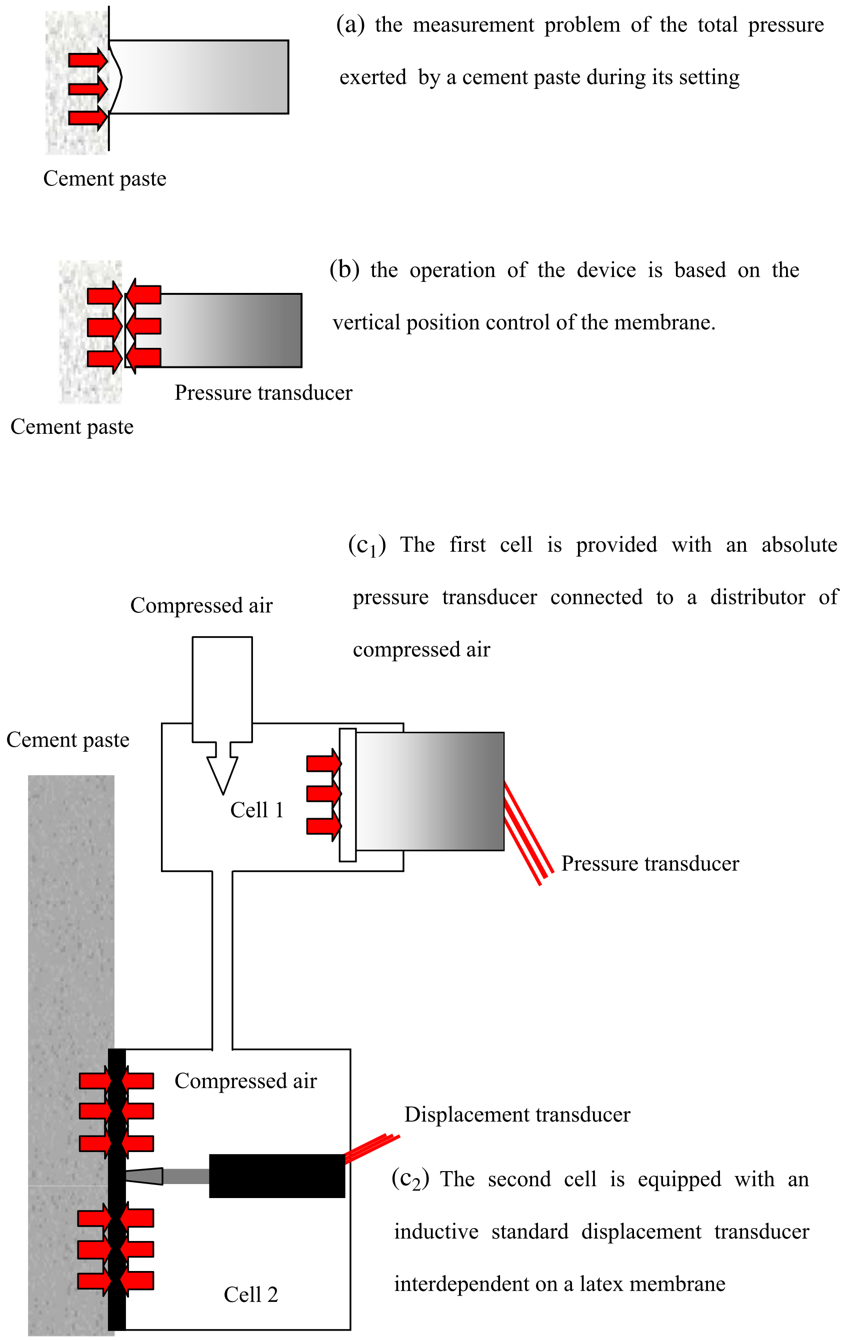

Fig. 2. Design of the total lateral pressure measurement device.

Consequently, an original device allowing for the measurement of the lateral pressure exerted by a hardening cement-based material has been developed (Fig. 2). The transducer operating principle is based on the implementation of a controlled air backpressure, which is continuously balanced with the pressure exerted by the tested medium (Fig. 2b).

The device is composed of two interconnected measuring chambers (Fig. 2c). The first chamber is equipped with an absolute pressure transducer connected to a compressed air control valve. The second chamber is equipped with an inductive standard displacement transducer attached to a thin elastometric latex membrane. The other side of the membrane is in direct contact with the material tested.

During the test, the pressure in both chambers is controlled so that the membrane is kept in a vertical position. This position, indeed, is indicative of the pressure equilibrium on both sides of the membrane. Consequently, the pressure exerted by the material on the formwork is equal to the pressure measured in the chambers.

2.1.2. The pore water pressure transducer

Measurement is carried out by adapting, the triaxial test, a method usually used in soil mechanics. Because this test is difficult to conduct on fluid materials, like fresh cement paste, a specific measurement system has been developed. (Fig. 3).

The system consists of a pressure transducer mounted on the formwork through the "deaerator block" filled with oil (Fig. 3). To separate the cement paste from the measurement system, a water-filtering device (compacted fiber cotton) 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 transfer of pressure through the filter. The tests carried out show that the response of our measuring apparatus to the variations of pore water pressure is instantaneous.

The transducer measures relative pressures; this is why it is unsuited to the measurement of strong depressions higher than the atmospheric pressure (≈ 100 kPa). Moreover, the exchanges of air between the mix and the deaerator block may induce errors on the measurement of the peak of depression. Therefore, measurements carried out in a depression state have above all a qualitative rather than a quantitative value.

2.2. Materials

It is futile to try to understand the behavior of fresh concrete while ignoring that of the paste that goes into it. For this reason, the present research is limited to the study of cement pastes. The tests have been carried out on cement pastes having a water/cement (W/C) mass ratio of 0.30, 0.36 and 0.45, respectively (Table 1).

Portland cement (CPA-CEM I-32.5 R EC NF) contains 75% clinker, 24% limestone and 1% filler. The specific Blaine surface is 3950 cm^2/g. The time, at which setting begins, is 2 h and 25 min (145 min). The cement density is 3050 kg/m^3.

According to standard NF EN 196-1, the mixing is prepared in a traditional 20-l mixer.

Table 1
Cement paste mix composition

Test number	Mix	W (l/m^3)	C (kg/m^3)	W/C	ϕ_0	ρ (kg/m^3)
1	$P_{1\text{-}1}$	478	1593	0.30	0.52	2070
2	$P_{1\text{-}5}$					
3	$P_{1\text{-}10}$					
4	$P_{2\text{-}1\ (v)}$	523	1454	0.36	0.48	1977
5	$P_{2\text{-}5\ (v)}$					
6	$P_{2\text{-}10\ (v)}$					
7	$P_{2\text{-}1\ (nv)}$					
8	$P_{2\text{-}5\ (nv)}$					
9	$P_{2\text{-}10\ (nv)}$					
10	$P_{3\text{-}1}$	579	1285	0.45	0.42	1864
11	$P_{3\text{-}5}$					
12	$P_{3\text{-}10}$					

$P_{i\text{-}j\ (\text{v or nv})}$: $P_{\text{type of the mix-height of the cement paste in meters (vibrated and nonvibrated)}}$.

Because concrete is composed of many materials with different densities, the characterization of the mixtures by the voluminal ratios is necessary. Frequently, the solid volume fraction (Eq. (1)) is used:

$$\phi_0 = \frac{V_s}{V_t - V_a} = \frac{V_s}{V_s + V_w} = \frac{1}{1 + \frac{\rho_s}{\rho_w} \times \frac{W}{S}} \tag{1}$$

where V_t represents the total volume, V_s the solid volume, V_a the air volume, V_w the water volume, ρ_s the density of the solids (cement), ρ_w the density of water and W/S the water/solid mass ratio. The mix compositions of the cement pastes studied are presented in Table 1. The air content of compacted fresh cement paste is roughly equal to 1.5% of the total volume.

2.3. Testing procedure

All the systems of measurement with compacted natural fibers and the "air fitting/deaerator block" are saturated before starting any acquisition. Immediately after the mixing of the cement–water mixture, the cement paste is poured

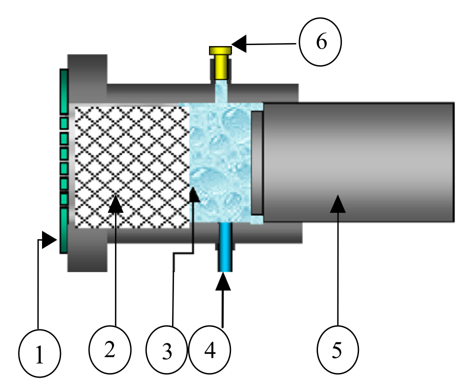

Fig. 3. Design of the pore water pressure measurement device.

into the tubular column at the rate of two 50-cm-thick layers. Each layer is vibrated for 15 s. For the consideration of the impact of the vibration on the kinetics of evolution of the pressures, some mixtures not subjected to vibration have also been prepared.

The temperature of the laboratory test chamber is 20 ± 2 °C, the relative humidity is 50 ± 6%. Moreover, 0.5 l of the mixture tested is sampled before each test to determine setting time through the Vicat test.

3. Experimental results

The results are presented in the form of diagrams, which describe the temporal evolution of the following parameters: pore water pressure, total lateral pressure, temperature, autogenous shrinkage and penetration of Vicat needle, respectively.

3.1. Evolution of the different pressures

At the initial state, pore water pressures and total lateral pressures measured are rigorously identical and are equal to the theoretical hydrostatic pressure $U_0 = \rho g z$ (with ρ, unit weight of the mix; g, gravity; and z, height of the mixture). Then, the kinetics of the recorded pressures presents three distinct phases (Figs. 4 and 5).

As shown in Fig. 4, the total lateral pressures and the pore water pressures first decrease slowly from the initial state until they cancel each other out completely in C (interval AC). During this step, the kinetics of decrease varies and two different slopes can be observed (interval AB and interval BC). For one constant W/C ratio and whatever the height of the cement paste, the (BC) step always occurs almost at the same moment (Fig. 5a, b and c). The instant of cancellation of the total lateral pressure and the pore water pressure (point C) corresponds to the moment when the material can recover its own weight. The cancellation time is strongly influenced by the W/C ratio and the depth of the cement paste inside the formwork. Table 2, which summarizes the results, shows that the higher the water content is, the more delayed the time of cancellation is. Thus, for a W/C ratio varying from 0.30 to 0.45, the cancellation of the total and interstitial pressures is put back by 1.73 h for a 5-m depth. The delay increases with the depth of cement paste. For a depth varying from 1 to 10 m and a W/C ratio equal to 0.30, cancellation time is put back by 1.04 h.

During the second step, the pore water pressure continues to decrease and becomes negative (interval CD), while the total lateral pressure remains null. The maximum level of interstitial depression is strongly influenced by the W/C ratio and the depth of cement paste. Unfortunately, as mentioned above, the unsuitable system of measurement does not allow us to draw conclusions on the exact influence of these parameters. Nevertheless, we observe that the amplitude of the depression increases with the depth of cement paste. Moreover, an increasing W/C ratio generates a delay in reaching the instant where the maximum value of the depression. During the last step (DE), the pore water pressure is null. The cancellation instant is reached either very abruptly or after a plateau.

The diagram of the evolution of the pore water pressure (Fig. 6a, b and c) according to the depth of cement paste deduced from Fig. 5a, b and c, presents, at the initial moment, a hydrostatic profile of pressure along the whole

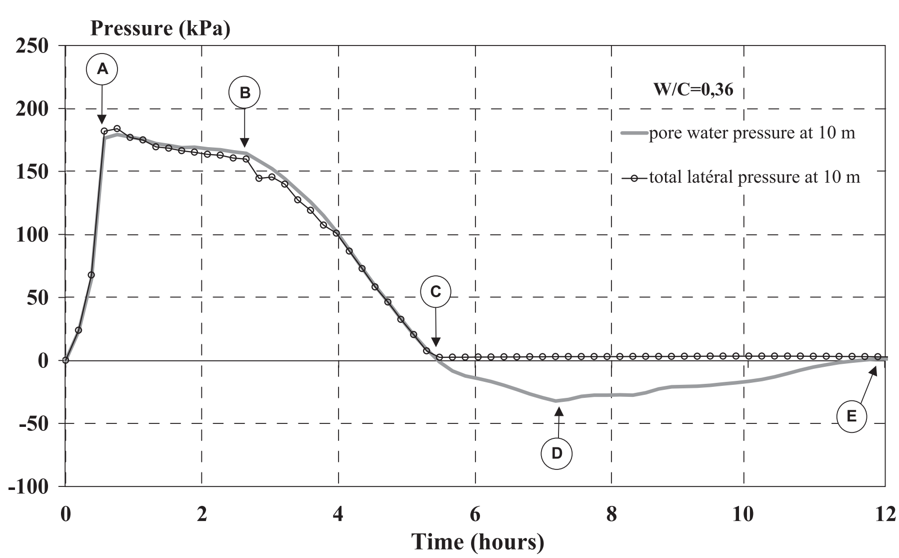

Fig. 4. Diagram of the evolution of pore water pressure and total lateral pressure.

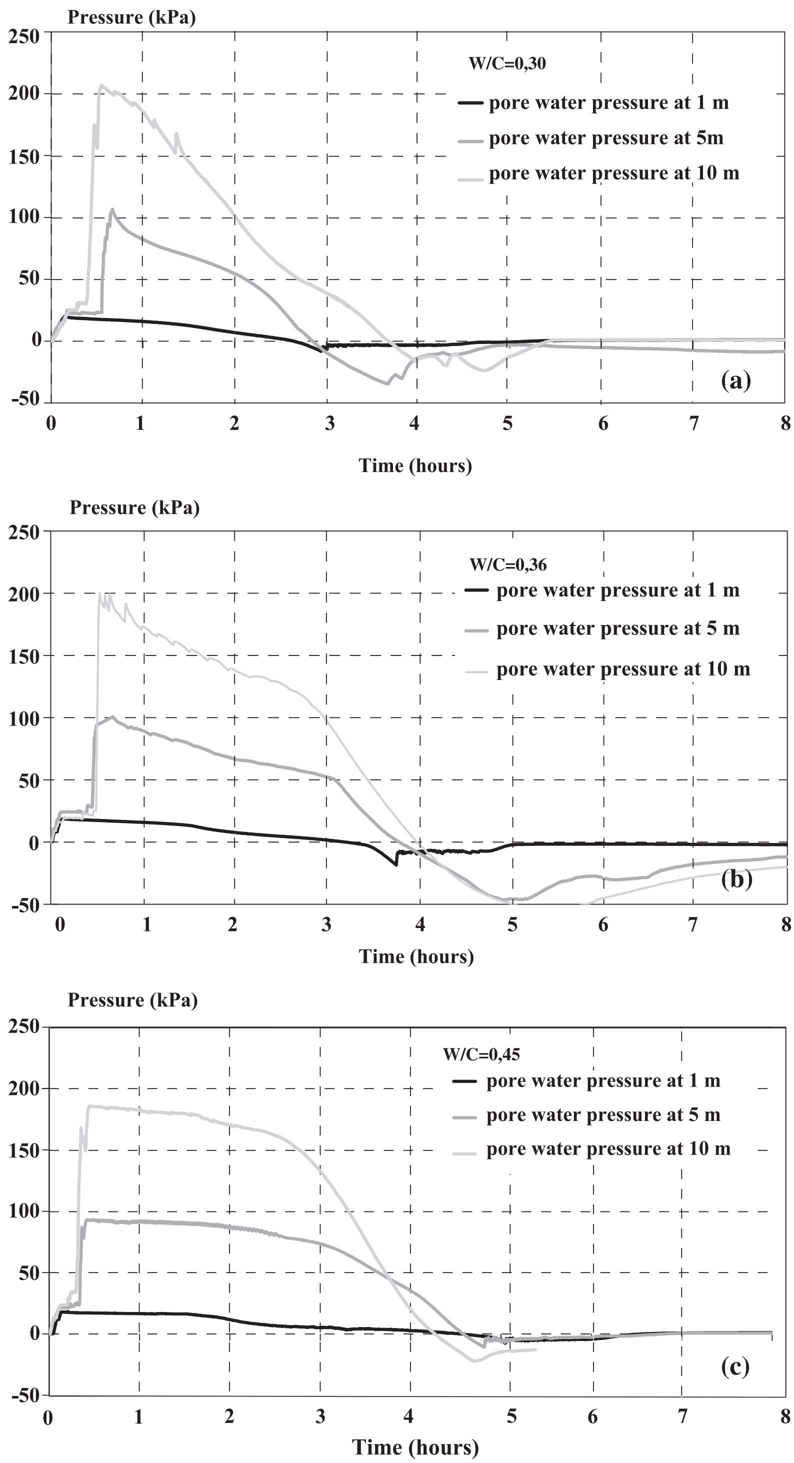

Fig. 5. The pore water pressure kinetics of the fresh cement paste with W/C equal to 0.30 (a), 0.36 (b) and 0.45 (c).

height of the column. The pore water pressure profile remains quasi-linear during the first 3 h and fall until cancellation. The kinetics of the decrease is accelerated during the test. This process is much slower for pastes with higher water content. During the first 3 h, the profile decreases quasi-linearly. Depending on the mix design, an interstitial depression profile is thereafter observed.

3.2. The influence of vibration

The influence of vibration on the kinetics of the pressures for $P_{2\text{-}j}$ (W/C = 0.36) pastes is studied. In the absence of vibration, the progress of the different steps is slowed down (Fig. 7). This slowing down is all the more significant because the material depth increases. For a $P_{2\text{-}1}$ paste, the

Table 2
Comparison of the results

Type of the test		Pressure	Temperature	Time of setting		
Number of the test	Mix	W/C	T_C[a]	T°_M[b]	T_0[c]	T_f[d]
1	P_{1-1}	0.3	2.64	–	2.25	4.00
2	P_{1-5}		2.85	–		
3	P_{1-10}		3.68	9.33		
4	$P_{2-1\ (v)}$	0.36	3.20	–	5.25	6.42
5	$P_{2-5\ (v)}$		3.78	–		
6	$P_{2-10\ (v)}$		3.97	9.83		
7	$P_{2-1\ (nv)}$	0.36	3.14	–		
8	$P_{2-5\ (nv)}$		–	–		
9	$P_{2-10\ (nv)}$		5.46	–		
10	P_{3-1}	0.45	4.56	11.16	6.55	8.27
11	P_{3-5}		4.58	12.16		
12	P_{3-10}		4.27	11.16		

[a] T_C: time corresponding to the first cancellation of the pore water pressure and the total lateral pressure.
[b] T_M: the time when the maximal temperature is recorded.
[c] T_0: the initial setting time (Vicat test).
[d] T_f: the final setting time (Vicat test).

vibration does not affect the length of the steps, whereas, for a P_{2-10} mixture, the absence of vibration generates a 90-min delay for reaching the point where the pressures cancel each other out.

3.3. Evolution of the temperature

During the first 3 h, a low thermal activity is observed. This stage is followed by a sharp increase in the temperature. The maximum temperature is reached within an interval ranging between 9 and 12 h depending on the mixture studied (Fig. 8).

For a constant depth of cement paste, the increase in the W/C ratio from 0.30 to 0.45 causes a reduction of 3 °C in the maximum temperature. This temperature is reached after 9.1 h for a W/C equal to 0.30 and 11 h for a W/C equal to 0.45.

Regarding depth, there is no difference whether the depth is 1 or 10 m. For a 5-m-deep paste, on the other hand, a different kinetics is observed. In this case, it appears that the starting temperature is slightly lower than for the other tests with other depths. This difference can be explained by the existence of differences in the initial conditions, which undergo some variations as regards hygroscopy, air velocity and environmental temperature.

3.4. Setting time test with the Vicat needle

The setting time tests are carried out on the samples of cement pastes P_1 to P_3 using the Vicat method. The penetration depth of the Vicat needle is measured and the initial setting time is reached when the penetration of the needle is 36 ± 1 mm, according to the NF EN 196-3 code.

As illustrated in Fig. 9, the increase in the W/C produces a delay of the cement paste setting. The initial setting time is 2.25 h for P_1 paste, 5.25 h for P_2 and 6.55 h for P_3, respectively.

The end of setting time is reached when the end of setting time needle does not go in more than 0.5 mm deep. The ends of setting times here are 4 h for P_1 paste, 6.42 h for P_2 and 8.27 h for P_3, respectively.

4. Discussion

The purpose of this study is to understand the evolution of the pressures by analyzing the transformation process of the cement pastes from the fluid to the rigidified state inside formworks using the results obtained experimentally, which describe the typical evolution parameters of cement paste (setting, shrinkage and temperature).

The comparison of the times obtained in Table 2 at all key stages clearly shows the difficulty to establish a simple relationship between the values achieved using the four different experimental techniques.

This difficulty is due to the complexity of cement pastes, whose behavior at this stage induces phenomena, which can be coupled or uncoupled depending on the maturing stage, on the one hand, and to the measurement techniques employed, on the other hand:

– Concerning the complexity of cement pastes: over the period within the range of the initial moment and 3 h, a significant variation of the pore water pressure and of the volume (shrinkage) is observed when the thermal activity seems null. The strain vs. time diagram (Fig. 10) [4,11] show that the absolute amount of autogenous shrinkage tends to increase, and the shrinkage tends to start at earlier ages, as the W/C ratio decreases. This observation, largely checked using a lineic method of the shrinkage measurement, is sometimes contradicted by the results obtained using a volumic method of measurement. This is due to the difficulty in the implementing of a special procedure to avoid artificially high values caused by imbibition of "bleeding" water. After 3 h, the thermal action directly related to the cement hydration reactions is activated at the same time as pressure evolution and cefment paste deformations.

– Concerning the measurement techniques: all the tests are conducted to quantify the different types of physical and mechanical phenomena: the pressure (for the internal and external state of stress), the temperature (for the hydration activity), the shear strength (deduced from the Vicat test, which makes it possible to estimate the rigidifying state of the paste) and finally, the variations of the volume (determine through the autog-

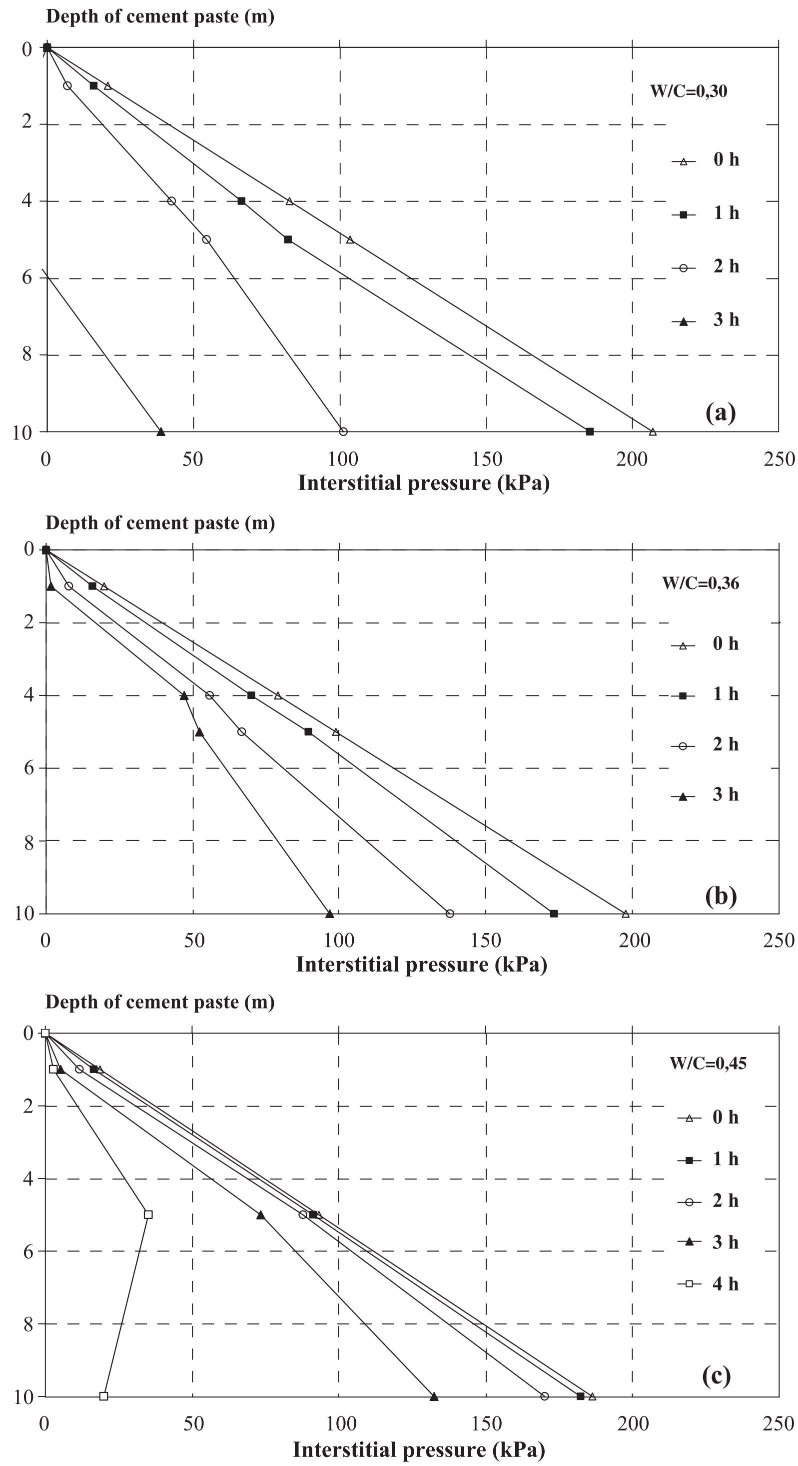

Fig. 6. The pore water pressure profile of fresh cement paste with W/C equal to 0.30 (a), 0.36 (b) and 0.45 (c).

enous shrinkage test). Moreover, both shrinkage and Vicat needle measurements are carried out at a very low state of stress (quasi-null) compared to the other tests (pressure and temperature within the formwork) carried out under higher pressures (25, 100 and 200 kPa).

Therefore, considering these remarks, a sequence of the phenomena begins to emerge, which leads to a state of structure of the cement paste within the formwork. The main steps observed are discussed below.

Initially, we have a medium, which undergoes three successive phases, composed of water, air and cement in

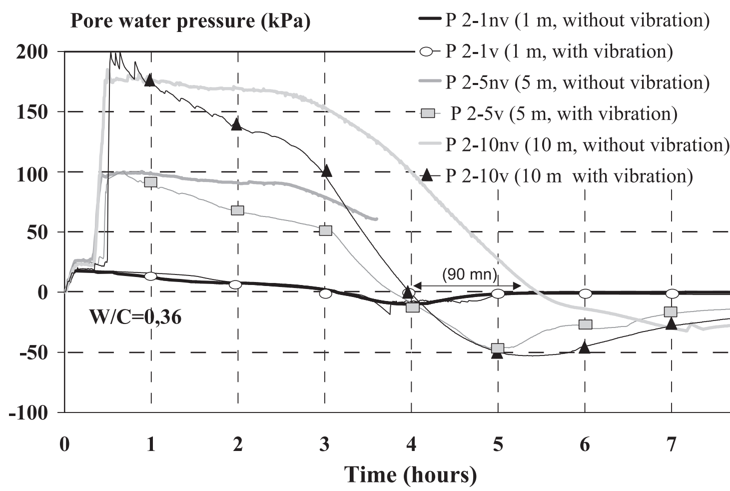

Fig. 7. Effect of the vibration on the evolution of the pore water pressure.

suspension. The mixture is subjected to hydraulic, chemical and mechanical forces due to the mixing. The paste, at this moment, is in a disorganized state. Solid particles are suspended in the liquid phase, which bears all forces fully. The pore water pressure U_0 is then equal to the total lateral pressure ($U_0 = \rho g z$).

The presence of air and water creates a capillary network and, consequently, generates suction (capillary tension), which places the liquid phase in a depression state. For that reason, the evolution of the measured pore water pressure is directly a function of the level of tension/pressure deficiency in the capillaries. Unfortunately, for lack of appropriate measuring device, actual suction phenomenon recording is beyond the scope of this study. On that subject, the classical theories found in the literature about the capillary principle reveal that the tension, U_s, is a function of the air pressure, U_a (dry air + water vapour) and of the water pressure, U_w (Fig. 11). By neglecting the osmotic suction and the adsorption phenomenon of water on the solid particles, suction is equal (Eq. (2)) to:

$$U_s = U_a - U_w \tag{2}$$

The tension can also be determined as a function of the capillary pore radius [Jurin's law (Eq. (3)) for cylindrical pores]:

$$U_s = 2 \times \sigma \times \cos\theta \times r^{-1} \tag{3}$$

where σ is the superficial tensile stress of the water/air interface, θ is the wetting angle and r is the pore radius.

The relative humidity (RH) in the pores is a significant parameter which affects the level of the suction and then

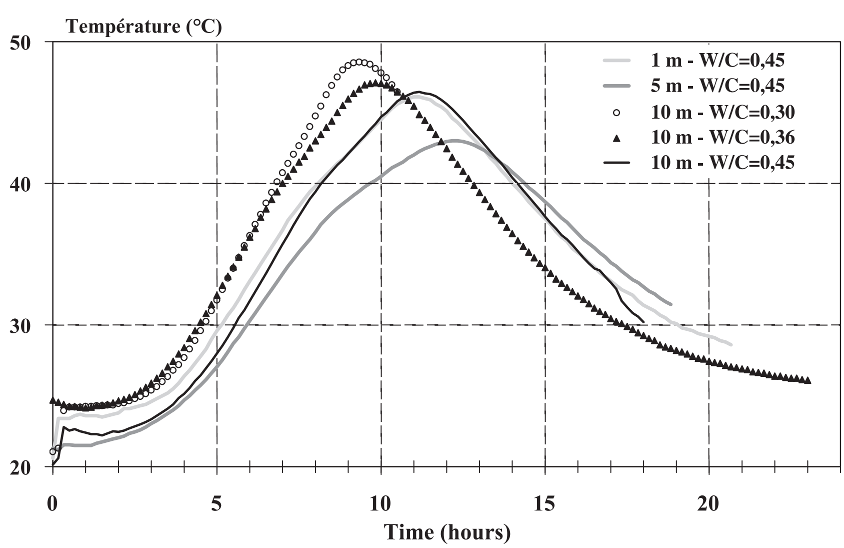

Fig. 8. Evolution of the temperature of the cement paste in the formwork.

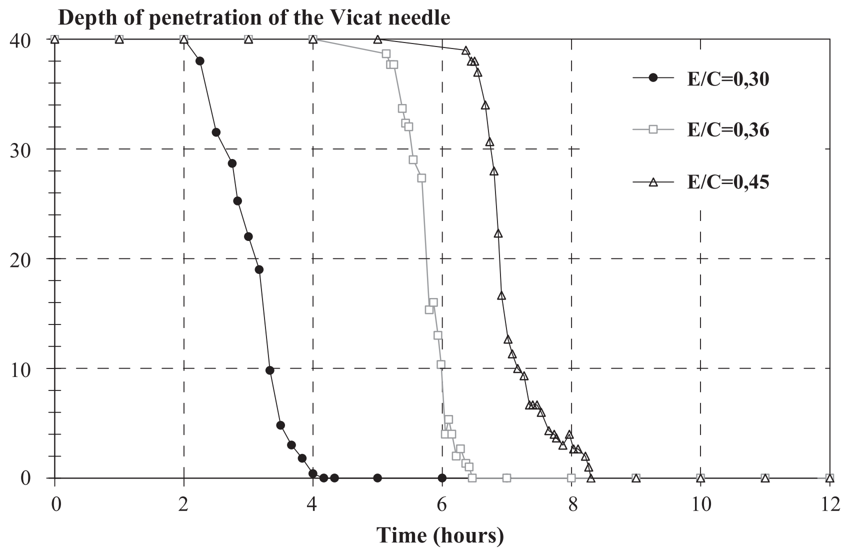

Fig. 9. Evolution of the depth penetration of the Vicat needle.

the decrease of pore water pressure. Thus, the authors in Ref. [10] demonstrate that the initial rise observed in RH does not reach 100% because of the RH decrease caused by the dissolved ions (Ca^{++}, Na^{+}, etc.) present in the cement pore solution. The RH initially recorded stabilize in the pore solution around 97 ± 2%. For example, according to the theoretical Kelvin law (Eq. (4)), a fall of the relative humidity of 2%, i.e., 98% RH, for instance, involves a suction force of 2.8 MPa.

$$U_s = U_a - U_w = \sigma_{cap} = \frac{-\ln(\mathrm{RH})RT}{gM} \quad (4)$$

where RH (%) is the relative humidity, M is the molar mass of water (M = 18.016 g mol^{-1}), g is the acceleration due to the gravity (g = 9.81 m s^{-2}), R is the universal gas constant (R = 8.3143 J. mol^{-1} K^{-1}), T is the thermodynamic temperature in Kelvin degrees, and σ_{cap} is the capillary stress (MPa; (Eq. (5)) or suction. At 20 °C:

$$\begin{aligned}\sigma_{cap} &= -\frac{\ln(\mathrm{RH})RT}{gM} \\ &= -10 \times \frac{-\ln(0.98 \times 8.3143 \times (20+273))}{9.81 \times 18.016}[\mathrm{MPa}] \\ &= 2.8\ \mathrm{MPa}\end{aligned} \quad (5)$$

In addition to the capillary forces mentioned before and under the impulse of gravity, as well as the attractive forces of

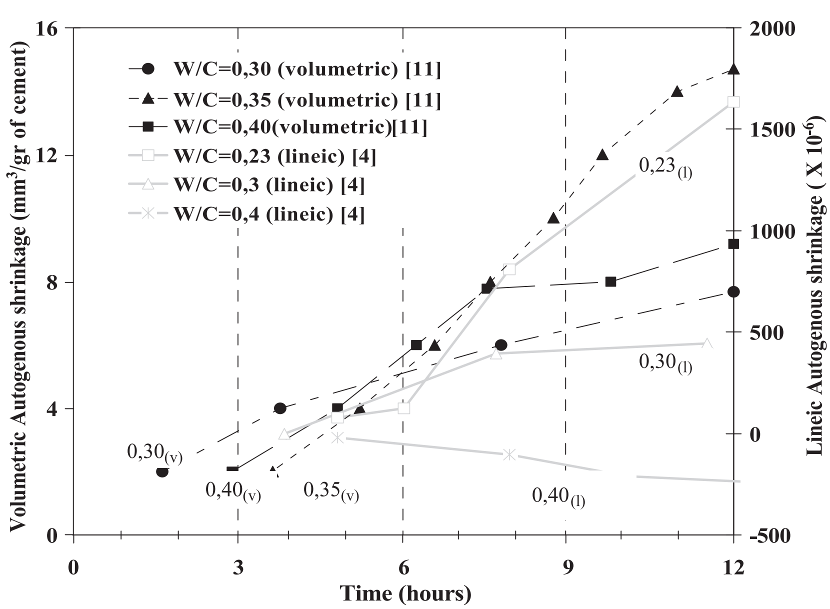

Fig. 10. Evolution of the autogenous shrinkage of the fresh cement paste.

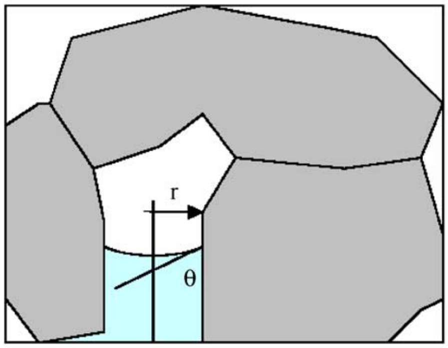

Fig. 11. The water–air menisci in the pore fluid.

Van der Waals and the electrostatic forces, the solid particles get nearer (the pore radius decreases). Consequently, the tension increases whereas the total lateral pressure, U, decreases.

In the present study, two parameters result in the variation of the suction:

– The vibration, which is used to reduce the volume of air bubbles trapped in the paste, and, thus, the capillary pores radius. The finer porosity of the mixture generates a quick appearance of high capillary depressions. Consequently, the pore water pressure decreases quickly for the vibrated mixtures (Fig. 8).

– The increase in the depth of cement, which results in higher compression rates for the paste. Because of the presence of air within the material, the cement grains get nearer under the action of compression and consequently, the capillary pores begin to shrink. This phenomenon accelerates the fall of the pore water pressures in the paste. An increase in the depth of cement paste, on the other hand, does not put back the moment where the pore water pressures cancel each other out radically, as shown in Fig. 6a, b and c.

Subsequently, when the level of depression, U_s, reaches the value of the initial pore water pressure, U_0, the cement paste is mechanically balanced with its own weight. At this moment, the cancellation of the total lateral pressure is achieved.

Once mechanical stability is acquired, an abrupt acceleration of the interstitial depression is recorded. As previously mentioned, the peak of actual interstitial depression (Table 3) is undoubtedly higher than the one experimentally measured for lack of appropriate measurement device.

Moreover, the evolution of the depression in the liquid phase is at the origin of the compression of the solid phase, which accounts for the autogenous shrinkage observed during the period ranging between 0 and 3 h [4,11]. The hydration activation simultaneously with the evolution of the depression state demonstrate the matching of both phenomena after 3 h.

5. Conclusion

The results based on the tests of characterization carried out on the cement paste combine with the tests conducted in 1- to 10-m formworks make it possible to draw the following conclusions:

– For the cement paste, the profiles of the pore water pressures and the total lateral pressures are hydrostatic, from the initial state until cancellation. During this period, the kinetics of evolution of both pressures is perfectly identical. Once the total lateral pressure is null, the pore water pressure passes to a depression state.

– The autogenous shrinkage test shows that the contraction of the paste is activated from the beginning because of the formation of the interstitial depression state related to the capillarity phenomenon.

– The W/C mass ratios, the depth of the poured cement pastes and the vibration have a considerable impact on the kinetics of the pressures. These parameters have a particular influence on the compactness of the material and, consequently, on the size of the capillaries and on the depression level. The absence of vibration, for instance, for a cement paste depth of 10 m, with a W/C=0.36, produces a 1.30-h delay on the cancellation of the total lateral pressure.

Table 3
The maximum depression level

W/C	h = 1 m			h = 5 m			h = 10 m		
	Test	T_D[a](h)	P_{MAX}[b](kPa)	Test	T_D[a](h)	P_{MAX}[b] (kPa)	Test	T_D[a](h)	P_{MAX}[b] (kPa)
0.30	P_{1-1}	2.94	− 8.21	P_{1-5}	3.69	− 31.92	P_{1-10}	4.72	− 24.00
0.36	$P_{2-1\ (v)}$	3.75	− 18.53	$P_{2-5\ (v)}$	5.07	− 46.08	$P_{2-10\ (v)}$	5.28	− 52.8
	$P_{2-1\ (nv)}$	3.84	− 9.75	$P_{2-5\ (nv)}$	–	–	$P_{2-10\ (nv)}$	7.16	− 32.16
0.45	P_{3-1}	5.05	− 7.73	P_{3-5}	4.82	− 10.85	P_{3-10}	4.72	− 22.08

[a] T_D: the time of the peak depression.
[b] P_{MAX} : the maximal depression recorded.

– The hydraulic stresses affect essentially the behavior of the cement paste during the first 3 h of its maturation. The thermochemical stresses, which appear later, will only increase this impact.

References

[1] V. Baroghel-Bouny, Caractérisation des pâtes de ciment et des bétons. Méthodes, analyse, interprétations, Laboratoire central des ponts et chaussées, France, ISBN 2-7208-5030-1, 1994.

[2] F. De Larrard, Concrete mixture-proportioning—A scientific approach, Modern Concrete Technology Series, vol. 9, E&FN Spon, London, 1999.

[3] A. Loukili, D. Chopin, A. Khelidj, J.Y. Le Touzo, A new approach to determine autogenous shrinkage at an early age considering temperature history, Cem Concr Res 30 (2) (2000) 915–955.

[4] E. Tazawa, S. Miyazawa, T. Kasai, Chemical shrinkage and autogenous shrinkage of hydrating cement paste, Cem Concr Res 25 (2) (1995) 288–292.

[5] C. Hua, P. Acker, A. Arlacher, Analyses and models of the autogenous shrinkage of hardening cement paste: I. Modelling at macroscopic scale, Cem Concr Res 25 (7) (1995) 1457–1468.

[6] N.J. Gardner, Pressure of concrete on formwork—A review, ACI Journal 5 (82) September/October (1985) Title no. 82-69 744-753.

[7] Y. Vanhove, Contribution à l'étude du frottement d'un béton autoplaç ant contre une surface métallique—Application aux poussées contre les coffrages, Thèse de la Faculté des Sciences Appliquées de Béthune de l'Université d'Artois, France, 2001.

[8] ASTM Annual Book of Standards, Vol. 04.01, Cement; Lime, Gypsum, American Society for Testing and Materials, West Conshohocken, PA, 1999.

[9] M. Geiker, Studies of Portland Cement Hydration: Measurement of Chemical Shrinkage and a Systematic Evaluation of Hydration Curves by Means of the Dispersion Model, PhD thesis, Technical University of Denmark, Lyngby, Denmark, 1983.

[10] D.P. Bentz, O.M. Jensen, K.K. Hansen, J.F. Olesen, H. Stang, C.J. Haecker, Influence of cement particle size distribution on early age autogenous strains and stresses in cement-based materials, J Am Ceram Soc 84 (1) (2001) 129–135.

[11] S.G. Boivin, Retrait au jeune âge du béton, développement d'une méthode expérimentale et contribution à l'analyse physique du retrait endogène. Thèse de doctorat du Laboratoire Centrale des Ponts et Chaussées, 2001.

[12] H. Justnes, A. Van Gemert, F. Verboven, E.J. Sellevold, Total and external chemical shrinkage of low w/c ratio cement pastes, Adv Cem Res 8 (31) (1996) 121–126.