From Rheology of Fresh Concrete to Casting Processes

Correlating properties with field performance

BY NICOLAS ROUSSEL

What are the final objectives of the extensive research that has been carried out in the last 50 years on the rheology of fresh concrete? A researcher's answer might be: "the understanding of the correlation between mixture proportioning and rheological properties" or "the ability to correctly measure and quantify the rheological properties of concrete." These points are of great interest, but a practitioner would probably answer: "the ability to predict whether or not a given concrete will correctly fill a given formwork."

A lot of research has been carried out to understand the correlation between mechanical properties and mixture proportioning,[1] and many tests have been developed to measure these mechanical properties, such as strength and delayed deformations. But many developments were also made to correlate the properties of the concrete to be cast with the structure to be built. This last step has been missing for years in the rheology field. Only recently have researchers from various parts of the world started working on casting prediction tools.

It should be noted that this new research area has appeared on the scene at the same time as self-consolidating concrete (SCC). This extremely fluid type of concrete was expected to be the answer to casting problems. No matter how fluid a concrete is, however, there will always be formwork and reinforcement configurations that present casting problems.

SCIENTIFIC BACKGROUND

Fresh cementitious materials behave as fluids with a yield stress, which is the minimum stress for flow to occur. The behavior of fresh concrete is thus often approximated by a yield stress model of the following general form[2,3]:

$$\dot{\gamma} = 0 \rightarrow \tau < \tau_{00} \qquad \text{Eq. (1a)}$$

$$\dot{\gamma} \neq 0 \rightarrow \tau = \tau_{00} + \mu_p \dot{\gamma} \qquad \text{Eq. (1b)}$$

where τ_{00} is the yield stress, $\dot{\gamma}$ is the shear rate, and μ_p is the plastic viscosity.

From a practical point of view, yield stress may be associated with filling capacity and, more generally, with whether or not concrete will flow or stop flowing under an applied stress, whereas plastic viscosity may be associated with the velocity at which a given concrete will flow once flow is initiated. In the field of concrete casting, unlike polymer or metal casting, the applied stress is mainly due to gravity, as injection under pressure is very rare.

Although measurements of plastic viscosity have several practical applications, such as pumping and casting rates, yield stress is the most important parameter for formwork filling. If we consider, for instance, the casting of a wall such as the one in Fig. 1(a), a purely

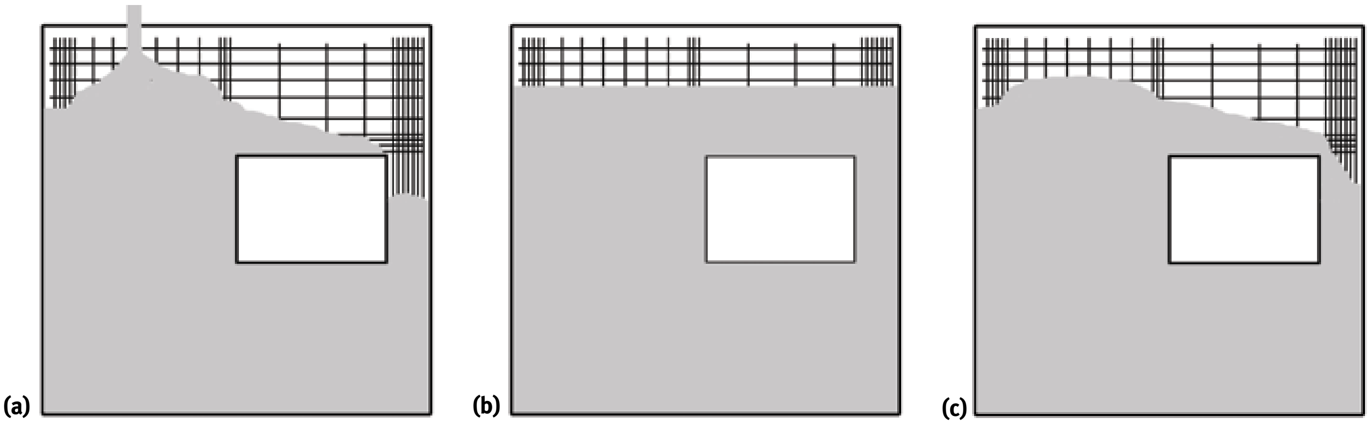

Fig. 1: Formwork filling process: (a) casting process; (b) final shape of the material in the case of a purely viscous fluid; and (c) final shape of the material in the case of a fluid with a yield stress

viscous fluid (one with a zero yield stress) would self level under the effect of gravity, as shown in Fig. 1(b). Gravity would indeed induce a pressure gradient in the fluid if the upper surface of the material is not horizontal. This pressure gradient would generate a shear stress in the material that creates a shear rate and forces the material to flow until the upper surface becomes horizontal and the pressure gradient at the origin of the flow has disappeared. The viscosity of the material will only play a role in the time needed to obtain a horizontal surface.

In the case of a fluid with a yield stress, such as concrete, gravity and the pressure gradient also generate a shear stress. If this shear stress, which is a complex function of the formwork thickness and the density of reinforcement, becomes lower than the yield stress of the concrete, flow stops before the concrete self levels, as shown in Fig. 1(c).

This example teaches us two things. First, the best way to fill formwork is to fill it with a purely viscous fluid, which is useless in practice as we will never be able to produce stable concrete with no yield stress at all. Second, to predict whether a given concrete will fill a given formwork, we must have the ability to measure the yield stress of the material to be cast.

It must be noted that the knowledge of the yield stress at the end of the mixing phase may not always be sufficient to describe the behavior of fresh concrete after transportation from the concrete plant to the job site. A change in the material yield stress is often noted during this time period. In many cases, the material yield stress increases, causing a workability loss. Delayed actions of high-range water-reducing admixtures, however, may also decrease the material yield stress.

YIELD STRESS MEASUREMENTS

In the case of cement pastes, yield stress may be measured using conventional rheological tools.[4,5] For concrete containing coarse aggregate, however, large-scale rheometers have been developed (BTRheom[6], BML[7], or two-point test[8]). Even though simpler and cheaper tests such as the slump test[9] are still often preferred on the job site, these rheometers represent a big step forward in the field of concrete science. A discrepancy still exists, however, between the various rheometers.[10,11] They give the same rheological classification of materials, but they do not give the same absolute values of the rheological parameters τ_{00} and μ_p. The slump test, the most common empirical test for fresh concrete, does not give any value of a physical parameter at all. In fact, the results could not be expressed in physical rheological units until recently. But it has also proved through the years to be able to classify different materials in terms of their abilities to fill formwork.

Several attempts to relate slump to yield stress can be found in literature. Murata[12] first wrote of a relation between the final height of the cone and the yield stress of the material. Subsequent works established analogous relationships either for conical or cylindrical forms.[13-16] It's recently been shown that two very different regimes (slump regime and spreading regime) may be identified, deriving two analytical solutions suitable for asymptomatic regimes, namely low-slump or large-slump flow diameter.[17] Numerical simulations of the slump test were also carried out for the ASTM Abrams cone.[18] An excellent agreement between the predicted and measured slumps over a wide range of yield stress was obtained. As an example, the obtained correlation[18] between slump and yield stress for slump values ranging from 50 to 250 mm (2 to 10 in.) is written:

$$S = 255 - 176\frac{\tau_{00}}{\rho} \qquad \text{Eq. (2) (SI units)}$$

$$S = 10 - 2980\frac{\tau_{00}}{\rho} \qquad \text{Eq. (2) (in.-lb units)}$$

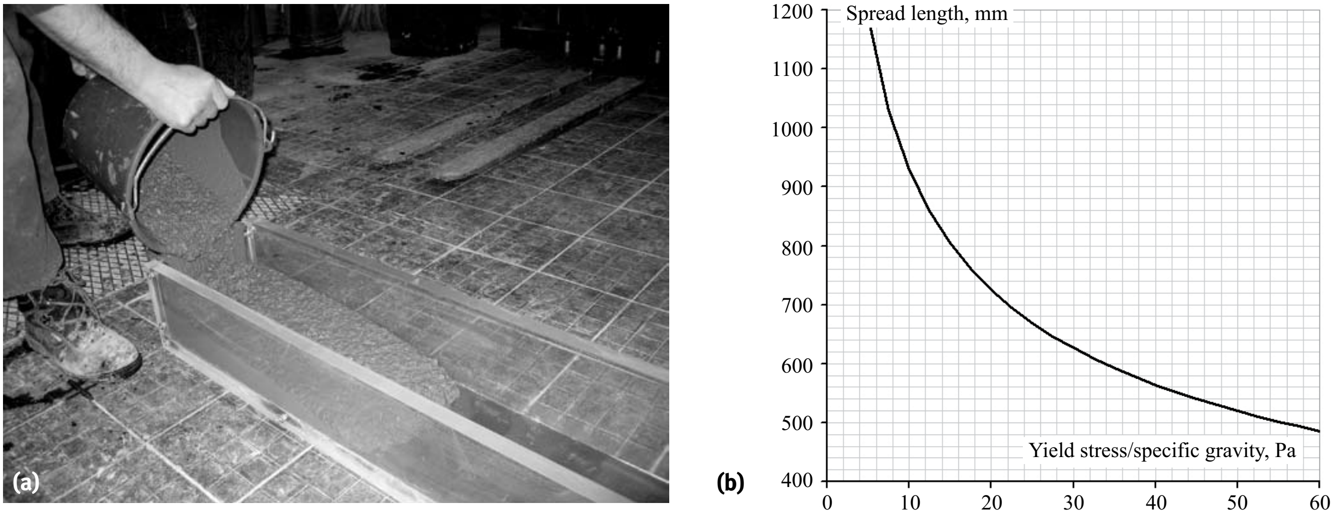

Fig. 2: The LCPC Box test for SCC: (a) the SCC is slowly poured into the box at one end; and (b) correlation between measured spread length and a yield stress of the tested material (1 in. = 25.4 mm, 1 psi = 6890 kPa)

where S is the measured slump, mm (in.), τ_{00} is the yield stress, Pa (psi), and ρ is the density of the concrete, kg/m^3 (lb/ft^3).

In the case of SCC, it was demonstrated that the slump flow test cannot be universally correlated to the rheological parameters of the concrete.[19] Indeed, the thickness of the sample when flow stops is of the same order as the largest particles. This does not mean that slump flow cannot be used as an acceptance test. For a given SCC with a given granular skeleton, the slump flow value is indeed a handy tool to spot, for example, a variation in water amount during production. But the measured spread (or slump flow value) cannot be directly and universally correlated to the yield stress of the SCC.

An alternate test method is the recently proposed "LCPC Box" test shown in Fig. 2(a). The width of the channel is 200 mm (7.9 in.) and the length is 1200 mm (47.2 in.). The studied volume of SCC is the same as the one used in the slump flow test, 6 L (0.21 ft^3). As the flow is almost unidirectional, the thickness of the sample at stoppage for the same sample volume is greater than in the slump flow test. Moreover, it was verified that the final shape does not depend on the pouring speed of the concrete to be tested. This new test is a cheap and easy way to measure the yield stress of fluid concrete when trying to reach the optimum mixture design or to compare the rheology of various SCC mixtures. Unlike the slump flow test, the measured spread length is correlated to the yield stress of the material via the unique law[19, 20] shown in Fig. 2(b).

As an intermediate conclusion, it should be kept in mind that these correlations between geometrical measurements, such as slump or spread length, allow measurement of the yield stress of any concrete without the use of a rheometer. They easily give access to this fundamental and intrinsic rheological parameter and therefore open the door to the use of this measurement in casting prediction tools.

CASTING PREDICTIONS

The ideal mixture proportions for fluid concrete are located somewhere between two opposite objectives. The concrete has to be as fluid as possible to ensure that it will fill the formwork under its own weight, but it has to be stable enough to withstand the high strain rates generated by flow in a confined zone. Therefore, a compromise between stability and fluidity has to be reached.

The most straightforward approach is to find the minimum fluidity (or workability) that will guarantee adequate filling of the formwork and assume that this minimum fluidity will ensure the maximum acceptable stability. The only traditional way to do this is to try various mixture proportions, cast a full-size element with each of them, and choose the most suitable mixture (if there is one). This is expensive and time consuming and does not guarantee an answer. In the case of sufficiently fluid concretes, however, the numerical tools of non-Newtonian fluid mechanics allow numerical simulation of the casting process and, for a very low cost, the determination of the minimum fluidity.

The applicability of the viscoplastic divided element method (VDEM) for simulating the flow of concrete in a reinforced beam section and the filling of a reinforced wall has already been demonstrated,[21] and the applicability of 2-D VDEM to simulate the flow of fresh concrete in formwork has been confirmed.[22] The results of a form-filling experiment in a vertical wall have also been compared with the corresponding 3-D simulation.[23] The results show high correlation with respect to detection of the free surface location, dead zones, and particle paths.

Numerical simulations were also recently applied to an industrial casting of a very high-strength concrete precambered composite beam.[24] The results of the simulations carried out for various values of the rheological parameters helped determine the value of the minimum fluidity needed to cast the element. The LCPC Box mentioned previously was used to measure the yield stress of the prepared SCCs. The numerical calculations were able to predict the experimental observations carried out during two trial castings (Fig. 3). In the case of SCC with 120 Pa (0.017 psi) yield stress, some voids were found below the steel girders after the removal of the form 1 day after casting. After casting SCC with 60 Pa (0.0087 psi) yield stress, no voids were visible.

Although the assumptions needed to carry out the simulations were overly simplistic (only 2-D simulations were carried out), a satisfactory agreement was found between the predicted and actual flow. It is my opinion that, in the future, computational modeling of flow could become a practical tool for allowing the simulation of either total form filling or detailed flow behavior such as particle migration and formation of granular arches between reinforcement (also known as "blocking").[25,26] These methods could then be gathered to create a casting process engineering toolbox and bring rheology from the laboratory to the field.

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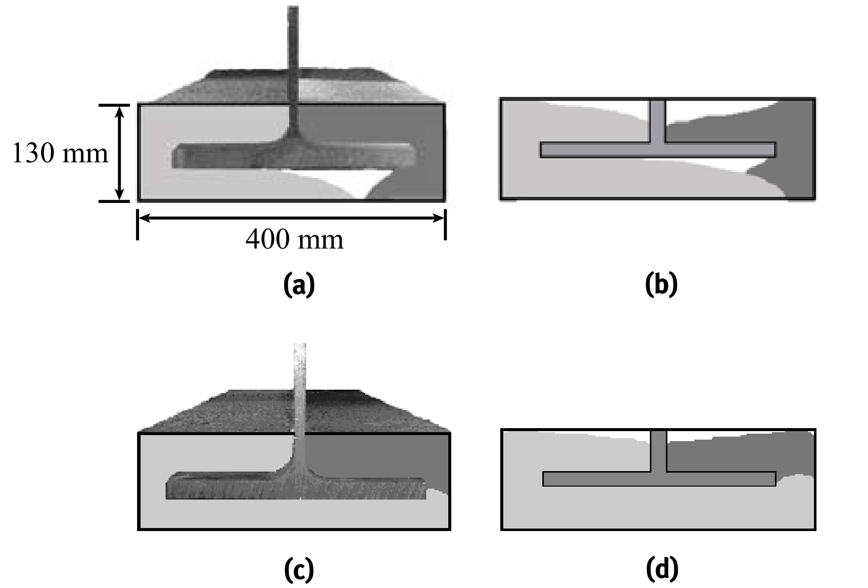

Fig. 3: Comparison between numerical predictions and actual casting of a precambered beam. The concrete was first poured from one side of the steel girder (light gray). The concrete was then poured from the other side of the steel girder to complete the filling (dark gray): (a) actual casting results using concrete with a yield stress of 120 Pa (0.017 psi); (b) numerical simulation results for concrete with a yield stress of 120 Pa (0.017 psi); (c) actual casting results using concrete with a yield stress of 60 Pa (0.0087 psi); and (d) numerical simulation results for concrete with a yield stress of 60 Pa (0.0087 psi) (1 in. = 25.4 mm)

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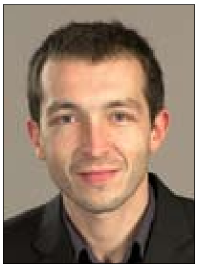

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