CONCRETE RHEOLOGY: WHAT IS IT AND WHY DO WE NEED IT?

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Abstract

The design of concrete with specified properties for an application is not a new science, but it has taken on a new meaning with the wide use of self compacting concrete (SCC). In this industry, general terms such as “flow under its own weight” and “filling capacity”, or workability, flowability, compactibility, stability, finishability, pumpability, and/or consistency are currently used interchangeably without a definition based on fundamental measurements of properties. Several attempts have been made to better relate fresh concrete properties with measurable quantities. Some researchers treated fresh concrete as a fluid and used fluid rheology methods to describe concrete flow. This approach, the most fundamental one, is reviewed in this paper. The main topics that will be addressed are: 1) Review the fundamental definitions of quantities used to uniquely describe the flow of concrete; 2) Give an overview of the tests that are commonly used to measure the rheology of fresh concrete, partially based also on the completed comparison of concrete rheometers sponsored by ACI; 3) Describe methods to predict the flow of concrete from either composition or laboratory tests, including some simulation techniques developed at NIST. A conclusion will present some thoughts on research needed to design SCC with the flow properties required for a given application.

1. INTRODUCTION

The design of concrete with specified rheological properties for an application is not a new science, but it has taken on a new meaning with the wide use of self compacting concrete (SCC). In this industry, general terms such as “flow under its own weight”, and “filling capacity”, or workability, flowability, compactibility, stability, finishability, pumpability, and/or consistency are currently used interchangeably without a definition based on fundamental measurements of properties. Several attempts have been made to better relate fresh concrete properties with measurable quantities. Some researchers have treated fresh concrete as a fluid and used fluid rheology methods to describe concrete flow.

This approach implies the definition of rheological properties adapted to concrete. The difficulty of this approach is the granular composition of concrete with particle size ranging from micrometers (cement or supplementary cementitious materials) to tens of millimeters (coarse aggregates). This wide range in granular sizes does not allow the direct application to concrete of the science of rheology developed for fluids. Several methods have been designed: 1) empirical methods that simulate field use of the concrete; 2) measurements of concrete using a rheometer adapted to concrete; and 3) models that simulate concrete flow.

Each method has its merits. The empirical tests are usually cheap, easy to use on the field, and give some information on the properties of concrete during placement. The design of concrete rheometers is a step forward because they provide measurements of physical entities related to fundamental flow properties. These values can be used to predict the behavior of concrete for various applications, and to select concrete on performance during trial mixes. The last approach, modeling the flow, is the hardest one but the one with the most potential once fully developed. It is the only approach that will allow a true prediction of the flow of concrete from its composition.

In this paper, a review of fundamental definitions used to uniquely describe the flow of concrete as well as an overview of the tests commonly used will be presented. Finally, the methods to predict the flow of concrete from either composition or laboratory tests, including some simulation techniques developed at NIST, will be discussed. In conclusion, we will present some thoughts on research needed to design SCC with the flow properties required for a given application.

2. SOME RHEOLOGICAL DEFINITIONS

A full list of definitions of the terms related to concrete rheology will occupy more pages than allowed in this conference. Therefore, only the most common definition will be discussed here. A more extensive list can be found in Refs. [1, 2].

Concrete is considered by most researchers in most circumstances to behave like a Bingham fluid. A Bingham fluid flow is characterized by two entities: the yield stress and the plastic viscosity. The yield stress is the stress needed to start moving the concrete, while the plastic viscosity is a characterization of the flow of the concrete once the stress is higher than the yield stress. A Bingham fluid is characterized by a linear relationship between shear rate and shear stress as shown in equation 1.

$$\sigma = \sigma_B + \eta_{pl}\dot{\gamma} \qquad (1)$$

where σ = Shear stress, σ_B = yield stress, η_{pl} = Plastic viscosity, and $\dot{\gamma}$ = Shear rate.

Most of the rheometers used for concrete apply a shear rate and measure the shear stress response of the fluid. The Bingham equation, although widely used, is not the only one that can be used to describe the flow of concrete. In certain cases, such as cement paste near setting time or very flowable concrete, the value obtained for yield stress or plastic viscosity using the Bingham equation could be negative [3, 4, 5], which are not considered physically valid.

When concrete or cement paste is measured at a wide range of shear rate it could be considered to be *shear thinning [pseudoplastic] with yield response* [1]. The significance of this characteristic is that the shear stress vs. shear rate slope depends on the range of shear rate selected. It is not a constant. Therefore, the plastic viscosity calculated using the Bingham equation would depend on the experimental set-up.

Another factor to take into consideration is that the yield stress, calculated from the Bingham equation is an extrapolation of a curve obtained by sweeping shear rate from high to low. The yield stress obtained in this manner is usually lower than the yield stress obtained by increasing shear stress until flow in obtained ($\dot{\gamma} > 0$). The yield stress obtained by increasing shear stress should be considered the stress that really characterize the initiation of flow but it is impossible to measure this stress using concrete rheometers because they are not stress controlled but shear controlled. Also, if the slope depends on the shear rates selected, as concrete is pseudoplastic, the extrapolation used to calculate the yield stress is affected as well.

Another approach used to measure the yield stress, which seems more appropriate than the Bingham method, is the *stress growth method*. This method shears the material at a very low constant shear rate, usually selected as the lowest shear rate permitted by the rheometer used. The shear stress is measured as the response of the material vs. time. A typical curve obtained is shown in Figure 1. The end of the linear initial portion of the curve is defined as the yield stress. This point is often difficult to determine using most commercially available rheometers because only few points can be measured on this linear portion of the curve, due to the lack of sensitivity of most rheometers to measure very small stress values. Therefore, as a good approximation, the stress at the peak (Fig. 1) is defined as the best approximation of the yield stress. This value is a better description of the yield stress than the Bingham equation yields because it is not an extrapolation and the microstructure was not disturbed before the measurement.

Both methods, Bingham or stress growth, could be used in cement paste, mortar and concrete using most of the available rotational rheometers. Other equations exist to describe the flow of concrete but they are not widely used and thus will not be described here [1]. Despite all the shortcomings of the Bingham equation, it is still the most used method on account of its simplicity.

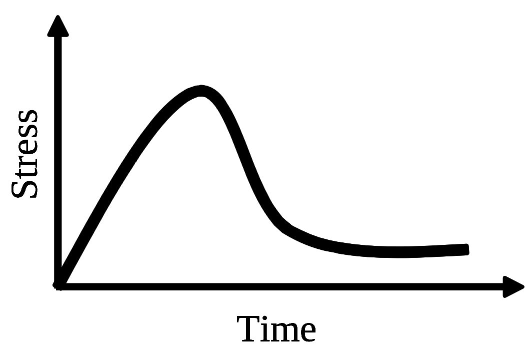

Figure 1: Stress growth schematic

3. CONCRETE RHEOLOGICAL TESTS

The methods used to measure flow properties of concrete are very numerous, with over 60 tests identified [5]. Most of the tests (over 70 %) only measure one parameter. This parameter could be related to either the yield stress or the plastic viscosity but not in a direct manner. The rest of the methods measure two values that could be related to both Bingham parameters. Nevertheless, the relationship between the Bingham parameters and the test results is not simple and often is not known. Some attempts at correlation were done. For example, the slump test results are related to the yield stress [13].

In summary, test methods applied to concrete are either empirical or they are scaled up versions of techniques used for fine particle systems. The empirical tests generally represent an attempt to "imitate" a mode of placement or flow of the concrete during production. The rheological test methods for concrete tend to fall into one of four general categories [1]: Confined flow, free flow, vibration and rotational rheometers. These categories were selected to describe the mode by which the concrete is forced to flow and are defined as follows:

- **confined flow** The material *flows* under its own weight or under an applied pressure through a narrow orifice. The orifice is defined as an opening roughly three to five times larger than the maximum particle size. Because coarse aggregates are often on the order of 30 mm in size, the orifice must typically be 90 mm to 150 mm in diameter. Confined flow methods include *flow cone, filling ability* devices, *flow test* through an opening.
- **free flow** The material either flows under its own weight, without any confinement, or an object penetrates the material by gravitational settling. Free flow methods include *slump, modified slump, penetrating* rod and *turning tube viscometer*.
- **vibration** The material flows under the influence of applied vibration. The vibration is applied by using a vibrating table (e.g., *Ve-Be time*), dropping the base supporting the material (*DIN slump cone test*), an external vibrator, or an internal vibrator (e.g., *settling method*).
- **rotational rheometers** The material is sheared between two parallel surfaces, one or both of which are rotating. These tests are analogous to *rheometers* described in the previous section, except in this case the gap between surfaces must be scaled up to reflect the much larger dimensions of the concrete particles. Full description of the rheometers can be found in [6,7].

Cement paste and mortar measurements are also available. They are mainly laboratory devices that are used either for research or for determining the influence of chemical admixtures on the flow of cement paste.

The cement paste measurement device can be done using conventional rotational rheometers designed for oils. The most common configurations used are coaxial [14] or parallel plate [15]. The advantage of the parallel plate configuration is that the gap between the plates and the texture of the plate surface can be easily modified. The gap variation allows accommodation of suspensions with various particle sizes. Figure 2a shows the type of rheometer used at NIST for cement paste. The calculation of the shear stress and shear rate in fundamental units could be done using the conventional method used for oils. Nevertheless, some discussion on the influence of the surface texture and gap on the results persists and so further tests are being performed at NIST. An artificial high stress could be created due to blockage of the two plates depending on the ratio of the gap to the maximum particle size. Slippage is always a possibility if the texture of the plates is not selected properly.

The mortar rheometer developed at NIST is a modification of the cement paste rheometer using a different size plate and plate texture (Fig. 2b). This rheometer has an added feature compared to the cement paste rheometer, which is a confinement ring. This confinement ring is necessary to contain the mortar between the two plates (gap of 10 mm). The confinement ring is not necessary for cement paste because the gaps are less than 1 mm and so capillary forces will hold the material between the two plates. Obviously, the presence of the confinement ring transforms this rheometer into a non-fundamental parallel plate rheometer for which flow patterns cannot be easily calculated. NIST is studying the problem of the calibration of such devices by a combination of known fluids and simulation. Other mortar rheometers are in use in the world but they encounter the same pitfalls, i.e., no clear calibration and flow patterns that do not allow the calculation of rheological parameters in fundamental units.

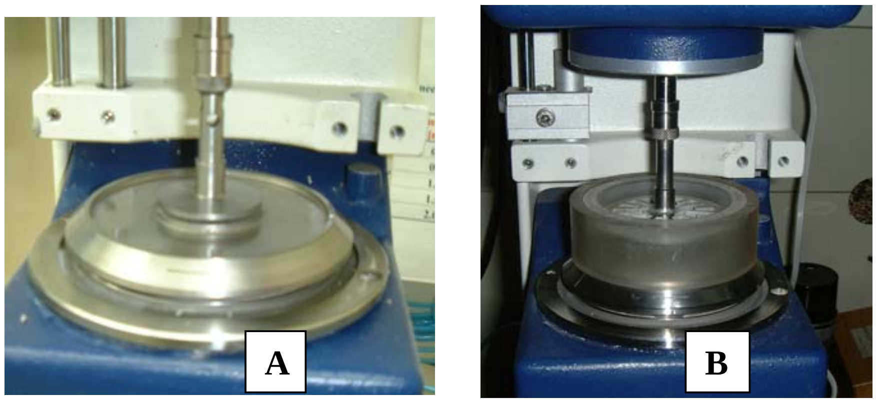

Figure 2: Cement paste rheometer (a) and mortar rheometer (b) schematic

Concrete measurements can be done using any of the existing concrete rotational rheometers. ACI 236A committee has sponsored two round-robins to compare all the concrete rheometers available [6,7]. The main conclusion reached is that the rheometers rank a series of concretes in the same order for yield stress and plastic viscosity, and that they can be pair-correlated with linear functions. On the other hand, the values obtained by the various rheometers differ sometimes by an order of magnitude. Therefore, a lot of comparative measurements should be done with vastly different concrete compositions to establish a correlation function that could be trusted to convert the results of one rheometer to the results of another one. Obviously, this is costly and not easily feasible. This situation led the committee to decide that it is imperative that a reference material be developed. The committee has started a study to select the material. It should be oil based with granular particles. The oil has been selected but there is still discussion on what kind of particles should be used.

The concept of relative viscosity [8] could be used to compare the results obtained from various rheometers. The relative viscosity is defined as the ratio between the plastic viscosity of a concrete with the mortar or a reference mixture. Both viscosities need to be measured using the same rheometer. If this concept is applied, the results of very different rheometers can be plotted on the same graph and they follow the same curve (Fig. 3). It would allow researchers from different laboratories to at least be able to compare their data while using different rheometers.

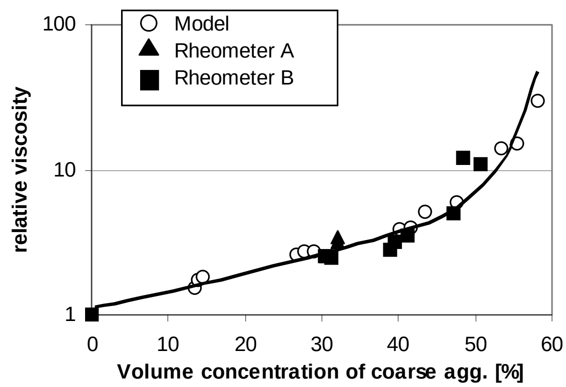

Figure 3: Relative viscosity example

Finally, It could be stated that there are numerous methods available to measure the flow of concrete and some progress is being made to obtain data that could be used for designing a performance based concrete.

4. HOW TO PREDICT THE FLOW OF CONCRETE?

The prediction of concrete flow from its composition is the paramount goal in rheology. Without an answer to this question, concrete will continue to be designed by trial and error to fit the performance needed for a specific application. Today, most commercial concretes are designed using guidelines provided by ACI and the field knowledge of engineers. This is not a desirable situation and it becomes more difficult as concrete raw materials increase in number and diversity.

The problem of prediction could be divided in two parts: plastic viscosity and yield stress. The plastic viscosity prediction is more advanced and has been implemented in some cases. The yield stress calculation is more difficult and therefore a proper method is still being developed.

A multi-scale approach was adopted by NIST to predict the plastic viscosity. This implies that the concrete plastic viscosity is determined from the mortar plastic viscosity and the coarse aggregates shape and size distribution. The mortar plastic viscosity is calculated from the cement paste properties and the fine aggregates shape and size distribution. The cement paste should include any chemical and mineral admixtures that are selected and only its global rheological properties are used as the input to the model. The link between the various scales, concrete-mortar-cement paste, is a simulation model based on the *dissipative particle dynamics* (DPD) algorithm [10, 11]. This model is similar to a molecular dynamics algorithm but with the major difference that the suspension particles representation is not atomistic but mesoscopic, i.e., the particles are “lumps” of fluid. The rigid body is approximated by “freezing” a set of randomly placed particles, centered where the solid inclusion is located, and updating their position according to the Euler equations. The particles are submitted to interaction forces that govern their movements. The output of the simulation is the flow of the particles vs. time under an applied external shear force.

The shape and size distribution of the aggregates need to be known so that the simulation would properly predict the concrete rheology. Garboczi [12] used X-ray tomography and spherical harmonics to digitize aggregate shape. The size distribution can be obtained easily by traditional methods such as sieving for the coarse aggregates and laser diffraction and sieving for the fine aggregates.

In summary, the concrete viscosity could be simulated using the cement paste or mortar measured rheological properties, the shape and size distribution of the aggregates, and the DPD model. More research is in progress to validate the method and to render it easier to use.

The prediction of yield stress is more difficult as it is necessary to determine what are the fundamental factors that affect the yield stress. The particle concentration and shape must play a role, but in cement the interaction between the particles also needs to be addressed. At the mortar level, the particles need to be arranged so that flow can start. The yield stress is really the force that is needed to start movement; therefore, to determine the yield stress by simulation, the logical way will be by simulating a stress growth type of experiment. The Bingham equation would require performing simulations at various shear rates and then extrapolating to zero shear rate. Preliminary simulations on stress growth were performed and research is on going to better characterize the cement interparticle interactions responsible for the yield stress in cement.

5. WHAT'S NEXT? RESEARCH NEEDS

The concrete community has, at this point many concrete rheometers and other measurement devices, models, and some understanding of the flow of concrete and what is affecting it. This should be the time were it could be stated that the empirical design of concrete to achieve a certain flow for a specified application is an artifact of the past. But, why is this is not the case?

It is not the case because there are still a lot of issues that are not well understood. For instance, the interaction of the cement with chemical admixtures, the control of the air bubble size distribution, the role of supplementary cementitious materials, and the influence of the shape of aggregates, to cite a few, are not all well understood or controlled. The numerous concrete rheometers cannot be calibrated due to the lack of reference materials and not having a full calculation of the flow patterns. Maybe we should think out of the box to design ***the** concrete/mortar rheometer* of the future. Prediction models are germinating but they are not fully operational as yet.

Therefore, research is needed in numerous areas, such as the development of a granular reference material that could be used both as concrete and mortar and even cement replacement to calibrate all rheometers. Today oil is used to calibrate rheometers, but oil is a Newtonian liquid, which means that the shear stress vs. shear rate slope (or the viscosity) is not dependent to the shear rate. The development of a proper reference material cannot be achieved without a close collaboration between experiment and computer modeling. This collaboration will allow the understanding of the factors affecting the flow of concrete or a suspension in the rheometers. The flow pattern might be able to be simulated and therefore a better plastic viscosity and yield stress can be determined.

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