Development of a Measuring Procedure of Rheological Behavior for Self Compacting Concrete

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Abstract

The objective of this study is to propose a rheological model for a self-compacting concrete (SCC) on a reduced scale in which a mobile (with 4 vanes) rotating at an imposed speed is immersed. This model allows to describe the rheological behaviour of concrete (at full scale) and to acquire its intrinsic parameters, namely the yield stress and the plastic viscosity. The validation of this approach is established first of all from the realization of six self-compacting concretes (at the real scale). The intrinsic rheological parameters given by their reduced concretes confirm their self plasticity by referring to the rheological results obtained with three other rheometers of international references. Indeed, a very good correlation is obtained between the slump flow of these six SCC and the yield stress of their reduced concretes. Moreover, a design of experiments with three variables is used to demonstrate that this approach is suitable for providing a mathematical model of the intrinsic rheological parameters (yield stress and viscosity) of SCC. The results showed that the yield stress is governed by the interactions (paste-superplasticizer) and (paste-aggregate) while the viscosity is exclusively governed by the paste.

1. Introduction

Recently, several studies have treated fresh concrete as a fluid and used the methods of fluid rheology to describe the flow of concrete (NIST 2001, 2004; Ferraris 1999; Delarrard 2000; Sedran 1999).

However, the rheology of concretes remains a little exploited field. The difficulties arise, on the one hand, from the complexity of these materials, which consist of several components of different nature: aggregates, cement, water, air, possibly fillers and admixtures, and on the other hand, from their large particle size range (particles smaller than micron to the gravels of a few centimeters). Indeed, these different phases give the concrete material an important heterogeneity, leading to the appearance of several interaction kinds. The purpose of rheology is to establish the relationships between the stress and strain rates of sufficiently fluid mixtures such as self-compacting concretes. The latter show no excessive segregation during the shear test.

Several previous studies (NIST 2001, 2004; Ferraris 1999) have shown that tests using concrete rheometers can be used to analyze the intrinsic properties of fresh concrete such as yield stress and plastic viscosity. Despite the considerable difference between the geometry of these concrete rheometers, the basic principle is to measure the relationship between the resistive torque (N) and the speed (V) of a rotating mobile by shearing the studied mixture.

According to Tattersal and Banfill (1983), the rheology of concrete can be represented by a linear model \([\tau = f(\dot{\gamma})]\) called "Bingham model" in the form \((\tau = \tau_y + \mu \dot{\gamma})\), where \(\tau\) is the shear stress, and \(\dot{\gamma}\) is the shear strain rate. This model is characterized by two independent parameters, namely, the yield stress \(\tau_y\) and the plastic viscosity \(\mu\). The yield stress is closely related to the slump flow concrete while the viscosity is closely related to the deformation rates of this flow.

Using the “BTRHEOM” rheometer, Sedran (1999) has shown that the non-linear model of Hershel-Bulkley, given in form \((\tau = \tau_y + m \dot{\gamma}^n)\), allows a good description of the rheological behavior of self compacting concretes. However, many difficulties are related to the use of this model with three parameters \((\tau_y, m, n)\), such as the uncertainty on each parameter's value compared to the two-parameter model when the number of experimental points is limited.

In order to explain Bingham's model physically, Delarrard (2000) considers that the yield stress is the contribution of the solid phase (all particles). It is controlled by the number and nature of intergranular contacts and not by the liquid phase whose only role is to influence the distance between particles. While the viscosity and through the term \(\mu \dot{\gamma}\) appears as the exclusive contribution of the liquid phase.

According to Reinhardt and Wustholz (2006) a self-compacting concrete can be composed of two phases,
solid (represented by the aggregates) and liquid (represented by the paste). The rheological parameters (yield stress and viscosity) are controlled by solid-fluid and solid-solid interactions under the effect of paste in excess. The total paste volume is divided between that needed to fill the intergranular voids and the remainder being in excess. The latter is useful for covering the aggregates so as to minimize friction between them and give the mixtures the best fluidity. In fact, the rheological parameters are closely related to a thickness of this excess paste. When this thickness increases, the two parameters (yield stress and viscosity) decrease.

According to Wallevik and Wallevik (2011), the self-compacting property of a concrete is only checked if there is an equilibrium between the two rheological parameters (yield stress and viscosity). A range of values for these two parameters is proposed to achieve a self-compacting flow. According to this range, the yield stress of self-compacting concrete can vary between 0 and 10 Pa, and the viscosity between 5 and 120 Pa·s. When the viscosity is below 40 Pa·s, self-compacting concrete must have a sufficient yield stress to maintain a good stability against segregation. On the other hand, if the viscosity is too high (greater than 80 Pa·s), the yield stress must be close to zero (below 15 Pa) to maintain a good filling capacity.

In various studies such as those of Shwartzentruber et al. (2006), Jau and Yang (2010), Wallevik (2006) and Reinhardt and Wustholz (2006), the two rheological parameters, namely the yield stress and viscosity are closely related to the test results of slump flow of fresh concrete and its flow time value (T500). In particular, the yield stress is closely related to the slump flow either by a linear correlation (Jau and Yang 2010; Wallevik 2006), or by a power correlation (Reinhardt and Wustholz 2006; Shwartzentruber et al. 2006). Indeed, as the yield stress increases the slump flow is reduced. The viscosity, according to Reinhardt and Wustholz (2006) and Shwartzentruber et al. (2006) is related to the flow time (T500). As this flow time increases, the viscosity is increased.

However, the rheological behavior of fluid concretes remains a relevant area of research. Indeed, this is the context of this study whose objective is to propose a rheological model for a self-compacting concrete from its equivalent reduced concrete. This latter is subjected to a shearing action through the rotation of a four-vane mobile rotating at an imposed speed.

This model allows, firstly, to describe the rheological behavior of a self-compacting concrete and to acquire its intrinsic parameters such as the yield stress and the plastic viscosity, and secondly to investigate the variation of these rheological parameters according to the composition factors such as the paste volume, the gravel-sand ratio (G/S) and the adjuvant (additive) dosage. The interest of this approach is to limit the heaviness of concrete studies on a real scale and to reduce the time needed to acquire the appropriate results.

2. Rheometric modeling

A rheometer is used to quantify the intrinsic rheological parameters of self-compacting concrete such as yield stress and plastic viscosity. The gross results of a test carried out with this rheometer are presented in a rheogram \([M = f(V)]\). This is presented by the variation of torque \((M)\) according to the rotation speed \((V)\) of a mobile (with four vanes) immersed in the fresh concrete. With linear variation \((M = M_0 + kV)\), the rheological behaviour is of the “Binghamian” type. The two parameters of this rheogram are the torque \((M_0)\) and the linear coefficient \((k)\). \((M_0)\) is the yield torque from which the mobile (immersed in concrete) is able to rotate and "\(k\)" is the slope of this variation.

However, the gross results of these two parameters \((M_0)\) and \((k)\) must pass to the fundamental values expressed by the stress quantities namely the yield stress \((\tau_0)\) and the plastic viscosity \((\mu)\). This is a general calculation allowing the transition from the torque value \((M)\) to the shear stress \((\tau)\) applied in self compacting concrete. This type of calculation is often used by other researchers in the field of concretes rheology (Sedran 1999; Ngo et al. 2010; Cyr 1999).

By analogy to the equation \(M = f(V)\), the stress equation \(\tau = f(\dot{\gamma})\) is obtained, where "\(\tau\)" is the shear stress, and "\(\dot{\gamma}\)" is the speed gradient or the rate of deformation.

When the rheological behavior is of the “Binghamian” type, the stress-strain equation is given by 
\[
\tau = \tau_0 + \mu \dot{\gamma}
\]

The two parameters are respectively the yield stress \((\tau_0)\) and the plastic viscosity \((\mu)\).

By considering the concrete surface sheared by the rotating mobile as cylindrical, the tangential stress \((\tau_p)\) according to the torque \((M)\) is given in the following form:

\[
\tau_p = \frac{M}{2\pi R^2 \left( \frac{H}{R} + \frac{1}{m+3} \right)}
\]

where \(R\) and \(H\) are respectively the radius and the height of the mobile and "\(m\)" is the constant describing the distribution of stresses \((\tau_e)\) in the lower end of the mobile; \((m = 0)\) for a uniform distribution and \((m = 1)\) for a linear distribution.

As shown in Fig. 1, the moment \((M)\) is the addition of wall moment \((M_w)\) and bottom moment \((M_b)\) such that:

\[
M = M_w + M_b
\]

Many researchers (Sedran 1999) have used a constant distribution of stresses \((\tau_e)\) with \((m = 0)\). Hence for a yield moment \((M_0)\) corresponds to a yield stress given by the equation below.

\[
\tau_0 = \frac{M_0}{2\pi R^2 H + \frac{2\pi R^3}{3}}
\]

Knowing that the speed gradient or rate of deformation "\(\dot{\gamma}\)" is a linear function according the angular
speed \((\Omega)\) on the sheared surface of which \(\Omega = \frac{V}{2\pi}\) (rad/s). And knowing that \(\mu = \frac{d\tau}{d\Omega}\), hence for a coefficient linear \((k)\) (the slope of variation \(M = f(V)\), corresponds a viscosity \(\mu\) given by:

\[
\mu = \frac{k}{(2\pi)^2 R^2 H + \frac{(2\pi)^2 R^3}{3}}
\]  

(3)

For a mobile with four vanes with a diameter \((D = 5\) cm) and height \((H = 7.5\) cm), the transition to the fundamental parameters \((\tau_0\) and \(\mu)\) is as follows: The yield stress \((\text{Pa})\) is given by \(\tau_0 = 3.06M_0\) and the plastic viscosity \((\text{Pa·s})\) is given by \(\mu = 29.18k\) (Pa·s).

However, the yield moment quantities \((M_0)\) and the slope \((k)\) are gross. To keep only the intrinsic effect of the mixture, the inertia effect of the mobile in rotation is deducted.

3. Concrete modeling

A reduced concrete is used simulating the rheological behavior of the whole concrete (with all its granular components). The largest granular fraction (gravel 8/15) is substituted by a quantity of the smallest granular fraction (gravel 3/8), as its equivalent in specific surface area. The equivalence error is less because it is a gravel-gravel substitution (same shape and aspect), especially since this one is based on the specific surface area achieved from the shape of the aggregates.

4. Experimental program

4.1 Rheometer used

The concrete rheometer used in rheological measurements mainly consists of a computer-controlled agitator model "ZRZ 2102 control" (see Fig. 2). The torque of a concrete sample subjected to shearing by a rotating mobile is measured. The mobile is equipped with four vanes (5 cm of width and 7.5 cm of height) fixed on a vertical axis.

The operation is established at imposed of speed according to a load program which can vary from 12 to 120 rpm. The container in which the concrete flows is cylindrical in diameter \((D = 15\) cm).

Loading in imposed speed is carried out once when ascending up to 96 rpm for destructuring the material and erasing the memory of its structure and another time when descending. During the descent, the torques according to the speeds (kept constant for a given period of time) are collected (see Fig. 3). This measurement mode has been already used by several researchers, including Mouret and Cyr (2003), Hu and Wang (2011), Legrand (1972) and Cyr (1999).

4.2 Materials used

The cement used is of type CEM II A 42.5 N. For the variation of the compositions of self-compacting concretes, three sands are used (one crushed of limestone origin, one rolled and another dune sand) and two fillers of limestone and marble origin.

The gravel used is of crushed type of limestone origin, of granulometric classes 3/8 and 8/15. The superplasti-
in the relationship between a quantity of fines and the variables \(y^n\) and the variables \(x^m\). The principle of this method is to vary the levels of one or more factors simultaneously at each test. This will allow on the one hand to significantly reduce the number of experiments to be carried out while increasing the number of factors to be studied and on the other hand to detect the interactions between the factors and the determination of the optimal domain of these factors in relation to a given response. There are currently many different designs such as full or partial two-level factorial designs, centered composite designs and Taguchi design.

In this study, a full (two-level) factorial design was used in order to assess the influence of three variables on the measured rheological parameters. According to the design of experiments method, these three variables are taken between two levels of value (minimum and maximum) for each, which is \(2^k\) with \(k = 3\), thus resulting in eight mixtures to be tested. The relevant variables selected to formulate the mathematical models of the rheological parameters are: the paste volume \(V_p\), the superplasticizer percentage \(SP\) (versus the cement dosage) taken between two levels (350 l/m³ and 380 l/m³), the mass ratio of gravel to sand \(G/S\) taken between two levels (0.85 and 1.05). It should be noted that the water/binder ratio \(E/L\) is fixed at 0.35, and the quantity of fines \(F\) is set at 50% of that of cement.

According to Table 3, for the eight possible combinations, the appropriate compositions at the real scale and then at the reduced scale are obtained. These are then subjected to rheological tests with a rheometer.

### 4.3 Experimental program

Two steps of experimental tests are proposed in order to validate the rheological model. In the first, six self-compacting concretes (on the real scale) are carried out by respecting the three classical self compacting criteria of the tests in the fresh state - i.e., the slump flow test, the stability test at sieve and the L-box test.

The compositions and fresh results for these six self-compacting concretes are given in Tables 1 and 2. The six self-compacting concretes are prepared with the same type of cement, the same adjuvant and the same type of gravel.

These six self-compacting concretes are represented and reformulated at reduced scale by substituting, only, the gravel class (8/15) by an equivalent amount (in specific surface area) of the class (3/8). With the exception of the gravel fraction, the six reduced self-compacting concretes therefore have the same composition as their corresponding ones at the real scale and these were subjected to rheological tests with a rheometer. The volume of each mix of self-compacting concrete is 1.65 liters.

In the second step, a three-variable experimental plan is used according to the design of experiments method. This method allows the best organization of tests interested in finding the relationship between a quantity of interest \(y^n\) and the variables \(x^m\). The principle of this method is to vary the levels of one or more factors simultaneously at each test. This will allow on the one hand to significantly reduce the number of experiments to be carried out while increasing the number of factors to be studied and on the other hand to detect the interactions between the factors and the determination of the optimal domain of these factors in relation to a given response. There are currently many different designs such as full or partial two-level factorial designs, centered composite designs and Taguchi design.

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### 4.4 Mixing procedure

The mixing procedure used to produce a 1.65 liter volume of reduced concrete is described below:

1. Dry homogenization of sand, gravel, cement, and fillers in the mixing container for 30 seconds.
2. Adding water and mixing for 2 min 30 s.
3. Adding superplasticizer and mixing for 2 min 30 s.

### 4.5 Rheology test procedure

The rheological tests in rheometer on all self-compacting concretes are carried out according to the following

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Table 1 Compositions of the six self compacting concretes.

|                | Cement (Kg) | Filler (Kg) | Water (L) | SP (Kg) | Sand (Kg) | Gravel (3/8) (Kg) | Gravel (8/15) (Kg) | Type of sand | Type of filler |
|----------------|-------------|-------------|-----------|---------|-----------|------------------|-------------------|--------------|---------------|
| SCC1           | 320         | 120         | 176       | 6       | 940       | 506              | 337               | Rolled       | Marble        |
| SCC2           | 344         | 172         | 183       | 5.5     | 856       | 342              | 514               | Rolled       | Limestone     |
| SCC3           | 350         | 136         | 180       | 4.9     | 693       | 420              | 420               | Crushed      | Crushed Limestone |
| SCC4           | 350         | 136         | 180       | 4.9     | 693       | 505              | 345               | Crushed      | Crushed Limestone |
| SCC5           | 385         | -           | 179       | 5.4     | 656       | 408              | 408               | Crushed      | Without filler |
| SCC6           | 350         | 136         | 180       | 4.9     | 693       | 420              | 420               | Crushed      | Crushed Marble  |

Table 2 Rheological characteristics of the six self compacting concretes.

|                | Slump flow (cm) | Stability test at sieve (%) | L box test \((H_1/H_2)\) |
|----------------|-----------------|-----------------------------|--------------------------|
| SCC1           | 75              | 8                           | 0.85                     |
| SCC2           | 70              | 2                           | 0.85                     |
| SCC3           | 69              | 5                           | 0.80                     |
| SCC4           | 67              | 6                           | 0.80                     |
| SCC5           | 65              | 10                          | 0.80                     |
| SCC6           | 71              | 4                           | 0.84                     |
Table 3 Compositions of eight studied concretes from the three variables according to the experimental design.

| Parameters | Compositions (Kg) |
|------------|-------------------|
| $V_p$ (L)  | $SP$ (%) | G/S | Cement | Filler | Water | $SP$ | Sand | Gravel (3/8) | Gravel (8/15) | $G_{eq}(3/8)^*$ |
| B1         | 350     | 1.6  | 0.85  | 334    | 167   | 171.6 | 5.34 | 941    | 400     | 400     | 152.5  |
| B2         | 380     | 1.6  | 0.85  | 362.5  | 181.2 | 186.2 | 5.8  | 897    | 381     | 381     | 145.2  |
| B3         | 350     | 1.8  | 0.85  | 333.5  | 166.7 | 170.9 | 6.0  | 941    | 400     | 400     | 152.5  |
| B4         | 380     | 1.8  | 0.85  | 362.5  | 181.2 | 185.7 | 6.53 | 897    | 381     | 381     | 145.2  |
| B5         | 350     | 1.6  | 1.05  | 334    | 167   | 171.6 | 5.34 | 848    | 445     | 445     | 169.6  |
| B6         | 380     | 1.6  | 1.05  | 362.5  | 181.2 | 186.2 | 5.8  | 809    | 425     | 425     | 162.0  |
| B7         | 350     | 1.8  | 1.05  | 333.5  | 166.7 | 170.9 | 6.0  | 848    | 446     | 446     | 170.0  |
| B8         | 380     | 1.8  | 1.05  | 362.5  | 181.2 | 185.7 | 6.53 | 809    | 425     | 425     | 162.0  |

$G_{eq}(3/8)^*$ denotes the equivalent amount of the gravel fraction (3/8) to replace that of (8/15) in order to get the reduced concrete.

5. Results and discussion

5.1 Validation of the model

The validation of the rheological approach is developed in the following three steps:

1. The rheological parameter values (yield stress and plastic viscosity) of the six reduced self-compacting concretes are compared to other results available in the literature.
2. The relationship between the yield stress of the reduced concretes and the slump flow of the same concretes at the real scale is established and checked.
3. From the tests carried out in the second experimental stage (design of experiment), a mathematical model of the rheological parameters is validated by an uncertainty calculation (between the estimated and experimental values).

For the six reduced self compacting concretes, the curves of torque versus speed are plotted. Figure 4 shows the curve (torque versus rotation speed) of the self compacting concrete (SCC1) as an example. The experimental points are fitted with a linear curve ($M = a + bV$) where its parameters are the yield moment ($M_0$), given by the value "a" and the slope given by the value "b".

As seen in Figure 4, rheological behaviour of the Bingham type is observed. The same behaviour is recorded for all the concretes studied, with a correlation coefficient ($R^2$) higher than 0.99.

The transition to fundamental parameters (yield stress and plastic viscosity) is performed according to the method given in Section 2. For example, for the case given in Figure 4, the yield stress is $\tau_0 = 3.056a_{n\text{et}}$, where $a_{n\text{et}} = a - a_{\text{mobile}}$, and $a_{\text{mobile}}$ is the effect of mass inertia of the mobile alone in rotation on the total yield torque (in our case, $a_{\text{mobile}} = 98.4 \text{ N}\cdot\text{mm}$). Thus, $\tau_0 = 34.94 \text{ Pa}$. The plastic viscosity is $\mu = 29.18b_{n\text{et}}$, where $b_{n\text{et}} = b - b_{\text{mobile}}$, and $b_{\text{mobile}}$ is the effect of mass inertia of the mobile alone in rotation on the total slope. In our case, $b_{\text{mobile}} = 0.77 \text{ N}\cdot\text{mm}\cdot\text{min/rot}$. Consequently, $\mu = 16.98 \text{ Pa}\cdot\text{s}$.

The results of the intrinsic rheological parameters ($\tau_0$ and $\mu$) of the six self compacting concretes studied on a reduced scale are given in Table 4.

As presented in Figure 5, the rheological parameters ($\tau_0$, $\mu$) developed in the six concretes studied (SCC1 to SCC6) are compared to other results available in the literature.
SCC6) fall perfectly within the range of SCC values given by three other Icelandic rheometers (MK, Contec and BML), according to the work of Wallevik and Wallevik (2011). These six concretes, according to Table 2, are really self-compacting concretes (at the real scale), so their rheological results at the reduced scale confirm this. At this level of validation, the adopted approach is able to reproduce correctly the rheological behavior of a fluid concrete such as self-compacting concrete.

As shown in Fig. 6, the yield stress of reduced self-compacting concretes is closely related to the slump flow of their corresponding concretes (at the real scale). Indeed, when the yield stress is reduced, the self-compacting concrete may have a greater flow capacity leading to higher slump. This result linking the yield stress with the slump flow of self-compacting concrete is confirmed by several other studies, including those by Reinhardt and Wustholz (2006), Shwartzentruber et al. (2006), Jau and Yang (2010) and Wallevik and Wallevik (2011).

The mathematical model used for the design of experiments studied (factorial design) is of the polynomial form. This model relates the response \( Y \) (yield stress and viscosity) to the studied factors \( (x_1, x_2, x_3) \) which are the paste volume \( (V_p) \), the superplasticizer dosage \( (SP) \) and the \((G/S)\) ratio. It contains the simple terms of type \((a_i x_i)\) representing the level of factors \( (x_i) \) assigned to their respective coefficients of effects and the product terms of type \((a_{ij} x_i x_j)\) corresponding to the interactions between two factors.

The general form of the mathematical model is given by:

\[
Y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{i,j=1, i\neq j}^{3} a_{ij} x_i x_j \ldots
\]

(4)

where

- \( a_0 \): constant term of the regression equation
- \( a_i \): linear effects
- \( a_{ij} \): interaction effects

The regression equation is obtained from the experimental data using statistical software (Minitab). The coefficients of the regression equation are determined by the least squares method. The experimental results of the rheological parameters (yield stress and plastic viscosity) of the eight concretes, studied according to the experimental design, are given in Table 5.

As a result, the suggested mathematical models for the two rheological parameters (yield stress and plastic viscosity) are given by Eqs. (5) and (6).

\[
\tau_p(Pa) = 62.22 + 3.84V_p - 0.55SP + 0.51G/S + 3.91V_p \cdot SP + 2.6V_p \cdot G/S + 1.07SP \cdot G/S
\]

(5)

\[
\mu(\text{Pa s}) = 11.47 - 5.19V_p - 3SP - 2.41G/S - 0.34V_p \cdot SP + 0.58V_p \cdot G/S + 0.32SP \cdot G/S
\]

(6)

For Eq. (5), \( R^2 = 98.65\% \) and for Eq. (6), \( R^2 = 99.84\% \).

To test and check the proposed mathematical models, four concretes are chosen in order to determine their experimental rheological parameters (yield stress and plastic viscosity). The compositions of these four selected concretes for the model testing are given in Table 6. These concretes have compositions that are intermediate with regards to the studied experimental design (in relation to which the modelling was carried out) (see Table 6).

The error calculation between the experimental and estimated values of the rheological parameters is given in Table 7. The results showed that the estimation errors (imprecisions) are insignificant (on mean) in the case of the yield stress (the mean value of the error is less than 5%). However, for plastic viscosity, these estimation

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**Table 5 Rheological results of the eight concretes studied according to the design of experiments.**

| Composition | Yield Stress (Pa) | Plastic Viscosity (Pa·s) |
|-------------|-------------------|--------------------------|
| B1          | 65.22             | 22.88                    |
| B2          | 61.33             | 11.51                    |
| B3          | 55.71             | 16.42                    |
| B4          | 64.57             | 4.72                     |
| B5          | 60.35             | 15.74                    |
| B6          | 63.96             | 7.74                     |
| B7          | 52.22             | 11.59                    |
| B8          | 74.38             | 1.38                     |

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![Fig. 5 Rheological parameters (\( \tau_p, \mu \)) of the 6 tested concretes compared to the values area of a Wallevik SCC domain (Wallevik and Wallevik 2011), which is shown by the continuous line.](image)

![Fig. 6 Relationship between the slump flow and the yield stress of the tested self compacting concrete.](image)
errors are greater (the mean value of the error is greater than 5%). Nevertheless, in a few cases of compositions, the imprecisions of the proposed models can exceed 5% for the yield stress and 10% for the plastic viscosity. In overall, the results showed, thus, that the validity of the proposed models can be good for the yield stress and moderately good (less good) for the plastic viscosity. However, in order to provide a global and more accurate statement, the number of tests needs to be increased.

5.2 Exploitation of the experimental design

The identification of statistically influential factors on rheological parameters was performed using the design of experiments method. In this method, Pareto charts are often used. According to Fig. 7, this chart displays the absolute value of the effects and draws a reference line on the chart. Any effect that extends past this reference line is statistically significant. The effect of a factor is the variation between the middle of the result domain (mean) and the mean response when that factor reaches its highest level. While the effect of two interacting factors is the difference between the mean response in the presence of the first factor when the second factor reaches its high level compared to that when it reaches its low level.

As seen in Fig. 7(a), the yield stress is governed mainly, without reaching the state of significant dominance, by the interactions between the composition parameters of a self-compacting concrete. These interactions are of type (paste-superplasticizer) and (paste-aggregates).

According to previous studies (Bossis and Brady 1989; D’haen et al. 1993; Legrand 1982; Ducerf 1995), the rheological properties of suspensions are highly dependent on the inter-particle forces acting between the particles, especially as their sizes are small. Indeed, the behaviour given by Fig. 7(a) can be explained by the dominance of these interaction forces (inter-particle forces) that occur between all the components of a self-compacting concrete in the case of the yield stress. In the studied design of experiments, the interaction forces between paste and admixture were found to be the most important.

In the case of (paste-admixture) interaction and based on the studies of Bossis and Brady (1989) and D’haen et al. (1993), the forces are of the (repulsive-attractive)
The repulsive forces caused by the adjuvant interact with the attractive forces caused by the cementitious particles. Whereas in the interaction case (paste-aggregate), the forces of type (attraction-repulsion) found in the paste interact with the contact forces caused by the aggregates.

Legrand (1971), Cyr (1999) and Nguyen (2004) have shown that the yield stress is essentially dependent on the specific surface area of the particles used. When the latter increases (high dosage of fine elements), the yield stress increases. This is explained by the increase in interaction forces (more stress to break the links).

Furthermore, Nguyen (2004) has shown that the effect of particle size on the yield stress variation is greater for fine particles (nanosilica) than for larger particles (sand). This confirms the results given in Fig. 7(a) where the effect of the (paste-adjuvant) interaction is more important than the (paste-aggregate) interaction.

Whereas the plastic viscosity is governed exclusively by the paste. As presented in Fig. 7(b), the dominance of paste volume effect on viscosity is significant, while the influence of the other parameters and their interactions are insignificant. Such results, showing that viscosity is related to the paste, have been confirmed by other researchers, for example Delarrard (2000) and Cyr et al. (2000).

By analyzing the variation of the yield stress according to each factor (separately) shown in Fig. 8(a), it is found that the concrete yield stress performance is strongly influenced by the paste volume and slightly influenced by the other two factors (superplasticizer dosage and G/S ratio). As presented in Fig. 8(b) and especially in the interaction (paste-adjuvant) curve, the superplasticizer dosage has a strong impact on the yield of the available paste in the concrete. Indeed, the yield stress of the latter is significantly affected by the dosage of superplasticizer according to the existing paste volume.

Furthermore and as seen from the (paste-G/S ratio) interaction curve, the performance of the concrete yield stress is also affected by the distribution of the paste in the granular structure (gravel and sand) allowing a favorable packing for a good flow. For example, in the studied case, the favorable packing for a minimum yield stress corresponds to a paste volume of \( V_p = 350 \) Liters and a ratio \( G/S = 1.05 \). In this case, the aggregates are sufficiently coated by paste with the availability of another amount in excess necessary for a better flow.

According to Fig. 9(a), when the three composition factors \( (V_p, SP, \text{and } G/S) \) increase, the viscosity decreases. Indeed, the increase of these 3 factors is detrimental to the segregation stability (resistance to segregation). However, as shown in Fig. 9(b), the interactions between these studied factors to produce a viscosity are negligible (all interaction curves are parallel).

In order to link the decrease in viscosity to segregation, sieve stability tests (sieve segregation tests) are carried out on the eight concretes involved in the studied design of experiments. The curve that provides this relationship is shown in Fig. 10. In fact, as the viscosity decreases, the concrete gets less and less resistant to segregation (unstable) giving a large amount of laitance.

According to Fig. 11, for a specific adjuvant dosage, the mixture is in rheological equilibrium as long as the paste volume is below a given value \( V_{pe} \). This value is a function of the superplasticizer (SP) dosage and increases when this decreases. For example for \( SP = 1.6\% \), \( V_{pe} = 368 \) Liters, for \( SP = 1.7\% \), \( V_{pe} = 362 \) Liters and for \( SP = 1.8\% \), \( V_{pe} = 356 \) Litres. The mixture is in a packing state (paste-aggregate) favorable to a good flow (low yield stress and suitable viscosity).

As shown in Fig. 11(a), if \( V_p < V_{pe} \), the flow capacity (represented by the yield stress) is improved with increasing ratio \( (G/S) \). Indeed, the flow is improved in the positive packing direction. The aggregates are coated by paste with availability of another amount in excess (just needed). As the ratio \( (G/S) \) increases (specific surface area of the aggregates decreases), the paste is progressively in excess allowing the flow to improve (yield stress decreases). If \( V_p > V_{pe} \), the flow mechanism is reversed and the mixture packing is not the same. When the ratio \( (G/S) \) increases, the yield stress increases.
Indeed, beyond paste amount ($V_{PE}$), the favorable packing begins to lose its equilibrium. As seen in Fig. 11(b), segregation begins to set in especially as the viscosity decreases. When the latter is too low, segregation is associated with an increase in laitance. Under these conditions and according to a visual observation, the aggregates are beginning to be in direct contact with each other to cause an increase in the yield stress (the aggregates are not correctly coated by the paste).

To optimize the rheological behavior of SCC, superimposed contour curves of the two parameters (yield stress and viscosity) are used. By delimiting the two rheological parameters (yield stress and viscosity) in targeted value zones, ensuring optimal self compacting behavior, the corresponding composition factors ($G/S$ and $V_p$) can be determined for any adjuvant dosage. According to Fig. 12, at a superplasticizer dosage ($SP$) of 1.6%, the rheological behaviour of the studied self-compacting concrete is optimized for a $G/S$ ratio close to 1 and a paste volume of 350 liters.
of self compacting concrete. 

Fig. 12 Optimization curve of the rheological parameters of self compacting concrete.

6. Conclusion

The main objective of this study is to suggest a rheological model represented by an equivalent reduced concrete subjected to shearing by a rotating mobile. At the end of this work, this reduced concrete model appears to be suitable to describe the rheological behavior of self compacting concrete (SCC) and to provide its intrinsic parameters which are the yield stress and the plastic viscosity.

According to the rheological parameter values (yield stress and viscosity), the self-compacting behavior of the studied reduced SCCs was checked by their correspondents at the real scale and also by the SCC value range offered by the literature. Moreover, the yield stress of the reduced self-compacting concrete is closely related to the slump flow of the corresponding concrete at the real scale.

The exploitation of this measurement model using the experimental design method has shown that the flow capacity represented by the yield stress is mainly governed by interactions, particularly those of types (paste-adjuvant) and (paste-aggregates). These results are explained by the existence of a mode of interaction forces between all the particles allowing equilibrium to reach the good rheological behavior. However, the resistance to segregation represented by viscosity is governed exclusively by the paste volume. Indeed, to produce a given viscous dissipation, each grain must be coated with an adequate thickness of paste.

To optimize the rheological behavior of the SCC, superimposed contours of the two parameters (yield stress and viscosity) can be used. For a given superplasticizer (SP) dosage, the amounts of the other two factors ($V_p$ and $G/S$) can be estimated for better rheological behaviour. For the studied self-compacting concrete, the paste volume should not exceed (358 Liters) with a ($G/S$) ratio between 0.99 and 1.05 at a superplasticizer (SP) dosage of 1.6%.

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