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Distinct-layer casting of SCC: The mechanical consequences of thixotropy

N. Roussel [a,*], F. Cussigh [b]

[a] LCPC, Paris, France
[b] VINCI Construction, France

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Abstract

It is demonstrated in this paper that thixotropic behavior of Self Compacting Concrete (SCC) may induce, in specific conditions, distinct-layer casting of the material that can generate lowered mechanical resistances in the final structure. First, the distinct-layer casting phenomenon is defined and described along with its potential consequences. Then, experimental results obtained for various SCC show that there exists a critical delay between layers casting above which separated layers are created in the element and generate losses of mechanical strength. This critical delay depends strongly on the thixotropic behavior of the SCC, the thickness of the layers and on the roughness of the interface between the two layers. Finally, an analytical method allowing for a rough prediction of this critical delay is proposed.

Keywords: Fresh concrete; Rheology; Workability; Thixotropy

1. Introduction

At the building site, a given SCC is empirically classified in terms of its filling ability (estimated most of the time by its slump flow value), passing ability (estimated by its L-Box or J-Ring value) and its stability (estimated for example by the sieve test). From a physical point of view, the filling ability is directly linked to the yield stress of the mixture as it is the rheological parameter that conditions the flow stoppage of the concrete during casting. Indeed, the stress generated by gravity during casting (or during slump flow) in the flowing concrete decreases until it may become equal to the yield stress of the material, at which point the flow stops [1–4]. The passing ability, on the other hand, shows the compatibility between the size of the coarsest particles of the concrete and the gap between the reinforcing steel bars in the structure to be cast. The L-Box ratio associated most of the time to the passing ability is also representative of the yield stress of the material and thus its filling ability as, if a mortar is tested in a L-box, no granular blocking will of course occur but the ratio h_1/h_2 would still not equal 1 [5]. Stability, finally, is the ability of the material to stay homogeneous under the action of gravity. It is to be associated to the yield stress of the cement paste and the properties of the granular skeleton (diameter, granular distribution, density, etc.) [6].

It can be seen from the above that thixotropy of a given SCC is not measured nor even estimated in any acceptance test. One could of course answer that SCC should be as thixotropic as possible. It was indeed demonstrated that formwork pressure strongly decreases for highly thixotropic SCC [7–9]. It was also shown that stability of SCC can be improved when the constitutive cement paste of the SCC is highly thixotropic [6, 10–12].

However, we will show here that highly thixotropic SCC may induce, in specific conditions, distinct-layer casting of the material that can generate lowered mechanical resistances in the final structure. As a consequence, just as the SCC should be as fluid as possible but not too much in order to obtain a stable self compacting material, there also exists an optimum thixotropic behavior for a given concrete, casting process and element to be cast.

In the first part of this paper, we define what we call distinct-layer casting and its potential consequences. In a second part, we present a thixotropy model able to describe the evolution of the apparent yield stress of the material at rest. In a third part, we present experimental results for 4 SCCs with various thixotropic behaviors. We measured their structuration rates (*i.e.* ability to build a structure up at rest) and cast distinct-layer samples in

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

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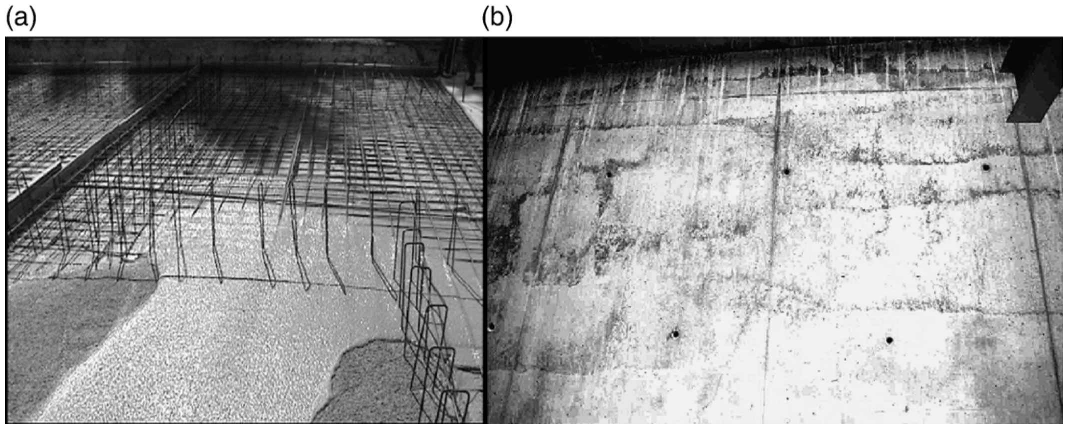

Fig. 1. Distinct-layer casting. (a) Slab. The second layer (shining gray) is flowing above the first layer (dark grey) without any remixing. (b) Wall. The layers of concrete that formed during casting can be visually spotted after the removal of the formwork.

order to measure the mechanical consequences of distinct-layer casting. Finally, in the last part of this paper, we propose an analytical prediction of the maximum delay between two layers above which separated layers are created in the element and generate losses of mechanical strength.

2. What is distinct-layer casting?

During placing, a layer of thixotropic SCC has a short time to rest and build structure before a second layer of concrete is cast above it (Cf. Fig. 1a). If it builds structure 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, a weak interface between the concrete layers may appear in the final structure. The first consequence is often only visual (Cf. Fig. 1b) but losses of mechanical strength of more than 40% have also been reported [13]. Moreover, it can be expected that this weak interface may locally increase the porosity and thus the permeability to aggressive substances. It seems thus necessary to be able to predict the conditions under which such a phenomenon may occur.

3. Modeling of fresh concrete thixotropy

Cement based suspensions such as cement pastes or concretes are suspensions consisting of particles dispersed in a liquid. Interactions among the finest particles in the mixture may lead to a structured out of equilibrium network in the suspension (*i.e.* like a gel or a colloidal glass [14]) which generates a macroscopic thixotropic behaviour. According to the “dictionnaire de Rhéologie” [15], bodies are said to be thixotropic if (i) after a long rest when a shear stress or strain rate is applied suddenly and then held constant, the apparent viscosity is a diminishing function of the time of flow (ii) the body recovers its initial state following a long enough interval after the cessation of the flow. This time-dependant decrease in the viscosity may be explained by a reversible change of the suspension microstructure during shear. In the absence of shear, the damaged structure rebuilds. The physical origin of this rebuilding might find its foundations in the Brownian motion that could induce a slow rearrangement of the particles configuration or in an evolution of the colloidal interactions between the particles although it has to be noted that this aspect is still unclear.

Most macroscopic thixotropy models are derived from the same general form [16,17]. This general mathematical form describes the equation of state of a thixotropic material and relates the shear stress to the shear rate via an apparent viscosity function:

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

where λ is a state parameter related to the structuration level inside the material. An evolution equation of this parameter is then added:

$$\frac{d\lambda}{dt} = f(\lambda,\dot{\gamma}) \tag{2}$$

Recently, a thixotropy model for fresh concrete that follows the principles described above was proposed [18]. This model assumes that a Bingham model is sufficient for the description of the steady state flow of fresh concrete. Moreover, it is considered that the rate of change of the structuration state λ is equal to the difference between a rate of “natural” structuration of the material and a rate of de-structuration due to flow, which is proportional to the rate of shear [19]. Finally, it is assumed that the yield stress at rest increases as a linear function of time. This is true for many materials [20] and seems true for concretes [9,18].

This model writes:

$$\tau = (1+\lambda)\tau_{00} + \mu_{\mathrm{p}}\dot{\gamma} \tag{3}$$

$$\frac{\partial\lambda}{\partial \mathrm{t}} = \frac{\mathrm{A_{thix}}}{\tau_{00}} - \alpha\lambda\dot{\gamma} \tag{4}$$

where λ is the flocculation state of the material. This 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 $\lambda\tau_{00}$ 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. (4) and an apparent yield stress (static yield stress) greater than the intrinsic and initial yield stress (dynamic yield stress) will appear.

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

$$\tau_0(t) = \tau_{00} + A_{\mathrm{thix}} t \tag{5}$$

This model predictions were compared to experimental results obtained using a BTRheom concrete rheometer and it proved able to predict the behavior of the tested concrete as a function of its flow history [18]. Moreover, the linear increase with time of the apparent yield stress during the first hour (*i.e.* before the hydration processes start to play a major role and deeply affect the rheological behaviour) has never proved wrong according to the knowledge of the present authors.

It may be noted that, between the two aspects of thixotropy (structuration at rest and destructuration under flow), the understanding and measuring of the first one is far more important in terms of potential applications. In the cases of pressure formwork and stability of SCC for example, concrete (or its constitutive cement paste) is not flowing. It is at rest and what really matters is the increase of the apparent yield stress of the concrete 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 structuration at rest only [9,18,21] showing that the most important parameter in the model proposed above is the structuration rate A_{thix}. It is the rate of increase of the apparent yield stress of the material at rest and is between 0 for non thixotropic concretes and, to the best of our knowledge, 2 Pa/s for the most thixotropic concretes [18].

4. Distinct-layer casting: experimental results

4.1. Materials and mix proportioning

Four different SCC with various structuration rates were prepared. Their slump flow values were between 630 and 700mm. It has to be noted that the literature dealing specifically with the correlation between structuration rate and mix proportioning is very poor [22,23]. Most experimental results such as the ones obtained by measuring thixotropic loops [24] do not allow for a distinction between structuration and de-structuration abilities of the studied material. We identified however from the literature and from our own experiments five factors that may affect the configuration of the finest particle in the mixture and their interactions and therefore the structuration rate.

- The total amount of powders in the mixture as the particles contained in these various powders are the only particles that are at the origin of the thixotropic behavior of a given SCC. The structuration rate should thus increase when the powder content increases, *i.e.* when the amount of granular skeleton (sand and gravel) in the mixture decreases [25].
- The weight ratio between water and powders W/P as it directly affects the average distance between cement (or alternative powders) particles and therefore their mutual interactions. The structuration rate should increase when the ratio W/P decreases.
- The fineness of the powders as the amplitudes of Brownian and colloidal effects increase when the particle size decreases. The structuration rate should thus increase with the specific surface of the powders in the mixture and temperature.
- The superplasticizer amount as these polymers directly affect the colloidal interactions between particles by introducing into the interaction network additional electrostatic and steric repulsions [26,27]. However, according to the knowledge of the present authors, there are no physical reasons to predict *a priori* whether or not super-plasticizer would increase the structuration rate. However, our trials have shown that for the super-plasticizer used in this study (Glénium 27©), the structuration rate decreases when the super-plasticizer content in the mixture increases.
- The viscosity agent amount in the mixture as it increases the thixotropic behavior of the cement paste [23,28–32]. This admixture can be of two types: mineral or organic. The first type simply introduces in the mixture very small particles (several nanometers) that are strongly subjected to Brownian and colloidal effects and may thus generate strong thixotropic behavior. Silica particles are the most common because of their ability to form loose three dimensional structures at rest [33]. The second type of viscosity agents often contains polymer or organic molecules that entangle at rest and that are stretched under shear. Their behavior is however still not well understood. It is this last type of viscosity agent that is used in this work.

Moreover, we tried to introduce, in the most thixotropic mixtures, an accelerating admixture. This could at first seem contradictory with the definition of thixotropy and the reversible aspect of this phenomenon. The accelerator indeed modifies the chemical reactions that occur in the first few hours after mixing. These are irreversible reactions unlike thixotropy, which is defined as a reversible property. However, as we will see in the next section, most of the structuration chemically gained using this admixture can be broken during remixing and thus appears to be as reversible as the physical structuration due to Brownian and colloidal effects. The mix proportioning of the tested concretes are given in Table 1.

4.2. Rheological behaviour and assessment of thixotropy

Two types of rheological test were carried out on the studied concretes: slump flow test and scissometer test. The geometry of the scissometer used in this work is shown in Fig. 2. It follows the recommendations made by Nguyen and Boger [34]

Table 1
Mix proportioning of the tested SCC (units are kg/m3)

Components	Product	SCC No. 1	SCC No. 2	SCC No. 3	SCC No. 4
Cement	CEM I 52.5 N CE PMES CALCIA	330	310	310	310
Addition	Fly ash	120	210	210	210
Small sand	0/0.3 La Chapelle	230	225	225	225
Sand	0/4 CBN Yville	655	635	635	635
Gravel	4/10 Vignats	780	775	775	775
Viscosity Agent	Rhéomac 890F DEGUSSA	0	1.8	1.8	1,8
Superplasticizer	Glénium 27 DEGUSSA	7.1	10.8	10.8	5,2
Accelerator	Pozzolith 555 DEGUSSA	0	0	6.2	9,2
Water		209	193	183	173

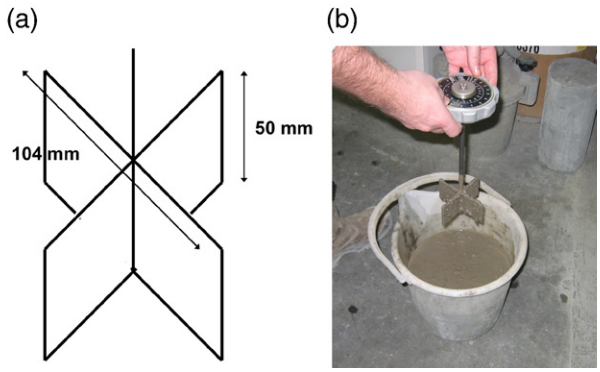

Fig. 2. The scissometer test.(a) geometry; (b) measurement in a bucket filled with concrete.

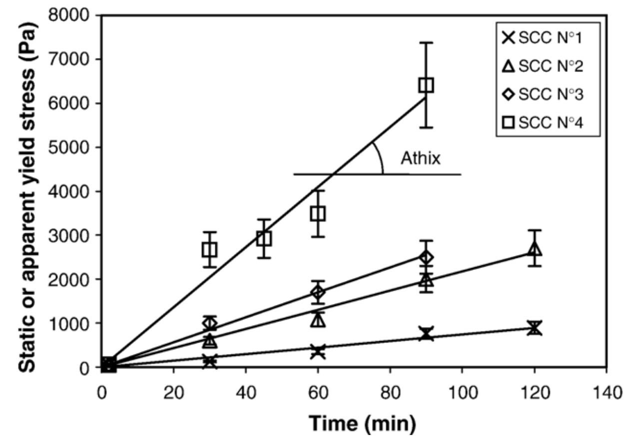

Fig. 3. Static or apparent yield stress as a function of the resting time.

considering the size of the constitutive particles of the mixture (Fig. 2(b)). The apparatus used here records the highest torque needed to initiate flow after a time of rest. It is, in several aspects, very similar to the apparatus used by Billberg [21] or Assaad et al. [23] to measure the apparent (or static) yield stress. The measured torque is proportional to the shear stress on the external surface of the tool via a coefficient α linked to the geometry of the tool.

$$C = \alpha\tau \tag{6}$$

The highest torque measured is thus either proportional to the yield stress of the material τ_{00} if the test is carried out just after mixing or to the apparent yield stress of the material $\tau_0(t)$ after a time of rest t. The α coefficient, from a theoretical point of view, is equal to $1.44.10^{-3}$ Pa/N/m according to the following equation:

$$\alpha = 2\pi r^3\left(\frac{h}{r}+\frac{2}{3}\right) \tag{7}$$

where h is the height of the tool and r the radius of the blades.

The scissometer used here was moreover calibrated on reference yield stress fluids (carbopol suspensions) and a value of $1.20.10^{-3}$ Pa/N/m was obtained for α in broad agreement with the above theoretical value. The uncertainty of the measurement was estimated to be around 15%. In parallel, standard slump flow tests were carried out. It has to be noted that these tests were systematically carried out after a remixing of the concrete. As the structural build-up of the material is broken by the remixing, these tests are representative of the intrinsic behaviour of the mixture and the evolution of the slump flow value is representative of the irreversible changes in the material behaviour (dynamic or intrinsic yield stress). The experimental measurements were carried out on the studied SCC at GTM Construction laboratory and are gathered in Table 2 and Fig. 3. It has to be noted that all scissometer measurements were carried out on different buckets in which concrete was poured at the end of mixing and left at rest until the yield stress measurement.

4.3. Analysis of the rheological measurements

It can first be noted that the evolution of the apparent yield stress of these concretes is, as already specified in Section 3, linear with the resting time.

Moreover, although all these concretes have almost the same initial slump flow (from 630 mm to 700 mm) and almost the same initial yield stress after mixing (from 48 to 70 Pa), their thixotropic behaviors are very different leading to structuration rates from 0.12 Pa/s to 1.14 Pa/s (7 Pa/min to 68 Pa/min).

By increasing the total amount of powders, by increasing the fineness of the powders (addition of fly ash) and by adding a viscosity agent, we finally managed to obtain a SCC (SCC No. 2) three times more thixotropic than our reference (SCC No. 1).

In order to further increase the structuration rate, we introduced in the mixture an accelerator admixture. For an amount equal to 2% of the cement weight, the structuration rate was 4 times higher than the reference whereas, for an amount equal to 3% of the cement weight, it increases by a factor 10. It can be seen in Table 2 that there is a decrease in the slump flow values measured after remixing at 80 min. This means that the accelerator admixture induces a thickening of the material that is not reversible, at least with the mixers that were available in the laboratory. However, this irreversible thickening can be

Table 2
Rheological measurements

Measurement	SCC No. 1	SCC No. 2	SCC No. 3	SCC No. 4
Initial Slump flow (mm)	630	670	700	630
Slump flow after remixing at 80 min (Pa)	630	–	450	–
Initial yield stress measured with scissometer (Pa)	54	40	50	70
Structuration rate A_{thix}	0.12 Pa/s (7 Pa/min)	0.36 Pa/s (22 Pa/min)	0.47 Pa/s (28 Pa/min)	1.14 Pa/s (68 Pa/min)

Fig. 4. Casting protocol. (left) After the first layer casting; (right) after the second layer casting.

neglected compared to the reversible part. The apparent yield stress of SCC No. 3 and No. 4 indeed reaches at rest values of the order of several thousands Pa whereas the slump flow after mixing of SCC No. 3 only decreases from 700mm to 450mm (*i.e.* a change in intrinsic (or dynamic) yield stress of the order of a couple hundred Pa [3]).

4.4. Mechanical strengths

Small slabs were cast in two layers for various delays between layers (see Fig. 4). These slabs were 40 × 45 × 20 cm and the thickness of each layer was 10 cm (see Fig. 5). The delay between layers was varied between 30 and 180 min. After the end of casting, the slabs were covered with a plastic film and kept for 28 days at 20 °C. After 28 days, cylindrical core samples were drilled and extracted from the slabs and prepared as shown in Fig. 5 (right). Because of the shape, the location and the asymmetric preparation chosen, we were then able to measure the shear strength of the interface using a simple compression test (see Fig. 5 (right)). These mechanical strengths measurements were carried out with a stress rate of 0.05 Mpa/s. The experimental results are shown in Fig. 6. It should be noted that the plotted results are the average mechanical shear strengths of the three extracted samples. However, it must also be noted (See Table 3) that, despite the preparation of the samples, some of them did not break at the interface of the two layers especially for short delays between the two layers (*i.e.* no weak interfaces between the layers as we will discuss further).

4.5. Analysis of the mechanical strengths

For all the SCC studied here, the interface between the two layers could be visually identified when the delay between the two layers was longer than 60 min. The longer the delay between the two layers, the easier it was to identify.

Moreover, an overall decrease of the mechanical strength with the delay between the two layers can be spotted in Fig. 6 (left). However, this decrease does not seem at first to depend on

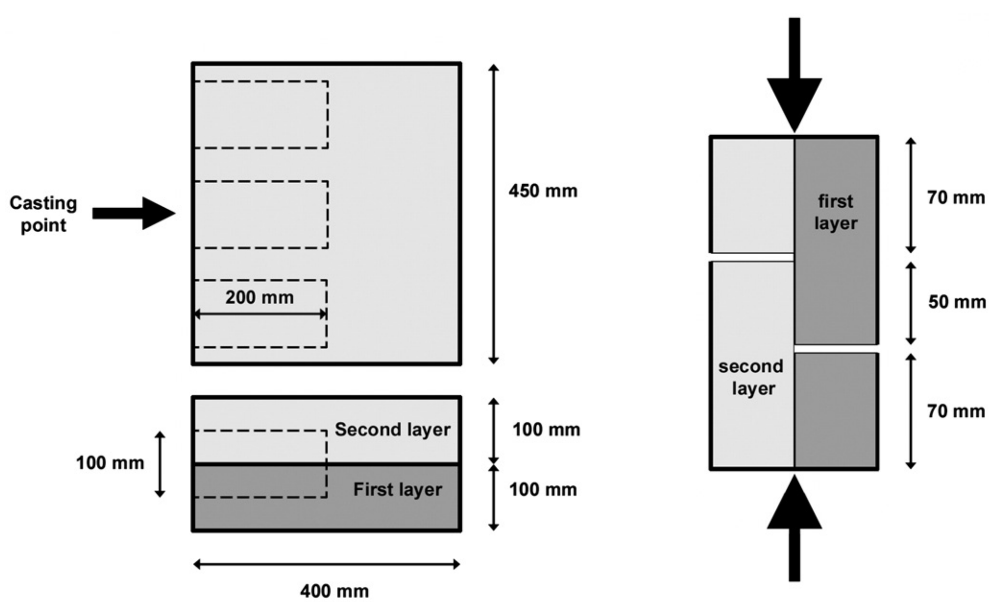

Fig. 5. (left) Casting protocol and sample sawing and extraction (dashed line); (right) Preparation of the sample for the mechanical shear strength measurements.

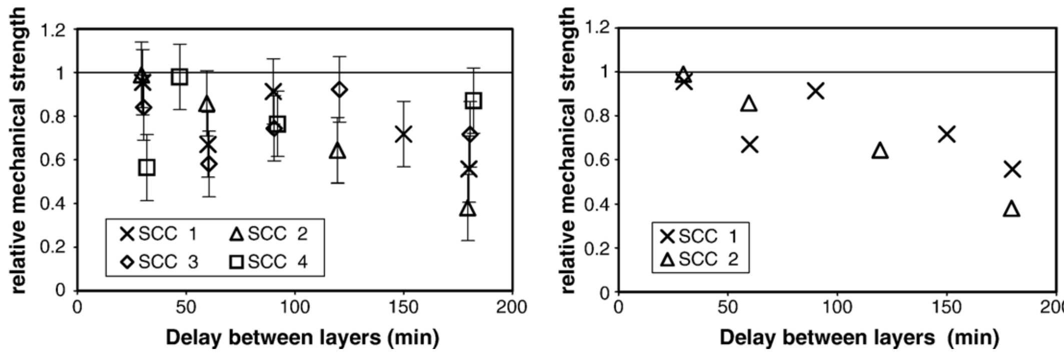

Fig. 6. Relative mechanical strength (ratio between the measured mechanical strength and the mechanical strength of a sample cast in one layer) as a function of the delay between layers. (left) All results; (right) experimental results for a smooth interface between layers, see text for further details.

the structuration rate of the concretes tested as there is almost no decrease in the mechanical strengths of the most thixotropic SCC tested here (SCC N°3 and SCC N°4).

Another parameter has to be introduced in order to properly analyze the experimental measurements: the surface roughness of the first layer. Indeed, even if the two layers do not remix at all, the surface roughness of the first layer can be sufficient to ensure that the final mechanical strengths will not be affected by distinct-layer casting. It is known that increasing thixotropy of the constitutive cement paste increases the stability of the mixture and thus the presence of the coarsest particles at the surface of the concrete [6,10–12]. That is how viscosity agents work to improve the stability of a given SCC. The two very thixotropic SCC tested here were very stable and the upper surface of the first layer displayed a roughness with a characteristic size of the order of the coarsest grains of the concrete (see Fig. 7).

This experimental observation has two consequences:

– The distinct-layer casting problem may only occur in the case of a smooth interface between the two layers (*i.e.* no coarse particles at the surface of the first layer) and thus in the case of slightly unstable mixtures.
– It is useless to study the distinct-layer casting phenomenon in the case of mortars or cement pastes. It has to be studied on real concrete as the roughness of the interface between the two layers plays a major role and is dictated by the coarsest particles in the mixture.

Table 3
Mechanical strength measurements for each sample

Resting time between layers	SCC No. 1	SCC No. 2	SCC No. 3	SCC No. 4
30 min	3/3	2/3	3/3	1/3
45 min	0/0	0/0	0/0	2/3
60 min	3/3	3/3	2/3	0/3
90 min	2/3	0/0	3/3	3/3
120 min	0/0	2/3	3/3	0/0
150 min	3/3	0/0	0/0	0/0
180 min	3/3	2/3	3/3	2/3

The first figure is the number of samples which did break at the interface of the two layers. The second figure is the total number of samples tested. On the whole, 79% of the samples broke at the interface.

Let us plot now in Fig. 6 (right) only the results obtained for smooth interfaces between the two layers. A decrease in the shear strength can now be clearly spotted, which increases with the thixotropy of the tested SCC. It could seem at first that the highly thixotropic SCC studied here do not exist in actual practice. However, their structuration rate (from 0.12 Pa.s to 1.14 Pa.s) are of the same order of magnitude as other results in the literature (up to 1.7 Pa/s in 7, 21].

5. Prediction of distinct-layer casting

We carried out many numerical simulations using the software Flow3D® and the thixotropy model described in Section 3 and proposed in [18]. These simulations have shown that it was possible to spot two distinct regimes in the distinct-layer casting process. In the first one, the stresses generated by the flow of the second layer were sufficient to initiate flow in the resting first layer. The two layers were then mixed together more or less quickly according to the flow rate in the second layer and no sharp interface between the layers could be spotted at the end of the numerical simulation (Fig. 8(left)). In the second regime, the stresses generated by the flow of the second layer were not sufficient to initiate flow. The first layer more or less deformed under the weight of the second layer and the shear stress generated by the second layer casting but the interface between the two layers always remained sharp (Fig. 8 (right)).

In order to obtain a simple analytical description of the problem, we can assume, as a first approximation that the stresses generated at the interface of the two layers can be decomposed into non dependant normal stresses due to the weight of the second layer and shear stress due to the viscous shearing generated by the second layer casting.

The shear stress generated at the interface between the two layers by the casting of the second layer is of the same order as $\tau_{00}+\mu_p\dot{\gamma}_{xz}$ where the shear rate $\dot{\gamma}_{xz}$ at the interface between the two layers is roughly equal to the horizontal flowing speed of the concrete V divided by the average thickness $h/2$ of the second layer (Cf. Fig. 9):

$$\tau_{xz} = \tau_0 + \mu_p \frac{2V}{h} \tag{8}$$

Fig. 7. Surface roughnesses for SCC N°1 (left) and SCC N°4 (right).

The normal stresses if we consider the flow as extensional [3], follow:

$$\sigma_{xx} = \sigma_{yy} = -\sigma_{zz}/2 = \rho g\, h/6 \tag{9}$$

In order to mix the two layers, flow has to be initiated. This is the case when a plasticity criterion is fulfilled (*i.e.* the normal and shear stresses are sufficient to initiate flow). We choose here to consider a Von Misès criterion. In 3D this is:

$$\left(\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2\right)/2 + \tau_{xz}^2 = \tau_0^2(t_{\text{rest}}) \tag{10}$$

where $\tau_0(t_{\text{rest}})$ is the apparent or static yield stress of the first layer after a resting time t_{rest} (*i.e.* the delay between the two layers). According to the thixotropy model used here, this apparent yield stress is:

$$\tau_0(t_{\text{rest}}) = \tau_{00} + A_{\text{thix}} t_{\text{rest}} \tag{11}$$

A critical value t_{rest}^C for the delay between the two layers may then be estimated from Eqs. (8), (9) and (10).

$$t_{\text{rest}}^C = \frac{\sqrt{(\rho g h)^2/12 + \left(2\mu_p V/h\right)^2}}{A_{\text{thix}}} \tag{12}$$

6. Analysis

We show in Fig. 10 many experimental results obtained in this work at GTM and in other studies at LERM and LCPC [35]. The interface surfaces between layers were all smooth. For each concrete studied, the critical time given by Eq. (12) was estimated by considering, when the rheological parameters were unknown, that the plastic viscosity of these French SCCs was of the order of 50 Pa/s. The flowing speed of the second layer was considered to be of the order of 5 cm/s except in the case of the samples tested at LCPC that were cast at 1 cm/s.

The only parameter, that was systematically measured, was the structuration rate of the material A_{thix}. It was measured using a concrete rheometer for the concretes tested in the French National Research Project about SCC at LERM [9,36] (A_{thix}= 0.1 Pa/s) and using a Vane test and a high torque viscometer for the concretes tested at LCPC [18] (A_{thix}=0.3 Pa/s). In Fig. 10, the relative mechanical strength (ratio between the measured mechanical strength and the mechanical strength of a sample cast in one layer) is plotted in term of the relative delay between the two layers (ratio between the delay, t_{rest}, and the critical delay, t_{rest}^C).

It can be seen on this figure that, if the relative delay is higher than 1, a strong decrease in the mechanical properties of the element occurs.

Most of the time, a highly thixotropic SCC is also highly viscous and stable. This means that a highly thixotropic SCC could induce a rough interface between the two layers that may prevent distinct-layer casting or at least its mechanical consequences. Moreover, the high plastic viscosity of these materials generates a strong shearing between the two layers that improves the mixing of the two layers.

Conversely, a low thixotropy SCC displays a low plastic viscosity and may display low stability. This means that the

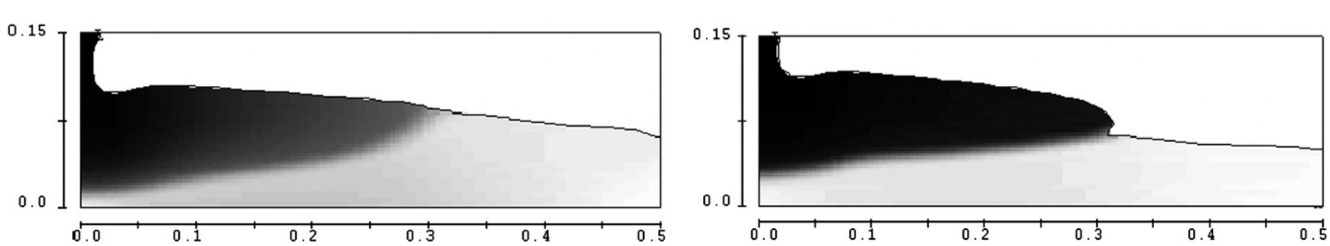

Fig. 8. Exemples of numerical simulations of distinct-layers casting of a thixotropic SCC. Units are meters. τ_0=50 Pa, μ_p=50 Pa s, A_{thix}=0.5 Pa/s, α=0.005. (left) 300 s resting time between the two layers; the two layers mix perfectly (right) 1200 s resting time between the two layers. the two layers do not mix at all.

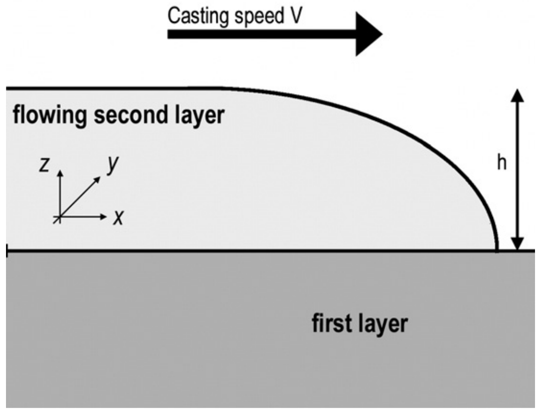

Fig. 9. Distinct-layers casting process and notations.

interface between the two layers is smooth and thus increases the risk of mechanical strength losses. Moreover, because of the low plastic viscosity, the shearing generated by the second layer is weak. However, the apparent yield stress of the first layer does not increase very fast as the structuration rate of this type of material is low.

It seems that the critical cases of distinct-layer casting should concern moderately thixotropic SCC. In these cases, the model predicts that distinct-layer casting could appear, for example, for a SCC with $A_{\mathrm{thix}}=0.5$ Pa/s cast slowly ($V=0.2$ m/s) in two layers (5 cm) after a delay of 15 minutes. This delay is extremely short compared to typical working conditions at the building site. It should thus be kept in mind that, in the case of smooth interfaces and SCC with A_{thix} higher than 0.2 Pa/s, it might be useful to check by specific studies such as the ones presented here the maximum acceptable delay between two successive layers.

From a practical point of view, it can be easily shown that, even for the most viscous SCC and the highest flowing speeds, the shear stress at the interface can be neglected in front of the effect of the weight of the second layer as soon as the thickness of the second layer is higher than 10 cm. In this case, the expression of the critical delay between the two layers simplifies to:

$$T_c = \frac{\rho g h}{3.5 A_{\mathrm{thix}}} \tag{13}$$

This means that for traditional SCC mixes with structuration rate of the order of 0.3–0.5 Pa/s, the critical delay is of the order of 20 to 30 min.

7. Conclusion

We have defined from experimental results on SCC in which conditions distinct-layer casting may occur. The following specific conditions have to be fulfilled:

– the interface between two layers of fresh concrete must be smooth. Our results have indeed shown that a rough layer can prevent the mechanical consequences of distinct-layer casting as the roughness at the interface creates a bond between the two layers even if they do not mix.

– the structuration rate at rest of the first layer has to be high enough in order to prevent the stresses generated at the interface between the two layers by the casting of the second layer (normal stresses due to the weight of the material and shear stress due to flow) from being able to re-initiate flow in the first layer. This may be the case if the SCC is highly thixotropic, the SCC plastic viscosity is low and/or if the thickness of the second layer is thin.

Considering the number of parameters involved in the problem, we have proposed a simple modeling of the phenomenon. The obtained equations (based simply upon the thickness of the second layer, its density, its flowing speed and the structuration rate of the SCC) allow for the calculation of the critical delay between the casting of the two layers, above which separated layers may be created. This relation was validated on new experimental results and experimental results from the literature.

It can also be kept in mind that by adjusting the mix proportioning of a given SCC, we were able to multiply its structuration rate by a factor 10 without greatly affecting its slump flow value. The main factors are:

– The total amount of powders in the mixture.
– The weight ratio between water and powders W/P.
– The fineness of the powders.
– The amount of superplasticizer.
– The amount of viscosity agent.

This means that more or less thixotropic SCC can be prepared according to the element to be cast. In the opinion of the present authors, the major trends should be the following:

– for wall casting, SCC should be highly thixotropic in order to decrease formwork pressure and increase the stability of the mixture;

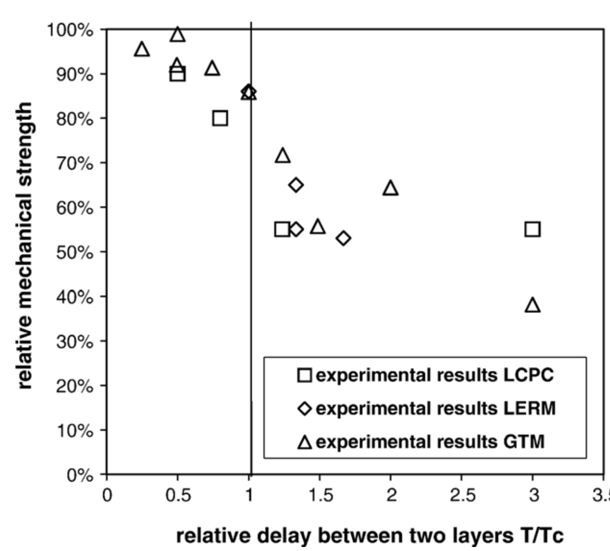

Fig. 10. Relative mechanical strength (ratio between the measured mechanical strength and the mechanical strength of a sample cast in one layer) in term of the relative delay between the two layers (ratio between the delay and the critical delay).

– inversely, for slab casting, the main difficulty could come from the risk of distinct-layer casting and SCC should thus be as non thixotropic as possible (low structuration rate: lower than 0.1 Pa/s for example) [18].

In other words, self *leveling* concrete should be non thixotropic whereas self *compacting* concrete should be highly thixotropic. However, a lot of work is still needed in order to understand the effect of each component on the structuration rate of the final mixture.

Moreover, to come back to the introduction of this paper, if thixotropy of SCC becomes a mix proportioning objective such as yield stress or plastic viscosity, our community will have to invent a simple acceptance test in order to qualify or even quantify the SCC structuration rate at the building site.

References

[1] N. Roussel, S. Staquet, L. D'Aloia Schwarzentruber, R. Le Roy, F. Toutlemonde, SCC casting prediction for the realization of prototype VHPC-precambered composite beams, RILEM Mat. Struct. 40 (N°9) (2007).

[2] N. Roussel, Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results, RILEM Mat. Struct. 39 (N°4) (2006) 501–509.

[3] N. Roussel, P. Coussot, "Fifty-cent rheometer" for yield stress measurements: from slump to spreading flow, J. Rheol. 49 (2005) 705–718.

[4] P. Coussot, S. Boyer, Determination of yield stress fluid behaviour from inclined plane test, Rheol. Acta 34 (N°6) (1995) 534–543.

[5] T.L.H. Nguyen, N. Roussel, P. Coussot, Correlation between L-box test and rheological parameters of an homogeneous yield stress fluid, Cem. Concr. Res. 36 (N°10) (2006) 1789–1796.

[6] N. Roussel, A theoretical frame to study stability of fresh concrete, RILEM Mat. Struct. 39 (N°1) (2006) 81–91.

[7] P. Billberg, Form pressure generated by self-compacting concrete, Proceedings of the 3rd international RILEM Symposium on Self-Compacting Concrete, RILEM PRO33 Reykjavik, Iceland, 2003, pp. 271–280.

[8] K.H. Khayat, J. Assad, H. Mesbah, M. Lessard, Effect of section width and casting rate on variations of formwork pressure of self-consolidating concrete, RILEM Mat. Struct. 38 (N°1) (2005) 73–78.

[9] G. Ovarlez, N. Roussel, A physical model for the prediction of lateral stress exerted by self-compacting concrete on formwork, RILEM Mat. Struct. 39 (N°2) (2006) 269–279.

[10] M. Lachemi, K.M.A. Hossain, V. Lambros, P.C. Nkinamubanzi, N. Bouzoubaâ, Self-consolidating concrete incorporating new viscosity modifying admixtures, Cem. Concr. Res. 34 (N°6) (2004) 917–926.

[11] K.H. Khayat, Z. Guizani, Use of viscosity modifying admixtures to enhance stability of fluid concrete, ACI Mater. J. 94 (N°4) (1997) 332–340.

[12] S. Rols, J. Ambroise, J. Péra, Effects of different viscosity agents on the properties of self-leveling concrete, Cem. Concr. Res. 29 (N°2) (1999) 261–266.

[13] P. Coussot, N. Roussel, Quantification de la thixotropie des matériaux cimentaires et de ses effets, Rev. Eur. de Génie Civ. 10 (N°1) (2006) 45–63 (in French).

[14] P. Coussot, C. Ancey, Rheophysical classification of concentrated suspensions and granular pastes, Phys. Rev., E 59 (N°4) (1999).

[15] Dictionnaire de Rhéologie, Edited and published by the Groupe Français de Rhéologie (GFR), p. 44, (1990) (in French).

[16] D.H. Cheng, F. Evans, Phenomenological characterization of the rheological behaviour of inelastic reversible thixotropic and anti-thixotropic fluids, Br. J. Appl. Phys. 16 (1965) 1599.

[17] N. Roussel, Steady and transient flow behaviour of fresh cement pastes, Cem. Concr. Res. 35 (N°9) (2005) 1656–1664.

[18] N. Roussel, A thixotropy model for fresh fluid concretes: theory, validation and applications, Cem. Concr. Res. 36 (N°10) (2006) 1797–1806.

[19] N. Roussel, R. Le Roy, P. Coussot, Thixotropy modelling at local and macroscopic scales, J. Non-Newton. Fluid Mech. 117 (N°2–3) (2004) 85–95.

[20] H.T. Huynh, N. Roussel, P. Coussot, Aging and free surface flow of a thixotropic fluid, Phys. Fluids 17 (N°3) (2005) Art. No. 033101.

[21] P. Billberg, Development of SCC static yield stress at rest and its effect on the lateral form pressure, in: S.P. Shah (Ed.), Proceedings of the Second North American Conference on the Design and use of Self-Consolidating Concrete and the Fourth International RILEM Symposium on Self-Compacting Concrete, October 30 – November 3 2005. Chicago, USA, Chicago: Hanley Wood, LLC, ISBN: 0924659645, 2005.

[22] W. Vom Berg, Influence of specific surface and concentration of solids upon the flow behaviour of cement pastes, Mag. Concr. Res. 31 (N°109) (1979) 211–216.

[23] J. Assaad, K.H. Khayat, H. Mesbah, Assessment of Thixotropy of Flowable and Self-Consolidating Concrete, ACI Mater. J. 100 (N°2) (2003) 99–107.

[24] P.F.G. Banfill, D.C. Saunders, Viscometric examination of cement pastes, Cem. Concr. Res. 11 (N°3) (1981) 363–370.

[25] B. Felekoglu, K. Tosun, B. Baradam, A. Altun, B. Uyulgan, The effect of fly ash and limestone fillers on the viscosity and compressive strength of self-compacting mortars, Cem. Concr. Res. 36 (2006) 1719–1726.

[26] R.J. Flatt, Dispersion forces in cement suspensions, Cem. Concr. Res. 34 (N°3) (2004) 399–408.

[27] T.H. Phan, M. Chaouche, M. Moranville, Influence of organic admixtures on the rheological behaviour of cement pastes, Cem. Concr. Res. 36 (2006) 1807–1813.

[28] K.H. Khayat, Viscosity-enhancing admixtures for cement-based materials — an overview, Cem. Concr. Comp. 20 (1998) 171–188.

[29] V.A. Ghio, P.J. Monteiro, L.A. Demsetz, The rheology of fresh cement paste containing poly-saccharide gums, Cem. Concr. Res. 24 (2) (1994) 243–249.

[30] V.A. Ghio, P.J. Monteiro, O.E. Gjorv, Effects of poly-saccharide gums on fresh concrete, ACI Mater. J. 91 (6) (1994) 602–606.

[31] M. Saric-Coric, K.H. Khayat, A. Tagnit-Hamou, Performance characteristics of cement grouts made with various combinations of high-range water reducer and cellulose-based viscosity modifier, Cem. Concr. Res. 33 (2003) 1999–2008.

[32] M. Sonebi, Rheological properties of grouts with viscosity modifying agents as diutan gum and welan gum incorporating fly ash, Cem. Concr. Res. 36 (2006) 1609–1618.

[33] R.J. Hunter, Introduction to modern colloid Sciences, 1994, Oxford University Press New York, Oxford UK.

[34] Q.D. Nguyen, D.V. Boger, Direct yield stress measurement with the vane method, J. Rheol. 29 (N°3) (1985) 335–347.

[35] Report of the french « Projet National PN BAP », Etude de la relation entre la thixotropie et le délai maximal de recouvrement d'un BAP, (2006), (in French).

[36] Z. Toutou, M. Cador, N. Roussel, L. D'Aloia Schwartzentruber, E. Vilbé, R. Le Roy, Rhéologie des bétons autoplaçants: évaluation de la thixotropie, Bull. Liaison Ponts Chausseées 258–259 (2005) 15–27 (in French).