

Steady-state rheological properties of fresh Self Compacting Concrete and their evolution in time

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ABSTRACT

In literature, fresh concrete has been described as a thixotropic Bingham liquid, having variable parameters in function of time. In this paper, the rheological properties of fresh Self Compacting Concrete (SCC), together with their evolution in time are described, applying the modified Bingham model.

INTRODUCTION

Self Compacting Concrete (SCC) is a relatively new type of concrete which does not need any form of external compaction which is needed for traditional concrete to avoid excessive air content causing low strength and durability¹. This can be achieved by reducing the amount of coarse aggregates, increasing the amount of fine materials and adding superplasticizers (SP), which are chemical products, avoiding the flocculation of cement particles. As a result, SCC is in fresh state much more fluid compared to traditional concrete^{2,3}.

In this paper, the rheological properties of fresh SCC, together with their evolution in time, are described, applying the modified Bingham model. These properties have been measured with the Tattersall Mk-II rheometer after elimination of thixotropy. The study of the thixotropic properties of SCC is beyond the scope of this paper.

MATERIALS AND METHODS

Self Compacting Concrete

In total, more than 60 different SCC-mixes have been tested in the rheometer. The most important variations in the composition were the amount of water – related to the amount of cement (W/C) or the amount of powder (=cement + other fine particles) (W/P) – and the type and amount of SP.

Two different types of SP have been used, of which SP 1 is the most efficient one, but it has a short workability retention and SP 2 is less efficient, but it has a longer workability retention.

The rheological properties of SCC will mainly be discussed using the reference mixes, of which the composition is shown in Table 1.

Table 1. Composition of reference mixes (kg/m³)

	SCC 1	SCC 2
Gravel 8/16	434	434
Gravel 2/8	263	263
Sand 0/4	853	853
CEM I 52.5 N	360	360
Limestone filler	240	240
Water	165	165
SP 1	4.7	
SP 2		10

Remark: limestone filler is an inert type of fine particles. The amount of powder is the sum of filler and cement.

Tattersall Mk-II rheometer

The rheological properties have been tested in an adapted Tattersall Mk-II rheometer^{4,5}, depicted in Fig. 1. The outer radius measures 12.5 cm, the distance between the outer edges of the blades is 8 cm in horizontal direction and 14 cm in vertical direction. The inner and outer cylinder are equipped with blades and ribs respectively in order to prevent slippage between the concrete and steel surface. The inner cylinder is equipped with a torque transducer which measures the rotational velocity (N) and the induced torque (T) at a rate of 5 kHz. The results of 2000 measuring points are averaged and saved into a data file.

Due to the complex geometry of the inner cylinder, no fundamental formulae, applicable to coaxial cylinder rheometers⁶, are valid. Instead, a calibration procedure with oil (Newtonian liquid) and honey (Bingham liquid) has been performed in order to obtain the relationships between torque and shear stress and between rotational velocity and shear rate⁷.



Fig. 1. Tattersall Mk-II rheometer.

Testing procedure

In most cases, a sample of the concrete has been tested a first time 15 minutes after the addition of the water. The rheometer tests have been performed as follows:

- Elimination of thixotropy by maintaining a high velocity during the preshearing period (in the order of 20 s). (see Fig. 2)
- Decreasing the rotational velocity in steps of 5 seconds. (see Fig. 2)
- Averaging the data of T and N for each step, as long as the values of both parameters remained approximately constant.
- Transforming T and N to shear stress and shear rate, according to the calibration procedure.

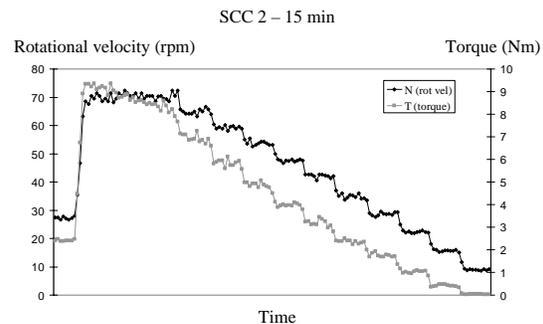


Fig. 2. Preshearing and stepwise decrease of rot. vel. in order to eliminate thixotropy.

In this way, thixotropy has been eliminated and the results have been obtained in steady state⁸.

If the workability of the concrete remained sufficiently high, similar tests have been performed at ages of 30, 60, 90, 120 and even 150 minutes. These test results, when available, have been used to determine the influence of the time on the rheological properties of SCC.

Together with the rheometer tests, standard tests on SCC have been performed also, of which the most important one is the slump flow⁹. The slump flow is deducted from the slump test for traditional concrete, where the decrease in height of a concrete pile is measured after lifting the conical

mould. For SCC, the decrease in height is that large (almost the height of the conical mould itself) and as a result, the diameter of the resulting ‘concrete cake’ is measured instead. The higher the diameter, the more fluid the SCC.

RHEOLOGICAL MODELS

In this section, the Bingham model and the modified Bingham model are applied to the results of reference mix 2 (SCC 2), obtained at 15 minutes of age.

Bingham model

The Bingham model, describing a yield-stress liquid with a constant plastic viscosity, has already been applied on traditional concrete with success⁴. Also, most researchers apply the Bingham model on the rheological properties of SCC⁹.

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \quad (1)$$

Applying the Bingham model to the data of SCC 2 results in the generation of a negative yield stress, which is physically impossible (Fig. 3). Examination of the rheological curve indicates non-linear behaviour.

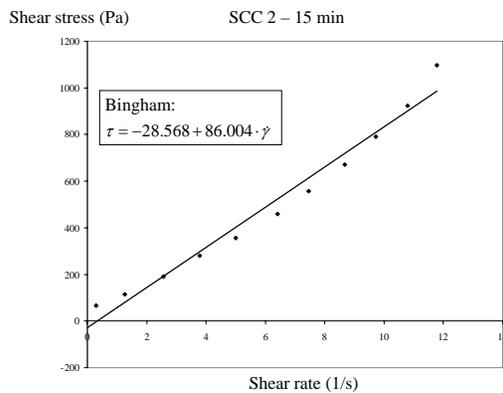


Fig. 3: Application of the Bingham model results in negative yield stresses.

Modified Bingham model

In order to avoid the generation of negative yield stresses, a non-linear model must be applied to the rheological data. In the Herschel-Bulkley model, the consistency factor ‘K’ is not suitable for physical interpretation due to its variable dimension⁷. As a result, the modified Bingham model^{7,10} (Eq. 2) has been chosen to describe the rheological properties of fresh SCC.

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} + c \cdot \dot{\gamma}^2 \quad (2)$$

This model is the Bingham model, extended with a second order term. Shear thickening can be described by the ratio of c/μ , indicating shear thinning ($c < 0$), shear thickening ($c > 0$) or the Bingham model ($c = 0$). The application of the modified Bingham model on the data of SCC 2 can be seen in Fig. 4, showing far better fitting to the test results and a realistic value of the yield stress.

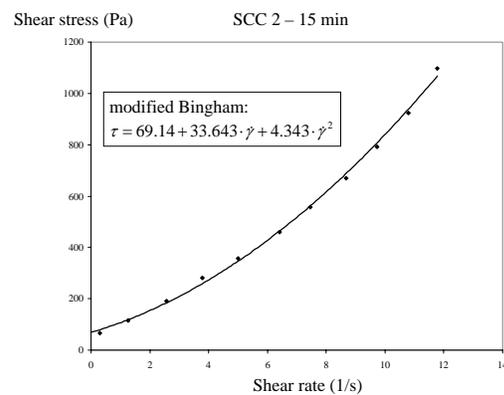


Fig. 4. Application of the modified Bingham model.

SHEAR THICKENING

As stated in the previous section, the shear thickening behaviour of SCC can be described by the ratio of c to μ . Shear thickening is mainly influenced by the water to powder ratio (W/P) of the composition and the slump flow achieved at 15 min of

age. Shear thickening is increasing when W/P is decreasing and the slump flow (and as a consequence the fluidity) is increasing. This increase in shear thickening is mainly dependent on the type of SP, the type of filler and the grain size distribution of the coarse aggregates. The amount of SP does not show a clear correlation with shear thickening, but it is in some way linked with the slump flow: the more SP added, the higher the slump flow.

Traditional concrete has a lower amount of powder due to the lack of filler material and does not show the high fluidity of SCC. As a consequence, W/P is higher compared to SCC and the slump flow is that small it can not be measured. Extending the results for SCC leads to the conclusion that traditional concrete should not show shear thickening.

In Fig. 5, the results of the rheological tests on SCC 1 (standard mix), SCC 3 (mix with higher amount of powder – lower W/P) and TC 1 (C = 360 kg, W = 165 kg, without filler and SP) are shown. As can be seen, SCC 3 shows more shear thickening compared to SCC 1, and TC 1 can be represented perfectly by the Bingham model.

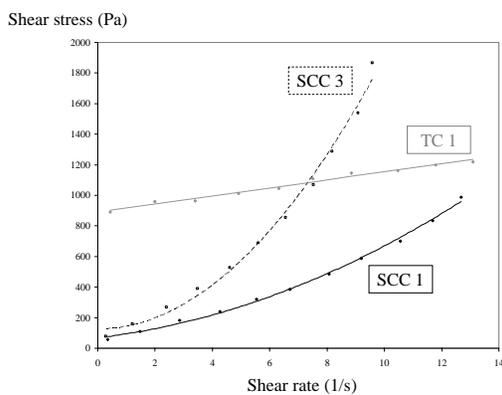


Fig.5. SCC 3 (dashed black line) shows more shear thickening than SCC 1 (full black line). TC 1 (grey line) does not show any shear thickening.

The influence of the type of filler material has been investigated by producing 4 times the same concrete, with a different filler, keeping the volume of filler constant in the mix. The amount of SP has been adapted to reach an equal slump flow for each SCC. Fig. 6 shows the remarkable difference between silica fume and the other fillers. SCC with silica fume is much more fluid compared to the others, and does not show any shear thickening at all. However, SCC with silica fume is not of commercial interest in Belgium due to its high cost and a higher amount of SP that is required.

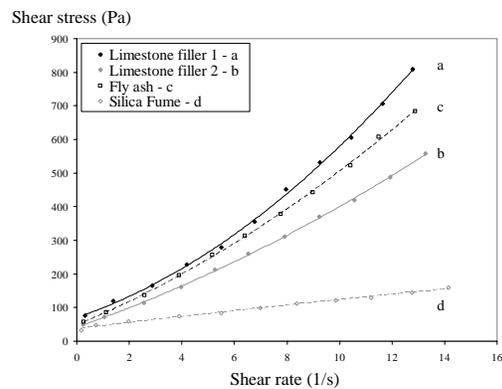


Fig. 6. Rheological behaviour of SCC made with different filler materials.

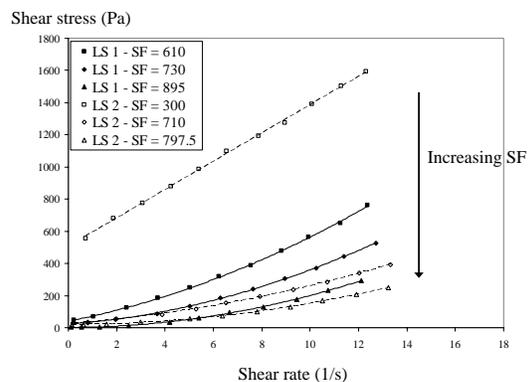


Fig. 7. Increasing the SF leads to a decrease in viscosity and yield stress and an increase of shear thickening.

SCC with limestone filler 1 and 2 (LS 1, LS 2) also shows a difference in fluidity and in shear thickening behaviour. This could be due to small differences in the grain size distribution of these materials. Further study on this topic is still going on.

For LS 1 and LS 2, the influence of the slump flow is shown in Fig. 7. When the slump flow is increasing, and as a consequence the fluidity is increasing, the viscosity and yield stress are decreasing, but shear thickening is increasing.

Remark: it is more convenient to classify a SCC with a slump flow of 300 mm as a plasticized TC than as a SCC. In Fig 7, also the different behaviour for SCC with both LS is visible again.

The authors would like to remark also that shear thickening appears to be a local phenomenon, depending on the production site of the composing materials. Shear thickening has been observed in Belgium and its surrounding countries (The Netherlands, France, Germany), but not e.g. in the Nordic countries. The mechanisms causing shear thickening are at this moment still unknown and will be investigated in the future.

EVOLUTION IN TIME

Concrete is getting its strength by the chemical reactions between cement and water. From the first contact, reactions do occur, but they are very short in time and do not make the concrete hard. This first reaction peak is followed by a dormant period in which not much is happening. This dormant period lasts for approximately 4 hours after which the setting and hardening starts. In the dormant period, concrete shows a certain degree of workability, depending on the amount of free water between the particles and on the amount of SP, which makes it possible to cast it into a formwork^{1,3}. During this dormant period, workability is decreasing, especially in case of SCC where a higher amount of SP is used. As a result, this loss of workability

will have an effect on the rheological properties.

In this section, the values of yield stress, viscosity (defined as the inclination of the curve at a shear rate of 5/s) and shear thickening will be evaluated based on the test results obtained at 15, 30 and when available: 60, 90, 120 and 150 minutes after addition of the water.

Mathematical description

In order to have a single-parameter relation with time, all values of yield stress, viscosity and shear thickening are normalized to the value obtained at 15 min of age. As a result, for each concrete, the relative values of yield stress, ... always have a value equal to 1 at 15 min.

Based on the results of all available tests, single-parameter mathematical equations (eq. 3 – 4) have been derived to describe the evolution in time.

$$\frac{YS_t}{YS_0} = \exp(A_{YS} \cdot (t - t_0)) \quad (3)$$

$$\frac{\mu'_t}{\mu'_0} = 1 + A_{\mu'} \cdot (t - t_0) \quad (4)$$

Where:

YS = yield stress

μ' = viscosity at 5/s

t = time

t_0 = reference time (15 min)

subscript “t” means at time t

subscript “0” means at 15 min

Eq. 3 and 4 are indicating respectively that the yield stress is increasing exponentially in time and that the viscosity is increasing linearly. The shear thickening (c/μ) does not show an evolution in time and is said to remain constant. As a result, the increase of the values of μ' are not influenced by shear thickening.

Differences between SP

Two different types of SP have been investigated. In Fig. 8, the time evolution of

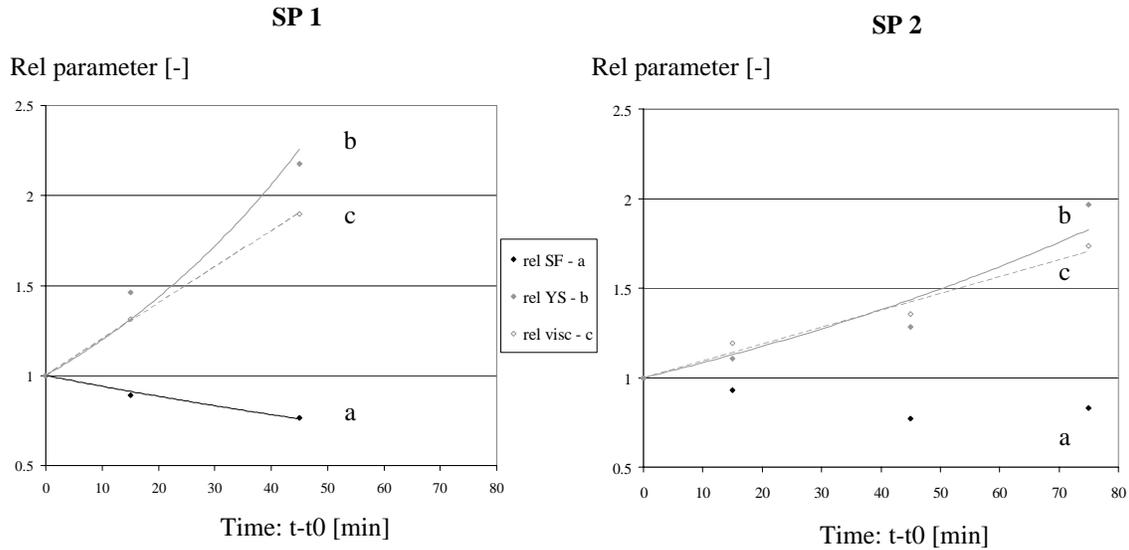


Fig. 8. Time evolution of relative yield stress (full grey line), relative viscosity (dashed grey line) and relative slump flow (black line), for SCC 1 (left) and SCC 2 (right).

the rheological parameters and the slump flow of both reference mixes (SCC 1 and SCC 2) is shown. It can be clearly seen that SCC 1, made with SP 1, is losing more rapidly its fluidity (characterised by the loss in slump flow). As a result, both the yield stress and the viscosity are increasing more rapidly compared to SCC 2.

Influence of composition and temperature

For each concrete, a different value for A_{YS} and $A_{\mu'}$ has been obtained. When the concrete has been tested at least 3 times and the correlation of the data with eq. 3 or 4 was sufficiently high, the corresponding values of A have been taken into account to investigate the influence of the composition of the concrete and the temperature on the time dependent behaviour.

The results in Table 2 indicate that for SP 1 and SP 2, the same parameters have an influence on yield stress and viscosity respectively, but the direction of the influence is in most cases completely opposite. This means that the SP act differently and they must be examined separately.

Table 2. Influence of composition and temperature on the evolution of yield stress and viscosity in time. A “+”-sign indicates that an increase of the concerning parameter causes an increase in A-value. A “-”-sign indicates the opposite. The more signs displayed, the more important is the influence of the parameter.

	SP 1		SP 2	
	A_{YS}	$A_{\mu'}$	A_{YS}	$A_{\mu'}$
W/C	++	++	--	---
SP/C	+	+	---	---
T	+++	+++		--
P	+++		++	

For SP 1, the most important parameter is the temperature, followed by the water-to-cement ratio. For SP 2, the time dependency is mostly influenced by the SP/C and the W/C amount.

Unfortunately, the irreversible time dependent rheological behaviour of SCC is not only influenced by the mentioned parameters, but also by a lot of other parameters which have not been taken into account for the analysis.

CONCLUSIONS

The rheological properties of fresh Self Compacting Concrete and the evolution in time have been tested using an adapted Tattersall Mk-II rheometer. Test results have been obtained in steady state, after elimination of thixotropy.

The results obtained 15 min after the addition of the water indicate that SCC shows slightly non-linear behaviour. As a result, the Bingham model is not applicable and the modified Bingham model has been chosen as most suitable one.

Shear thickening appears to be increasing when W/P is decreasing or when the slump flow is increasing, dependent on the type of SP and the type of filler.

Yield stress and viscosity (which is set as the inclination of the curve at a shear rate of 5/s) are rising in time exponentially and linearly respectively. Shear thickening remains constant.

Analysis of the time dependent behaviour shows the difference in workability retention between the two SP used.

The increases in yield stress and viscosity are mainly influenced by the temperature and the W/C ratio for SP 1 and by the SP/C and W/C ratio for SP 2. The effect of the main influencing parameters on the evolution of the rheological parameters is mostly opposite for SP 2 when compared to SP 1.

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