Development of abacus for determining the rheological behavior of self-compacting concrete

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Abstract
Widely used by architects and builders for its many qualities: strength, durability and also for its great adaptability to shapes, the self-compacting concrete (SCC) remains a material of great future both for major infrastructure works and for quality architectural achievements. Currently, to measure the rheological properties of the fresh concrete (plastic viscosity $\mu_p$ and yield stress $\tau_0$), the widely adopted test is the “concrete rheometer.” However, the use of a rheometer on site is a very complex operation, because it is too expensive, and in addition, it requires a qualified person to move, handle or repair it. Hence, many laboratories use other empirical tests to predict the rheological behavior of concrete. Each of these tests characterizes only one of the two rheological parameters ($\mu_p$ or $\tau_0$) and depends on the operator. In several cases, these constraints lead to a false characterization of the concrete behavior. To remedy these problems, this work aims to develop another means of rheological characterization of SCCs. This test will represent total independence from the operator and will quantify both the plastic viscosity and the yield stress of the self-compacting concrete. The proposed approach, verified both by experimental results and correlation studies, represents an economical and simple tool, that can be used efficiently on the building site, and it makes it possible to characterize the SCC rheology from its flow.

KEYWORDS
building site, characterization, charts, plastic viscosity, self-compacting concrete, yield stress

1 INTRODUCTION

One of the challenges of concrete construction is finding the right proportions between the components of the constituent mixture of the material. Increasing the proportion of water in the mix makes it easier to flow and use, but at a hardened state, this addition decreases the ultimate strength and durability of the concrete. Builders
often have to agree to work with viscous concrete in order to ensure the safety and aesthetic quality of the building.

Self-compacting concrete was developed in part to solve this dilemma. It consists of optimized aggregates, cement and additives such as superplasticizers that make the mixture exceptionally fluid throughout the casting process, without decreasing the strength of the material once in place.

Unlike conventional concrete, it is not necessary to vibrate it to eliminate air pockets and ensure even distribution of aggregate. It can therefore be used for works that are delicate to flow, such as those which use reinforcement of an unusual density or those which involve the liquid concrete being diffused in narrow conduits. SCC can also be poured into very fine and complex casts, ultimately producing a remarkably delicate textured surface.¹

SCC is a complex composite material to which different rheological approaches can be applied. The behavior of a fresh mixture can be considered as that of a solid phase in granular form with a very wide range of interacting particle sizes. Each of these is lubricated with different amounts of a fluid phase (paste or water), possibly including a small amount of a gas phase (air). The deformation of this material type depends on the interaction of the particles, with an important role in the rheological properties of the fluid phase.

The SCC's formulation is an adjustment between an adequately high fluidity and a sufficient consistency. This compromise is to enable a complete filling (without risk of segregation or bleeding) of the formwork without vibration.²

The appearance of the SCCs increases the need to characterize, in a precise manner, their behavior during the flow.³–¹⁰

Most SCCs are currently designed empirically and therefore must meet the several tests recommended by the EFNARC standard and described by the AFGC.¹¹,¹²

In this regard, there are three characterization tests for SCCs in the fresh state: slump flow test (Figure 1), V-funnel flow test (Figure 2), and L-box test (Figure 3).

To determine the slump flow, the same cone is used as that prescribed by standard EN 12350–2. The cone, filled with concrete, is placed on a sufficiently large flat plate (900 × 900 mm). Once the cone is lifted, the SCC flows out under the effect of gravity without a vibration tool.

The slump flow test is traditionally used to define the plastic nature of concrete (standard NF EN 206). The greater the fluidity deviation (\(\varnothing = d_1 + d_2/2\)), the greater the filling capacity of the fresh mixture (Figure 1).

The test presented in Figure 2 consists of placing a container under the V-shaped funnel, closing the V-funnel trap before filling it with concrete without any compaction, and waiting for about 10 s before quickly opening the hatch. The concrete then flows through the orifice of the V-funnel. The complete emptying time of

FIGURE 1 Slump flow test

FIGURE 2 V-funnel test
the V-funnel is recorded using a stopwatch to the nearest 0.1 s.

The higher the flow time \( (T_v) \), the greater the plastic viscosity, and therefore, the smaller the filling capacity of the fresh mixture.

The test presented in Figure 3 makes it possible to estimate the risks of blocking large aggregates at the level of the reinforcements.

The fresh concrete is introduced into the vertical part of the L-box which is separated by a trap from the horizontal part. Behind the hatch are two or three rebars, between which the concrete flows after opening the hatch (Figure 3).

At the end of the flow movement, the level in the vertical part \( (H_1) \) and the level at the end of the horizontal part \( (H_2) \) are measured to the nearest 0.05. The \( H_2/H_1 \) ratio is the measure of flowability.

Nevertheless, several scientific studies have demonstrated that the empirical tests include many defects related to the operator and hence influence the obtained results. Besides, in some situations as shown in Figure 4, the mixture exceeds the needed limit by the slump flow test (the concrete surpasses the slump test table).

To overcome those problems, LCPC laboratory has proposed the LCPC box test\(^{13}\) (Figure 5). However, in this test, the use of a bucket can disrupt the speed of the concrete flow. Hence, the LCPC test is not very practical because it depends on the operator.

On the other hand, the most approved test to quantify the rheological parameters of SCCs is to evaluate experimentally the yield stress and the plastic viscosity using a rheometer (Figure 6).

Even so, the use of a concrete rheometer on site is a very complex operation because it is too expensive, and as noted above, it has other disadvantages.

To enhance the measured parameters by LCPC box, empirical tests or concrete rheometer, we have developed another test of rheological characterization of SCCs. It is about the “V-funnel coupled to horizontal channel” test (Figure 7).

Compared to the LCPC box, the developed test proves that the flow velocity presents complete independence regarding the operator owing to the use of a standard V-funnel.\(^{14,15}\)

The proposed test also allows a complete rheological characterization estimating both plastic viscosity and yield stress, which is not possible with empirical tests.

In the face of the rheometer test, the developed tool in this study is economical, fast, simple and it can be used in the laboratory or on building site.

Using the Plexiglas canal has the advantage of analyzing, at any time, the flow profile of studied concrete (Figure 8). This observation allows us to analyze the flow numeric profile and to compare it to the experimental profile.\(^{16,17}\)
The main objective of the proposed tool, and therefore of this study, is to measure and calculate, for a studied self-compacting concrete, the rheological parameters (plastic viscosity and yield stress) from the workability properties such as the V-funnel time and the geometric parameters of the flow profile (flow length $L$, the initial height $h_i$ and the final height $h_f$ of flow—Figure 9).

Determination of the plastic viscosity and the yield stress is based on the use of charts that we have developed to simplify the analysis of these parameters on-site or in laboratory. The proposed charts will be illustrated at the end of this article.

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**EXPERIMENTAL DESCRIPTION AND TEST PROCEDURE**

The proposed experimental tool, as shown in Figure 10, is a V-funnel, which contains approximately 12 L of fresh concrete, coupled to a Plexiglas channel of a length of 0.90 m (the same length as the slump flow table), of a width and a height of 20 and 16 cm, respectively. These dimensions are proposed in order to facilitate the comparison of the used test and empirical testing (more precisely the L-box test). The experimental procedure of this tool is described in References 15,17.

- The first step of this manipulation is to fill the V-funnel with fresh concrete.
- The second step is the measurement of the final emptying time of the V-funnel after opening the hatch.
- The third step is the filling of the horizontal Plexiglas channel by the concrete resulting from the emptying of the V-funnel.
- The fourth step is the measurement of the length, the initial height and the final filling height.
- The last step is the calculation of plastic viscosity and yield stress using charts which are developed in this study, through the measured rheological parameters such as the emptying time of V-funnel, the length, the initial height and the final height of flow in the horizontal channel.

**EXPERIMENTAL STUDY**

**3.1 Materials and mixture proportions**

Considering the recommendations indicated in the literature regarding the formulation of self-compacting concrete mixture, the first phase is to develop the self-compacting concretes from cement CEM I 52.5 R (which has a density of the order of 3150 kg/m$^3$, while
changing the dosage of mineral additions (silica fume or limestone filler) and superplasticizer (KRONO 20 type). The quantity of binder (cement + a type of mineral additions) is around 470 kg/m³. All concretes are manufactured with a ratio “Water/Binder” of 0.34. The proportions of mixtures, analyzed in this study, are presented. The physical properties and chemical composition of the used materials, namely cement, aggregates, and mineral additives are given in References 22,23.

3.2 | Fresh properties of SCCs

The rheological tests (concrete flow into the V-funnel coupled to a Plexiglas horizontal channel) and the experimental values of the yield stress and the plastic viscosity of various SCCs are presented in References 22,23. The given results are the average of six measurements.

4 | THEORETICAL CALCULATION AND CHARTS DEVELOPMENT

The experimental device of the V-funnel test is described in Figure 11.

Equation (1) was found by taking into account the energy balance between surfaces $S_0$ and $S_1$, the mass conservation, and the regular and singular head losses. Thus, we used the Runge–Kutta method for the resolution of this differential equation. 15
To verify the validity of this approach on concrete and more precisely on self-compacting concrete, we compared the experimental values of plastic viscosity obtained by a concrete rheometer with those calculated theoretically by our Equation (1).

Example of used Runge–Kutta method (Matlab program):

The correlation among the values of plastic viscosity measured by the concrete rheometer (reported $\mu_{p,\text{exp}}$), and those calculated by means of Equation (1) (reported $\mu_{p,\text{theo}}$) was found to be more precise, as shown in Figure 12. The best-fitting curve illustrating this correlation is given by: $\mu_{p,\text{theo}} = 1.0832\mu_{p,\text{exp}} + 5.4123$, represented by the linear regression model of $R^2 = 0.9784$.

\[
\mu_p = \left[ -\frac{8H\tau_0}{3} \left( \frac{2(z\tan\alpha + d) + e}{(z\tan\alpha + d) - e} \right) \rho \frac{dz}{dt} + \rho \left( 1 - \frac{z\tan\alpha + d}{d} \right)^2 - \varepsilon \right] \frac{dz}{dt} \right]
\]

(1)

with $d, H, a, e$ are the geometric parameters; $dz/dt$ is the flow velocity; $\rho$ is the density; $g$ is the gravity; $\mu_p$ is the plastic viscosity; and $\tau_0$ is the yield stress. This parameter is proposed by Roussel\textsuperscript{13,24} as follows:

\[
\tau_0 = \frac{\rho g l_0}{2L} \left[ (H_i - H_f) + \frac{l_0}{2} \ln \left( \frac{l_0 + 2H_f}{l_0} \right) \right]
\]

(2)

where $\rho$ is the density of mixture, $L$ and $l_0$ are the length and the width of channel, respectively; $H_i$ and $H_f$ are the initial height and final height of flow in channel, respectively.

The analysis of the experimental values and the comparison between them and the proposed approach has shown that the characterization, in the laboratory or on-site, of the rheology of a SCC and its behavior can be carried out with the approach proposed in this study instead of a rheometer.

In a practical manner, for concretes which satisfy the conditions required to be qualified as self-compacting concrete, the method of determining the yield stress and the plastic viscosity values can be generalized in the following abacuses (Figures 13–16). The proposed abacuses are very simple means which allows...
the direct determination of the plastic viscosity and the yield stress based on the V-funnel flow time values, the density, and the final and initial flow ratio ($h_f$ and $h_i$).

In general, the yield stress $\tau_0$ of a SCC (whatever its density) is written:

$$\tau_0 = \tau_{0i} + x$$

With $\tau_{0i}$ the yield stress of SCC whose density is 2400 kg/m$^3$ (Figure 13). To determine the coefficient “$x$” we use the graph presented in Figure 14.

In general, the plastic viscosity $\mu_p$ of a SCC (whatever its density) is written:

$$\mu_p = \mu_{pi} + x$$

With $\mu_{pi}$ the plastic viscosity of SCC whose density is 2400 kg/m$^3$ (Figure 15). To determine the coefficient “$x$” we use the graph presented in Figure 16.

5 | CASE STUDY

On a construction site, the project manager wants to characterize the concrete delivered by the concrete plant,
using the approach developed in this study: the flow of concrete in a V-funnel coupled to a horizontal plexiglass channel.

- Knowing that the density of the concrete tested is given by the concrete plant or measured directly on-site (density \( \rho \) = mass/volume). For the example treated below, we take \( \rho = 2480 \, \text{kg/m}^3 \).

- With the same mixture, using the developed experimental test (Figure 10), we have: \( T_v = 12 \, \text{s}; h_i = 0.14 \, \text{m}; H_f = 0.065 \, \text{m}; L_{\text{max}} = 0.90 \, \text{m} \).
- We calculate \( (h_i - h_f) \) and from the abacus of Figure 13 we determine the yield stress. In our case: \( \tau_{0i} = 70 \, \text{Pa} \).
- For \( \rho = 2480 \, \text{kg/m}^3 \) and from the abacus of Figure 14, we find (Figure 17): yield stress \( \tau_0 = 70 + 4.80 = 74.80 \, \text{Pa} \).
From the abacus of Figure 15, we find, for the flow time 12 s, the initial plastic viscosity $\mu_{pi} = 90$ Pa s.

For $\rho = 2480$ kg/m$^3$ and from the abacus of Figure 16, we find (Figure 18): plastic viscosity ($\mu_p$) = 90 + 0.512 = 90.512 Pa s.

6 | CONCLUSION

Based on the results of tests carried out on more than 500 compositions, it can be concluded that using the new test proposed in this study (V-funnel coupled to a horizontal Plexiglas channel) makes it possible to
characterize the filling capacity of concrete by visualizing its flow profile \((h_f/h_i, \text{ratio, flow length, etc.)})\.

We have succeeded in proposing a correlation between the plastic viscosity of SCCs and the flow time in the V-funnel and the rheological characteristics of the flow profile in a horizontal channel. The proposed approaches have been verified by experimental results. Now, we have an experimental tool to characterize the concrete flow from its rheological characteristics.

The comparison among the experimental analysis of the values of flow threshold and plastic viscosity, and the theoretical analysis of these parameters showed that, instead of using a concrete rheometer, the characterization, in the laboratory or on site, of the rheology of a SCC and its behavior can be carried out with the charts developed in this study.

**DATA AVAILABILITY STATEMENT**

Data openly available in a public repository that issues datasets with DOIs.

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