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Lateral stress exerted by fresh cement paste on formwork: Laboratory experiments

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Abstract

In the present paper, experimental results from laboratory testing on cement pastes are presented. The validity of both the predictions of the model proposed by Ovarlez and Roussel [Mat. and Struct. 39(2) (2006)] and the assumptions on which the model is based in the case of rough interfaces between the cement paste and the formwork surface are validated. The consistency of the underlying theory is tested in several different configurations (plate test with large and narrow gaps and a column test). Finally, the concept of a new test allowing the measurement of the structuration at rest of a cementitious material is proposed. Such a simple test might be used to assess the input parameters needed to predict formwork pressure without the need for a rheometer.

Keywords: Rheology; Fresh concrete; Thixotropy; Formwork

1. Introduction

During casting, given the high fluidity of some modern concretes such as self consolidating concrete (SCC), it can be expected that hydrostatic pressure will be reached in the formwork. However, in many studies, high and low formwork pressures were, when monitored, reported. It was concluded that the thixotropic behaviour of the SCC had to play a role [1–3]. During placing, the material indeed behaves as a fluid but, if cast slowly enough or if at rest, it builds up an internal structure and has the ability to withstand the load from concrete cast above it without increasing the lateral stress against the formwork. This conclusion was drawn by observing the decrease in pressure in the first few hours after casting. Even though the hydration process has not yet started [4,5], the lateral stress on the formwork wall steadily decreases. The only phenomenon that can occur after casting at this time in the fresh concrete is the build up of internal structure (structuration) at rest [6,7] if we assume that the material is stable. Indeed, if segregation occurs in the material, it becomes possible to imagine that some of the coarsest particles come into strong frictional contacts and develop a continuous contacts network which may turn the material into a pseudo-solid and thus reduce the formwork pressure. The structuration of an homogenous concrete is a consequence of the strong thixotropic behavior of these modern concretes, namely the fact that the apparent viscosity of the material strongly depends on the flow history. This structuration and the associated de-structuration phenomena have recently been studied by Jarny and co-workers [8] in the case of a white cement paste. In the case of concrete, a simple model has been proposed by Roussel [9]. When the material is left at rest, its apparent yield stress increases: $\tau_0 = \tau_{0i} + A_{\text{thix}} t$ where A_{thix} is the structuration rate due to the thixotropy of the material in Pa/s and τ_{0i} is the initial yield stress of the concrete before the resting period.

The most complete experimental work linking thixotropy and formwork pressure found in the literature was carried out by J. Assaad, K.H. Khayat and their co-workers [2,5–7,10–11]. It

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deals with the two aspects of the above-quoted problem: quantifying the thixotropic behavior and measuring the formwork pressure.

Ovarlez and Roussel [3] have recently proposed a model to account for the influence of the structuration of SCC on the lateral stress during and after casting. Details on this model will be given in Section 2. The predictions of this model were compared by Ovarlez and Roussel [3] to measurements of post-casting pressure drop carried out on real formworks simultaneously with measurements of the apparent yield stress of the concrete for various times of rest. The predictions of the model were also compared to results from the literature, showing the ability of the model to explain and predict most of the experimental observations and measured pressures during casting. This model predicts an evolution of the pressure drop $\Delta\sigma'$ with the time t after casting equal to:

$$\Delta\sigma' = -\frac{2A_{\mathrm{thix}}H}{e}t \tag{1}$$

and a relative lateral pressure σ' (*i.e.* ratio between pressure and hydrostatic pressure) during casting equal to:

$$\sigma' = 1 - \frac{HA_{\mathrm{thix}}}{\rho geR} \tag{2}$$

where H is the height of concrete in the formwork in m, A_{thix} the structuration rate in Pa/s, R the casting rate in m/s, e the width of the formwork in m and ρ the density of the concrete.

In the present paper, experimental results from laboratory testing on cement pastes will be presented. They confirm the validity of both the predictions of the model proposed by Ovarlez and Roussel [3] and the assumptions on which the model is based in the case of rough interfaces between the cement paste and the formwork surface. The consistency of the theory is tested in several different configurations. Moreover, it is shown that, in the case of smooth interfaces between the material and the wall, the effect of the thixotropic structuration of the material on the lateral stress is decreased. Finally, the concept of a new test allowing for the measurement of the structuration at rest of a cementitious material is proposed. This simple test might be used to assess the input parameters needed to predict the formwork pressure without a rheometer.

2. Theoretical frame

Calculations of the stress field performed in a rectangular formwork with an elastic modelling and a Tresca plasticity criterion were carried out by Ovarlez and Roussel [3] using the following assumption: the concrete was assumed to display a yield stress $\tau_0(t)$, which is an increasing function of the resting time t. At stresses below the yield stress and, if the deformation rate can be neglected (*i.e.* no viscous contribution to the stress), SCC, as any other fresh cementitious material, behaves as an elastic material [12]. It was then demonstrated that, for an elastic medium confined in a formwork and only submitted to gravity forces, the lateral stress σ_{lat} at the walls may be less than the hydrostatic pressure for two reasons: if the stress redirection parameter K due to the Poisson ratio effect is less than 1, or if some shear stress τ_{wall} is supported by the walls. The lateral stress $\sigma_{\mathrm{lat}}(z)$ at the walls at a depth z below the top of the material, in a rectangular formwork of length L and width e can indeed be computed as [3]:

$$\sigma_{\mathrm{lat}}(z) = K(\rho g - 2\tau_{\mathrm{wall}}(1/L + 1/e))z \tag{3}$$

However, it was also shown that, in the case of SCC with standard air contents, K value is near 1, so that the Poisson ratio effect may be neglected; in the following, all the analysis will be performed with $K=1$. It has to be noted that, in such an approach, the shear stress $\tau_{\mathrm{wall}}(\boldsymbol{t})$ at the walls at a time t is between 0 and the yield stress $\tau_0(t)$, depending on local deformation. For a non compressible fluid in transition towards a solid behavior, this means that, even if the yield stress of the material evolves with time, there should not be any change at the walls. Indeed, the pressure should be hydrostatic when the material is cast as a fluid and should then remain hydrostatic during and after the liquid–solid transition as the material is non compressible and there is thus neither strain nor deviatoric stress in the bulk.

However, in the case of concrete, this deformation can occur as the material slightly consolidates under its own weight [7] and settlement of the surface can be measured. A vertical deformation of order 0.003 was measured by [7] several hours after the end of the casting. As shown on Fig. 1, it induces a shear deformation at the walls in the order of $0.003(2H/e)\cong 0.05$ for $H=4$ m and $e=20$ cm. This is sufficient to enable full shear stress mobilization as the critical deformation of cement paste below which the material can be considered as an elastic solid is of the order of 5.10^{-4} [13,14]. This means that the shear stress reaches the value of the yield stress at the wall. It is worth noting that the estimated deformation could be sufficient to create a shear stress at the wall higher than the yield stress. This cannot

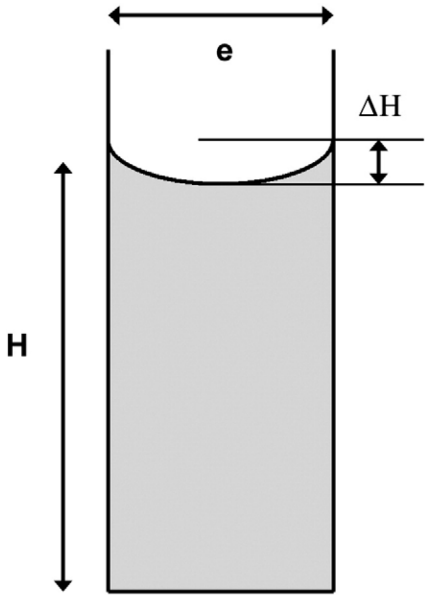

Fig. 1. Deformation state in a consolidating cementitious material.

however occur as it would mean that the material would be flowing which cannot be the case here according to the boundary conditions of the problem. The shear strain at the wall (and the global deformation of the material) is thus limited by the value of the shear stress that cannot exceed the value of the yield stress, which itself increases with time because of thixotropy. Finally, if there is no sliding at the interface between the material and the formwork, the yield stress (not less or not more) is fully mobilized at the wall and a fraction of the pressure is transferred vertically to the formwork. The remaining lateral stress is then lower than the value of the hydrostatic pressure: as $\tau_{\text{wall}}(\boldsymbol{t})=\tau_0(\boldsymbol{t})$, Eq. (3) then becomes:

$$\sigma_{\text{lat}}(z) = K(\rho g - 2\tau_0(1/L + 1/e))z \tag{4}$$

It can be noted that this lateral stress is abusively called pressure as it is not isotropic anymore. However, in the following, for the sake of simplicity, we will keep on calling it pressure.

In the following sections, we will aim at demonstrating that the simple scheme described above is able to describe our experiments and, from a more general point of view, the behavior of a given concrete in a formwork. In order to achieve this goal, we need to do the following: (i) show that there exists a shear stress at the walls; (ii) show that there is a correlation between the shear stress at the walls and the lateral stress that follows Eq. (4); (iii) compare the shear stress at the walls and the material yield stress, and their evolutions with time. That is why, in the following, we will compare the results of 3 experiments: in a first experiment, the shear stress exerted by a thixotropic material on a wall will be measured with an original and simple technique; in a second experiment, the vertical and lateral stresses will be measured in a cylindrical formwork filled with the same material; in a third experiment, we will measure the yield stress of the material.

3. Materials and procedures

The cement used in this study was a CEM I 52.5 N with a density of 3160 kg/m^3. The water to cement ratio W/C was equal to 0.36. 50 l of the mixture were prepared with distilled water. At the end of the mixing phase, 3 types of tests were carried out simultaneously at a constant temperature of 20 °C and a constant relative humidity of 60%:

- a plate test
- a column test
- a Vane test for various resting times

In order to prevent evaporation from affecting the measurements, a thin layer of glycerol was applied to the exposed parts of the sample in all tests.

3.1. The plate test

A plate was rigidly bound to a metallic frame above a recipient containing fresh cement paste (see Fig. 2). The plate was then sunk into the cement paste sample. Once the plate was in the cement paste, the paste was deflocculated using a small vibrating needle. The apparent weight of the cement paste was then continuously measured using the balance for a couple of hours within an uncertainty of ±0.01 g. With this simple device, the apparent weight (as measured by the balance) of the cement paste is the cement paste actual weight minus the weight supported by the plate thanks to shear stress. The shear stress acting on the surface of the plate was calculated from the measured apparent mass evolution using the following relation:

$$\tau(t) = g\Delta M(t)/2S \tag{5}$$

where $\Delta M(t)$ is the measured variation in the apparent mass of the cement paste and S is the immerged surface of the plate.

The recipient was a PVC rectangular box of 8 × 12 cm section with an height of 22 cm. The sunken plate was parallel to the box walls. During the tests, it was filled with cement paste up to H=18 cm.

Two different plates with different roughness were used. The first plate was 0.2 cm thick, 7.5 cm large and 16.2 cm high. It was covered with P80 sand paper (average roughness of the order of 200 µm) and partially immerged in the cement paste. The immersion depth needed for the calculation of the shear stress on the plate was measured before the test and was in the

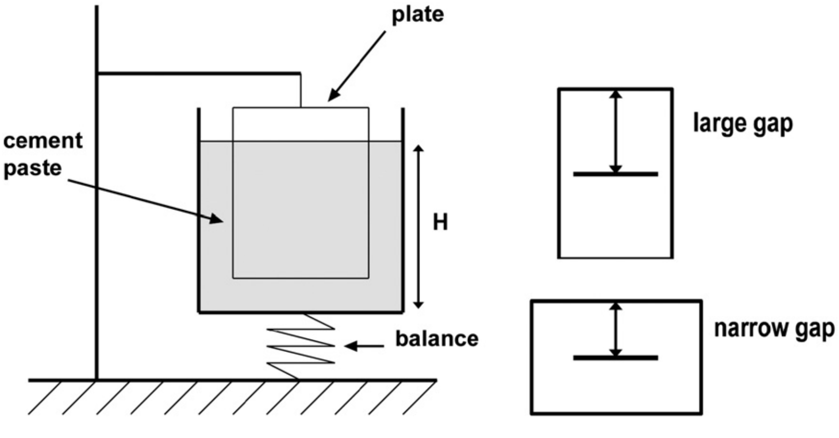

Fig. 2. The plate test (left), cross section of the test; (right), geometric configurations (plan).

order of 15 cm. The second plate had the same dimensions but its surface was smooth (it was made of PVC).

Two geometrical configurations can then be studied (Cf. Fig. 2 (right)). In the case of the first configuration, the lateral gap between the plate and the box walls is equal to 4 cm. This will be called here the narrow gap configuration. In the case of the second configuration, the lateral gap is equal to 6 cm. This will be called the large gap configuration.

It can be noted that the test is very sensitive to very small vibrations (especially at short times of rest when the material is still not far from being a liquid) which may create sudden decreases in the calculated shear stress which can be plotted in the most of the figures in this paper.

3.2. The column test

Two columns were studied. The first column was made of the same PVC as the 2nd plate tested (see previous section). This is what will be called here the smooth column whereas a column covered with the P80 sand paper was also tested and will be called the rough column in the rest of this paper. The column's inner diameter was equal to 10 cm. Each column was 130 cm high. The thickness of the plastic wall was 5.3 mm. It was initially filled with cement paste. It was then vibrated using a vibrating needle to ensure a complete destructuration of the tested material before the test. The pressure sensor was located 10 cm above the bottom of the column whereas the force acting on the bottom of the column (weight) was also measured (see Fig. 3). For more details on the pressure sensor, read [15]. The evolutions of the pressure acting on the lateral wall p and of the force F acting on the bottom of the column were recorded for a couple hours following the filling and vibrating. The force F acting on the bottom of the column is equal to the paste actual weight $\rho g S(H+0.1)$ minus the weight supported by the walls $\tau_{\text{wall}} 2\pi R(H+0.1)$, where τ_{wall} is the average shear stress at the walls. τ_{wall} is then:

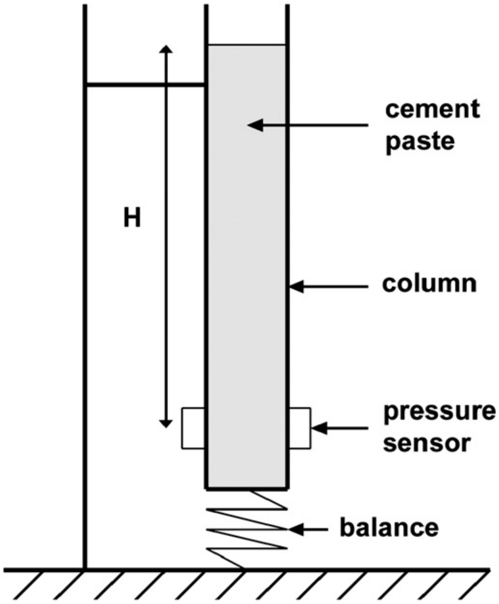

Fig. 3. The column test.

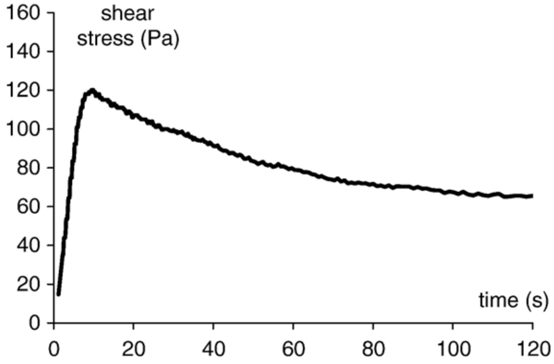

Fig. 4. A typical measurement obtained with a Vane test method. The peak allows for the measurement of the apparent yield stress after a given resting time (here 120 Pa).

$$\tau_{\text{wall}} = \frac{\rho g S(H+0.1) - F}{2\pi R(H+0.1)} \tag{6}$$

From Eq. (4), adapted in the case of a cylindrical formwork (see [3] for details), the theoretical average shear stress τ_{theo} on the column wall that would explain the difference between the measured pressure p at the walls and the expected hydrostatic pressure $\rho g H$ can be calculated as:

$$\tau_{\text{theo}} = (\rho g H - p)\frac{R}{2H}$$

From the experimental results, τ_{wall} and τ_{theo} will be calculated and compared; if the model is exact, we should then have $\tau_{\text{theo}} = \tau_{\text{wall}}$.

3.3. The Vane test

The yield stress of the cement paste was determined independently and simultaneously using a BOHLIN Gemini®200 viscometer equipped with a Vane geometry following the procedure described by N'Guyen and Boger [16] with an apparent shear rate of 10^{-3} s^{-1}. The Vane geometry used in this study consisted of four 2 mm thick blades around a cylindrical shaft of 6 mm diameter. The blade height was 37 mm and its diameter was 25 mm. A typical measurement is shown on Fig. 4. The obtained peak allows the measurement of the apparent yield stress of the tested material after a given time of rest. The results for the cement paste tested here are gathered on Fig. 5 as a function of the resting time. After each measurement, the paste was sheared at 100 s^{-1} in order to break any previous structuration of the material and to come back to the same initial reference state. Of course, working with the same sample does not allow for the distinction between the non-reversible evolution of the behavior due to the hydration of the cement particles and the reversible evolution of the behavior due to thixotropy [17,18]. It can be noted that the final age of the studied system (*i.e.* from the beginning of the mixing step to the last Vane test

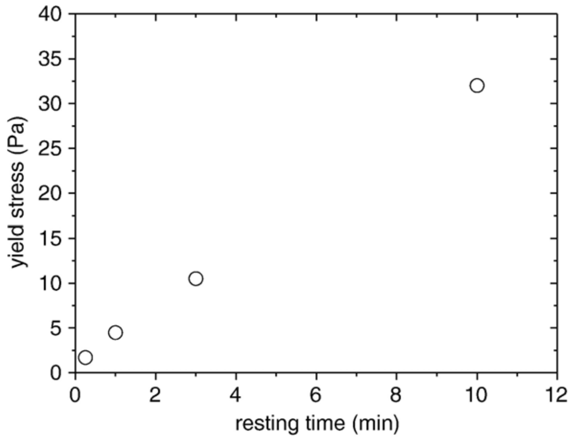

Fig. 5. Evolution of the apparent yield stress of the cement paste in terms of the resting time (Viscometer measurements).

measurement) was of the order of 45 min. Although Jarny and co-workers [8] have recently shown, using MRI velocimetry, that a period of around 30 min exists, for which irreversible effects have not yet become significant compared to reversible ones, the final age of the system in the present study was over this period. However, no strong stiffening of the sample was visually spotted nor measured (see Fig. 5).

As already pointed out by [3,9,19,20], the evolution of the apparent yield stress is more or less linear with the resting time and can be described within the frame of the simple thixotropy model for fresh concrete proposed by Roussel [3] ($\tau_0 = \tau_{0i} + A_{\mathrm{thix}} t$). The value of the structuration rate A_{thix} for the cement paste studied here can be calculated from Fig. 5. It is equal to 0.055 Pa/s (or 3.3 Pa/min).

4. Experimental results and analysis

4.1. Plate test

4.1.1. Shear stress on the rough plate

It can be seen on Fig. 6 that the shear stress variation in time on the rough plate surface calculated using Eq. (3) is equal to the yield stress of the material measured with the Vane test for both gaps. This means that the decrease of the apparent mass of the cement paste can be explained by the fact that the cement paste transfers a part of its weight to the plate by the mobilization of a shear stress on the plate. This shear stress is equal to the maximum value physically acceptable, the yield stress.

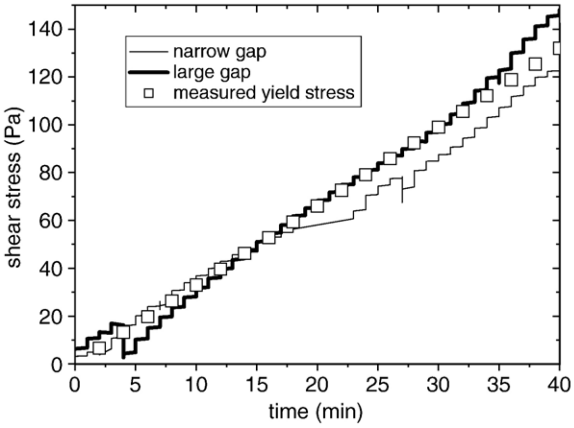

Fig. 6. Measured shear stress as a function of time. Narrow gap vs. large gap.

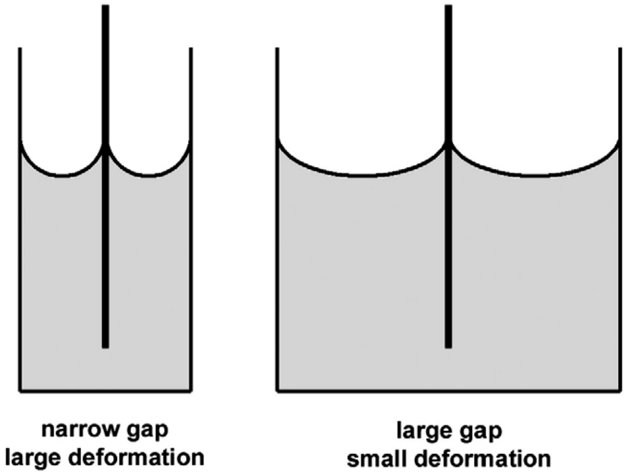

Fig. 7. Deformation state for the narrow gap and large gap plate test.

4.1.2. Effect of the recipient geometry

The comparison between the apparent weight variation is plotted for the two container geometries (narrow and large gap) in Fig. 6. The same rough plate was used in both geometries and the immersion depth was kept constant. No effect of the geometry on the apparent weight variations can be seen. This experimental fact contains a very interesting piece of information about the behavior of the cement paste at the interface. Indeed, as the cement paste at rest (below the yield stress) behaves as an elastic solid, a deformation (shear strain) must be at the origin of the shear stress that is exerted on the plate by the cement paste. The origin of this deformation was explained by Ovarlez and Roussel [3] by the small settlement that can always be measured at the surface of any freshly cast concrete. However, no matter what the origin of the deformation is as long as it exists, the shear stress generated by this deformation has a limit: the yield stress of the studied material. Indeed, let us imagine a vertical consolidation or a vertical deformation under the cement paste's own weight of an order of magnitude of 1‰. The shear strain at the plate would be of the order of $0.001*2H/e=0.01$ for the large gap and 0.02 for the narrow gap (see Fig. 7). If the material was purely elastic, the shear stress at the plate would then be higher in the case of the narrow gap than in the case of the large gap. However, the material displays a yield stress (elasto-plastic behavior) that limits the shear stress at the plate as both strain rates for both containers are above the critical value for a cement paste (0.0005 [13]). This means that the natural deformation of cement pastes is sufficient to create shear strain itself sufficient for the shear stress to reach the yield stress, no matter the geometric configuration (*i.e.* the formwork size).

This is not the case of all materials as shown on Fig. 8 where the same test procedure has been applied to a bentonite

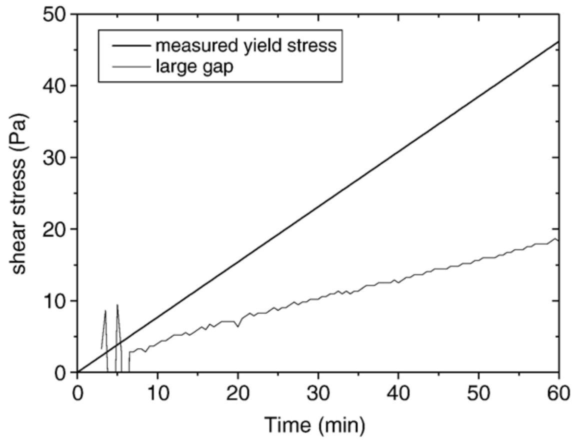

Fig. 8. Measured shear stress as a function of time. Plate test on bentonite suspension in the large gap configuration.

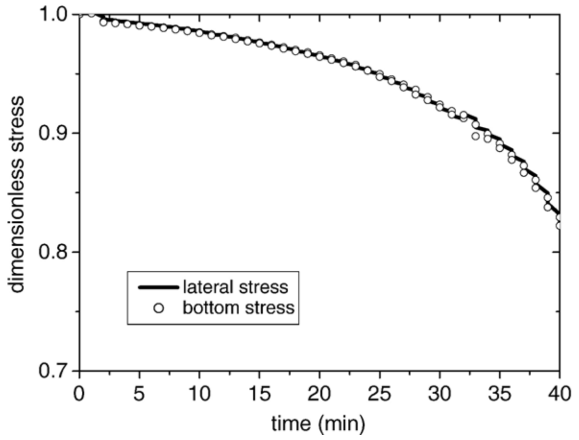

Fig. 10. Measured lateral vs. bottom dimensionless stress as a function of the resting time.

suspension (9% mass fraction mixed with water for 8 days), which is also a thixotropic material [21]. This material has a lower natural deformation under its own weight (*i.e.* it does not consolidate as fast as cement paste) and a higher critical strain rate (of the order of 0.1 for the material tested here). In this case, the strain rate generated at the interface between the plate and the material is small and always lower than the critical strain rate. This means that the shear stress on the plate has an unknown value between 0 and the yield stress. If cement paste (or concrete) had these types of properties, it would be very difficult to predict the shear stress at the interface and the derivation of the pressure during casting would be impossible. Luckily for the civil engineering community, it is not the case of cementitious materials.

4.1.3. Effect of the plate roughness

The decrease in apparent mass with time is lower in the case of the smooth plate than in the case of the rough plate. Conversely, the calculated shear stress that is exerted by the cement paste on the plate is lower as shown in Fig. 9. This means that the material is not able to mobilize a shear stress on the smooth plate up to the yield stress. As the plate and recipient geometries are identical to the previous section, this is linked to the ability of the interface to withstand this shear stress. It can be assumed that the material slightly slides at the interface. We will come back to this point when dealing with the smooth column test.

4.2. Column tests

4.2.1. Rough column

The dimensionless bottom (from the bottom balance) and lateral (from the pressure sensor) stresses are plotted in Fig. 10 in terms of resting time. As it could have been expected, the two dimensionless stresses are identical. It however once again confirms the fact that the pressure and the apparent mass decreases are due to the increasing shear stress at the wall of the formwork. The same comments as in the previous section can be made as exactly the same physical phenomenon are involved. The deformation under its own weight of the cement paste in the column is sufficient to create shear strain itself sufficient for the shear stress to reach the yield stress (Fig. 11).

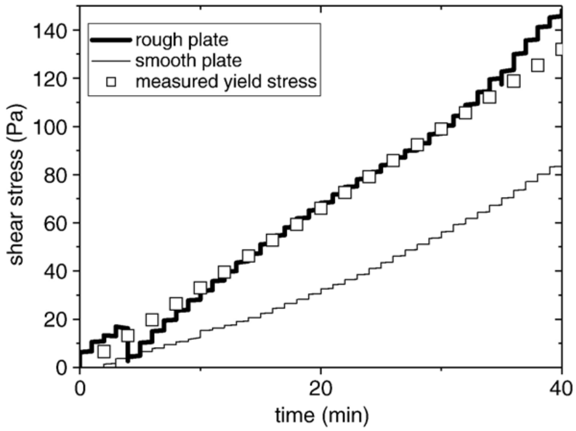

Fig. 9. Measured shear stress as a function of the resting time. Rough plate vs. smooth plate and yield stress variation.

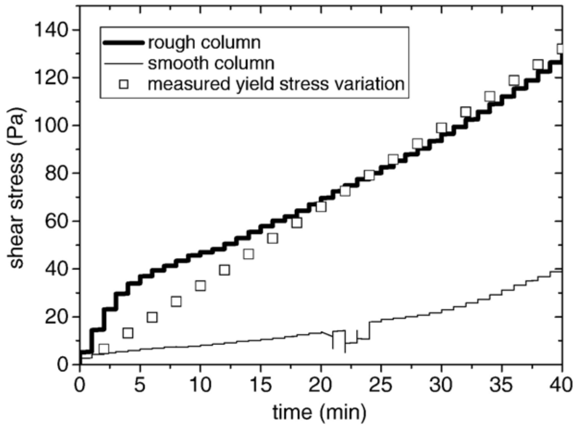

Fig. 11. Measured shear stress as a function of the resting time. Rough column vs. smooth column.

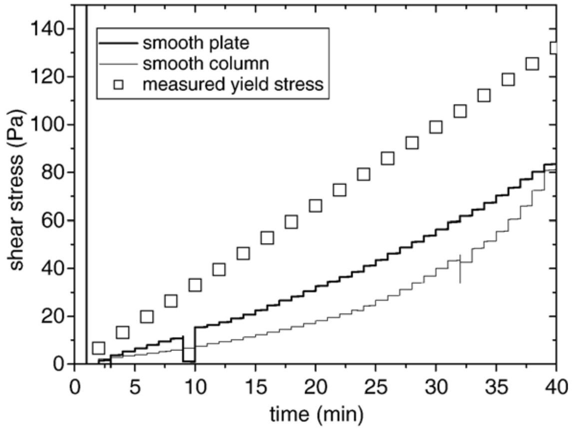

Fig. 12. Measured shear stress at the interface as a function of the resting time for smooth plate and smooth column.

This reduces the apparent mass of material at the bottom of the column or the measured pressure on the walls.

4.2.2. Smooth column

The calculated shear stress on the smooth column is plotted in Fig. 12 along with the shear stress calculated on the smooth plate. Both are below the yield stress of the material, indicating that a slight sliding of the material may occur at the smooth interface. However, the two stresses for the same PVC surface and the same material but for very different geometries are of the same order (*i.e.* around 50% of the material yield stress). There thus seems to exist what could be called a “friction yield stress”. It has to be noted that this critical stress could depend on local normal stress. If it was proven that the same type of phenomenon could occur in the case of real formwork and concrete, it would then be possible to imagine that this “friction yield stress” is the limiting value of the shear stress at the interface. On a casting prediction point of view, the same concept of pressure prediction model developed by Ovarlez and Roussel [3] could be used by replacing the value of the yield stress increase in Eq. (2) by the “friction yield stress” variation, which can be considered as a specific kind of critical shear stress the value of which is between 0 and the material yield stress. The remaining question would however be “how do we easily measure the value of this parameter ?”

5. Comparison plate/column/Vane test

The results obtained in the case of a rough interface for all geometries tested in this paper are gathered in Fig. 13. Although the strain fields generated by gravity and potential consolidation do not have anything in common, one thing of high importance for the prediction of formwork pressure should be kept in mind while reading this figure: the shear stress at the interface is equal to the yield stress of the material no matter the formwork geometry, the resting time or the depth considered.

As a consequence, the relation proposed by Ovarlez and Roussel [3] which was fully based on this assumption is justified and can be very useful in order to predict the formwork pressure as long as the value of A_{thix} is measured using a concrete rheometer. Moreover, if the value of A_{thix} is unknown, it has been shown here that measuring the apparent weight of a cement paste into which a rough plate is sunk or the apparent weight of a rough plate sunk in the material involves the same physical mechanisms as the reduction of formwork pressure after casting. From this simple measurement, the value of A_{thix} could be identified and the formwork pressure predicted. The development of such a test and its validation on site will be the subject of a future publication.

5.1. What about concrete?

The experimental results presented here deals with fresh cement paste. In this paper, we showed that the shear strain generated by gravity in a cement paste is sufficient to reach the value of the critical strain rate at the wall. What about real concrete in real formwork? As sand and gravel are inert rigid particles, cement paste is the only potential source of deformation in a given concrete. It can thus be expected that the deformation under gravity of concrete will be lower. However, the shear strain should be concentrated in the cement paste and higher than the average shear strain of the concrete. Moreover, because of the so-called wall effect, it is cement paste that is located at the interface between the formwork and the material itself. This means that, on the whole, it has to be expected that the ability to mobilize the yield stress at the interface should be equivalent in the case of concrete and in the case of cement paste.

Moreover, it has to be kept in mind that, when real concrete is cast in real formworks, the concrete-formwork interface is not the only zone where the weight of the material can be transferred. Indeed, reinforcement steel bars are also non deformable (at least partially) obstacles at the surface of which the deformation may reach a critical value and where the shear stress may thus reach the yield stress value. The state of deformation of the material is however very complicated at the vicinity of cylindrical steel bars (either vertical or horizontal) and further work is needed in order

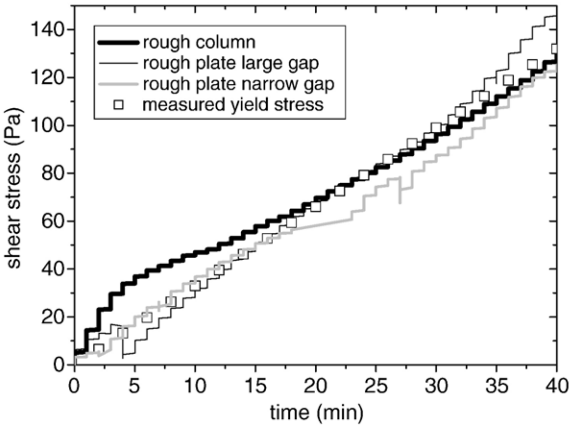

Fig. 13. Measured yield stress and shear stress at the interface in the case of a rough interface.

to take into account the effect of the reinforcements on the formwork pressure.

Finally, the work presented here has demonstrated that the strong assumptions made by Ovarlez and Roussel in [3] were legitimate. It is thus possible to predict the relative formwork pressure $p/\rho gH$ at the bottom of the formwork (formwork thickness e, concrete height H, density of the concrete ρ and casting rate R (m/s)) as soon as the yield stress increase rate (structuration rate) A_{thix} (Pa/s) at rest of the concrete is known.

$$\frac{p}{\rho gH} = 1 - \frac{HA_{\text{thix}}}{\rho geR}$$

Up to the knowledge of the present authors [9], the structuration rate A_{thix} varies between 0.1 Pa/s and 2 Pa/s and may be measured using a plate test as described above but with dimensions suitable for concrete testing.

Finally, it is possible to estimate the importance of the roughness of the formwork on the resulting pressure in regard to mix design or casting process. As stated above, structuration rate which depends on mix design (and probably on temperature as well) introduces a factor from 1 to 20 in the relative pressure. If we consider that practical limits bound casting rate between 1 m/h to 20 m/h, this introduces a factor from 1 to 20. Finally, according to the experimental results presented here, the roughness of the formwork introduces a factor from 1 to 2 in the relative pressure. It seems therefore that, although structuration rate and casting rate are the dominant parameters, knowledge of the formwork roughness is needed if precise pressure predictions are the final objectives.

6. Conclusions

In the present paper, experimental results from the laboratory testing on cement pastes have been presented. The validity of both the predictions of the model proposed by Ovarlez and Roussel [3] and the assumptions on which the model is based in the case of rough interfaces between the cement paste and the formwork surface have been validated. The consistency of the theory has been tested in several different configurations (plate test with large and narrow gaps and a column test). However, it has been noted that, in the case of smooth interfaces between the material and the wall, the effect of the thixotropic structuration of the material on the lateral stress was decreased. Finally, the concept of a new test based on the plate test presented here and allowing the measurement of the structuration at rest of a cementitious material was proposed. Such a simple test might be used to assess the input parameters needed to predict the formwork pressure without the use of a rheometer.

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