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Fresh self compacting concrete, a shear thickening material

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ABSTRACT

In literature, the rheological properties of concrete have been investigated thoroughly, resulting in a simple description, in steady state, by means of the Bingham model. Self compacting concrete shows a lower yield stress, which in some cases is very close to zero, or can even appear to be negative when extrapolating the Bingham model. In the latter case, the Bingham model is not valid and other solutions must be found.
In this paper, the non-linearity – or shear thickening – in the rheological behaviour of fresh SCC is described with the modified Bingham model, after the elimination of possible measurement artefacts. Analysis indicates that shear thickening is mainly correlated with the type of superplasticizer, the type of filler, the *W*/*P*-ratio and the slump flow of the concrete.

1. Introduction

Concrete rheology in general has been studied extensively during the last decades, resulting in a simple formulation for the rheological properties of traditional concrete, determined in steady state, namely the Bingham equation (Eq. (1)) [1,2]. The validity of this equation has been verified using different types of rheometers (BML, BTRHEOM, Tattersall two-point, Cemagref-IMG, IBB, …), and different concrete compositions [3,4].

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

where:

τ	shear stress (Pa)
τ_0	yield stress (Pa)
μ	plastic viscosity (Pa s)
$d\gamma/dt$	shear rate (1/s)

The parameters in the Bingham equation, namely yield stress and viscosity, are not constant in time, due to the development of thixotropy and loss of workability [5–7]. Thixotropy, which is an apparent increase in flow resistance during a period of no-flow, can be eliminated by decreasing the shear rate during the test, after a sufficiently long period of pre-shearing. Loss of workability, causing a permanent increase in yield stress and in plastic viscosity, can not be eliminated and can only be estimated by performing several rheological tests in time. In this paper, both the effects of thixotropy and loss of workability are not considered. Appropriate actions, which will be described further, have been undertaken to minimize the influence of these time dependent properties.

In case of self compacting concrete (SCC), due to the addition of plasticizers or superplasticizers, it is known that the yield stress is much lower, compared to traditional concrete [8]. In order to maintain the stability of the concrete – to avoid segregation – the plastic viscosity must be higher, which can be achieved in several ways (adding more fine materials, adding a viscosity modifying agent, …) [9,10]. Due to the low yield stress, deviations from the Bingham model can occur, causing an apparent negative yield stress and resulting in a non-linear relationship between shear stress and shear rate [11,12]. In Belgium and some of its surrounding countries, shear thickening effects have been observed, and as a result, the Bingham model is mostly not applicable in these cases [13,14]. Most often, this shear thickening effect is regarded as a measurement artefact and is omitted in further analysis of the rheological properties of fresh SCC [15].

In the present paper, it will be proven by means of test results that the obtained measurements are minimally influenced by the mentioned artefacts [15] and that shear thickening effect is really occurring. Also, the influence of different elements in the composition of SCC and the temperature on the shear thickening behaviour will be discussed. As a final result, this paper will provide some general trends in order to estimate variations in shear thickening, but it can not provide a correct prediction of it, due to the large sensitivity of SCC to small variations in its composing elements.

2. Materials and methods

2.1. Self compacting concrete

During the testing program, the rheological properties of more than 50 different SCC mixes have been investigated. Two different kinds of superplasticizer (SP) have been used during the testing

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Table 1
Composition of reference mixes with SP 1 and SP 2 (units in kg/m^3)

	SP 1	SP 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 1	240	240
Water	165	165
SP (l/m^3)	3	14.55

program, of which one (SP 1) is very efficient, but has a short workability retention. SP 2 is less efficient, but has a longer workability retention (of approximately 60–90 min). Both SP are polycarboxylethers, having a double working principle: electrostatic repulsion and steric hindrance [16].

All SCC contained CEM I 52.5 N, which is an ordinary Portland cement with normal hydration speed. In order to achieve a sufficiently high viscosity to avoid segregation, fillers have been added to the SCC [10]. Four different kinds of filler have been tested: two types of limestone filler, one fly ash and one silica fume. The combined mass of cement (C) and filler is named as powder (P) in this paper.

Each SCC has been produced in a batch of 55 l. The mixing procedure is as follows: Mixing all dry components (aggregates, cement and filler) during 15 s. Adding water and mixing for an additional 2 min. Finally, the SP has been added and the concrete was mixed for 3 more minutes. If the workability of the SCC was not sufficient after the first addition of SP, some extra SP has been added and the concrete has been remixed for an extra 1.5 min. The moment of water addition is the reference starting time (t_0).

The composition of the reference mixes, for both SP, is shown in Table 1, and the range of the varying parameters in the composition is shown in Table 2.

2.2. Rheometers

In order to check the validity of the results, two different rheometers have been used: the Tattersall Mk-II rheometer [1,2], of which the results are discussed in this paper, has been the main instrument for testing. The Contec Viscometer 5 [8,17] has been used as a kind of verification tool, in order to validate the results from the Tattersall Mk-II rheometer. The tests on both rheometers have been done in different locations, with different concrete mixers, resulting in the opportunity of comparing the results qualitatively, but not quantitatively for each concrete produced at the two locations.

Both rheometers are based on the principle of the coaxial cylinders [18,19]. The outer radius of the Tattersall Mk-II rheometer and the Contec Viscometer 5 is 12.5 cm and 14.5 cm respectively. The inner radius of the Contec Viscometer 5 measures 10 cm, and the height of the inner cylinder, submerged in the concrete is 16 cm [17]. For the Tattersall Mk-II rheometer, the geometry of the inner cylinder is more complicated, due to the presence of a helicoidal screw [1,2]. The horizontal distance between the two outer edges measures 16 cm, while the vertical distance is 14 cm. Both rheometers are depicted in Figs. 1 and 2 respectively.

In case of the Tattersall Mk-II rheometer, the inner cylinder rotates. The resulting flow resistance generated by the concrete in the reservoir is also measured at the inner cylinder. For the Contec Viscometer 5, the outer cylinder is rotating, and the torque is measured at the fixed inner cylinder. All cylinders are provided with ribs in order to prevent slippage between the concrete and the steel surface.

Table 2
Variation of the different elements in the composition, for each SP

		SP 1		SP 2	
		Min	Max	Min	Max
C	(kg/m^3)	250	450	300	400
P	(kg/m^3)	400	700	500	700
C/P	(–)	0.417	0.75	0.5	0.67
W	(kg/m^3)	165	192.5	133.3	186.5
W/C	(–)	0.37	0.66	0.4	0.55
W/P	(–)	0.24	0.41	0.23	0.32
SP	(l/m^3)	1.8	4.7	7	18
SP/C	(–)	0.0063	0.0131	0.0192	0.0547

Fig. 1. Tattersall Mk-II rheometer.

Fig. 2. Contec Viscometer 5.

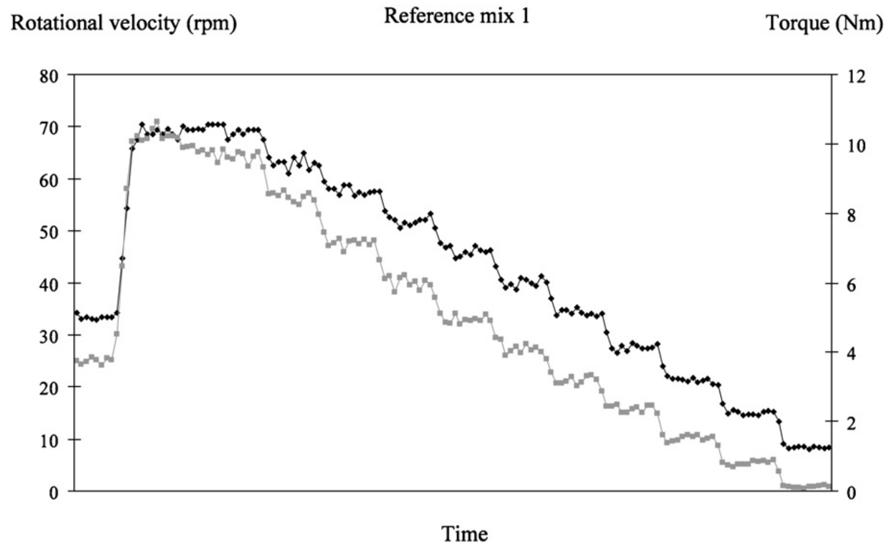

Fig. 3. Recorded rotational velocity (black) and torque data (grey) for reference mix 1 in the Tattersall Mk-II rheometer.

2.3. Testing procedure

Each concrete, if possible, has been tested at 15 min of age, which is 15 min after the water addition time (= t_0 + 15 min). Only the measurements performed at 15 min of age have been retained for further analysis, in order to eliminate the influence of the non-reversible time dependent effects (loss of workability). Thixotropy has been eliminated by stepwise decreasing the rotational velocity in the rheometers [5–7], after a sufficiently long pre-shearing period (in the order of 20 s). If the highest measuring point(s) did not reach equilibrium, it has been eliminated from the results. As a result, the data of torque and rotational velocity have been obtained in steady state. At each step, which takes 5 s, when the values of torque and rotational velocity have reached equilibrium, an average value of both parameters has been calculated.

These values of torque and rotational velocity need to be transformed into fundamental rheological units, in order to be valid for comparative purposes. For the Contec Viscometer 5, the transformation can be done by the Reiner–Riwlin equation (Eqs. (2a) and (2b)), although this transformation is only valid for Bingham materials [5].

$$\tau_0 = \frac{G}{4\pi h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right)\frac{1}{\ln\left(\frac{R_o}{R_i}\right)} \quad (2a)$$

$$\mu = \frac{H}{8\pi^2 h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \quad (2b)$$

Where:

G	'yield torque' obtained by the linear law between torque and rotational velocity (Nm)
h	height of the cylinder, submerged in the concrete (m)
R_i	inner radius (m)
R_o	outer radius (m)
H	inclination of the linear law between torque and rotational velocity (Nm s)

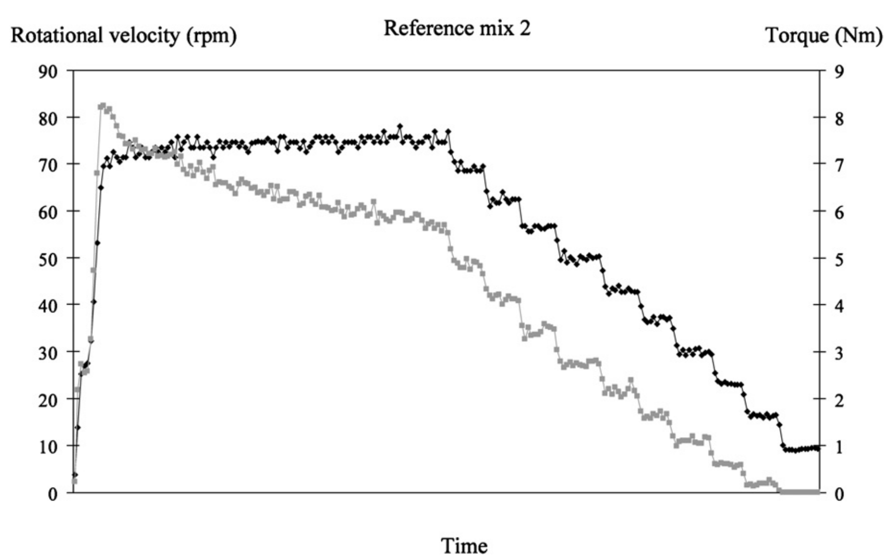

Fig. 4. Recorded rotational velocity (black) and torque data (grey) for reference mix 2 in the Tattersall Mk-II rheometer.

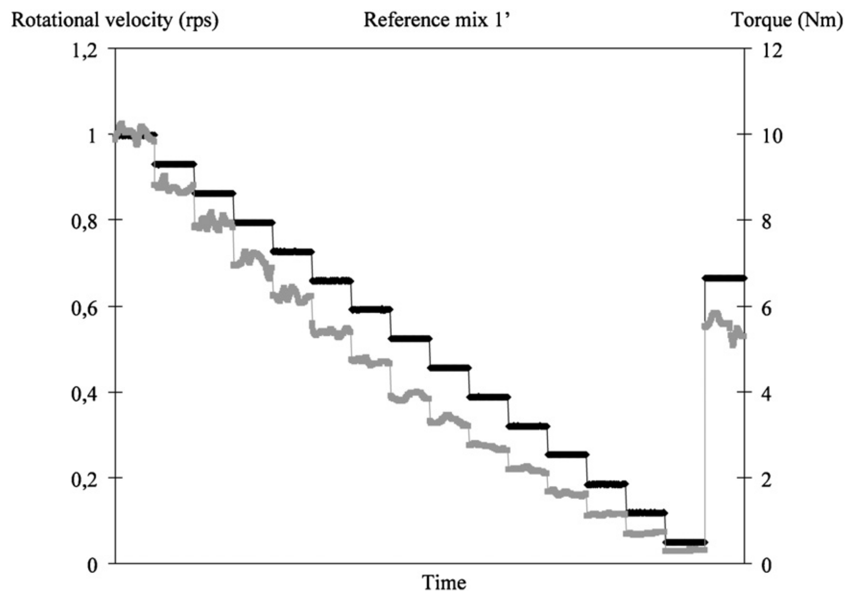

Fig. 5. Recorded rotational velocity (black) and torque data (grey) for reference mix 1′ in the Contec Viscometer 5. The pre-shearing period is not recorded.

As a result, any non-linearity in the rheological curve makes this method invalid. An extension of the Reiner–Riwlin equation for non-linear materials has been found very recently, only valid for the Herschel–Bulkley model [20]. The transformation formulae are shown in Eqs. (3)–(5).

$$\tau_0 = \frac{G_{\mathrm{HB}}}{4\pi h}\left(\frac{1}{R_{\mathrm{i}}^2} - \frac{1}{R_{\mathrm{o}}^2}\right)\frac{1}{\ln\left(R_{\mathrm{o}}/R_{\mathrm{i}}\right)} \tag{3}$$

$$K = \frac{H_{\mathrm{HB}}}{2^{2n+1}\pi^{n+1}h} n^n \left(\frac{1}{R_{\mathrm{i}}^{2/n}} - \frac{1}{R_{\mathrm{o}}^{2/n}}\right)^n \tag{4}$$

$$n = J \tag{5}$$

Where

G_{HB}, H_{HB}, J parameters predicted by Herschel–Bulkley for a T–N relationship
τ_0, K, n fundamental rheological Herschel–Bulkley parameters (Eq. (7))

For other material laws, no transformation formulae have been obtained.

In case of the Tattersall Mk-II rheometer, no transformation formulae are available due to the geometrical complexity of the inner cylinder. Instead, a calibration procedure has been carried out with oil (Newtonian liquid) and honey (Bingham liquid) in order to be able to transform torque and rotational velocity into fundamental rheological units and in order to eliminate the influence of secondary flows inside the rheometer [21].

Simultaneously to each rheometer test, the slump flow, V-funnel flow time and L-box ratio have been determined in order to verify the self compacting properties of the SCC [22].

3. Elimination of artefacts

3.1. Thixotropy

Thixotropy can disturb the measurements in two different ways: the structure level in the concrete can be too high or too low for a given shear rate [7]. In case the structure level is too high, the flow

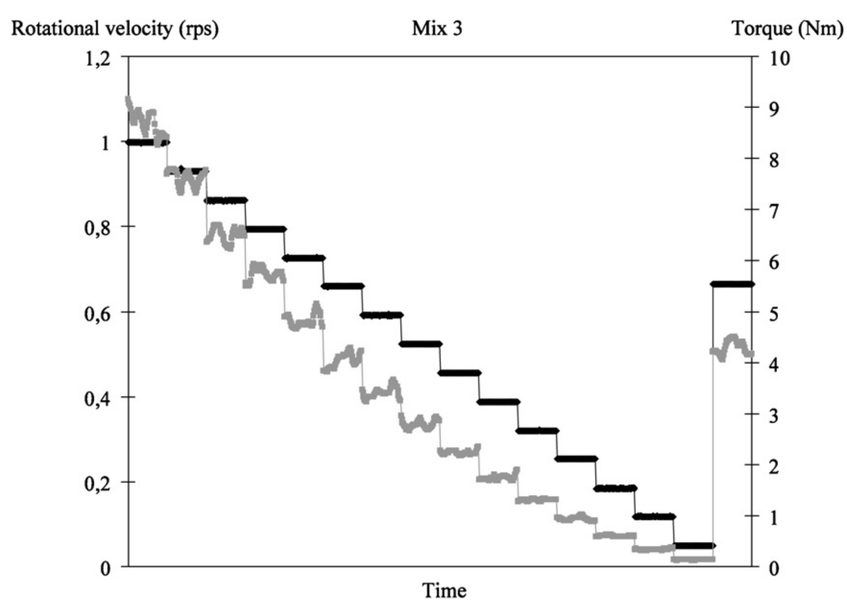

Fig. 6. Recorded rotational velocity (black) and torque data (grey) for mix 3 in the Contec Viscometer 5. The point at highest rotational velocity did not reach equilibrium, and is eliminated when analysing the results.

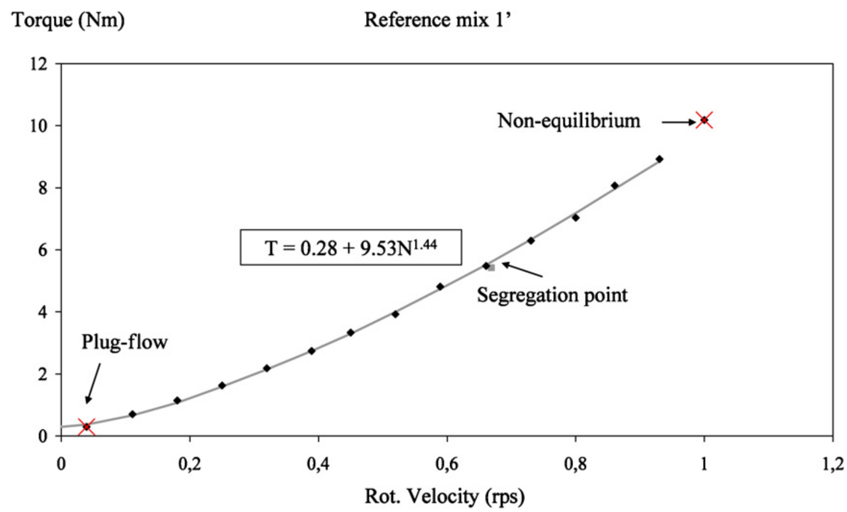

Fig. 7. Torque-rotational velocity relationship for reference mix 1′ (Contec Viscometer 5), showing no segregation.

resistance will decrease while maintaining a certain shear rate. This behaviour is mostly observed during the pre-shearing period, when starting the test. In the situation the structure level is too low, some rebuild can be obtained, which can be visible during the measurements at the lowest shear rates. Elimination of the first thixotropy phenomenon is far more important than the second one: being at too high shear stresses at higher shear rates overestimates shear thickening, but being at too low shear stresses at lower shear rates underestimates shear thickening. As it has been described in the previous section: a period of pre-shearing eliminated most of the thixotropy out of the test results, and if this was not sufficient, points not in equilibrium state have been omitted in the analysis. In Figs. 3 and 4, the time recording for the torque and rotational velocity data are shown, for reference mix 1 and 2, obtained with the Tattersall rheometer. Figs. 5 and 6 show a similar torque measurement, obtained with the Contec Viscometer 5, for reference mix 1′ (equal to reference mix 1, with a SP content of 2.83 l/m^3), and a more shear thickening mix (mix 3, with low W/P=0.236). The pre-shearing period is not visible in Figs. 5 and 6, because it has not been recorded and in these two cases, the point with the highest torque needed to be eliminated due to not reaching equilibrium.

3.2. Segregation

The elimination of segregation has only been measured with the Contec Viscometer 5. Immediately after the measuring of the point at lowest rotational velocity, the apparatus starts rotating at 2/3 of the maximal rotational velocity again (see Figs. 5 and 6). If the torque at this point is significantly lower than the obtained curve, it indicates that segregation has occurred. In Figs. 7 and 8, the relationship between torque and rotational velocity is shown for the concretes of Figs. 5 and 6, indicating no segregation in the last 2/3 of the duration of the test.

For the Tattersall Mk-II rheometer, no such point has been obtained, but it has been found that in case of very fluid SCC (and probably also segregating SCC), the Tattersall Mk-II rheometer is clearly overestimating shear thickening [23]. These results have been omitted in the analysis.

3.3. Plug flow

Plug flow occurs when the yield stress of the material is too high in order to have full shearing in the gap between the inner and outer

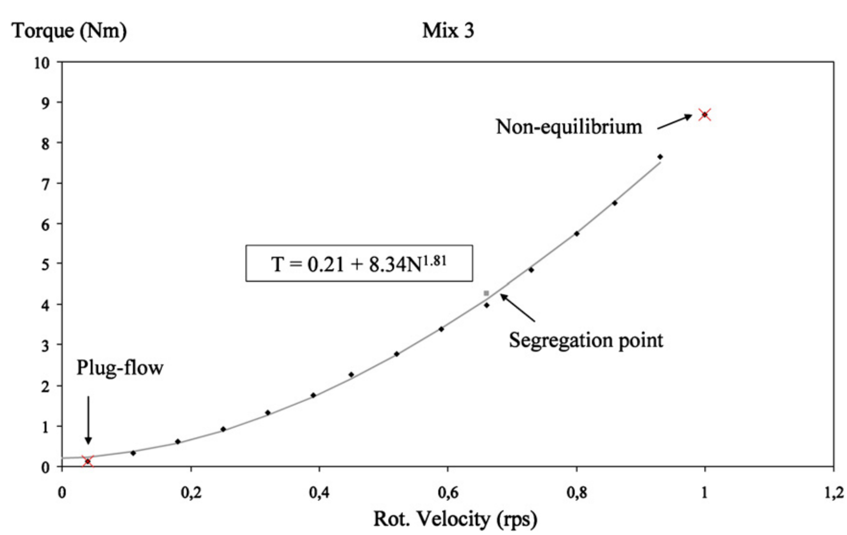

Fig. 8. Torque-rotational velocity relationship for mix 3 (Contec Viscometer 5), indicating highly shear thickening behaviour.

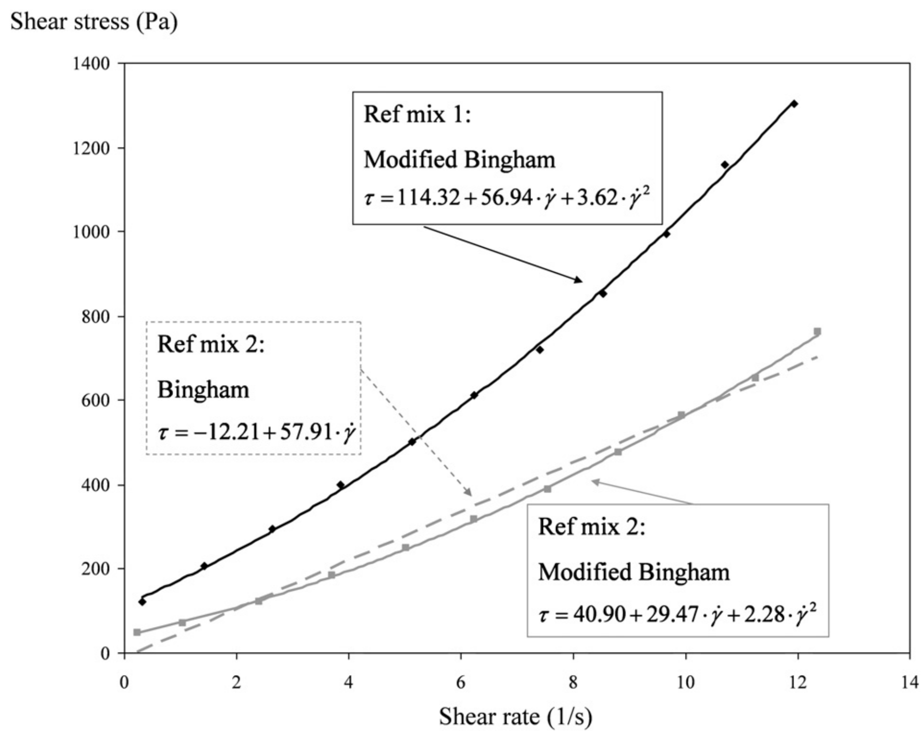

Fig. 9. Application of the modified Bingham model (full lines) on the reference mix with SP 1 (black dots) and on the reference mix with SP 2 (grey dots). Applying the Bingham model (dashed line) to the reference mix with SP 2 results in a negative yield stress. These results have been obtained with the Tattersall Mk-II rheometer.

cylinder. In the Contec Viscometer 5, for most measurements, the data point at the lowest rotational velocity occurs at plug flow. Also these points have been eliminated from the results. In case of the SCC of Figs. 7 and 8, the yield stresses are 19.49 Pa and 14.21 Pa respectively. For the data point at lowest rotational velocity (0.04 rps), the shear stress at the outer cylinder measures 13.38 Pa and 6.06 Pa respectively, indicating plug flow. The data points at 0.11 rps cause a shear stress at the outer cylinder of 32.60 Pa and 15.94 Pa respectively, indicating that at this rotational velocity, plug flow is not occurring. Elimination of this single data point does not significantly affect shear thickening behaviour, as there is a sufficient number of data points left.

For the Tattersall Mk-II rheometer, the calculation of the plug radius is much more difficult due to the complex flow pattern in the rheometer, but on the other hand, this rheometer has been calibrated with a Bingham liquid (honey), having a yield stress up to 700 Pa. The calculation of shear stress and shear rate is based on this calibration

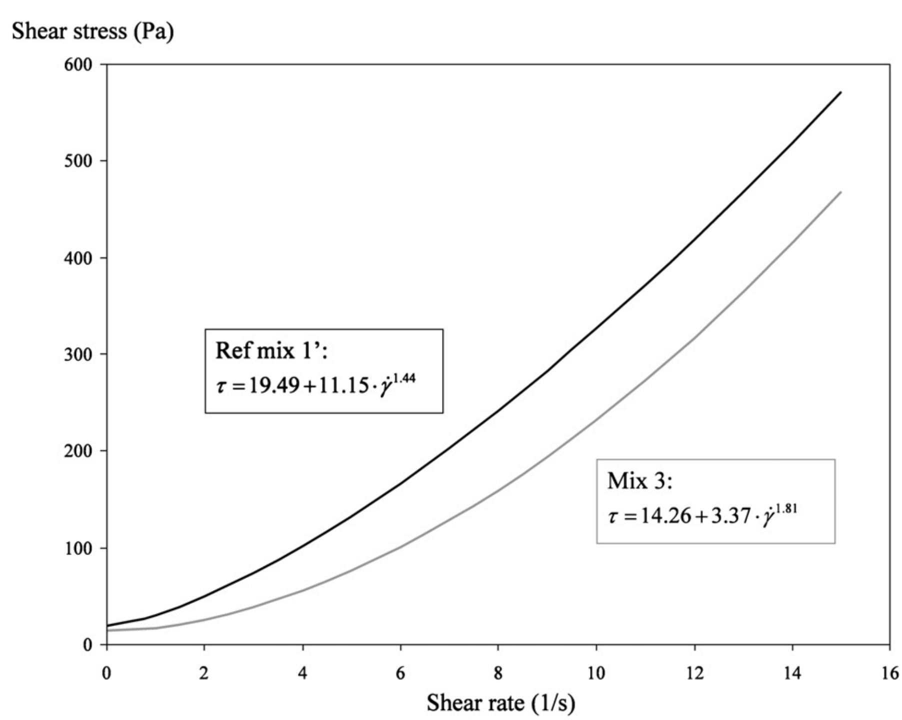

Fig. 10. Fundamental rheological data for reference mix 1′ and mix 3, obtained with the Contec Viscometer 5. The results are expressed with the Herschel–Bulkley equation, because no other transformations have been found yet.

Table 3
Absolute density (in kg/m^3) of filler materials

Limestone filler 1	2700
Limestone filler 2	2685
Fly ash	2055
Silica fume	1682

procedure [21]. In this procedure, any linear *T*–*N* relationship is transformed to a linear relationship in fundamental rheological units, and consequently, any non-linear relationship is transformed to a non-linear relationship.

4. Results and discussion

4.1. Rheological model

Application of the Bingham model (Eq. (1)) to the results obtained with the Tattersall Mk-II rheometer generates in approximately 50% of the tests, performed at 15 min of age, a negative yield stress. When investigating the rheological curves, a deviation from the linear law has been observed. The SCC tested behave as a shear thickening material. In order to be able to describe this behaviour, the modified Bingham model (Eq. (6)), being the Bingham model, extended with a second order term, has been applied [21,24].

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} + c \cdot \dot{\gamma}^2 \quad (6)$$

$$\tau = \tau_0 + K \cdot \dot{\gamma}^n \quad (7)$$

where:

c second order parameter (Pa s^2)
K consistency factor (Pa s ^{n})
n flow index (–)

This modified Bingham model is preferred to the Herschel–Bulkley (Eq. (7)) model for two reasons. The Herschel–Bulkley model contains a parameter with a variable dimension, and it has a major mathematical restriction in the region of low shear rates. The application of the modified Bingham model is justified, because the flow index *n* in Herschel–Bulkley rarely exceeds the value of 2. Mathematical analysis of the modified Bingham model indicates that the parameter c/μ is linked with the flow index *n* in Herschel–Bulkley, and as a result, this parameter describes shear thickening [13,21].

The application of the modified Bingham model on both reference mixes is shown in Fig. 9, in which the non-linearity of the rheological curves can be seen, as well as the negative yield stress for SP 2, when applying the Bingham model ($\tau_0 = -12.21$ Pa).

Similar results have been obtained with the Contec Viscometer 5, shown in Fig. 10, where the Herschel–Bulkley model necessarily needed to be applied, due to the lack of transformation formulae for other non-linear rheological models, like the modified Bingham model.

4.2. Parameters influencing shear thickening

In this section, the main parameters influencing shear thickening, being the type of filler, the *W*/*P*-ratio, the slump flow and the type of SP, will be discussed, based on the results obtained with the Tattersall Mk-II rheometer.

4.2.1. Type of filler

In total, four types of filler have been investigated, being two types of limestone filler from different suppliers (LS 1, LS 2), fly ash (FA) and silica fume (SiF). LS 1, LS 2 and FA have an approximately equal grain size distribution, while SiF has smaller grains. For each filler, the absolute density has been determined, which can be found in Table 3.

Each concrete produced contained an equal mass of aggregates, cement and water, while the volume of filler has been kept constant. The amount of SP has been adapted in order to reach an equal slump flow for the four mixes. Only SP 2 has been used to investigate the influence of the filler type.

The results shown in Fig. 11 indicate a difference between the two types of limestone filler. This could be due to a small difference in the amount of large grains. LS 2 contains a larger fraction of large grains, reducing the amount of absorbed water. As a result, the amount of free water increases, which causes a decrease in shear thickening (see Section 4.2.2).

The most striking effect is the influence of the silica fume: SCC with silica fume appears to have a much lower flow resistance (viscosity),

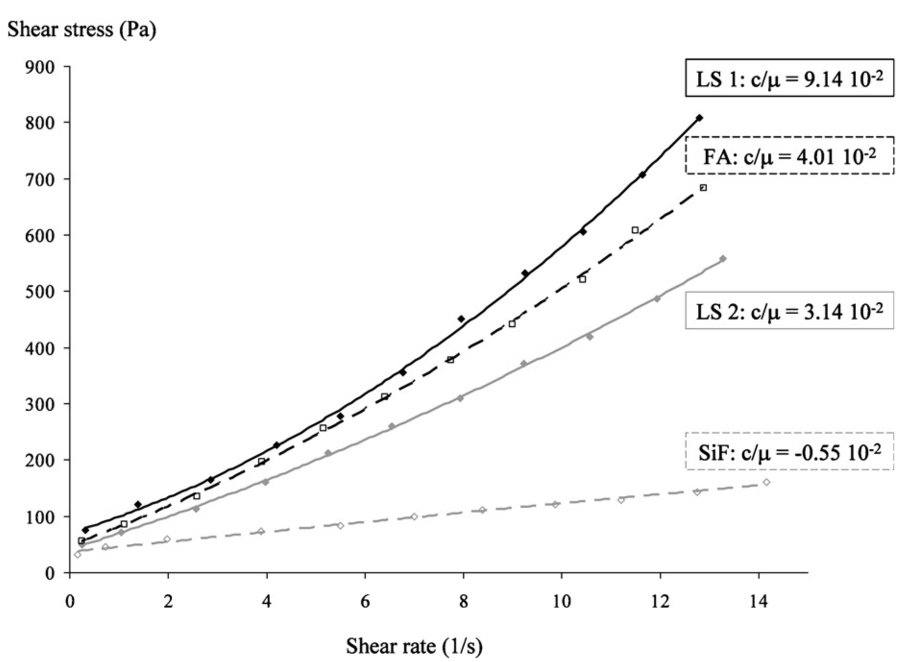

Fig. 11. Influence of filler type on shear thickening behaviour of SCC.

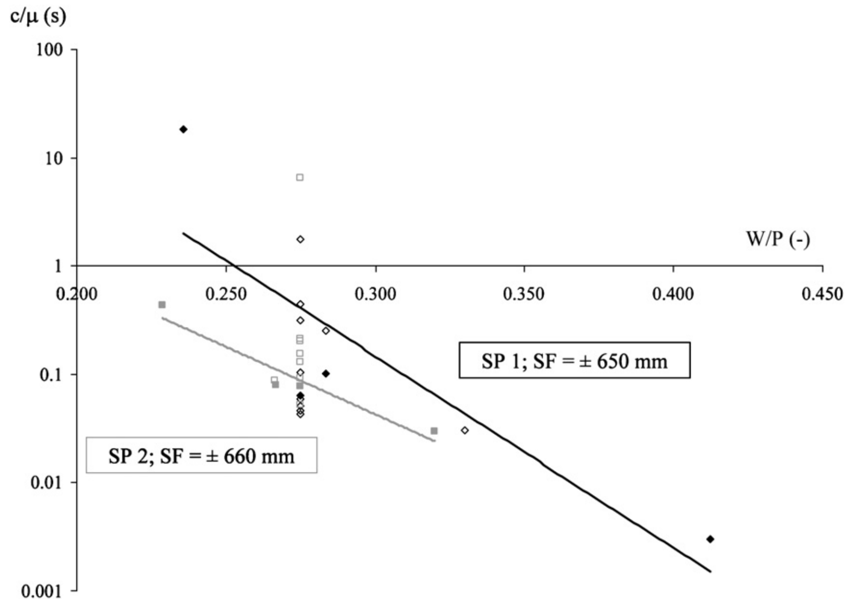

Fig. 12. Influence of *W*/*P*-ratio on shear thickening (c/μ) for SP 1 (black dots) and SP 2 (grey dots). Only the data with a slump flow approximately equal to 650 or 660 mm for SP 1 and SP 2 respectively (full dots), have been retained to determine the relationship.

and does not show any shear thickening at all. The specific reason for this behaviour is still unknown.

The application of fly ash results in a similar behaviour as for limestone filler.

4.2.2. W/P-ratio, slump flow and type of superplasticizer

Due to the significant influence of the type of filler, only the results of SCC made with LS 1 have been taken into account for further analysis. Statistical analysis shows that two main parameters are significantly correlated with shear thickening behaviour: the *W*/*P*-ratio and the slump flow.

Fig. 12 shows the effect of the *W*/*P*-ratio on the shear thickening behaviour of SCC. Due to the influence of the slump flow, only a relation is shown for the data with an approximately equal slump flow, being ±650 mm for SP 1 and ±660 mm for SP 2. Fig. 12 indicates that a decrease in *W*/*P* leads to an increase in shear thickening. The inclination of the relationship between *W*/*P* and ln (c/μ) is dependent on the type of SP, and especially for SP 1, a linear relationship between *W*/*P* and ln (c/μ) is not sufficient.

For a constant *W*/*P*-ratio, the correlation with the slump flow can be determined. In Fig. 13, the results are shown for all SCC with *W*/*P*=0.275 and with LS 1. These results indicate that shear thickening is increasing when the slump flow is increasing, dependent on the type of SP.

Specific tests performed with LS 1 and LS 2, a *W*/*P*=0.275 and made with SP 2 show similar results. A higher slump flow is related to a higher amount of shear thickening. This can be seen in Fig. 14.

Traditional concrete contains no filler material and as a consequence, it has a higher *W*/*P*-ratio. TC has also a very low slump flow (actually, it is not a slump flow anymore), and as a result, it should not

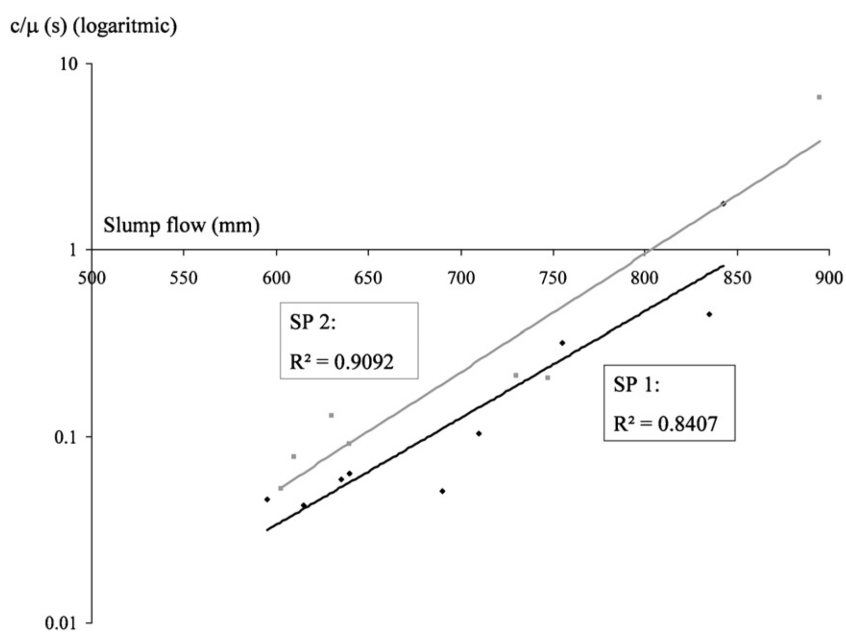

Fig. 13. Influence of slump flow on shear thickening (c/μ), for SP 1 (black) and SP 2 (grey), for SCC with a *W*/*P*-ratio equal to 0.275.

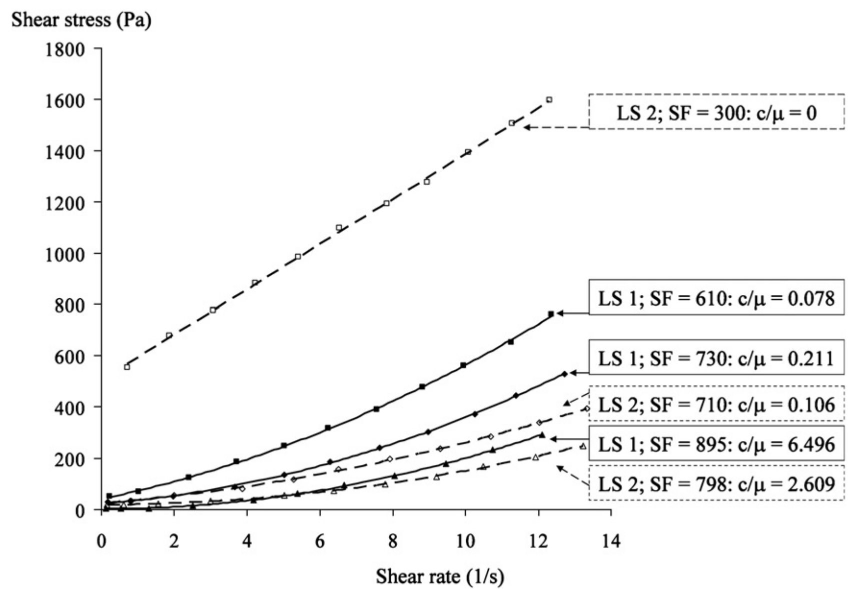

Fig. 14. Influence of slump flow (SF) on shear thickening behaviour for SCC with LS 1 (full) and LS 2 (dashed).

show any shear thickening at all. Tests performed on 3 TC, with different *W*/*C* (=*W*/*P*) ratios, confirm the theory: no shear thickening has been observed.

The authors would like to remark that the slump flow shows a much larger correlation with shear thickening compared to the amount of SP, possibly related to the cement or powder amount. Further analysis indicates also that there is no clear relation between the slump flow and the amount of SP added, or between the parameters SP/*C* or SP/P. The slump flow cannot be predicted based on the amount of SP, but on the other hand, an increase in the amount of SP causes a increase in slump flow.

4.2.3. Other parameters

Further analysis indicates the (smaller) influence of some other parameters. The grain size distribution, which has been investigated in this research project by substituting all gravel 2/8 by gravel 8/16, creating a gap graded grain size distribution, influences the shear thickening behaviour. Less gravel 2/8 results in lower shear thickening. This could be explained in a similar way as for the two types of LS: a lower content of small aggregates increases the amount of free water, resulting in a decrease in shear thickening.

Other influencing parameters are dependent on the type of SP. Shear thickening increases slightly, in case of SP 1 when the powder amount (*P*) is decreasing and when temperature is increasing. An increase in *C*/*P*-ratio for SP 2 leads to a small increase in shear thickening.

5. Conclusions

The results of testing SCC with the Tattersall Mk-II rheometer and the Contec Viscometer 5 at an age of 15 min after the addition of the water, indicate that the rheological curve, determined after elimination of possible measurement artefacts (thixotropy, loss of workability, segregation and plug flow), is not linear, resulting in apparently negative yield stresses when the Bingham model is applied.

Extending the Bingham model with a second order term, resulting in the modified Bingham model, delivers a tool to describe the shear thickening behaviour of fresh SCC, by means of the parameter c/μ.

From this research, it is clear that shear thickening behaviour is mainly influenced by the type of filler and the type of superplasticizer. The increase in shear thickening behaviour is significantly related with a decrease in *W*/*P*-ratio and an increase in slump flow. Other parameters have a smaller effect on the shear thickening.

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