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A thixotropy model for fresh fluid concretes: Theory, validation and applications

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Abstract

In this paper, the methods used to measure and model thixotropy of fresh concrete in the civil engineering field are described and a simple thixotropy model is presented. It is shown that this model is in agreement with the experimental observations that can be found in the literature and a classification of SCC according to their flocculation rate A_{thix} is proposed. The predictions of the model are compared with experimental measurements obtained with a concrete rheometer. In the last part, two applications of the model are briefly presented as examples (pressure formwork prediction and multi-layer casting of fluid concretes). It is shown that according to the element to be cast (slab or wall), a non-thixotropic SCC (low flocculation rate) or a highly thixotropic SCC (high flocculation rate) is respectively more adapted.

Keywords: Fresh concrete; Rheology; Thixotropy; Flocculation

1. Introduction

As long as steady state flow is reached, behavior of fresh concrete may be described using a yield stress model such as the Bingham or Hershel Bulkley models. However, between two successive steady states, there is a transient regime, during which a yield stress model is not sufficient to describe the observed behavior. Let us consider a typical torque measurement obtained from a concrete rheometer during an instantaneous rotating speed decrease (Fig. 1(a)) or increase (Fig. 1(b)). The bold line shows what should be expected from a simple yield stress fluid whereas the thin line shows the real measurement obtained in practice. The difference is due to the thixotropic behavior of the tested concrete that creates a delay in the material answer. It has been shown recently by Roussel [1] that this delay, in the case of cement pastes, can be correlated to the applied shear rate and to the recent flow history of the material. If the material is at rest before a low shear rate is applied to the sample, a typical Vane test answer is obtained as shown in Fig. 1(c). After a linear increase due to the elastic part of the behavior, a static yield stress τ_{0s} can be measured that increases with the resting time before the test whereas the dynamic yield stress τ_{0d} corresponding to steady state does not depend on the material flow history [1,2].

However, in the case of cementitious materials, things are not so simple as the hydration process starts as soon as cement and water are mixed together. The apparent viscosity of the material is permanently evolving as described by Otsubo et al. [3] and Banfill and Saunders [4]. Recently, Jarny et al. [5] have however shown using MRI velocimetry that, over short timescales flocculation and de-flocculation processes dominate, which lead to rapid thixotropic (reversible) effects, while over larger timescales hydration processes dominate, which lead to irreversible evolutions of the behavior of the fluid. These two effects might in fact act at any time but, according to the above scheme, they appear to have very different characteristic times. As a consequence it is reasonable to consider that there exists an intermediate period, say around a couple thousands seconds, for which irreversible effects have not yet become significant. This means that it seems possible to model thixotropy and only thixotropy on short periods of time (not more than 30 min as an order of magnitude) during which the irreversible evolutions of the concrete can be neglected.

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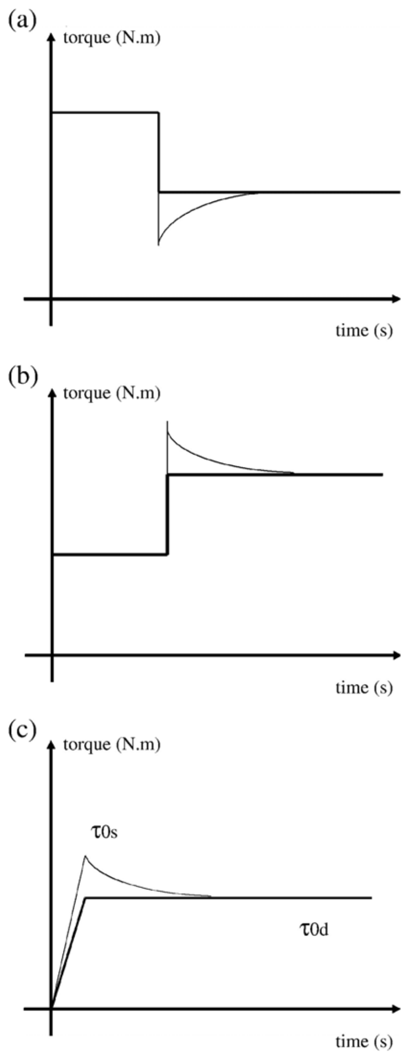

Fig. 1. Examples of transient flow behaviors. (a) rotating speed decrease; (b) rotating speed increase; (c) rotating speed increase after a resting period.

A non-exhaustive list of the applications of such a model that are *a priori* concerned by thixotropy could be the following:

– Self-Compacting Concrete (SCC) pressure formwork: during placing, the fresh SCC behaves as a fluid but, if cast slowly enough or if at rest, it flocculates and 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.
– Multi-layers casting: during placing, a layer of SCC has a short time to rest and flocculate before a second layer of concrete is cast above it. If it flocculates too much and its apparent yield stress increases above a critical value, then the two layers do not mix at all and, as vibrating is prohibited in the case of SCC, this creates a weak interface in the final structure. Loss of bending capacity in three points bending test of more than 40% has been reported [6].
– Stability of SCC: during placing, the cement paste is deflocculated because of the mixing and of the casting itself. This allows an easy placement of the material. However, as soon as casting is over and before setting, gravity may induce sedimentation of the coarsest particles. A thixotropic cement paste will flocculate once at rest. Its apparent yield stress will increase and will be sufficient to prevent the particles from settling [7].

In this paper, the methods used to measure or model thixotropy in the civil engineering field will be first described. Then a simple model will be presented that is in agreement with all the experimental observations listed in the first section. The predictions of the model will be compared with various experimental measurements using a concrete rheometer. Finally, two applications of the model will be briefly presented as examples (pressure formwork and multi-layer casting of fluid concretes).

2. Literature study

2.1. Physical explanation

A simple physical explanation of the thixotropic behavior can be found in [8]. The particle interactions forces (colloidal interactions in the case of cement pastes) determine for each particle a potential energy well as shown in Fig. 2(a) (i.e. there is an equilibrium position for each particle for which the energy is minimum). As long as the energy ΔE given to the system is lower than a given value, the particle does not leave this well (Fig. 2(b)). When the applied stress or strain stops, the particle comes back to its initial position (elastic solid behavior). However, if the energy given to the system is higher than a given value, the particle is then able to leave this potential energy well (Fig. 2(c)) and flow occurs (yield stress behavior). In the case of systems displaying thixotropic behavior, the depth of the potential energy well increases at rest with time because of Brownian motion and a possible evolution of the colloidal interactions.

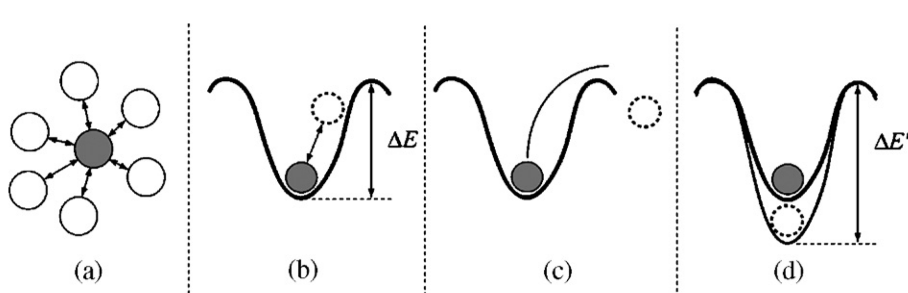

Fig. 2. A simple physical explanation of the thixotropic yield stress behavior of cementitious materials.

The needed energy $\Delta E'$ for the particle to leave the well increases (increase of the apparent yield stress in Fig. 2(d)). However, if the particle leaves the well, the well comes back to its initial depth.

2.2. Cement, mortar and concrete scales

This paper deals with fresh concrete. However, many experimental data from the literature that are gathered here were obtained on cement pastes, mortars or concretes. As sand and gravel are inert non-colloidal particles, cement and thus cement paste is the only potential source of thixotropy in a given concrete. This is why most results obtained either on concrete, cement pastes or mortar show similar rheological transient behavior. Most of the time, the only differences that can be spotted are due to the fact that cement pastes are often studied over a 0–100 or 0–200 s^{-1} shear rate range whereas concrete is most of the time studied over a 0–10 s^{-1} shear rate range.

However, the shear rate experienced by the cement paste in concrete is higher than the shear rate experienced by concrete itself when considered as an homogeneous fluid. If the cement paste was mixed and measured alone in the same mixers or rheometers than concrete, its behavior would be different (probably less fluid) from its behavior when mixed with coarse particles. A simple calculation of the respective shear rates can be done by assuming that shear is concentrated inside the paste while the granular skeleton is not deformed by the flow. If $\dot{\gamma}_{cp}$, $\dot{\gamma}_{conc}$ are respectively the shear rates applied to the cement paste and to the concrete and if Φ is the solid volume fraction of the granular skeleton, then the shear rate applied to the cement pastes writes $\dot{\gamma}_{cp}=\dot{\gamma}_{conc}/(1-\Phi)$. In the case of ordinary concrete, Φ is of the order of 0.8 whereas, in the case of SCC, it is of the order of 0.6. This means that the shear rate applied to cement paste is around five times higher than the shear rate applied to concrete in the case of ordinary concrete whereas it is around 2 or 3 times higher in the case of SCC. As the cement paste is submitted to higher shear rates when part of a given concrete, its state of flocculation would be lower.

2.3. Reference state

As the thixotropic behavior is reversible, one needs to have an agreed reference state around which the variations of the rheological behavior can be studied. Two potential reference states may be considered on a theoretical point of view: a completely flocculated state of the material or a completely de-flocculated state. However, in practice, none of these states can ever be reached. On one hand, the material at rest is still flocculating when setting occurs and the completely flocculated reference state can thus not be reached. Moreover, the irreversible changes due to hydration prevent the measurement of a unique reference state for a given material. On the other hand, no mixer is powerful enough to reach a completely de-flocculated state as this state, on a theoretical point of view, is only reached for infinite shear rates.

The only reference state that can be taken into account is the "most de-flocculated state". This is reached at the time point in the material flow history when it is submitted to the highest shear rate. Maximum shear rates in various flow patterns are gathered in Table 1. The complex geometries, the various flow rates and the sizes of the zones where "plug flow" occurs altogether make this estimation very rough and only order of magnitudes are to be considered. In the case of casting, a flowing speed of 1 m/s for a thickness of 10 cm gives a maximum shear rate of 10 s^{-1}. In the case of the mixing truck, the mixers and the Tattersall two-points device (MKIII), the maximum shear rate was calculated by dividing the highest tangential speed of the rotating tool by the smallest thickness of the flowing material.

Several information in Table 1 are already known. First, it has to be noted that, apart from the case when concrete is pumped, the most de-flocculated state is reached during mixing. Second, it can be seen in Table 1 that the maximum shear rate applied to the concrete in the mixer (between 10 and 60 s^{-1}) can greatly vary and modifies the flocculation state reached by the material and thus its rheological properties. For a given mixer, a suitable mix proportioning will not be appropriate for another mixer in terms of filling ability. Moreover, as the available power of the mixing tools decreases from the making of the concrete (plant mixer) to the building site (mixing truck), the flocculation of the material will increase and its fluidity will decrease. Finally, none of the available rheometers are able to completely break the "flocculation" state of the material after a resting period and bring it back to its flocculation state in the mixer as the maximum shear rate they can apply to the material is always lower than the shear rate during mixing. This means that the rheological behavior that is measured immediately after mixing will never be measured again if the sample stays in the rheometer.

As a consequence, the most suitable reference state for a given concrete is the flocculation state immediately after mixing. This is the most de-flocculated state in the concrete flow history. However, it should be kept in mind that, because of the limitations in rotation speed of the rheometers, this reference state and an apparent irreversible evolution of the material that is **not** due to the hydration process but to the rheometers limitations will be measured. Of course, if the sample is remixed in the initial mixer between each measurement, this artifact will not appear.

2.4. Existing models

The thixotropic behavior of a fluid is necessarily at least represented by an apparent viscosity, i.e. $\eta=\tau/\dot{\gamma}$ where τ and $\dot{\gamma}$

Table 1
Maximum shear rate in various steps of concrete flow history

Flow pattern	Approximate maximum shear rate (s^{-1})
Mixing [9]	10–60
Mixing truck (read text)	10
Pumping [10]	20–40
Casting (read text)	10
Tattersall two-point device (MKIII) [11]	5
BML rheometer [12]	10
BTRHEOM rheometer [13]	15

are respectively the shear stress and shear rate magnitudes, depending on the current state of flocculation (λ) of the material, or more generally its "degree of jamming" [14,15]. In literature more sophisticated models are generally used, which consider that the different terms of the constitutive equation in simple shear ($\tau(\dot{\gamma})$) depend on λ. In parallel, a "kinetic equation" describing the variations of λ in time (t) is needed. In literature the basic proposal consists in considering that the rate of change of λ is equal to the difference between a rate of "natural" flocculation of the material and a rate of de-flocculation due to flow, which is proportional to the rate of shear. Cheng and Evans [16] suggested a general mathematical form of the equation of state of a thixotropic material. The following relation links the shear stress to the shear rate:

$$\tau = \eta(\lambda,\ \dot{\gamma})\ \dot{\gamma} \tag{1}$$

$\frac{d\lambda}{dt} = f(\lambda,\ \dot{\gamma})$ is an evolution equation where λ (i.e. the flocculation parameter) is related to the flocculation level inside the material. The model of Coussot [17] uses the same simple, basic ideas and expresses as follows:

$$\eta = \eta_0(1+\lambda^n);\frac{d\lambda}{dt} = \frac{1}{\theta} - \alpha\ \dot{\gamma}\lambda \tag{2}$$

where η_0, n, θ and α are four material parameters, θ being the flocculation characteristic time. This model has been recently validated by local and macroscopic comparison between MRI experiments carried out on Bentonite suspensions and simulations [18]. The same work has been carried out in the case of white cement pastes [19]. This model has also been used by Roussel [1] to analyze rheological measurements obtained on cement pastes.

The interest of the recent approach developed by Wallevik [12] is that it is derived from a rather complete physical description of the flocculation and dispersion of the grains. It is demonstrated that, using these mechanisms, the steady state and transient behavior of fresh cement pastes can be described. Instead of using an evolution equation of structure parameter, fading memory integrals are used, which is equivalent.

It has to be noted that the main feature of these models is that both a natural flocculation and a de-flocculation under flow occur with their respective characteristic times. The shorter the characteristic time is, the stronger the influence of one or the other aspect gets.

In the cementitious materials field, models not following this general frame can also be found. These models are less general and aim mainly at describing the results of rheometric test. For example, Tattersall [20] showed in 1954 that cement pastes under constant shear in a coaxial viscometer suffered a structural breakdown characterized by the equation:

$$T = T_E + (T_0 - T_E)\exp(-Bt) \tag{3}$$

where T is torque at time t and the suffixes $_0$ and $_E$ refer to initial and equilibrium states. B in this case could be considered as the inverse of the de-flocculation characteristic time.

Papo [21] derived from his own experimental data a rather complete constitutive equation for cement pastes under constant shear.

$$\tau = \tau_{00} + \eta_\infty\ \dot{\gamma} + 2(\tau_{00}\eta_\infty\ \dot{\gamma})^{\frac{1}{2}} + \left[(\tau_{01} - \tau_{00}) + 2(\eta_\infty\ \dot{\gamma})^{\frac{1}{2}}\left(\tau_{01}^{\frac{1}{2}} - \tau_{00}^{\frac{1}{2}}\right)\right]\exp(-k_b t) \tag{4}$$

where η_∞ is the viscosity at infinite shear rate, k_b is called rate of de-flocculation playing the same role as B in Eq. (3), τ_{00} and τ_{01} are respectively the steady state yield stress and the initial yield tress. In this model, the de-flocculation rate is assumed not to depend on the shear rate. The flocculation process is neglected compared to the de-flocculation phenomenon. In the opinion of the present author, this is a valid assumption as long as the observation time is not more than the duration of a standard viscometric test cycle.

It can be noted that both Tattersall and Papo models predict an exponential decrease of the shear stress (or torque) if a constant shear rate is applied to the material.

2.5. Experimental quantification of thixotropy

2.5.1. What is in practice called a thixotropic concrete?

In practice, a concrete is called thixotropic if it seems to flocculate rather quickly at rest and it becomes apparently more and more fluid while flowing during typically several tens of seconds. It has to be noted that, to be rigorously correct, all concretes are thixotropic. Indeed, a pure yield stress behavior can be considered as a thixotropic behavior with very low flocculation rate (very long flocculation characteristic time) and very fast de-flocculation rate (very short de-flocculation characteristic time) so that there is no apparent increase of the yield stress at rest and that steady state is reached almost instantaneously. However, in the opinion of the present author, it can be admitted that, in practice, a "thixotropic concrete" is a concrete displaying a rather short flocculation characteristic time (typically several minutes) and a de-flocculation characteristic time of several tens of seconds in the 1 to 10 s^{-1} shear rate range.

2.5.2. Thixotropic loop

Thixotropy of cementitious materials in the last fifty years has often been quantified by measuring the surface of what is called the "thixotropic loop" or at least a surface linked to this thixotropic loop [22–24] although Banfill [4] in 1981 had already warned that this method was very dependant on test apparatus and procedure. This method is based on the fact that, because of the transient nature of thixotropy and the dependency of the rheological answer on the flow history, the stress/shear rate curves measured successively in a viscometer during increasing and decreasing sequences of applied shear rates will not superimpose. A typical viscometric test result is shown in Fig. 3. During the increasing shear rate ramp, de-flocculation occurs but not quickly enough to reach the steady state shear stress. The measured stress is thus always higher than what would be obtained if steady state was reached. On the other hand, during the decreasing shear rate ramp, flocculation occurs

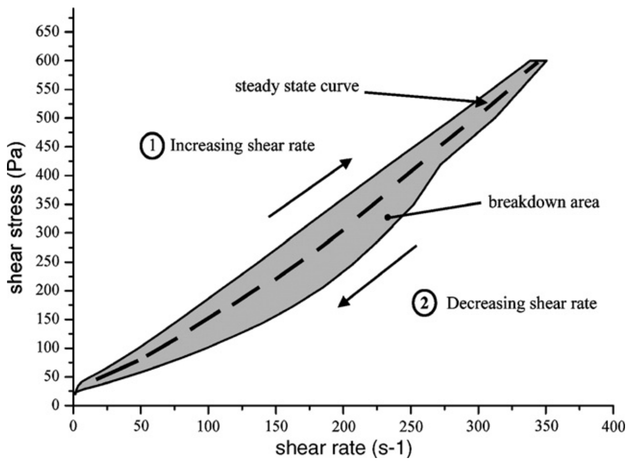

Fig. 3. Example of thixotropic loop obtained with a cement paste submitted successively to increasing and decreasing shear rate ramps.

but here again not quickly enough for steady state to be reached and the measured stress stays lower than steady state. The surface between the two curves is measured and is considered as representative of the work done per unit time and unit volume of the cement paste to break some of the initially present linkages. It has to be noted that, in the case of a succession of shear rate steps, this loop appears only if the duration of the applied shear rate step is of course not sufficient for steady state to be reached.

However, this method of measurement does not give an intrinsic value of any physical rheological parameter. There is thus no possibility apart from empirical correlations to use the measured result in the study of consequences of thixotropy (i.e. formwork pressure [25,26] or segregation [27,7]). It seems limited to be a way to get a relative classification of concretes or to compare qualitatively the effect of several admixtures.

Moreover, in the measured result, flocculation and de-flocculation cannot be separated. The measured surface can be the same for a mix displaying fast flocculation and fast de-flocculation and a mix displaying slow flocculation and slow de-flocculation although the two mixes will behave very differently in practice.

2.5.3. Measurement of the apparent yield stress evolution at rest

It has to be noted that, between the two aspects of thixotropy (flocculation at rest and de-flocculation under flow), the understanding and measuring of the first one is far more important in terms of potential applications. In the three points of interest listed in the introduction (pressure formwork, multi-layer casting and stability), concrete is not flowing. It is at rest and what really matters is the increase of the apparent yield stress or the apparent yield stress of the cement paste in the case of stability. That is why recent approaches to quantify thixotropic behavior have focused on the flocculation phenomenon only.

Billberg, in his recent work on thixotropy of SCC [2], has developed a very interesting method to measure the increase of the apparent yield stress at rest. The measurements are performed using a concrete rheometer slowly rotating. Both static and dynamic yield stresses are measured in order to distinguish the reversible flocculation due to thixotropy from the irreversible evolution due to normal slump loss. Using this methodology, Billberg showed that the static yield stress increases linearly with the resting time. This was also by Ovarlez and Roussel [26]. In both papers, the order of magnitude of the flocculation rate A_{thix} was between 0.1 and 1.7 Pa/s. Doing the same calculations on the experimental results obtained after a 2 min rest by Assaad et al. [24] on various SCC, values between 0.3 and 1.6 Pa/s are also obtained. According to these results, the author's own experience and to the associated formwork pressure measurements in these papers, the classification given in Table 2 could be proposed.

3. A simple thixotropy model for fresh concretes

3.1. General form of the model

In the case of a model suitable to describe flows of concrete **and** useful on a practical point of view, advantages other than scientific exactitude should be considered. First the model should be simple. Second, the number of parameters should stay low and these parameters should be easily measured.

A general form of the model based on the principles described in Section 2.4. **Existing models** can be written:

$$\tau = (1+\lambda)\tau_0 + k\ \dot{\gamma}^n \tag{5}$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T\lambda^m} - \alpha\lambda\ \dot{\gamma} \tag{6}$$

where λ is the flocculation state of the material and T, m and α are thixotropy parameters. The flocculation state depends on the flow history. Just after mixing, if the mixing phase is considered as the phase when the applied shear rate is maximum, λ is equal to zero. This means that the thixotropic apparent yield stress due to flocculation $\lambda\tau_0$ is also equal to zero. Through the successive steps in the casting process (rest phase, re-mixing phase, pumping phase...), λ will evolve from its initial zero value to a positive value according to the evolution Eq. (6) and an apparent yield stress greater than the initial yield stress will appear.

3.2. Simplified version of the model

First it is assumed that a Bingham model is sufficient for the description of the steady state flow of fresh concrete: $n=1$, $K=\mu_p$ (where μ_p is the plastic viscosity).

Second it is assumed that the yield stress at rest increases as a linear function of time: $m=0$. This is true for many materials [28] and seems true for concretes [2,26].

Table 2
Classification of SCC according to their flocculation rate

Flocculation rate A_{thix} (Pa/s)	SCC type
Less than 0.1	Non-thixotropic SCC
Between 0.1 and 0.5	Thixotropic SCC
Higher than 0.5	Highly thixotropic SCC

The model then becomes:

$$\tau = (1+\lambda)\tau_0 + \mu_p\, \dot{\gamma} \quad (7)$$

$$\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\, \dot{\gamma} \quad (8)$$

and 4 parameters have to be identified.

For a constant shear rate,

$$\frac{\partial\lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\, \dot{\gamma} \quad (9)$$

It is assumed here that the characteristic time of flocculation is long compared to the characteristic time of de-flocculation. This was reported by Papo [21] in his work on cement pastes and it will also be the case of the experimental results on concrete presented further in this paper. Eq. (9) simplifies to:

$$\frac{\partial\lambda}{\partial t} = -\alpha\lambda\, \dot{\gamma} \quad (10)$$

After integration, Eq. (11) is obtained.

$$\lambda = \lambda_0 e^{-\alpha\, \dot{\gamma} t} \quad (11)$$

The shear stress then writes

$$\tau = (1 + \lambda_0 e^{-\alpha\, \dot{\gamma} t})\tau_0 + \mu_p\, \dot{\gamma} \quad (12)$$

It can be noted that the model predicts, just as the Tattersall model (Eq. (3)) and Papo model (Eq. (4)), an exponential decrease of the shear stress under constant shear rate with a de-flocculation characteristic time equal to $1/(\alpha\dot{\gamma})$.

At rest, the shear rate equals zero and the evolution of the apparent yield stress is:

$$\tau_0(t) = (1+\lambda)\tau_0 = \tau_0 + \tau_0 \frac{t}{T} = \tau_0 + A_{\text{thix}} t \quad (13)$$

with

$$A_{\text{thix}} = \frac{\tau_0}{T} \quad (14)$$

4. Experimental results

4.1. Materials, mix proportioning and test methods

A HTS cement (class A) was used in this study. The aggregates were a Fontainebleau 0/1 mm sand, a Palvadeau 1/4 mm sand and a 4/8 mm gravel. Two admixtures were used. The first one is a superplasticizer, ChrysoFluid Optima 143 (SP). It is a modified phosphonate based polymer. This superplasticizer was chosen because of its ability to maintain the concrete rheology for 90 min. The second one is an anti-segregation and anti-bleeding agent, Nanometric Silica slurry Rhoximat™ CS 60 SL (NS). This product is amorphous silica in aqueous suspension. Its solid content is 22.5% and its density is 1.14. This admixture was used to prevent segregation from occurring during the rheological measurements. Twenty litres concrete batches were prepared using a SCHWELM ZK30E 30 l mixer with the mix proportioning given in Table 3. The dry ingredients were first mixed for 2 min, then the fluids (water, NS and SP) were added and the obtained suspension was mixed during 2 min at 70 rpm. The mixer was then stopped to scrape its edges. A 3 min mixing phase at the same 70 rpm rotation speed ended the mixing procedure. The slump flow value of this concrete was 640 mm.

Table 3
Mix proportioning of the concrete

Gravel 4/8	642 kg/m^3
Sand 0/1	393 kg/m^3
Sand 1/4	393 kg/m^3
Water	152 kg/m^3
Super Plasticizer (SP)	17 kg/m^3
Nano Silica (NS)	23 kg/m^3
HTS cement	787 kg/m^3

The rheometer used in this study was a parallel plate rheometer BTRHEOM [13], for soft-to-fluid concrete with a maximum aggregate size up to 25 mm. A 7 l specimen of concrete having the shape of a hollow cylinder is sheared between a fixed base and a rotating top section. The resulting torque is measured. The rheometer rotation speed, vibration and the measurements (torque and rotation speed) were controlled by a special program ADRHEO 13.1a, specially developed for this experimental campaign. The tests were carried out at the ambient temperature of the room (≈23 °C). It has to be noted that there still exists a discrepancy between the various concrete rheometers [29,30]. These apparatus give the same rheological classification of materials but they do not give the same absolute values of the rheological parameters. However, the difference between rheometers being more or less relative, the validity of the model should not be affected by the choice of a given rheometer. Only the absolute values of the model parameters could be.

4.2. Steady state behavior

The first standard step was to measure the steady state behavior of the studied concrete by applying successive shear rate steps. The duration of these steps has to be sufficient to indeed reach steady state [31]. From the measurements obtained with 60 s rotation speed steps, the value of the rheological parameters was determined by fitting a Bingham model to the measurements shown in Fig. 4 as, when steady state is reached, the flocculation parameter λ equals zero in Eq. (7). The extrapolated values of the yield stress and of the plastic viscosity were respectively equal to 45 Pa and 155 Pa s.

4.3. Apparent viscosity evolution under constant shear rate

The concrete was then sheared at a shear rate of 2.6 s^{-1} after various resting times. A new concrete batch was prepared for each measurement in order to prevent any irreversible evolution of the material from affecting the results. The expected steady state apparent viscosity at this shear rate was calculated from the

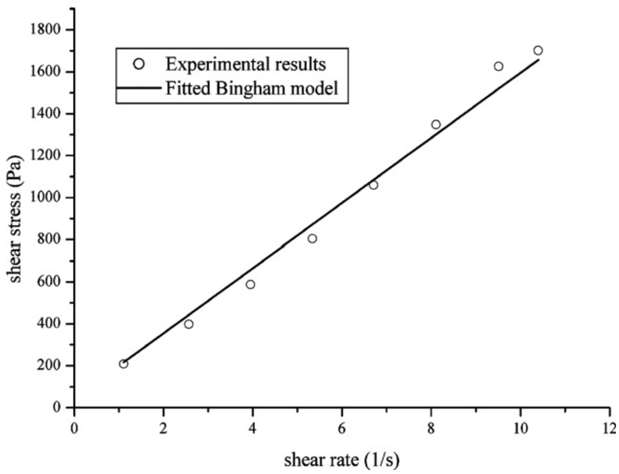

Fig. 4. Shear stress as a function of shear rate at steady state for the concrete studied in this paper.

rheological parameters measured in the previous section using Eq. (15) and was equal to 172 Pa s.

$$\mu_{app} = \frac{\tau_0}{\dot{\gamma}} + \mu_p \quad (15)$$

The relative viscosity (measured apparent viscosity divided by expected steady state apparent viscosity) is plotted in Fig. 5.

For every resting time, the apparent viscosity tends towards the expected steady state apparent viscosity. This means that the rheometer is able to break the state of flocculation built during rest and that there is no irreversible evolution of the concrete in the 450 first seconds. However, as expected, the time needed to reach steady state and the initial value of the apparent viscosity increase with the resting time. These observations are in agreement with the model. The λ parameter increases at rest following Eq. (8) for a shear rate equal to zero whereas, as soon as shearing starts, λ decreases still following Eq. (8), in which the de-flocculation term has become predominant until λ reaches zero at steady state.

4.4. Flocculation at rest

The value of the λ parameter was then calculated for each measurement points using Eq. (7). The initial λ values (i.e. at the beginning of the shearing) are plotted in Fig. 6 as a function of the resting time.

λ and thus the apparent thixotropic yield stress $\lambda\tau_0$ increase linearly with the resting time as already stated in Eq. (13). The rate of flocculation A_{thix} is equal to 0.26 Pa/s, which corresponds to a flocculation characteristic time T approximately equal to 200 s following Eq. (14). According to Table 2, this is thus a thixotropic SCC.

4.5. De-flocculation under shear

The comparison between the model predictions and the experimental results is plotted in Fig. 5 with $\alpha = 0.006$. The good agreement validates the model in this flow configuration. The de-flocculation characteristic time is $1/(\alpha\dot{\gamma})$ (playing the same role as k_b and B in Eqs. (3) and (4)) and thus roughly equal to 60 s making it three times lower than the flocculation characteristic time.

5. Practical applications

5.1. Pressure formwork

SCC flows readily under its own weight and achieves good consolidation without any mechanical vibration. During casting, given the high fluidity of this type of concrete, it can be expected that a hydrostatic pressure will be reached in the formwork and formworks are prudently designed by taking into account this high pressure. Such an approach, however, increases the cost of the formwork and limits the maximum allowable placement height, which was advertised as an advantage of SCC. From the literature, contradictory values of the pressures were reported depending on the cases [32]. It was concluded that the thixotropic behavior of the SCC had to play a role [25,32]. During placing, the material behaves indeed 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.

It is assumed here that the casting rate R(m/s) is constant. At a depth H(m) in the formwork, the lateral stress is equal to the hydrostatic pressure ρgH reduced by the amount of vertical stress supported by the walls. This vertical stress as demonstrated in [26] takes a value between 0 and the yield stress τ_0 of the concrete. It is also assumed that the vertical deformation of the concrete under its own weight is always sufficient for the shear stress at the wall to reach its maximum value τ_0. Because of the thixotropic behavior of concrete, this yield stress increases when the material is at rest, which is the case everywhere in the formwork except in the upper layer (thickness e (m)) where fresh concrete is still flowing. At the bottom of the zone where the 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

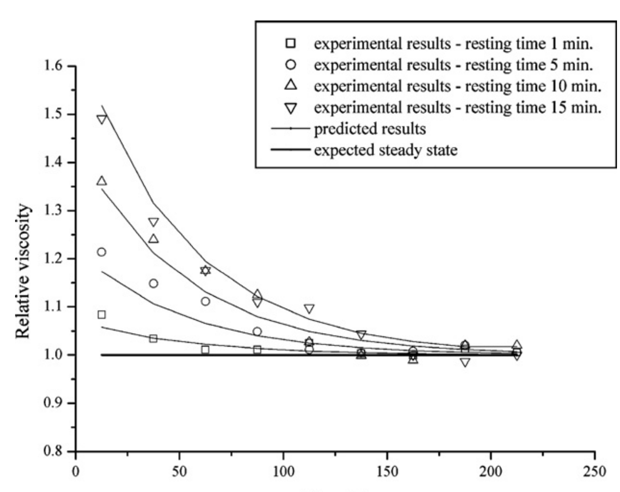

Fig. 5. Measured and predicted relative viscosity at constant shear rate.

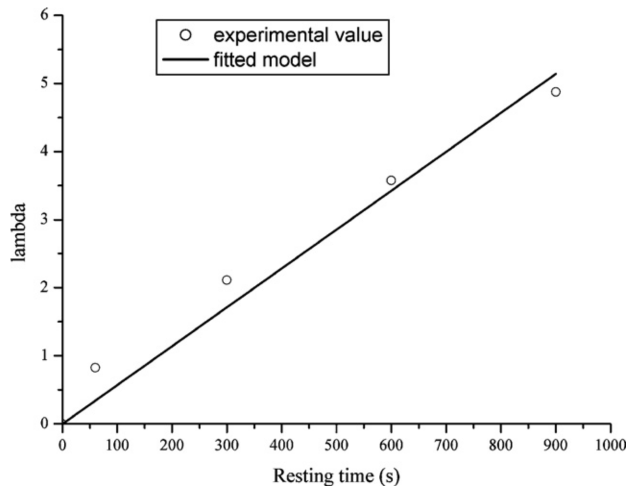

Fig. 6. State of flocculation λ as function of the resting time.

zero. The apparent yield stress of the concrete thus varies with depth and has to be integrated to compute the lateral stress at the bottom of the formwork using Eq. (14).

It was demonstrated in [26] that the relative formwork pressure (or relative lateral stress as the system is not hydrostatic) during casting of a wall of thickness e, height H at a casting rate of R could be predicted using the following relation:

$$\frac{\sigma_{xx}}{\rho g H} = 1 - \frac{H A_{\mathrm{thix}}}{\rho g e R} \quad (16)$$

This relation was validated using experimental results from [25,32,33] (read [26] for more details).

As an example, three virtual SCC are considered here: a non-thixotropic SCC (i.e. low flocculation rate) with $A_{\mathrm{thix}}=0.1$ Pa/s, a thixotropic SCC (normal flocculation rate) with $A_{\mathrm{thix}}=0.5$ Pa/s and a highly thixotropic SCC (high flocculation rate) with $A_{\mathrm{thix}}=1.5$ Pa/s. If a 6.00 m wall with a thickness of 0.2 m is cast at a casting rate of 10 m/h, the relative formwork pressure calculated from Eq. (16) is 95% for the non-thixotropic SCC, 75% for the thixotropic SCC and 30% for the highly thixotropic SCC. It can be noted that the variation in formwork pressure between the three materials is very high and that, for this application, the highly thixotropic SCC is the most suitable.

5.2. Multi-layer casting

During placing, a layer of SCC has a short time to rest and flocculate before a second layer of concrete is cast above it. If it flocculates too much and its apparent yield stress increases above a critical value, then the two layers do not mix at all and, as vibrating is prohibited in the case of SCC, this creates a weak interface in the final structure. Loss of resistance of more than 40% was reported in [6]. Two studies were carried out using the model proposed in this paper. The first one is a basic and rough analysis of the flow pattern whereas the second one is based on free surface numerical simulation as shown in Fig. 7. More details about the results obtained with these numerical simulations will be given in further publications.

However, as a first approach of the problem, it can be assumed that the stress generated by the casting of the second layer is of the same order as $\tau_0+\mu_p\dot{\gamma}$ where the shear rate at the interface between the two layers is roughly equal to the flowing speed of the concrete divided by the thickness h of the second layer. In order to mix the two layers, this stress has to be higher than the apparent yield stress of the first layer. This first layer has been resting for Δt and its apparent yield stress is thus given by Eq. (17):

$$\tau_0(\Delta t) = \tau_0 + A_{\mathrm{thix}}\Delta t \quad (17)$$

Δt_c is the time after which the two layers will not mix and it is equal to:

$$\Delta t_c = \frac{\mu_p V}{A_{\mathrm{thix}} h} \quad (18)$$

The same three SCC as above are considered with a plastic viscosity around 50 Pa s. For the non-thixotropic SCC, the critical time is around 40 min making it rather easy to cast. For the thixotropic SCC, the critical time becomes 8 min. This is still suitable for casting in most applications but care should be taken to prevent any stops during the casting process. For the highly thixotropic SCC, the critical time decreases to 3 min preventing large slabs from being cast without generation of weak interfaces in the final structure.

5.3. Perspectives

If thixotropy is mastered on a mix proportioning point of view, specific concrete displaying suitable flocculation rates could be prepared according to the element to be cast. As the multi-layer casting problem is dominant in concrete slabs, the SCC should be as non-thixotropic as possible (low flocculation rate). In the case of walls, where the formwork pressure problem dominates, the SCC should be as thixotropic as possible (high flocculation rate). Moreover, in the case of walls, the stability of

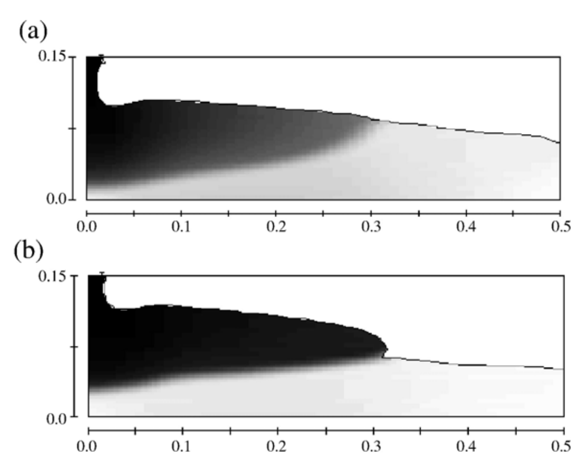

Fig. 7. Numerical simulations of the multi-layer casting phenomenon using the model proposed in this paper with $\tau_0=50$ Pa, $\mu_p=50$ Pa s, $A_{\mathrm{thinx}}=0.5$ Pa/s, $\alpha=0.005$. (a) For a 5-min resting time, the two layers mix perfectly (b) for a 20-min resting time, the two layers do not mix at all.

the concrete has to be higher than in the case of slabs as the potential sedimentation height is far higher. This brings an additional reason for the cement paste to flocculate quickly and develop an apparent yield stress sufficient to prevent the coarsest particles from settling. It is already known [24] that substituting cement with finer powders (higher surface area) such as silica fume or fly ash increases the flocculation rate. On the other hand, specific admixtures similar to the ones used in the case of laponite dispersions [34] proved to be able to increase the characteristic flocculation time of the mix, thus slowing down the flocculation process.

The Eqs. (16) and (18) presented in this paper might then be used to calculate the needed rate of flocculation A_{thix} for a given application, which will become a target value for the mix-proportioning engineer.

6. Conclusions

In this paper, the methods used to measure and model thixotropy of fresh concrete in the civil engineering field were described and a classification of SCC according to their flocculation rate A_{thix} was proposed. In a second part, a simple thixotropy model for fresh concretes was presented. It was shown that this model is in agreement with the experimental observations reported in the literature. In a third part, the predictions of the model were successfully compared with various experimental measurements obtained with a concrete rheometer and the parameters of the model were identified for the concrete studied in this paper. Finally, two applications of the model were briefly presented as examples (pressure formwork prediction and multi-layers casting of fluid concretes). It was shown that according to the element to be cast (slab or wall), the dominant problem concerning thixotropy was respectively the multi-layer casting or the pressure formwork. A non-thixotropic SCC (flocculation rate <0.1 Pa/s) was the most suitable for a slab whereas a highly thixotropic SCC (flocculation rate >1 Pa/s) was more adapted for a wall.

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