A THIXOTROPY MODEL FOR FRESH FLUID CONCRETES: THEORY AND APPLICATIONS

Nicolas Roussel

Laboratoire Central des Ponts et Chaussées, Paris, FRANCE

Abstract

In this paper, a simple thixotropy model for fresh concretes is presented. Two applications of the model are also briefly presented as examples of application (pressure formwork prediction and multilayer 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) are respectively more adapted.

1. INTRODUCTION

As long as steady state flow is reached, behaviour of Self-Compacting Concrete (SCC) may be described using a yield stress model such as the Bingham or Hershel Bulkley models. However, between two successive steady states, there exists a transient regime, during which a yield stress model is not sufficient to describe the observed behaviour. The difference is due to the thixotropic behaviour of the tested concrete that creates a delay in the material answer. It has been shown recently that this delay, in the case of cement pastes, can be quantitatively correlated to the recent flow history of the material [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 and co-workers [3] and Banfill [4]. Recently, Jarny and co-workers [5] have however shown using MRI velocimetry that, over short timescales flocculation and deflocculation processes dominate, which lead to rapid thixotropic (reversible) effects, while over larger timescales hydration processes dominate, which lead to irreversible evolutions of the behaviour 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 45 minutes as an order of magnitude) during which the irreversible evolutions of the concrete can be neglected.

A non-exhaustive list of the applications of such a model could be the following:

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-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 mechanical resistance of more than 40% has been reported [6].

- Stability of SCC: during placing, the cement paste is de-flocculated 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].

2. A SIMPLE THIXOTROPY MODEL FOR FRESH SCC

The building of the model is fully described in [8]. The main assumptions are that a Bingham model is sufficient for the description of the steady state flow of fresh concrete and that the apparent yield stress at rest increases as a linear function of time. This is true for many materials [9] and seems true for concretes [10, 11]. The proposed model then writes:

\[\tau = (1 + \lambda)\tau_0 + \mu_p \dot{\gamma} \quad (1)\]

\[\frac{\partial \lambda}{\partial t} = \frac{1}{T} - \alpha \lambda \dot{\gamma} \quad (2)\]

where \(\lambda\) is the flocculation state of the material. This state depends on the flow history. Just after mixing (or a high shearing phase in the life of the material) \(\lambda\) 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...), \(\lambda\) will evolve from its initial zero value to a positive value according to the evolution equation (2) and an apparent yield stress greater than the initial yield stress will appear.

For a constant shear rate, if it is assumed here that the characteristic time of flocculation is long compared to the characteristic time of de-flocculation [21], the shear stress writes

\[\tau = (1 + \lambda_0 \exp(-\alpha t))\tau_0 + \mu_p \dot{\gamma} \quad (3)\]

It can be noted that the model predicts, just as the Tatersall model [12] and Papo model [13] an exponential decrease of the shear stress under constant shear rate with a de-flocculation characteristic time equal to \(1/(a\dot{\gamma})\).

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

\[\tau_0(t) = (1 + \lambda)\tau_0 = \tau_0 + \frac{t}{T} = \tau_0 + A_{thix} t \quad (4)\]

where \(A_{thix} = \tau_0 / T\) is the flocculation (or structuration) rate of the concrete. This is the most important thixotropic parameter of a given concrete on an industrial application point of view. It can indeed 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.

3. VALIDATION

This model was validated in [8] where a complete description of the material and procedures used can be found. As shown in Fig. 1, it proved to be able to predict the rheological behavior of a given concrete in steady state and transient flows after a resting period. The fact that the apparent yield stress of the tested concrete increases linearly with the resting time was also confirmed in the case of the studied concrete.

![Figure 1. Comparison between the model and experimental results. The relative shear stress (measured shear stress divided by the steady state shear stress at the same shear rate (2.6 s⁻¹)) is plotted for various resting periods. The model is able to predict the shear stress needed to initiate flow (apparent yield stress) after a resting period, the deflocculation under shear and the steady state flow.](image)

4. PRACTICAL APPLICATIONS

4.1 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. In cases around the world, the pressure was, when monitored, reported as being very high but, in other cases, opposite results were
reported. It was concluded that the thixotropic behavior of the SCC had to play a role [14, 15]. 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 $\gamma g H$ reduced by the amount of vertical stress supported by the walls. This vertical stress as demonstrated in [11] takes a value between 0 and the yield stress $\tau_0$ 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 $\tau_0$. 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, 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 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. (5).

It was demonstrated in [11] 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:

$$\frac{\sigma_{xx}}{\rho g H} = 1 - \frac{H A_{\text{thix}}}{\rho g e R} \quad (5)$$

This relation was validated using experimental results from [14-16]. As an example, three imaginary SCC are considered here: a non-thixotropic SCC ($A_{\text{thix}} = 0.1$ Pa/s), a thixotropic SCC ($A_{\text{thix}} = 0.5$ Pa/s) and a highly thixotropic SCC ($A_{\text{thix}} = 1.5$ Pa/s). If a 6.00m wall with a thickness of 0.2m is cast at a casting rate of 10m/hour, the relative formwork pressure calculated from Eq. (5) 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.

### 4.2 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. 2. 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 $\tau_0 + \mu \dot{\gamma}$ where the shear rate at the interface between the two layers is roughly equal to the flowing speed of the concrete $V$ divided by the thickness $h$ of the second layer. In order to mix the two layers, this shear stress has to be higher than the apparent yield stress of the first layer. This first layer has been resting for $\Delta t$ and its apparent yield stress is thus given by Eq. (6):
\[ \tau_0(\Delta t) = \tau_0 + A_{\text{thix}} \Delta t \]  
\[ \Delta t_c = \frac{\mu_p V}{A_{\text{thix}} h} \]  

The same three imaginary SCC as above are considered with a plastic viscosity around 100 Pa.s. For the non-thixotropic SCC, the critical time is around 80 minutes making it rather easy to cast. For the thixotropic SCC, the critical time becomes 16 minutes. 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 6 minutes preventing large slabs from being cast without generation of weak interfaces in the final structure.

Figure 2. 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, \( A_{\text{thix}} = 0.5 \) Pa/s, \( \alpha = 0.005 \). (a) For a 5 min. resting time, the two layers mix perfectly (b) for a 20 minutes resting time, the two layers do not mix at all.

5. 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 chosen 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 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 [14] 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 [16] proved to be able to increase the characteristic flocculation time of the mixture, thus slowing down the flocculation process. The equations (5) and (7) presented in this paper might then be used as a basis to estimate the needed rate of flocculation $A_{\text{thix}}$ for a given application, which will become a target value for the mix-proportioning engineer.

REFERENCES