The Rheological Behaviour of Fresh Self-Compacting Concrete in the High Shear Rate Range

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Abstract. Fresh Self-Compacting Concrete is generally accepted to be a Bingham material in steady state conditions, at least, in the shear rate range applicable for regular casting operations except mixing and pumping. On the other hand, it is known from the general rheology literature that the rheological characteristics change depending on the shear rate range applied, even when not considering any transient flow conditions.

In order to investigate the behaviour of Self-Compacting Concrete during pumping, the standard shear rate range has been extended in rheometer tests executed in the laboratory. The results indicate a new region with different rheological characteristics: SCC shows shear thickening behaviour. This paper describes the different measurement artefacts which can lead to apparent, but not real shear thickening behaviour. Further it focuses on the influence of the mixture composition on the critical shear stress where shear thickening starts. Also attention is paid to the intensity of shear thickening as a function of the mixture composition.

Introduction

From a rheological point of view, fresh concrete is in literature generally described as a Bingham liquid [1, 2]. The Bingham model consists of two parameters, namely the yield stress, which is the stress that needs to be exceeded to initiate flow, and the plastic viscosity, describing the inclination of the shear stress - shear rate curve. Self-Consolidating Concrete (SCC) is generally characterized by a lower yield stress and a slightly higher plastic viscosity, compared to Conventional Vibrated Concrete (CVC) [2]. In some specific cases for SCC, a third parameter is included in the rheological model to describe non-linear, shear thickening behaviour. This parameter is the power "n" of the shear rate in case of Herschel-Bulkley (Eqn. 1) [3-6], or the second order term in the shear rate for the modified Bingham model (Eqn. 2) [6, 7]. The Bingham model is obtained for $n = 1$ or $c = 0$ in the Herschel-Bulkley and modified Bingham model respectively.

$$\tau = \tau_0 + K\dot{\gamma}^n \qquad (1)$$

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

In colloidal science, the rheological properties of suspensions are studied over several orders of magnitudes of shear rates [8-10]. In this large range of shear rates (or shear stresses), the viscosity can remain constant (representing Newtonian or Bingham fluids), it can decrease or increase with increasing shear rate, indicating shear thinning or shear thickening respectively (Fig. 1) [8-10]. Shear thickening is described by the critical shear stress, at which shear thickening starts [10], and the intensity, which is reflected by the ratio of the shear thickening parameter to the viscous term in the rheological model (the power n in Herschel-Bulkley or the c/μ in the modified Bingham model).

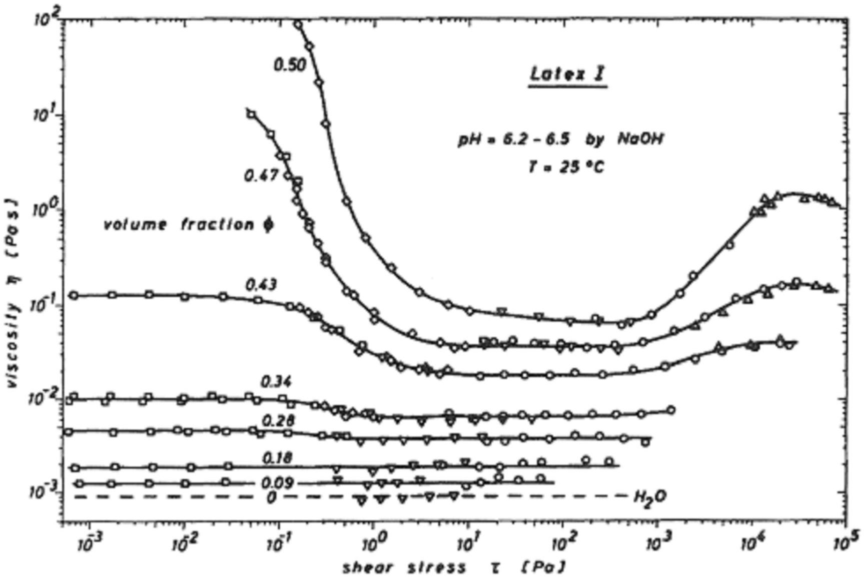

Figure 1. Behaviour of 250 nm latex particle-suspensions at different volume fractions. Following the curve for φ = 0.43, one can observe Newtonian behaviour until a shear stress of 0.1 Pa, shear thinning between 0.1 and 10 Pa, a Bingham plateau between 10 and 1000 Pa and shear thickening from 1000 Pa on. Note that the graph expresses apparent viscosity as a function of shear stress. Figure from [8].

This paper investigates the shear thickening behaviour of different SCC mixtures, after a description of the different measurement artefacts which can lead to an erroneous conclusion of shear thickening. The paper includes an overview of the most important parameters influencing the critical shear stress and the intensity of shear thickening. It is important to note that it is not necessary to investigate the rheological behaviour of concrete over a large range of shear rates, as it is done for colloidal suspensions. In normal applications of concrete, shear rates vary between 0 and 5, maximum 10/s [11]. Only in case of mixing, pumping and extrusion, higher shear rates can be observed, justifying the extension of the shear rate range studied.

Experimental research

Concrete compositions

More than 50 concrete mixtures were employed in this study. In most cases, the concretes were produced with rounded aggregates with a maximum size of 16 mm, river sand, ordinary Portland cement (CEM I 52.5 N), limestone filler (from two different suppliers) and water. Two different PCE superplasticizers (SP) were used, one with a short workability retention (SP 1), the other having a long retention (SP 2). Some mixtures were produced with fly ash or silica fume as filler materials. No VMA was employed. Table I shows the reference concrete composition, while Table II shows the maximum variations in composition of the concretes.

Table I. Mix design of reference mixtures (units in kg/m^3).

	REF 1	REF 2
Gravel 8/16	434	434
Gravel 2/8	263	263
Sand 0/4	853	853
CEM I 52.5 N	369	369
Limestone filler 1	240	240
Water	164	164
SP (l/m^3)	3 (SP 1)	14.55 (SP 2)

Table II. Range of parameters tested during the experimental program.

		Mixtures with SP 1		Mixtures with SP 2	
		Min	Max	Min	Max
Cement (C)	(kg/m^3)	250	450	300	400
Powder (P)	(kg/m^3)	400	700	500	700
C/P	(-)	0.417	0.75	0.5	0.67
Water (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	7.0	18.0
SP/C	(-)	0.0063	0.0131	0.0192	0.0547

The concretes were produced in 55 liter batches with a forced pan mixer. The dry components were mixed for 15 seconds, before water addition. After water addition, the concrete was mixed for 2 minutes, followed by the addition of the SP and 3 minutes of mixing. The fluidity was verified visually or by means of slump flow, and if necessary, an extra amount of SP was added to enhance the fluidity. At 15 min of age (relative to the water adding time), the slump flow, V-funnel flow time and L-box filling ability were measured and the steady-state rheological properties were evaluated by means of a concrete rheometer.

Concrete rheometers

The rheological parameters were determined using two different concrete rheometers: The ConTec Viscometer 5 and the Tattersall Mk-II rheometer. Both rheometers are based on the principle of the coaxial cylinders.

ConTec Viscometer. In the ConTec Viscometer (Fig. 2), the outer cylinder (R_o = 14.5 cm) rotates, while the inner cylinder (R_i = 10.0 cm) remains stationary [2]. The concept of the ConTec Viscometer eliminates the influence of the bottom effect on the results [12], as the torque measurements (T) are only conducted at the upper part of the inner cylinder (h = 12-13 cm). After a pre-shearing period of 30 seconds, the rotational velocity (N) is decreased from 1 rps to 0.04 rps in 15 steps of 5 seconds each. The obtained relationship between torque and rotational velocity was transformed into the Bingham or Herschel-Bulkley parameters by means of the Reiner-Riwlin equations [2, 11, 12].

Figure 2. Left: ConTec Viscometer. Right: Tattersall Mk-II rheometer.

Tattersall Mk-II rheometer. This rheometer has a stationary outer cylinder (R_o = 12.5 cm) and a rotating inner cylinder equipped with blades in the form of an interrupted helical screw (Fig. 2) [1]. The distances between the outer edges of the blades are 16 cm in horizontal direction and 14 cm in vertical direction. The rotational velocity is decreased from 80 rpm to 8 rpm in 11 steps of each 5 seconds. As the operation is manual, the pre-shearing period is determined by the operator. The data are transformed according to a calibration procedure. A comparative study has shown that the differences in obtained results between the ConTec Viscometer and the Tattersall Mk-II are small, especially when considering shear thickening [13].

Measurement artefacts

Thixotropy

As fresh concrete shows transient rheological behaviour, it is necessary to eliminate this effect to characterize the steady-state rheological properties. After a sudden increase in shear rate, thixotropy causes a decrease in stress with time at a constant shear rate (breakdown) [14]. As a result, if the equilibrium has not been reached, the shear stress at a certain shear rate is overestimated and the obtained non-linearity in the T-N curve is not the real material parameter. After a sudden decrease in shear rate, the shear stress increases with time at constant shear rate (rebuild), but generally at a slower rate than the breakdown.

In order to avoid the influence of thixotropy on the measured steady-state properties [15], it is advised to bring the concrete first in its reference state [16], corresponding to the highest shear rate applied. This can be achieved by applying the highest shear rate for a sufficiently long time in order to achieve the equilibrium shear stress. When decreasing the shear rate, the rebuild is not awaited, resulting in short steps. In the ConTec Viscometer, the pre-shearing period at the highest rotational velocity is 30 seconds. Verification of the equilibrium conditions of each step reveals whether equilibrium has been achieved. Data obtained that are not in equilibrium are eliminated from the results. During the tests with the Tattersall Mk-II rheometer, the operator observes the decrease in shear stress and can decide to start the test (manually) once equilibrium has been achieved.

Segregation and particle migration

When aggregates move away from the shearing zone [17], the resulting concrete or mortar has lower rheological properties. If this migration occurs entirely before the acquisition of the test data (e.g. in the pre-shearing period), the results obtained are those of the mortar. If this migration occurs during the test, the data are very difficult to interpret, as the properties of the tested material continuously vary. Segregation and particle migration are hard to avoid, as they are intrinsic material properties. One of the solutions to restrict their influence is to shorten shearing times, both the pre-shearing time and the measuring time at each step. Due to thixotropy, pre-shearing times cannot be chosen to be too short, but the duration for each step when decreasing the rotational velocity, is restricted to five seconds.

Particle migration during the test can be detected with the ConTec Viscometer, as after the test, the device imposes 2/3 of the maximum rotational velocity and measures the corresponding torque, which is the so-called segregation point. If the resulting torque is significantly different from the test data, segregation occurred during the test and the results should be omitted. Visual observation during and after testing (when emptying the concrete reservoir) can also indicate whether segregation has occurred.

Plug flow

In coaxial cylindrical rheometers, the shear stress decreases in the gap between the cylinders. If at a certain point in the gap, the shear stress is smaller than the yield stress of the material, no shearing will occur. As a result, the shearing is concentrated in a smaller zone, and not over the entire gap. In this case, the Reiner-Riwlin transformation procedure needs to be corrected, as in the equations R_o must be replaced by R_p, with R_p being the plug radius, which is the boundary between the sheared and the unsheared zone. The correction for the plug flow can only be done in an iterative way, as the plug radius is dependent on the (unknown) yield stress. Incorporation of points in plug flow will lead to an underestimation of shear thickening and can possibly result in apparent shear thinning behaviour.

In case of the ConTec Viscometer, the gap is rather small and for SCC, the ratio of yield stress to plastic viscosity is not elevated. In this case, the incorporation of data in plug flow will not have a significant influence on the obtained results. On the other hand, in this analysis, the data in plug flow have been eliminated from the results. The Tattersall Mk-II rheometer has been calibrated with a Newtonian and a Bingham liquid. The influence of plug flow is consequently incorporated in the transformation procedure.

Parameters influencing shear thickening

In this section, the influence of several parameters related to the concrete composition on shear thickening are discussed. The shear thickening behaviour is described by two properties: the critical shear stress, at which shear thickening starts and the intensity of shear thickening, which is the curvature of the relationship between shear stress and shear rate (Fig. 3). The intensity is described by the parameter "n" of Herschel-Bulkley or the ratio c/μ of the modified Bingham model.

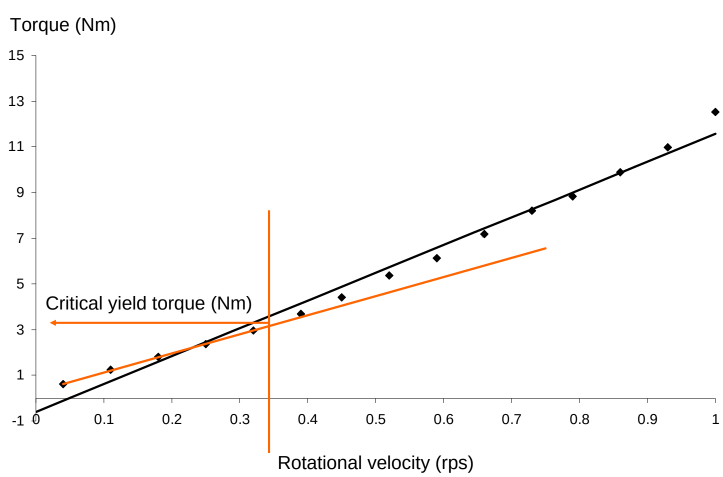

Figure 3. The critical yield stress (yield torque in a T-N diagram) is defined as the point where the Bingham relationship at low rotational velocities is no longer valid.

Cement paste

Fig. 4 shows the apparent viscosity (shear stress divided by shear rate) for a conventional cement paste and a self-consolidating cement paste, tested in a small coaxial cylinder rheometer. The conventional paste was produced with cement and water, at a w/c = 0.5. The self-consolidating paste was produced with cement, limestone filler, water and SP 1, according to the reference SCC-mixture presented in Table I. As can be seen, the conventional cement paste does not show any shear thickening in the shear rate range tested, while for the self-consolidating paste, the apparent viscosity increases from shear rates larger than 12/s. As a result, shear thickening is an intrinsic property of the self-consolidating paste.

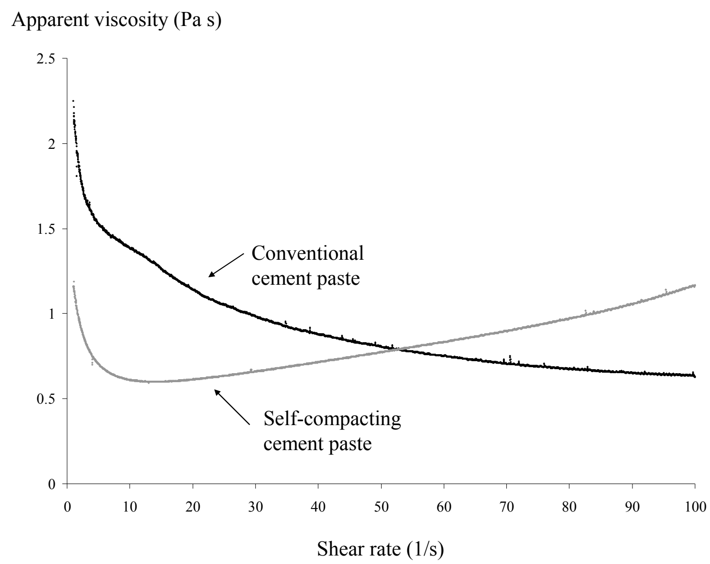

Figure 4. Apparent viscosity (shear stress/shear rate) as a function of shear rate, showing shear thickening in case of self-consolidating paste and no shear thickening in case of conventional paste. The critical shear stress corresponds to the minimum in apparent viscosity.

Slump flow – Superplasticizer content

Considering all results with equal w/p, the intensity of shear thickening increases and the critical shear stress decreases with increasing slump flow. The relationship between the intensity of shear thickening and the slump flow is dependent on the SP-type used, as can be seen in Fig. 5. Fig. 6 shows the result of four SCC mixtures with only a different content in SP, confirming the stated observations. This effect can be caused by an enhanced availability of colloidal cement particles due to the dispersing effect of the SP.

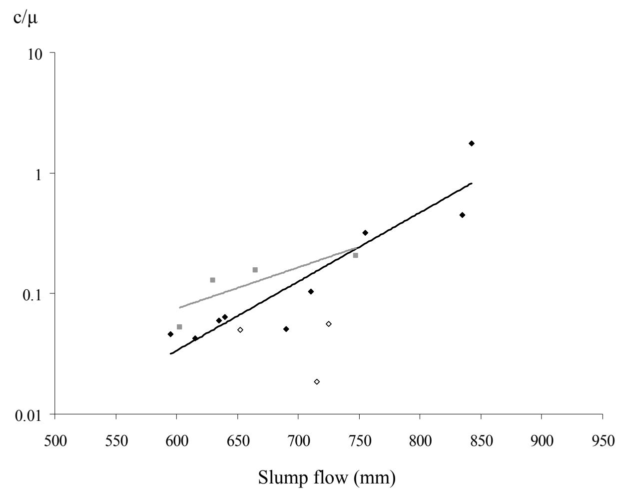

Figure 5. The intensity of shear thickening (c/μ) increases with increasing slump flow. Results for w/p = 0.275.

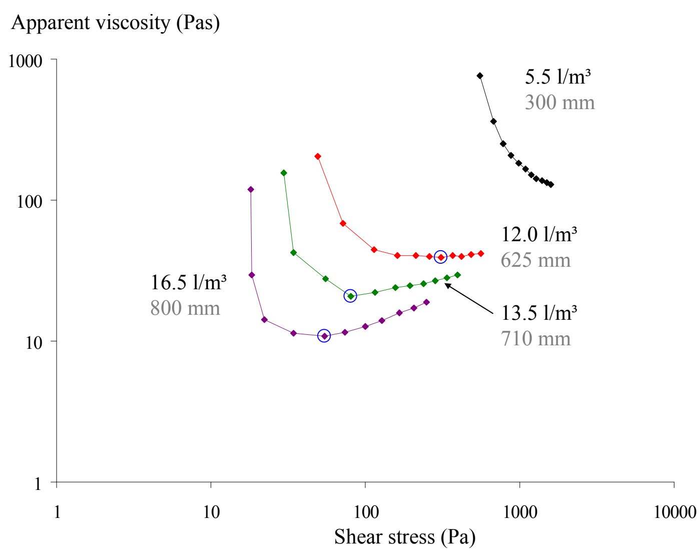

Figure 6. Apparent viscosity as a function of shear rate for four SCC mixtures with different SP-contents. The blue circles indicate the critical shear stress (lowest apparent viscosity) and the inclination of the curve indicates the intensity of shear thickening.

Water-to-powder ratio

Decreasing the water-to-powder ratio (in which powder is defined as cement + filler), results in a larger intensity for shear thickening. Fig. 7 shows all results for both SP. The solid points in Fig. 7 represent data with a slump flow of approximately 650 mm. The increase in intensity of shear thickening is probably due to the increase in the ratio between volume fraction and maximum volume fraction of solid materials. Note that at only very low w/p, shear thickening starts to have a significant effect. The values of the exponent of Herschel-Bulkley, observed in this project varied mainly between 1 and 1.4, but for mixtures with very low w/p, “n” increased up to 1.8 and 1.9.

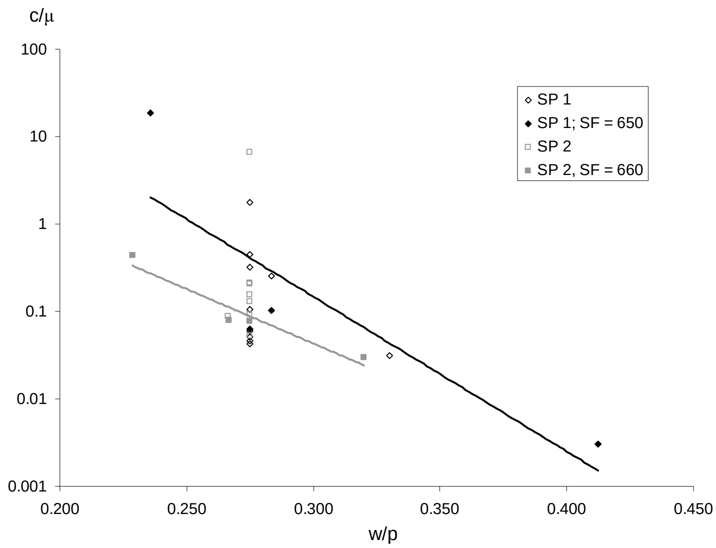

Figure 7. The intensity of shear thickening decreases with increase w/p.

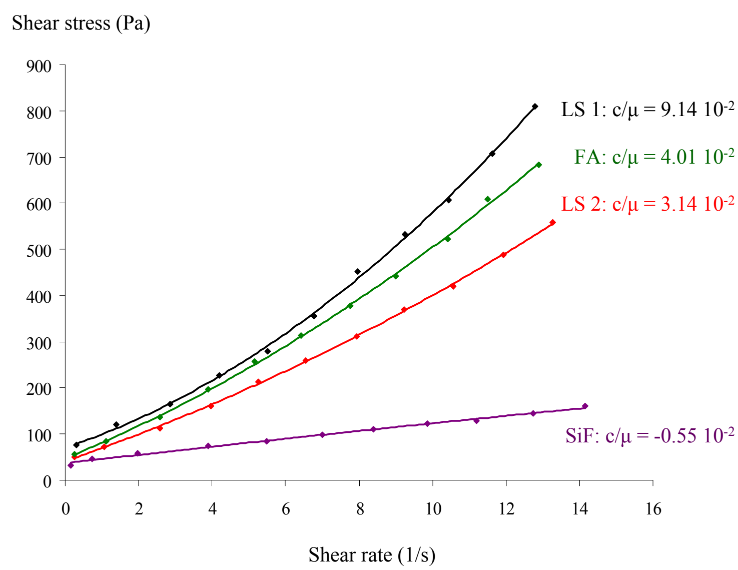

Figure 8. The SCC mixture with silica fume (SiF) shows no shear thickening, while the other mixtures with limestone filler (LS) and fly ash (FA) do.

Fillers

Applying different filler materials in the SCC results in different shear thickening behaviour. Fig. 8 represents the rheological curves for four different SCC with two limestone filler, fly ash and silica fume. The volume of filler was kept constant. The result of SCC with silica fume deviates significantly from the other results as no shear thickening was observed. This can be attributed to an increased maximum volume fraction, or to the low shear stress applied. The maximum shear stress applied to the silica fume mixture is approximately half of the critical shear stress of the other mixtures.

Conclusions

In the range of higher shear rates, which occur mainly during mixing and pumping, SCC shows shear thickening behaviour. Shear thickening can be described by two parameters, the intensity ("n" or "c/μ") and the critical shear stress. If the critical shear stress is not exceeded, which corresponds to normal applications of concrete, no shear thickening is observed.

The intensity of shear thickening increases with increasing slump flow and decreasing w/p. The critical shear stress decreases with increasing w/p. Both parameters are affected by the type of SP and type of filler applied. It is also concluded that shear thickening is an intrinsic property of the cement paste.

Measurement artefacts can lead to an erroneous conclusion on shear thickening behaviour. If due to thixotropic breakdown, no equilibrium is reached, shear thickening will be overestimated. Segregation and particle migration can lead to changing rheological properties of the material during measurements, making the results very difficult to interpret and can lead to an overestimation of shear thickening. Plug flow occurs when the sample is not sheared entirely in the gap, and can lead to an underestimation of shear thickening. For the concrete rheometers applied in this experimental program, especially thixotropy and particle migration can influence the obtained results.

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References

[1] Tattersall, G.H. and Banfill, P.F.G. (1983), The Rheology of Fresh Concrete, Pitman, London.

[2] Wallevik, O.H. (2003), Rheology – a Scientific Approach to Develop Self-Compacting Concrete, Proc. of the 3rd Int. Symp. on SCC, Reykjavik, pp. 23-31.

[3] de Larrard, F., Ferraris, C.F. and Sedran, T. (1998), Fresh Concrete: A Herschel-Bulkley Material, *Mat. Struct*., vol. 31, pp. 494-498.

[4] Cyr, M., Legrand, C. and Mouret, M. (2000), Study of the Shear Thickening Effect of Superplasticizers on the Rheological Behaviour of Cement Pastes Containing or not Mineral Additives, *Cem. Conc. Res*., vol. 30, pp. 1477-1483.

[5] Heirman, G., Vandewalle, L. and Van Gemert, D. (2008), An Analytical Solution of the Couette Inverse Problem for Shear Thickening SCC in a Wide-Gap Concentric Cylinder Rheometer, *J. non-Newt. Fluid Mech.*, vol. 150, pp. 93-103.
[6] Feys, D., Verhoeven, R. and De Schutter, G. (2008), Fresh Self Compacting Concrete: a Shear Thickening Material, *Cem. Conc. Res.*, vol. 38, pp. 920-929.
[7] Yahia, A. and Khayat, K.H. (2001), Analytical Models for Estimating Yield Stress of High-Performance Pseudoplastic Grout, *Cem. Conc. Res.*, vol. 31, pp. 731-738.
[8] Laun, H.M. (1984), Rheological Properties of Aqueous Polymer Dispersion, *Angew. Makromol. Chem.*, vol. 123, pp. 335-359.
[9] Bossis, G. and Brady, J.F. (1989), The Rheology of Brownian Suspensions, *J. Chem. Phys.*, vol. 91, n. 3, pp. 1866-1874.
[10] Bender, J. and Wagner, N.J. (1996), Reversible Shear Thickening in Monodisperse and Bidisperse Colloidal Suspensions, *J. Rheol.*, vol. 40, n. 5, pp. 899-916.
[11] Wallevik, O.H. and Geiker, M.R. (Eds.) (2007), Rheology of Cement Based Materials, Notes of the DTU-RILEM course, Lyngby.
[12] Wallevik, J.E. (2003), Rheology of Particle Suspensions, Fresh Concrete, Mortar and Cement Paste with Various Types of Lignosulphonates, Ph-D Thesis, The Norwegian University of Science and Technology, Trondheim.
[13] Feys, D., Heirman, G., De Schutter, G., Verhoeven, R., Vandewalle, L. and Van Gemert, D. (2007), Comparison of Two Concrete Rheometers for Shear Thickening Behaviour of SCC, Proc. of the 5th Int. Symp. on SCC, Gent, pp. 365-370.
[14] Barnes, H.A. (1997), Thixotropy – A Review, *J. non-Newt. Fluid Mech.*, vol. 70, pp. 1-33.
[15] Geiker, M.R., Brandl, M., Thrane, L.N., Bager, D.H. and Wallevik, O.H. (2002), The Effect of Measuring Procedure on the Apparent Rheological Properties of Self-Compacting Concrete, *Cem. Conc. Res.*, vol. 32, pp. 1791-1795.
[16] Roussel, N. (2006), A Thixotropy Model for Fresh Fluid Concretes: Theory, Validation and Applications, *Cem. Conc. Res.*, vol. 36, pp. 1797-1806.
[17] Ovarlez, G., Bertrand, F. and Rodts, S. (2006), Local Determination of the Constitutive Law of a Dense Suspension of Non-Colloidal Particles through MRI, *J. Rheol.*, vol. 50, pp. 259-292.