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SCC formwork pressure: Influence of steel rebars

A. Perrot [a], S. Amziane [a], G. Ovarlez [b], N. Roussel [c,*]

[a] Université de Bretagne Sud, LIMATB, Lorient, France
[b] Université Paris Est, Laboratoire Navier, LMSGC, Champs sur Marne, France
[c] Université Paris Est, LCPC, Paris, France

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ABSTRACT

The formwork pressure exerted by a given Self Compacting Concrete (SCC) depends on its thixotropic behavior, on the casting rate and on the shape of the formwork. It can moreover be expected that, in the case of a formwork containing steel rebars, these should also play a role. In first part, the specific case of a cylindrical formwork containing a single cylindrical steel rebar is studied. In second part, a comparison of the theoretical predictions to the experimental measurements of the pressure drop, after the end of casting SCC, was determined and the proposed model was validated. Finally, an extrapolation is suggested of the proposed method to the case of a rectangular formwork containing a given horizontal section of steel rebars, which could allow the prediction of the formwork pressure during casting.

1. Introduction

In most of the current building codes or technical recommendations [1–4], the main parameters affecting formwork pressure during casting are the density of concrete, the formwork dimensions, the pouring rate of concrete, the temperature, and the type of binder.

However, it was recently demonstrated that, in the case of SCC, the thixotropic behaviour of the material played a major role [5–8]. It can be noted that this influence is in fact indirectly taken into account in the above empirical technical recommendations via the effect of temperature and type of the binder, which are both strongly linked to the ability of the material to build up a structure at rest [9–11].

During placing, the material indeed behaves as a fluid but, if is 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. It was demonstrated in [7,8] that, for a SCC confined in a formwork and only submitted to gravity forces, the lateral stress (also called pressure) at the walls may be less than the hydrostatic pressure as some shear stress τ_{wall} is supported by the walls. It was also demonstrated that this shear stress reached the value of the yield stress, which itself increased with time because of thixotropy. Finally, if there is no sliding at the interface between the material and the formwork [8], the yield stress (not less or not more) is fully mobilized at the wall and a fraction of the material weight is supported (vertically) by the formwork. The pressure exerted by the material on the walls is then lower than the value of the hydrostatic pressure.

Based on these results, the model proposed by Ovarlez and Roussel [7] predicts a relative lateral pressure σ' (*i.e.* ratio between pressure and hydrostatic pressure) at the bottom of the formwork and at the end of casting equal to:

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

and a pressure drop $\Delta\sigma'(t)$ after casting equal to:

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

where H is the height of concrete in the formwork in m, A_{thix} the structuration rate in Pa/s [10], R is the casting rate in m/s, e is the width of the formwork in m, g is gravity, t is the time after the end of casting and ρ is the density of the concrete.

As it can be seen from the above, the key point for the pressure decrease is that the shear stress on each vertical boundary of the formwork equals the static yield stress of the material. It can then be expected that, in the case of a formwork containing steel rebars, the stress at the surface of the rebars should also play a role. It is the objective of this paper to start from the model developed by Ovarlez and Roussel [7] and extend it to the case of reinforced formworks. As the steel rebars should have a positive effect on formwork design (*i.e.* decreasing the formwork pressure), this could allow for a further reduction of the formwork size.

In first part, the specific case of a cylindrical formwork containing a single cylindrical steel rebar is studied. In second part, a comparison of the theoretical predictions to the experimental measurements of the pressure drop, after the end of casting SCC, is determined and the proposed model is validated. Finally, an extrapolation is suggested of

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* Corresponding author.
E-mail address: Nicolas.roussel@lcpc.fr (N. Roussel).

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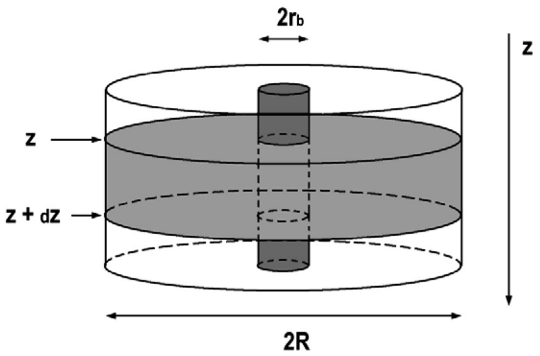

Fig. 1. Static equilibrium of a layer of SCC confined between two cylinders.

the proposed method to the case of a rectangular formwork containing a given horizontal section of steel rebars, which could allow the prediction of the formwork pressure during casting.

2. Influence of a vertical steel bar on the pressure decrease inside a cylindrical formwork

In this paper, SCC is considered as a yield stress material (in first step, thixotropy is neglected), and, for stresses below the yield stress, SCC behaves as an elastic material [7]. In the following, cylindrical coordinates are used with r in the radius direction; the vertical direction z is oriented downwards (see Fig. 1). The top surface (upper limit of the formwork) is the plane $z=0$; the formwork walls are at $r=R$. The bottom of the formwork is located at $z=H$. An elastic medium of density ρ is confined between the cylindrical formwork and an internal cylindrical steel rebar defined by the boundary ($r=r_b$). For the boundary condition, the Tresca conditions are imposed everywhere at the walls (*i.e.* it is assumed that the shear stress at the walls is equal to the yield stress τ_{00} as argued by Ovarlez and Roussel [7] and demonstrated in [8]). In order to compute the mean vertical stress $\sigma_{zz}(z)$ in the formwork, the static equilibrium equation projected on the z axis on an horizontal slice of material confined between two coaxial rigid cylinders can be written:

$$\begin{aligned}&-\pi\left(R^2-r_b^2\right)\sigma_{zz}(z)+\pi\left(R^2-r_b^2\right)\sigma_{zz}(z+\mathrm{d}z)\\&\quad+\rho g\pi\left(R^2-r_b^2\right)\mathrm{d}z-2\pi(R+r_b)\mathrm{d}z\tau_{00}=0\end{aligned} \tag{3}$$

The previous equilibrium simplifies to:

$$\frac{\partial\sigma_{zz}}{\partial z}=-\rho g+\frac{2\tau_{00}}{(R-r_b)} \tag{4}$$

Integrating Eq. (4) between 0 and z gives:

$$\sigma_{zz}(z)=\left(\rho g-\frac{2\tau_{00}}{R-r_b}\right)z \tag{5}$$

It can be noted that, according to Eq. (5), there seems to exist a yield stress value for which the lateral stress should be equal to zero. However, if the material had this yield stress, it would become very difficult to fill the formwork as gravity, the “engine” of the flow, would be of the same order as the resistance generated by shear at the solid interfaces. As a consequence, in practice, the vertical stress will always be positive.

The exact asymptotic elastic solution of the stress profile in the formwork can be easily computed as in [7,12]. It can be shown: (i) that the vertical stress is homogeneous along the radius, *i.e.* Eq. (5) holds anywhere between the wall and the bar, and is in particular the solution at the walls, and (ii) that the horizontal stress acting on the external tube surface (*i.e.* the formwork) is linearly linked to the vertical stress as in [7,12] via:

$$\sigma_H(z)=K\sigma_{zz}(z) \tag{6}$$

where K is linked to the Poisson ratio of the material. However, it was demonstrated in [7] that, in the case of SCC, K is roughly equal to 1. The horizontal stress at the bottom of the formwork is as follows:

$$\sigma_H(H)=\left(\rho g-\frac{2\tau_{00}}{R-r_b}\right)H \tag{7}$$

It can be seen in Eq. (7) that, as expected, the presence of the steel rebar of diameter d decreases the formwork pressure. A fraction of the weight of the material is transferred to the steel rebars via the shear stress at the interface.

It has however to be kept in mind that SCC is not only a yield stress fluid but is also a thixotropic material. The yield stress is therefore not constant and depends on the time of rest. The simple thixotropy model developed by Roussel [10] allows for the prediction of the apparent yield stress of the material as a function of its flow history. In its most simplified form, this model assumes that the apparent yield stress (or static yield stress) follows a linear evolution with the resting time:

$$\tau_0(t)=\tau_{00}+A_{\mathrm{thix}}t \tag{8}$$

Where τ_{00} is the dynamic yield stress (just after a strong shearing), A_{thix} is the structuration rate and t is the resting time (since the last strong shearing). This relation of course only holds on sufficiently short time scales as later or sooner, hydration reactions in the material will start to play a growing role and will fasten the structuration of the material, turning it into a solid.

If we assume that casting rate is fast enough to neglect any structuration during casting or that a strong vibration is applied to the material at the end of casting, the structuration state of the SCC inside the column can be considered as homogeneous (*i.e.* the static yield stress is the same everywhere in the material). Replacing the dynamic yield stress in Eq. (7) by the static yield stress, the lateral stress on the cylindrical formwork evolution in time can be written:

$$\sigma_H(z,t)=\left(\rho g-\frac{2(\tau_{00}+A_{\mathrm{thix}}t)}{R-r_b}\right)z \tag{8}$$

3. Comparison with experimental results

3.1. Materials

A CEM I 52.5 N (EN 197-1) cement having a specific gravity of 3.16 was used. The sand and coarse rounded aggregates were respectively between 0/3.15 mm and 4/10 mm. Their specific gravity was 2.58. The High-Range Water-Reducing Admixture (HRWRA) was a polycarboxylate-based admixture. The mix composition of SCC is presented in Table 1. All mixtures were prepared in a 100 L mixer.

Table 1
SCC mix proportions.

Gravel 4/10	kg/m^3	891
Sand 0/3.15	kg/m^3	735
Water	kg/m^3	218
HRWRA	l/m^3	2.85
Cement	kg/m^3	280
Limestone filler	kg/m^3	170
W/C		0.47
(W_{free}/C)		0.36
Volumic mass	kg/m^3	2404
Slump flow	cm	61

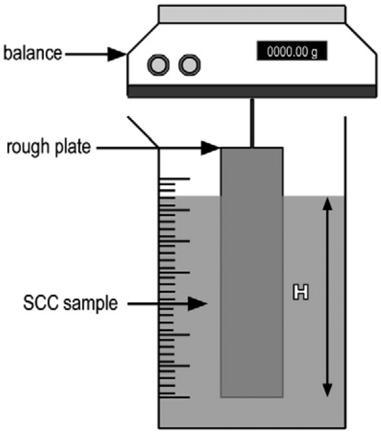

Fig. 2. Schematic of the plate test.

3.2. Evaluation of the structuration rate of SCC at rest

3.2.1. The vane test

The yield stress of the studied SCC was measured using a concrete rheometer equipped with a vane tool. The vane geometry used in this study consisted of four 10 mm thick blades around a cylindrical shaft of 120 mm diameter. The blade height was 60 mm and the vane diameter was 250 mm. The gap between the rotating tool and the external cylinder was equal to 90 mm which is sufficiently large to avoid any scaling effect due to the size of the gravel ($D_{\max}=$ 10 mm here).

Tests were performed for four different resting times after mixing on different samples from the same batch. Of course, working with the same batch 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 [9,10]. It can however be noted that the final age of the studied system (*i.e.* from the beginning of the mixing step to the last vane test measurement) was of the order of 70 min. Although Jarny et al. [13] 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 nor softening of the sample was visually spotted nor measured as it will be shown later. Finally, the data analysis proposed by Estellé et al. [14] was used for the yield stress calculation.

3.2.2. The plate test

The plate test appears to be a very convenient method to monitor the apparent yield stress evolution of a thixotropic material with time. It was first developed and used in [8] but more details about its application to other materials than cement can be found in [15].

The device is composed of a plate rigidly attached below a balance. The plate is lowered into a vessel containing the SCC (cf. Fig. 2). The apparent mass of the plate is continuously monitored versus time by recording the balance output with a computer. The balance measurements have an uncertainty of ±0.01 g. The vessel was made of smooth PVC and was cylindrical with a diameter of 200 mm and 200 mm in height. The plate was placed along the cylinder axis. During the tests, the vessel was filled with material to a height of 200 mm. The plate used was 3 mm thick, 75 mm wide and 100 mm long. It was covered with sand paper with an average roughness of 200 µm. The sand paper was used to avoid any slippage between the material and the plate [8]. The distance between the plate and the vessel walls was large enough compared to the size of the constitutive particles that the material can be considered as homogeneous [16,17]. The height H of the immersed portion of the plate was measured before the start of the test. To ensure that all tests start with the suspension in similar condition, vibration was applied (frequency of 50 Hz, amplitude of 5 mm) for 30 s. This step is critical in order to ensure tests reproducibility. Variations between tests performed on the same material in the same experimental conditions were then less than 5%.

The plate test analysis is based on the fact that the slight deformation of the cement paste under its own weight allows for the transfer of a part of this 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, which is the yield stress (more details were given in [8,15–17]). The variation in apparent yield stress with time can then be calculated from the measured apparent mass evolution of the plate with time using the following relation:

$$\Delta\tau_0(t) = g\Delta M(t)\,/\,2S \tag{9}$$

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

3.2.3. Laboratory cylindrical formworks

Two columns were simultaneously filled with the studied SCC. The columns were made of the same PVC covered with the same sand paper as the plate test. The columns inner diameters were equal to 100 mm. Each column was 1300 mm high. The thickness of the plastic wall was 5.3 mm. A 25 mm diameter steel bar was introduced in the second column (Fig. 3).

The pressure sensor was located 100 mm above the bottom of the column. More details on the pressure sensor can be found in [18]. The evolutions of the pressure acting on the lateral wall were recorded for a couple of hours following the filling and the initial vibration. The consequence of this initial vibration is that all structuration built during the filling of the columns is destroyed and that the pressure becomes hydrostatic, providing us with a repeatable reference state. In a traditional SCC casting, the formwork pressure at the end of the filling phase would of course not be hydrostatic as the material has already structured in some zones in the formwork (except when the pouring rate is so high that the material does not have time to build up a structure [6]) (see Section 4).

3.3. Results

We can first observe in Fig. 4 the good agreement between the two methods used here to measure the structuration rate of the tested material. It can however be noted that the plate test is far easier to handle, cheaper and gives a continuous measurement of the structuration of the material. Fitting Eq. (8) to experimental values led to $A_{\text{thix}}=4.3$ Pa min^{-1} and $\tau_{00}=50$ Pa.

Recorded pressure is plotted in Fig. 5 for tests performed with and without steel rebar. Time $t=0$ corresponds to the end of casting and to the initial vibration after which the measured lateral pressure starts to decrease. It can be noted that the additional contact area brought by the cylindrical steel rebar bar is of the order of 25% of the internal contact area of the PVC tube. At this interface and as predicted by the model developed

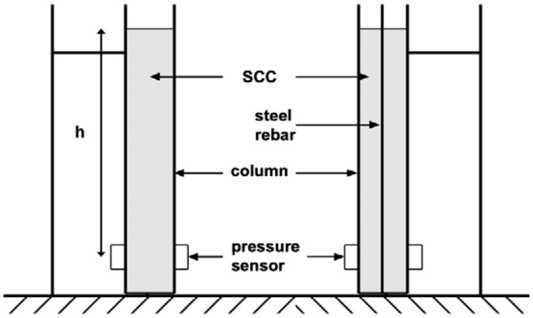

Fig. 3. Pressure device with and without the steel bar reinforcement.

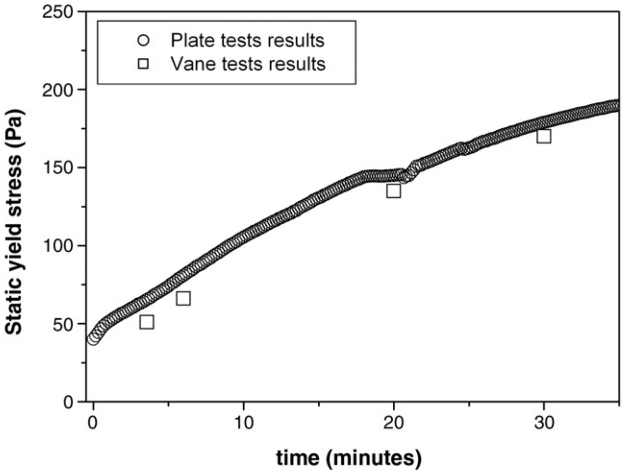

Fig. 4. Static yield stress evolution at rest measured using plate test and vane test.

in Section 2, the shear stress equals the yield stress of the material. The presence of steel reinforcements therefore decreased the material apparent weight. It also increased the rate at which the pressure decreased after the end of casting. This effect is not negligible as the pressure decrease during the first 30 min is of the order of 8 kPa for the test performed with steel rebar and 5 kPa for the test performed without.

During these 30 min, it seems that thixotropy of the material directly governs the pressure variation as a linear decrease of the pressure is measured [7,8]. We can now compute the lateral pressure using Eq. (8). The proposed modeling is in good agreement with experimental results. The modeled linear decrease is sufficient to describe the pressure decrease on the studied time scale although it can be noted that the pressure decrease rate seems to lower on longer time scales. During the first 30 min, the constant decrease rate seems to be governed by the geometry of both the formwork and the steel rebar via the geometrical parameter $4/(D-d)$.

It can however be noted that the model predicted an initial pressure lower than the hydrostatic pressure and, during a short initial period, the model underestimated the formwork pressure. Indeed, it is assumed in the model that the material has permanently a non-zero dynamic yield stress τ_{00}. Eq. (8) therefore predicts that the pressure at time $t=0$ will be lower than the hydrostatic pressure because of this permanent yield stress. The model, however, does not take into account the time needed for the shear stress at the interface to reach the value of the yield stress due to the sample deformations occurring inside the material.

Indeed, from an experimental point of view, as the filling of the formwork is immediately followed by vibration, the yield stress disappears (*i.e.* any interactions or contact networks inside the material is broken) and the stress state (and therefore the strain state) in the material becomes hydrostatic. However, when vibration stops, the dynamic yield stress of the material rebuilds instantaneously but not the shear strain and therefore the shear stress at the interface. During a short initial period, the shear stress at the interface is increasing at a speed dictated by the small deformation of the material. Once it has reached the apparent yield stress value, it becomes bounded by the evolution of the apparent yield stress and becomes thus dictated by structuration rate. It can be seen in Fig. 5 that the time needed for the shear stress to reach the value of the apparent yield stress, and be bounded by it, is of the order of 10 min and seems higher in the case of the formwork with steel bars.

4. General case

We have shown in the previous section that the proposed model was able to predict the formwork pressure decrease after the end of casting taking into account the presence of a vertical steel rebar. In this section, we will assume that the proposed approach still holds in the general case and write a general relation predicting the main parameter of industrial interest: the maximum formwork pressure during casting as a function of the steel rebars section and diameter, the casting rate, the structuration rate of the material and the geometry of the formwork. In this section, the casting rate was assumed to be sufficiently low to allow the structuration of SCC mix in the zones where it was no flowing (*i.e.* bottom of the formwork).

The casting rate R was also assumed to be constant (at a time t after the beginning of casting, the height of concrete inside the formwork is equal to $H=Rt$). The case of a rectangular formwork of width L and thickness e reinforced by steel rebars (horizontal steel section per linear meter of width S_b, average diameter of the vertical rebars ϕ_b) will be dealt with here. Only the effect of the vertical steel bars will be considered in the following. Horizontal steel rebars should of course play a role. However, keeping in mind that the objective here is to estimate the amount of formwork pressure that can be saved during formwork design by taking into account the positive influence of steel rebars, this means that the following computational method overestimates the formwork pressure, which is safer than the opposite.

In the following analysis, the perimeter of the steel rebars in a horizontal cross section of one meter width (*i.e.* the steel rebars perimeter in contact with SCC per linear meter of formwork width) is assumed to be equal to $4S_b/\phi_b$.

Only the lateral stress at the bottom of the formwork is considered here as it is the most important from a practical point of view (*i.e.* it is the maximum pressure). At a depth H, it is proportional to the vertical stress. The mean vertical stress may be computed as in Section 2 as the total force exerted by the material at the bottom of the formwork divided by the bottom area; this total force is equal to the material weight reduced by the weight supported by the walls and the steel bars. The weight supported by the walls and the steel bars, as demonstrated in [7,8] and confirmed here once again, is equal to the apparent yield stress $\tau_0(t)$ of the SCC multiplied by the area of the walls and the steel bars in contact with SCC.

Because of the thixotropic behaviour of concrete, this yield stress is increasing when the material is at rest, which is, as shown in [7], the case everywhere in the formwork except in the upper layer where the SCC is still flowing because of the casting process itself (see Fig. 6). It was demonstrated in [7] that the thickness of this layer (*i.e.* the only zone in the formwork where the SCC is not at rest) is of the order of the thickness of the formwork e. At the bottom of the zone where the

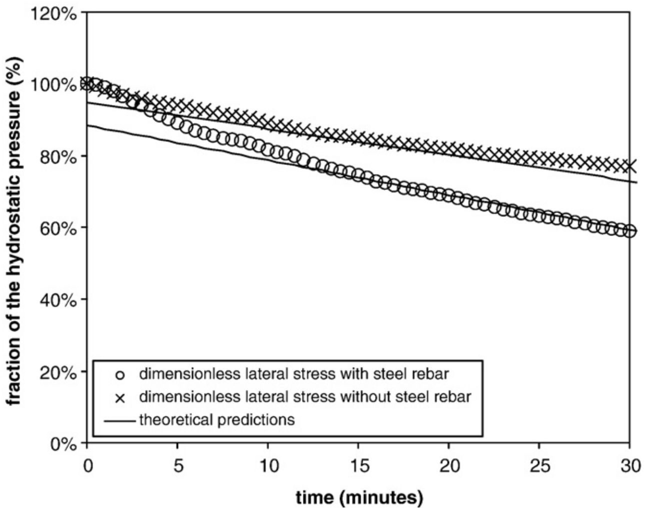

Fig. 5. Evolution of the dimensionless lateral stress. Comparison between experimental measurements and prediction of the model.

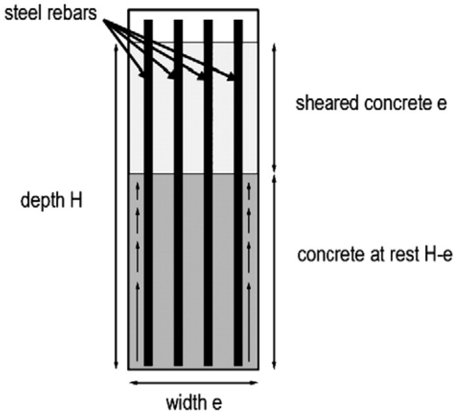

Fig. 6. Sheared and unsheared zones inside the SCC during casting of a formwork with steel rebars.

concrete is at rest, the resting time is maximum and is equal to $(H-e)/R$. At the top of this zone, it is equal to zero. The yield stress of the concrete is thus varying with depth and has to be integrated to compute the force F_z at the bottom of the formwork and then the mean vertical stress σ_{zz} at the bottom of the formwork.

$$\begin{aligned} F_z &= \sigma_{zz}(Le - LS_\mathrm{b}) \\ &= \rho g H(Le - LS_\mathrm{b}) - 2(L+e)\int_0^{H-e} \tau_0(z)\mathrm{d}z - 4LS_\mathrm{b} / \phi_\mathrm{b} \int_0^{H-e} \tau_0(z)\mathrm{d}z \end{aligned} \tag{10}$$

The lateral stress at the bottom of the formwork is then proportional to the vertical stress, with K defined as in Section 2:

$$\begin{aligned} \sigma_{xx} &= \sigma_{yy} \\ &= K\left(\rho g H - \frac{2(L+e)}{(Le - LS_\mathrm{b})}\int_0^{H-e} \tau_0(z)\mathrm{d}z - \frac{4LS_\mathrm{b}}{(Le - LS_\mathrm{b})\phi_\mathrm{b}}\int_0^{H-e} \tau_0(z)\mathrm{d}z\right) \end{aligned} \tag{11}$$

Using $\tau_0(t) = \tau_{00} + A_\mathrm{thix}t$, $K \cong 1$ and $z = Rt$, Eq. (10) becomes in the general case $L >> e$ and $H >> e$ and when the dynamic yield stress of the material can be neglected in front of the effect of the structuration rate (*i.e.* $\tau_{00} << A_\mathrm{thix}t$):

$$\sigma_{xx} = \sigma_{yy} = \left(\rho g H - \left(\frac{\phi_\mathrm{b} + 2S_\mathrm{b}}{(e - S_\mathrm{b})\phi_\mathrm{b}}\right)\frac{A_\mathrm{thix}H^2}{R}\right) \tag{12}$$

A dimensionless formwork pressure σ' (ratio between formwork pressure and hydrostatic pressure) can then be written under the following form:

$$\sigma' = 1 - \left(\frac{\phi_\mathrm{b} + 2S_\mathrm{b}}{(e - S_\mathrm{b})\phi_\mathrm{b}}\right)\frac{A_\mathrm{thix}H}{\rho g R} \tag{13}$$

which can be compared to the case without steel bars from [7]:

$$\sigma' = 1 - \frac{HA_\mathrm{thix}}{\rho g e R} \tag{14}$$

If the general case of a wall with a steel section of the order of 0.5% and steel rebars diameter of the order of 10 mm is considered as an example, Eq. (13) shows that the consequence of the presence of these vertical steel rebars is to double the reduction of formwork pressure due to thixotropy for a given formwork as compared to the formwork without steel rebars. This clearly means that their contribution has to be taken into account in any technical recommendation, which is not the case at the moment.

5. Conclusion

In the first part of this investigation, a specific case of a cylindrical formwork containing a single cylindrical steel rebar was studied. In the second part, a comparison between the theoretical predictions and the experimental measurements of SCC mix was carried out and the proposed model was validated. In final part, an extrapolation of the proposed method in the case of a rectangular formwork containing a given horizontal section of steel rebar was suggested. The proposed practical relation may prove useful when it is used to design formwork dedicated to SCC casting. The fact that the steel rebars were taken into account, allowed the design of formwork, in case of SCC, to be closer to the expected formwork pressure in the practice. For traditional reinforcement, it seems that the steel rebars had a twice contribution of thixotropic behaviour in a reduction of the pressure formwork.

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