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# Evaluation of Time Independent Rheological Models Applicable to Fresh Self-Compacting Concrete

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**Abstract:**
Self-Compacting Concrete is a new type of concrete which is more liquid compared to traditional concrete and which does not need any form of external compaction. As a result this type of concrete is suitable for a new placing technique: pumping SCC from the bottom in the formwork and letting it rise in the formwork due to the applied pressure. In order to understand the phenomena occurring during pumping operations, the rheological properties of SCC must be investigated and controlled. Tests have been performed with two different rheometers, which are described in this paper. For the Tattersall Mk-II rheometer, a calibration procedure has been worked out to eliminate secondary flows in the rheometer. Test results indicate that SCC is a thixotropic liquid, having a yield stress, showing shear thickening and having varying properties in time due to the occurring chemical reactions. In this paper, the time dependent effects will not be described. When trying to apply a rheological model to the obtained results, only the modified Bingham model seems appropriate. Applying the Bingham model results in the generation of negative yield stresses while the Herschel-Bulkley model has a parameter with a variable dimension and has a major mathematical restriction. The rheological properties of fresh SCC can be described with the modified Bingham model. A suitable parameter to describe shear thickening is defined as the ratio of the second order term in the shear rate of the modified Bingham model to the linear term (= $c/\mu$).

**Zusammenfassung:**
Selbstverdichtender Beton (SCC) ist eine neue Form von Beton, die flüssiger ist als traditioneller Beton und keine Art von externer Verdichtung benötigt. Daher ist dieser Typ von Beton für eine neue Betoniertechnik geeignet: Pumpen des SCC vom Boden der Schalung und Aufsteigen des Betons in der Schalung aufgrund des auferlegten Druckes. Um die Phänomene zu verstehen, die während des Pumpens auftreten, müssen die rheologischen Eigenschaften von SCC verstanden und kontrolliert werden. Tests wurden mit Hilfe zweier unterschiedlicher Rheometer durchgeführt, die in diesem Artikel beschrieben werden. Für das Tattersall Mk-II-Rheometer wurde ein Kalibrationsverfahren ausgearbeitet, um die sekundären Strömungen im Rheometer zu eliminieren. Die Testergebnisse zeigen, dass SCC eine thixotrope Flüssigkeit mit einer Fliessgrenze ist, Scherverdickung aufweist und zeitlich variierende Eigenschaften aufgrund der auftretenden chemischen Reaktionen besitzt. In diesem Artikel werden die zeitabhängigen Phänomene nicht beschrieben. Beim Versuch, die erhaltenen Resultate durch ein rheologisches Modell zu beschreiben, erschien nur das modifizierte Bingham-Modell adäquat. Die Anwendung des Bingham-Modells führte zu negativen Fliessspannungen, während das Herschel-Bulkley-Modell einen Parameter mit variabler Dimension und eine grössere mathematische Einschränkung besitzt. Die rheologischen Eigenschaften von einem „frischen“ SCC können durch das modifizierte Bingham-Modell beschrieben werden. Ein geeigneter Parameter, um die Scherverdickung zu beschreiben, ist das Verhältnis des Terms zweiter Ordnung in der Schergeschwindigkeit des modifizierten Bingham-Modells zu dem linearen Term (=$c/\mu$).

**Résumé:**
Le béton autoplaçant est un nouveau type de béton qui est plus fluide, comparé avec le béton traditionnel. Ce béton n'a pas de besoin d'une autre source de compaction que de la gravité. Pour cela, ce type de béton est approprié pour un nouveau moyen de placement: le béton est pompé au dessous du coffrage et monte à cause de la pression appliquée. Pour mieux comprendre le comportement du béton pendant le pompage, les propriétés rhéologiques de ce béton doivent être étudiées. Des essais avec deux rhéomètres différents, décris dans cet article, ont été effectués. Pour le rhéomètre Tattersall Mk-II une procédure de calibration est proposée afin d' éliminer les courants secondaires dans le rhéomètre. Les essais indiquent que le béton autoplaçant est un liquide thixotropique, ayant un seuil de cisaillement, de la dilatation et des propriétés variantes dans le temps causées par des réactions chimiques. Dans cet article, seulement les effets indépendants du temps seront décrits. En appliquant des modèles rhéologiques, seulement le modèle Bingham modifié (modified Bingham model) semble utilisable. Le modèle Bingham genère des seuils de cisaillement négatifs et le modèle Herschel-Bulkley contient un paramètre avec une dimension variante et une grande réstriction mathématique. La dilatation peut être decrite par le quotient des termes quadratiques et linéaires dans l'équation du modèle Bingham modifié (= $c/\mu$).

**Key words:** concrete, self-compacting concrete, Tattersall rheometer, Bingham model, Herschel-Bulkley model

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## 1 INTRODUCTION

When casting traditional concrete in a formwork, a high amount of air is entrained and must be removed in order to obtain the desired properties in hardened state, in terms of strength and durability. As a result, the concrete needs to be compacted by applying an external source of energy, mostly vibration. This procedure slows down the casting process and makes the properties of the structure dependent on the skills of the workmen in situ. Insufficient compaction results in a high air content and in a reduction in both strength and durability. On the other hand, too much compaction can lead to segregation resulting in an inhomogeneous product. As a result, a perfectly suitable concrete for a certain application can result in a low quality product if the compaction was not appropriate [1].

Self-Compacting Concrete (SCC) does not need any form of external compaction, due to its high fluidity and deformation capability. The application of SCC speeds up the casting process and makes the final product less dependent on the skills of the workmen. As there is no compaction needed, this type of concrete allows the producers to fill any formwork in one single operation, avoiding the disadvantages related to casting joints [2]. SCC is also suitable for a new placing technique: the concrete will be pumped in the formwork from the bottom and will rise due to the applied pressure. In order to be able to investigate the phenomena occurring in the pipes and the formwork during pumping operations, the rheological properties of SCC must be studied and controlled [3 - 5].

In this paper, the results of the rheological tests performed on SCC, together with the applied rheometers and the test procedure, will be discussed. In fresh state, SCC behaves as a thixotropic liquid, having a yield stress and losing workability, due to the chemical reactions developing in the concrete [6]. In this paper, we will only focus on the steady-state properties, the discussion of the time dependent effects both reversible (thixotropy) and non-reversible (loss of workability) are beyond the scope of this paper.

## 2 MATERIALS: SELF-COMPACTING CONCRETE

### 2.1 WHAT IS SELF-COMPACTING CONCRETE?

Self-Compacting Concrete is defined as a special type of concrete which must fulfil the following three basic properties [2, 7]:

- Filling ability: the concrete must be able to flow freely both in horizontal and vertical direction – even upwards if needed – and fill the formwork of almost any shape completely under its own weight only.
- Passing ability: the concrete is not allowed to cause any blocking when passing trough narrow gaps caused by the geometry of the formwork or by a dense reinforcement grid.
- Stability: during mixing, placement and after casting, the concrete is not allowed to segregate, causing an inhomogeneous mixture.

These three basic properties, combined with the absence of the need for compaction make the application of SCC very advantageous in cases of complex geometries of the formwork, cases with dense reinforcement grids and difficultly attainable places.

### 2.2 COMPOSITION OF SELF-COMPACTING CONCRETE

Since the properties of the constituent materials of concrete differ from country to country, from site to site, there is no universal rule to make a good Self-Compacting Concrete. Over the world, small and even large differences in the composition of SCC can be observed [8]. In the following section, the composition of SCC, made in Western-Europe will be described.

As stated in the previous section, the concrete must be very liquid and is not allowed to cause any blocking, which is mainly caused by the coarse aggregates due to a bridging effect. Reducing the amount of coarse aggregates increases the distance between two particles and as a result, the probability of collisions between the particles is reduced [9]. With the mortar fraction of the concrete thereby acting as a kind of lubricant, the fluidity and deformability is increased significantly. In literature, the total amount of coarse aggregates is set at 50% of the volume the aggregates would take in case of closest packing [10].

Since the amount of coarse aggregates is reduced, one must increase the mortar fraction in order to obtain an equal volume of concrete. The total volume of sand in SCC is set at maximally 40% of the mortar volume and as a result, compared with traditional concrete, a large amount of fine particles ($d$ < 0.090 mm) must be added [10]. This can be achieved by adding cement only, although this is not advantageous neither from an economical point of view, neither for some concrete properties like heat of hydration and shrinkage [2]. Large amounts of cement cause a high thermal gradient in the concrete structure during hardening, causing thermal cracking of the final structure. In order to avoid this thermal cracking, a certain amount of cement is replaced by another fine material of which limestone filler and fly ash are most common in Belgium. Silica fume – which is much finer than cement – and high-fineness ground granulated blast furnace slag can also be applied. Adding a sufficient amount of cement and filler contributes largely to the resistance to segregation of SCC, but in some cases, a viscosity modifying agent, being a material which increases the viscosity of the mixture, can be added.

The amount of water is kept the same as in traditional concrete, in order to achieve at least an equal magnitude of strength. In most cases, the strength of SCC is higher compared to TC with an equal water/cement ratio. This small amount of water results in a very stiff mixture and in order to achieve the desired fluidity, superplasticizers are added [11]. Superplasticizers (SP) are polymers added to the concrete in very small amounts, which interact with the cement particles, avoiding flocculation of these particles. In this way, a better dispersion of the fine particles is obtained and the fluidity is enhanced. Nowadays, different kinds of SP are available, but the one being most effective is polycarboxylic ether based. This kind of SP has a double working principle: it has both an electrostatic repulsion effect, caused by the electrical loads, and a steric hindrance effect, caused by long polymer chains [12].

Until now, since no rule has been developed for the amount of SP that needs to be added to the concrete, the amount of SP is still determined by trial and error. Not enough SP results in low fluidity and a non-self-compacting concrete. Too much SP can result in segregation of the concrete, causing an inhomogeneous material. The workability of the produced SCC has been analysed using the standard tests described in [13].

### 2.3 CONCRETES TESTED

In total, more than 60 different SCC mixtures have been tested in the rheometers. The composition of the reference mix is given in Table 1. Within the research project, other compositions have been experimentally verified as well, changing different properties like gravel type, cement type, filler type, type of superplasticizer, amount of cement, amount of water, amount of filler, ... . In this paper, the applicability of different rheological models is described based on the experimental results obtained for the reference mix. For the other compositions, similar results have been obtained. Any time-dependent behaviour has been excluded in this paper. As chemical reactions occur in the concrete, all properties vary in time. In order to make an analysis of the time independent behaviour, the test results obtained at 15 minutes of age, which corresponds to 15 minutes after water addition, are considered in this paper. No results have been obtained at earlier ages, because the SCC needs time to be mixed (at least 5 min), to be sampled and the equipment needs to be filled properly.

## 3 METHODS: RHEOMETERS AND TESTING PROCEDURE

### 3.1 CONTEC VISCOMETER 5

This type of rheometer, which has been explicitly designed to measure the rheological properties of concrete, is based on the principle of the coaxial cylinders [6, 14, 15]. A set of rotational velocities is imposed at the outer cylinder and the resulting torque is measured at the upper part of the inner cylinder. The lower part of the inner

| | |
|---|---|
| Gravel 8/16 | 434 |
| Gravel 2/8 | 263 |
| Sand 0/4 | 853 |
| CEM I 52.5 N | 360 |
| Limestone filler | 240 |
| Water | 165 |
| Superplasticizer Glenium 27 | 10 |

*Table 1: Composition of reference mix (kg/m³).*

*Figure 1 (left): Contec Viscometer 5.*

*Figure 2: Tattersall Mk-II rheometer.*

cylinder is fixed and does not participate in the measurement of the torque. As a result, no complex 3-D flow-effects at the bottom of the reservoir are taken into account, and the pure coaxial flow has been realized in the section of the rheometer where the measurements are being performed [6, 16].

The radii of the inner cylinder, $R_i$, and outer cylinder, $R_o$, are 100 and 145 mm, respectively. The heigth, $h$, of the upper inner cylinder which is submerged into the concrete measures 160 mm. Both the inner and outer cylinders are equipped with ribs to prevent slippage between the concrete and the steel surface [17]. The Contec viscometer 5 is depicted in Figure 1. To perform a measurement, the rotational velocity decreases in function of time in steps of 3 seconds (see also Section 3.3). The first second of each step serves for the decrease in rotational velocity and during the remaining two seconds, measurements of the rotational velocity and the torque are performed at a rate of 50 Hz. For each time step, the five lowest values of rotational velocity, $N$, and torque, $T$, are averaged and represent a single point in a $T$-$N$-diagram. In total 15 data points are generated and the best fitting line is calculated. The intercept of this line with the $T$-axis is called '$G$' and the inclination of this line is '$H$'. With these values of $G$ and $H$, the Reiner-Riwlin equation (Eq. 1 - 2) [6, 18] can be applied in order to obtain yield stress, $\tau_o$, and plastic viscosity, $\mu$, independently of the velocity distribution in the gap between outer and inner cylinder.

$$\tau_o = \frac{G}{4\pi h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right)\frac{1}{\ln\left(R_o/R_i\right)} \tag{1}$$

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

The major disadvantage of this method is the application of a linear rheological model to the obtained results, which is necessary to apply the Reiner-Riwlin equation. In order to be able to describe non-linear rheological properties, the obtained data of rotational velocity and torque must be processed in another way. In [19] formulae are available to transform $N$ and $T$ into the fundamental rheological parameters shear stress and shear rate. These formulae have been adapted by [20] and have the following form (Eq. 3 - 4):

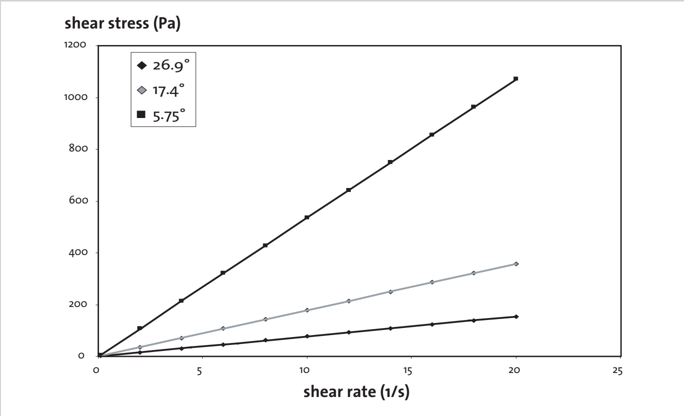
$$\tau = \frac{\left(R_i^2 + R_o^2\right)}{4\pi h R_i^2 R_o^2} T \tag{3}$$

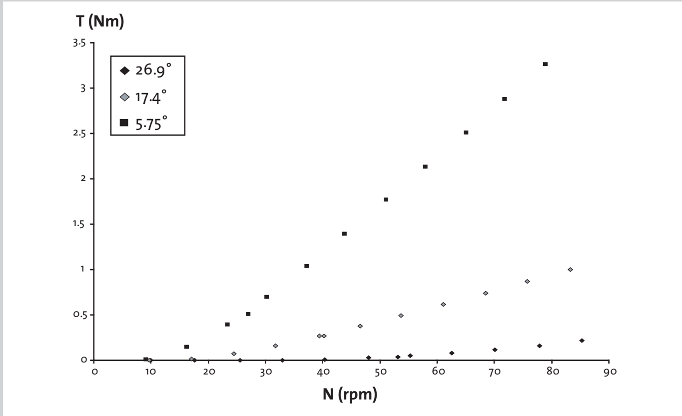
$$\dot{\gamma} = \frac{\left(R_o^2 + R_i^2\right)}{\left(R_o^2 - R_i^2\right)} N \tag{4}$$

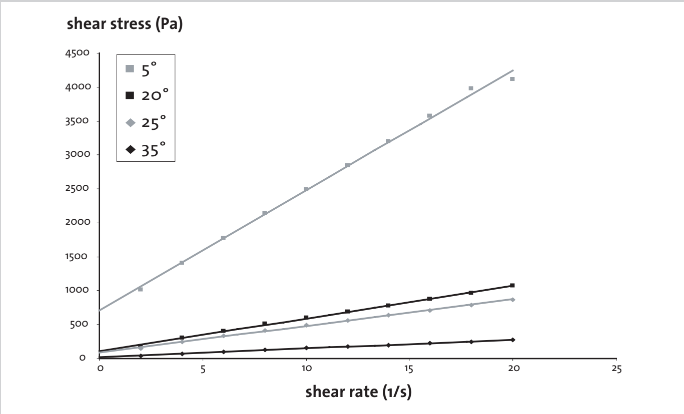
These formulae can be used for any material, independently from the real rheological properties. The only requirement is that the velocity distribution in the gap must be linear, which can be achieved if the gap is small ($R_i/R_o$ > 0.99). This requirement is not fulfilled in this case, resulting in a small error in the test results [16, 20].

### 3.2 TATTERSALL MK-II RHEOMETER

This rheometer, which is depicted in Figure 2, has been developed by Tattersall in the 1970's in order to measure the rheological properties of traditional concrete [21 - 23]. The inner cylinder



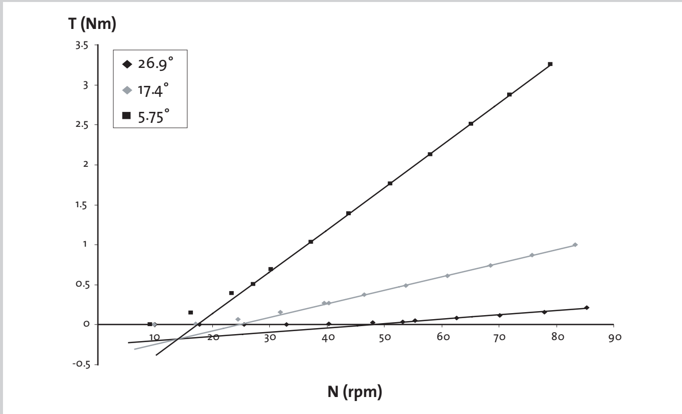




*Figure 3 (left above): Tests with PiB (Newtonian liquid) in cone and plate rheometer, at 3 different temperatures.*

*Figure 4 (right above): Tests with PiB in Tattersall Mk-II rheometer, at 3 different temperatures.*

*Figure 5 (left below): Tests with honey (Bingham material) in cone and plate rheometer, at 4 different temperatures.*

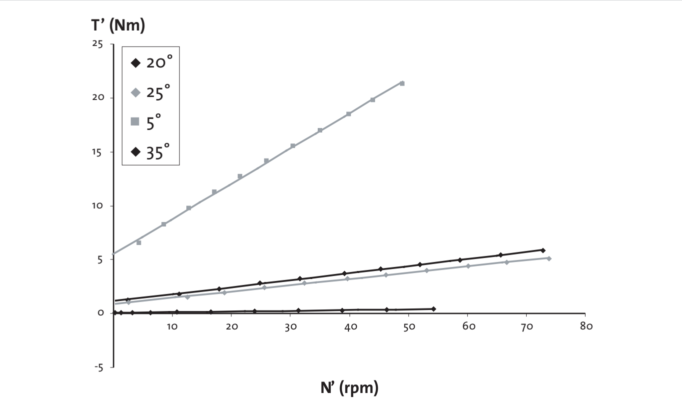
*Figure 6 (right below): Definition of the zone of non-linearity. Extrapolation of the linear relationship of the data outside this zone leads to one single point of intersection.*

has been equipped with blades from a historical point of view, in order to remix the concrete to avoid segregation. The outer cylinder is also provided with ribs to prevent slippage between the concrete and the steel surface. This rheometer is also based on the principle of the coaxial cylinders, but the rotational velocity is imposed at the inner cylinder in steps of 5 seconds. The resulting torque is also measured on the inner cylinder. Both rotational velocity and torque are measured at a frequency of 5000 Hz. For each 2000 measurements, an average value is displayed and saved in a data file. The radius of the outer cylinder is 125 mm, the distance between the edges of the blades is 160 mm in horizontal direction and 140 mm in vertical direction. In this configuration, it is not evident to define the radius of the inner cylinder in order to apply the formulae mentioned in Section 3.1. Therefore, a calibration procedure has been performed with a Newtonian liquid (polyisobutene) and a Bingham liquid (honey) [23]. These liquids have been tested in the Tattersall Mk-II rheometer and in a cone and plate rheometer [16].

The polyisobutene (PiB) has been tested three times at each of the three different temperatures: 26.9°, 17.4° and 5.75° C. The results from the cone and plate rheometer, on which the same measurement procedure has been applied, indicate that PiB is a Newtonian liquid, having large variations in viscosity due to temperature changes (Figure 3). When testing this liquid in the Tattersall Mk-II rheometer, no perfect linearity has been obtained, which can be seen in Figure 4. A certain deviation from the linear law occurs in cases of a low torque and low rotational velocity together. If one of those parameters is high enough, a linear relation is obtained. Based on the tests performed, a region can be described as the "zone of non-linearity", and is defined by $T = 1 - N/55$. Outside this region, the linear behaviour is perfect; inside the region, the relation can be described as $T = AN^{2.55}$.

These phenomena are possibly caused by the structure of the rheometer. At low torque and low rotational velocity, it could be that the liquid only flows between the blades, describing a non-linear relation. When increasing *T* and *N*, the flow also develops in the other part of the rheometer (where normally the flow should occur), describing a linear relation. At a random value of *T* and *N*, both phenomena are superposed.

Results from the tests with the cone and plate rheometer indicate that honey can be classified as a Bingham liquid, having a yield stress and a plastic viscosity (Figure 5). This material has been tested at four different temperatures: 34.5°, 23.5°, 20.9° and 6.9°C. For each temperature, three tests have been performed on the cone and plate rheometer and five tests on the Tattersall rheometer. Results with the Tattersall rheometer indicate again the same zone of non-lineari-



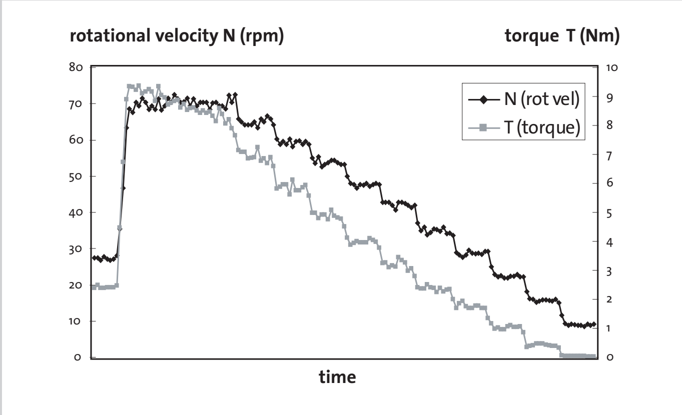




*Figure 7 (left): Test results for honey in Tattersall Mk-II rheometer, after correction.*

*Figure 8: Stepwise evolution of rotational velocity, N, and torque, T, in function of time, for the reference SCC mix in the Tattersall Mk-II rheometer.*

ty. In order to obtain comparable results with the Tattersall rheometer and the cone and plate rheometer, the following corrections on the data of the Tattersall rheometer must be performed:

1) When extrapolating the regression line of the data points in the linear zone, all lines intersect in one point, in case of a Newtonian liquid (Figure 6). If a material has a yield stress, the line will be situated above the line of a material having an equal viscosity and no yield stress. The difference of the intersection of those two lines (with and without yield stress, but having the same inclination) with the *T* - axis results in the real "yield torque".
2) In the zone of non-linearity, a curve of the following form $T = T_o + AN^{2.55}$ is fitted on the data. On the extrapolated line of the linear zone, the value of *N*, corresponding to $T_o$ is calculated and is called $N_a$.
3) With this value of $N_a$, all *N*-values in the linear zone are corrected by $N' = N - N_a$, which corresponds a horizontal translation of the points to the left side in the curve over a distance $N_a$.
4) Inside the zone of non-linearity, the data points are corrected in the following way: $N' = (N_i - N_a)(N/N_i)^{2.55}$.
   Where $N_i$ represents the *N* value of the intersection of the original *N* - *T* curve with the edge of the zone of non-linearity. This procedure leads to a linearization of the data points and a shrinkage of the zone. Step 3 and 4 lead to an equal result for *N'* in case a data point is situated on the edge of the zone of non-linearity.
5) The obtained torques must be corrected in order to obtain the real "yield torque" obtained in step 1.

The application of these 5 steps to the test results from the Tattersall Mk-II rheometer are shown in Figure 7 for honey. By comparing Figure 7 with the results obtained with the cone and plate rheometer (Figure 5), the calibration constants to transform torque to shear stress and rotational velocity to shear rate can be calculated. The results obtained at 34.5°C have been omitted, because the resulting values obtained with the Tattersall rheometer are very low and cannot be considered as accurate.

In case the material does not show a linear relationship between shear stress and shear rate, as it is for SCC, some modifications can be applied:

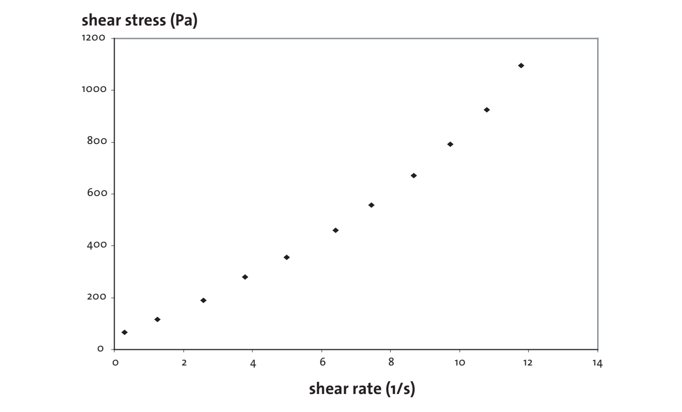
1) Instead of extrapolating the data from the zone of linearity, the best fitting line through the first five data points is used to calculate the real yield stress. This is justified since in most cases maximum 2 data points (of 11 in total) are in the zone of non-linearity.
2) The value of $N_a$ is calculated as the *N* value corresponding to $T_o$ for the line obtained in the previous step.

These modifications lead to the introduction of a new error, but comparison of the results obtained with equivalent SCCs with both the Contec Viscometer 5 and the Tattersall Mk-II rheometer indicate that a similar plastic viscosity and a slightly higher (± 30 Pa) yield stress is obtained in case of the Tattersall MK-II rheometer.

### *3.3 MEASUREMENT PROCEDURE*

Each concrete mixture has been tested in the rheometer at different ages after the time the water has been added. Most concretes have been tested at 15 and 30 minutes after water-adding-time. If the workability remained sufficiently good during time, the rheological properties were also evaluated at 60, 90, 120 and even 150 minutes of age. In this paper, only the results of the rheological tests performed on the reference mix at 15 min of age will be discussed. The other concretes show a similar behaviour and all concretes show a loss of fluidity as a function of time.

In order to obtain the rheological properties in equilibrium state, thixotropy must be eliminated. This is performed by decreasing the rotational velocity stepwise, in analogy with the Contec Viscometer 5, starting with a high value which is maintained long enough (in the order of 20 sec-



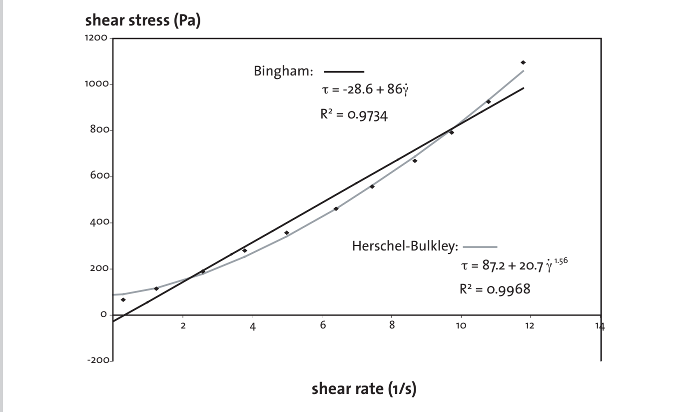




*Figure 9 (left): Rheological data for the reference mix.*

*Figure 10: Application of the Bingham model (black line) and the Herschel-Bulkley model (grey curve) to the rheological data of the reference mix.*

onds) to eliminate thixotropy. By decreasing the rotational velocity stepwise, the torque reaches the equilibrium very fast (Figure 8) [24]. All data points with a constant *N* and *T* are averaged per time step resulting in 11 (*N*, *T*)-points. If the torque at a certain rotational velocity was not constant during (a part of) the measuring period, the corresponding values of *N* and *T* have not been taken into account in the averaging procedure. The obtained results for *N* and *T* are transformed to shear stress and shear rate, applying the calibration constants, and the results for the reference mix are shown in Figure 9. The authors would like to remark that the test results are expressed in linear graphs, as this is traditional in concrete rheometry. Also, the maximum shear rate is kept very low (12 $s^{-1}$), since in practice, no higher shear rates will occur, and if they do, the constituent materials will separate and cause inhomogeneity of the concrete [3].

## 4 APPLICATION OF DIFFERENT RHEOLOGICAL MODELS

### 4.1 BINGHAM MODEL

The Bingham model, presented in Eq. 5, has two parameters: yield stress, $\tau_o$, and plastic viscosity, $\mu$. This model has been widely applied in the history of concrete rheometry to describe the rheological behaviour of both traditional and self-compacting concrete [6, 21].

$$\tau = \tau_o + \mu\dot{\gamma} \tag{5}$$

Applying this model to the data obtained from our reference mix (and also a lot of other mixes) results in a negative yield stress, which is physically impossible. In Figure 10, in the region of low shear rates, it can be seen that the Bingham model underestimates the shear stress. When looking at the full graph, shear thickening can be observed. As a result, this model is not valid to describe the rheological properties of this SCC.

### 4.2 HERSCHEL-BULKLEY MODEL

In order to solve the problems occurring with the application of the Bingham model, a non-linear model can be used to describe the rheological behaviour of SCC [25]. The most common non-linear model, having also a yield stress, is the Herschel-Bulkley model (Eq. 6). The non-linearity is expressed by the exponent, *n*, in the equation and indicates shear thinning if $n < 1$, shear thickening if $n > 1$ and the Bingham model if $n = 1$. This model has been applied to the test results and delivers a better fit of the test data, when compared with the Bingham model. Also a positive yield stress is obtained (Figure 10).

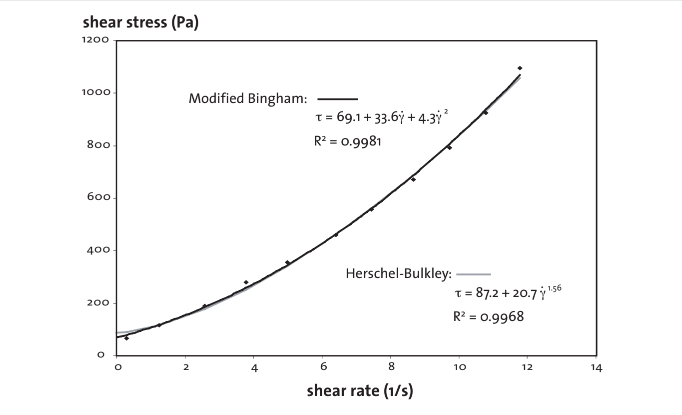
$$\tau = \tau_o + K\dot{\gamma}^n \tag{6}$$

$$\frac{d\tau}{d\dot{\gamma}} = nK\dot{\gamma}^{(n-1)} \tag{7}$$

On the other hand, this model has two major disadvantages. In Eq. 7, the derivative of the H-B equation to the shear rate indicates that, in case of shear thickening, the inclination of the curve approaches '0' for very low shear rates, resulting in an overestimation of the yield stress. This can also be seen in Figures 10 - 11, where the H-B-curve is situated above the data points from the tests.

When looking more in detail to the physical interpretation of the parameters, large difficulties arise when trying to analyse the parameter, *K*. The dimension of this parameter is [Pa·$s^n$], thus depending on *n* and as a result, the dimension of *K* is variable, having no physical meaning. In order to describe the rheological behaviour of SCC, a model with the following properties is needed:

- Resulting in a positive yield stress (non-linear model)
- Having a positive linear term in the shear rate (avoids the inclination being zero)
- Having parameters with fixed dimensions that can have a physical meaning



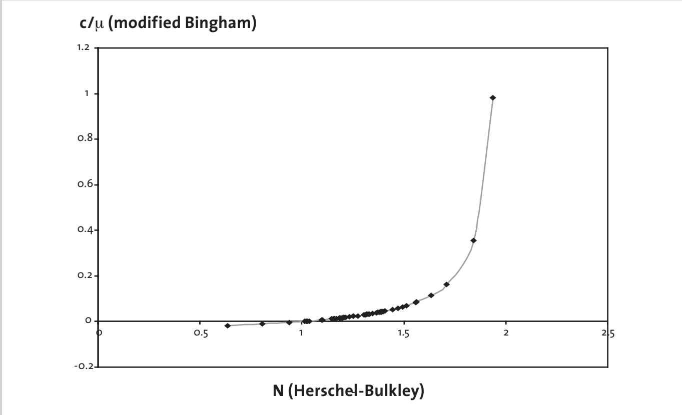




*Figure 11 (left): Application of the Herschel-Bulkley model (grey curve) and the modified Bingham model (black curve) to the rheological data of the reference mix.*

*Figure 12: Relationship between c/μ (modified Bingham) and n (Herschel-Bulkley), theoretically (grey curve) and experimentally (black dots).*

### 4.3 MODIFIED-BINGHAM MODEL

The modified-Bingham model has been applied in [26] to investigate the yield stress of cement pastes, determined by different models. This model, which is described in Eq. 8, has been applied to the test data and can be seen in Figure 11. This model fulfils the three criteria stated in Section 4.2 and as a result, it can be regarded as a model suitable to describe the rheological behaviour of the SCCs tested.

$$\tau = \tau_0 + \mu\dot{\gamma} + c\dot{\gamma}^2 \tag{8}$$

This model can be regarded as an extension of the Bingham model with a second order term, but also as a second order Taylor development of the Herschel-Bulkley equation, which is justified since the parameter *n* in H-B rarely exceeds the value 2. This Taylor development, taken around a random point 'a' is theoretically described in Eq. 9. Rearranging all terms and taking the ratio of the second order term to the linear term results in a theoretical relation between $c/\mu$ (modified-Bingham) and *n* (Herschel-Bulkley) (Eq. 10).

$$\tau = \tau_{0,HB} + Ka^n + \frac{Ka^n n}{a}\left(\dot{\gamma} - a\right) + \frac{Ka^n n\left(n-1\right)}{2a^2}\left(\dot{\gamma} - a\right)^2 \tag{9}$$

$$\frac{c}{\mu} = \frac{1}{2a}\left(\frac{n-1}{2-n}\right) \tag{10}$$

In practice, this relation has also been observed. In Figure 12, the black dots represent the obtained test data (from different mixes of SCC at different ages). The grey line represents Eq. 10 which has been fitted to the obtained results. As a result of this fitting, a value of the random parameter, *a*, equal to 7.5 $s^{-1}$ has been obtained for all the test data considered. This indicates that the parameter $c/\mu$ can be applied to describe non-linear behaviour, indicating shear thinning ($c/\mu < 0$), shear thickening ($c/\mu > 0$) and the Bingham model ($c/\mu = 0$).

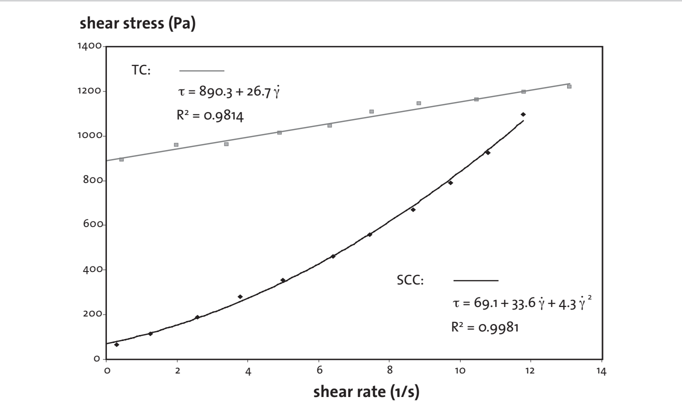
## 5 DIFFERENCES BETWEEN SCC AND TC

Comparing different concretes is a very difficult action, due to the dependency of a lot of properties on the composition of the concrete in fresh, hardening and hardened state [2]. Most properties in concrete science depend largely on the mass-ratio of water to cement. In Figure 13, the reference mix of Self-Compacting Concrete has been compared with a traditional concrete, having the same amount of cement and water (*w/c* = 0.45). It can be seen that SCC is much more fluid, compared to the traditional concrete: the yield stress is much lower, but a higher plastic viscosity can be observed. Traditional concrete does not show any shear thickening and can be described using the Bingham model.

In Figure 14, a very fluid SCC, having an equal composition as the reference mix, but a higher amount of superplasticizer, has been compared with a traditional concrete, having an equal amount of cement and a water-to-cement ratio, *w/c*, of 0.55. From a rheological point of view, both concretes are approximately equal, only the traditional concrete shows no shear thickening. According to the European standards on durability of concrete [27], SCC having a *w/c* of 0.45 can be applied in any construction. The application of the traditional concrete considered here, with a w/c of 0.55 is much more restricted. This SCC has also a significantly higher strength compared to this traditional concrete, because also strength is dependent on *w/c*.

## 6 CONCLUSIONS

In order to investigate the phenomena occurring during pumping of Self-Compacting Concrete, an extended experimental study of the rheology of SCC has been performed with two different rheometers. These two rheometers are based on the principle of the coaxial cylinders. The Contec-Viscometer 5 has a rather simple geometry and available formulae can be applied to calculate the shear stress and shear rate. The Tattersall-



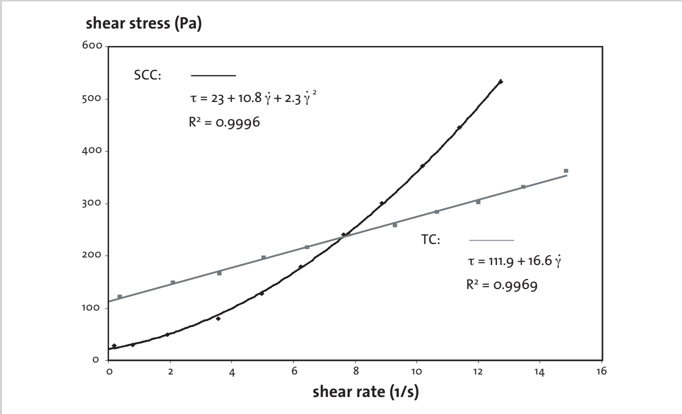




*Figure 13 (left): SCC is much more fluid compared to TC with an equal amount of water and cement.*

*Figure 14: SCC and TC with an equal fluidity: TC needs more water to achieve this fluidity.*

Mk-II rheometer has a more complex geometry. A calibration procedure has been worked out to eliminate secondary flows and transforming the data of torque and rotational velocity to shear stress and shear rate.

Self-Compacting Concrete can be classified as a thixotropic liquid having a yield stress, showing shear thickening and having a decrease in workability (fluidity) in time due to chemical reactions. The Bingham model cannot be applied to describe the rheological properties of SCC, due to the generation of negative yield stresses.

The Herschel-Bulkley model describes the behaviour better, but it has a parameter with a variable dimension and it overestimates the yield stress, due to a mathematical restriction in the region of low shear rates. The modified-Bingham model, being an extension of the Bingham model and a second order Taylor development of the Herschel-Bulkley model, is suitable to model the rheology of SCC. Shear thickening can be analysed by the parameter $c/\mu$.

When comparing a Self-Compacting and a traditional concrete, suitable for standard practical applications according to the European standards, SCC is much more fluid from a rheological point of view. Traditional concrete can be made as fluid as SCC, but the traditional concrete has less strength and cannot be applied in all situations when considering durability.

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## *REFERENCES*

[1] Neville AM, Brooks JJ: Concrete technology, Logman scientific and technical, Harlow (1987).

[2] Poppe A-M: Influence of filler on hydration and properties of Self-Compacting Concrete, Ph.D. thesis (in Dutch), Ghent University (2004).

[3] Kaplan D: Pompage des bétons, Ph.D. thesis (in French), Laboratoire Central des Ponts et des Chaussées, Paris (2001),

[4] Kaplan D, Sedran T, de Larrard F, Vachon M, Marchese G: Forecasting pumping parameters, Proceedings of the Second International Symposium of Self-Compacting Concrete, Tokyo (2001) 575-584.

[5] Haist M, Mechtcherine V, Beitzel H, Müller HS: Retrofitting of building structures using pumpable Self-Compacting lightweight concrete, Proceedings of the Third International Symposium on Self-Compacting Concrete, Reykjavik (2003) 776-785.

[6] Wallevik JE: Rheology of particle suspensions, Ph.D. thesis, The Norwegian University of Science and Technology, Trondheim (2003).

[7] Nogushi T, Mori H: State-of-the-art Report: Evaluation of Fresh Properties of Self-Compacting Concrete in Laboratory and on Site, International workshop on Self-Compacting Concrete (1998).

[8] Wallevik OH: Why is SCC Different from Country to Country, Fourth International Symposium on Self-Compacting Concrete, Chicago (2005) oral presentation.

[9] Bui VK, Akkaya Y, Shah SP: Rheological Model for Self-Compacting Concrete, ACI Materials Journal 99 (2002) 549-559.

[10] Okamura H, Ozawa K: Mix design for Self-Compacting Concrete, Concrete Library of JSCE 25 (1995) 107-120.

[11] Phan TH, Chaouche M: Rheology and stability of Self-Compacting Concrete cement pastes, Appl. Rheol. 15 (2005) 336-343.

[12] Takada K, Walraven J: Evaluation for the effect of different types of superplasticizers considering the mixing effect, Proceedings of the Third International Symposium on Self-Compacting Concrete, Reykjavik (2003) 403-414.

[13] De Schutter G: Guidelines for testing SCC, European Research Project Testing SCC (2005).

[14] Wallevik JE, Wallevik OH: Effect of eccentricity and tilting in coaxial cylinder viscometer when testing cement paste, Nordic Concrete Research, Oslo (1998) 144-152.

[15] Wallevik OH: Course on the rheology of cement based particle suspensions, BBRI, Limelette (2004) Lecture notes.

[16] Macosko CW: Rheology - Principles, Measurements and Applications, Wiley-VCH (1994).

[17] Saak AW, Jennings HM, Shah S: The influence of wall slip on yield stress and viscoelastic measurements of cement paste, Cement and Concrete Research 31 (2001) 205-212.
[18] Hu C, De Larrard F, Gjörv OE: Rheological testing and modelling of fresh high performance concrete, Materials and Structures 28 (1995) 1-7.
[19] Ferguson J, Kemblowski Z: Applied Fluid Rheology, Elsevier Applied Science, London (1991).
[20] Nehdi M, Rahman M-A: Effect of geometry and surface friction of test accessory on oscillatory rheological properties of cement pastes, ACI Materials Journal 101 (2004) 416-424.
[21] Tattersall GH, Banfill PFG: The rheology of fresh concrete, Pitman, London (1983).
[22] Tattersall GH: The rationale of a two-point workability test, Magazine of Concrete Research 25 (1973) 169-172.
[23] Tattersall GH, Bloomer SJ: Further development of the two-point test for workability and extension of its range, Magazine of Concrete Research 31 (1979) 202-210.
[24] Geiker MR, Brandl M, Thrane LN, Bager DH, Wallevik O: The effect of measuring procedure on the apparent rheological properties of self-compacting concrete, Cement and Concrete Research 32 (2002) 1791-1795.
[25] De Larrard F, Ferraris CF, Sedran T: Fresh Concrete: A Herschel-Bulkley material, Materials and Structures 31 (1998) 494-498.
[26] Yahia A, Khayat KH: Analytical models for estimating yield stress of high-performance pseudoplastic grout, Cement and Concrete Research 31 (2001) 731-738.
[27] EN 206-1 (2001): Concrete Part 1 – Specifications, Performance, Production, Conformity.