CONCRETE RHEOLOGY: KNOWLEDGE AND CHALLENGES

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Abstract

The design of concrete with properties specified for an application is not a new concept, but it has taken on a new meaning with the wide use of special concretes, such as self compacting concrete (SCC). 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 properties measurement. Several attempts have been made to better relate fresh concrete properties with measurable quantities. Some researchers treat 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) a review of the fundamental definitions of quantities used to uniquely describe the flow of concrete; 2) 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; and 3) discussion of the challenges that must be overcome to bring rheology to the construction site. A conclusion will present some thoughts on research needed.

1. INTRODUCTION

The design of concrete with specified rheological properties for an application is not a new concept. It has, in fact, become paramount as always more daring applications are becoming mainstream. Terms such as workability, flowability, compactibility, stability, finishability, pumpability, and/or consistency are currently used interchangeably without a definition based on fundamental measurements of properties. Today, concrete can be placed with or without vibration. Placement without vibration is commonly called self-compacting concrete (SCC), which should flow under its own weight to completely fill the form. On the other hand, the compaction of more "mundane" concrete is done using vibrators. The concrete needs to properly respond to the vibration imparted and flow to completely fill the form. In either case, the design of concrete with predictable flow properties or rheological properties is still difficult. Measurements of the rheological properties are not easy either, but progress has being made with the design and construction of various rheometers.

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 to measure concrete flow: 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 in the field, and give some information on the properties of concrete during placement. The design of concrete rheometers is a step forward, because rheometers 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 based on performance during trial mixes. The last approach, modeling the flow, is the hardest method 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 very brief 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 National Institute of Standard and Technology (NIST), will be discussed. In conclusion, we will present some thoughts on research needed to design concrete with the flow properties required for a given application.

2. SOME RHEOLOGICAL DEFINITIONS

Concrete is often considered to behave like a Bingham fluid. Bingham fluid flow is characterized by two entities: the yield stress and the plastic viscosity. 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 rheometers used for concrete control the shear rate and measure the shear stress response of the fluid. The measurements are done by increasing the shear rate and then decreasing it in steps. The decreasing part of the curve is used to calculate the yield stress and plastic viscosity. 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 can even be negative [1, 2, 3], which is not physically valid. Further discussion and definition of other terms related to concrete rheology can be found in Refs. [4, 5].

When concrete or cement paste is measured over a wide range of shear rates it is clear that the Bingham linear behavior cannot be applied and that a *shear thinning [pseudoplastic] with* *yield response* [4] could be a better model. 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 the shear rate from high to low values. The yield stress obtained in this manner is usually lower than the yield stress obtained by increasing shear stress until flow is obtained ($\dot{\gamma} > 0$) [3]. The yield stress obtained by increasing shear stress should be considered the stress that really characterizes 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. 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 a 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 gives, because it is not an extrapolation and the microstructure is not disturbed before the measurement.

Both methods, Bingham or stress growth, could be used for 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 [4]. Despite all the shortcomings of the Bingham equation, it is still the most common method because of its simplicity.

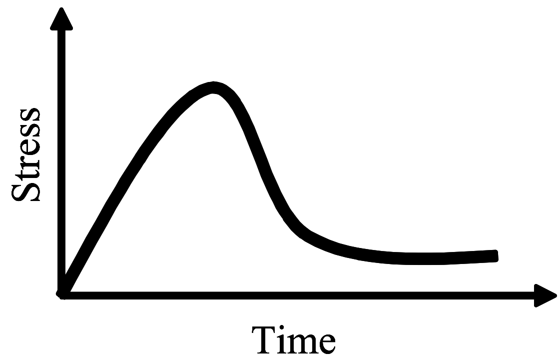

Figure 1: Stress growth schematic

3. CONCRETE RHEOLOGICAL TESTS

3.1 Experimental methods

The methods used to measure flow properties of concrete are numerous, with over 60 tests identified [3]. Most of the tests (over 70 %) measure only one parameter. This parameter can 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 can be related to both Bingham parameters. Nevertheless, the relationship between the Bingham parameters and the test results is usually not simple and often is not known. Some attempts at correlation have been done. For example, slump test results are related to the yield stress [6].

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. Both kinds of rheological test methods for concrete tend to fall into one of four general categories [4]: 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, and *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 various concrete rheometers can be found in [7, 8].

Cement paste and mortar measurements are also available and are performed using mainly laboratory devices. NIST has taken a multi-scale approach to predict the flow of concrete. Cement paste rheological properties are measured, and then mortar properties are predicted knowing the changes due to the addition of sand. The last step is to predict concrete properties from mortar by addition of coarse aggregates. The cement paste should include any chemical and mineral admixtures that are selected. To predict mortar from cement paste and concrete from mortar, a model is needed to determine the influence of the aggregate to either cement paste or mortar. If this approach is adopted then the measurement of cement paste properties are paramount.

The cement paste needs to be prepared and measured under conditions similar to those it experiences in concrete. To prepare cement paste with the same shear history (shear rate and temperature) as it would experience in concrete, Portland Cement Association (PCA) [9] has developed a methodology to mix the cement paste using a temperature controlled high shear blender. ASTM is in the process of standardizing this methodology (Committee C01.22). The cement paste measurement can be done using conventional rotational rheometers designed for oils. The most common configurations used are coaxial [10] or parallel plate [11, 12]. 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 and to mimic the distance between the aggregates in concrete that shear the cement paste during placement. 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 artificially 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.

Mortar testing can be done either using some of the concrete rheometers or by modifying existing paste rheometers to accommodate larger particles. 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 [7, 8]. 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, many comparative measurements should be done with vastly different concrete compositions to establish a correlation function that can reliably 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 as discussed in section 3.3.

Since the end goal is the characterization of concrete in the field, other methodologies should be considered. One method that was tested was to use a concrete truck as a rheometer. The concrete drum was rotated at various speeds and the torque measured. The plot of torque vs. speed should give an indication of the yield stress and plastic viscosity by fitting a straight line through the points. Preliminary tests were done [13, 14] and it was found that various concretes could be distinguished by their yield stress value (intercept) and plastic viscosity value (slope). Some correlation with a rheometer was found, but further tests are needed to finalize the methodology.

There are indeed 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.

3.2 Models

As stated above, one method to predict concrete plastic viscosity using the multi-scale approach is to use a model to link the various scales, i.e., cement paste and mortar, mortar and concrete. In other words, the concrete plastic viscosity is determined from the mortar and cement paste plastic viscosity and the coarse aggregates shape and size distribution. The link between the various scales, concrete-mortar-cement paste, is proposed by NIST [15,16] to be a simulation model, which describes the detailed motion of aggregates in a fluid. 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 or strain rate.

The shape and size distribution of the aggregates need to be known so that the simulation can properly predict the concrete rheology. Garboczi [17] used X-ray tomography and spherical harmonics to mathematically obtain the 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.

3.3 Reference material

The committee ACI 236 has started a study to select a reference material for concrete. NIST has started to study some possibilities for a reference material at the cement paste scale. The properties that the reference materials should have are: non-setting or non-time dependent rheological properties, not susceptible to segregation, particles of similar size as cement, have a yield stress, and preferably not thixotropic.

One option could be a non-reactive powder in a medium such water or oil. For instance fly ash in oil could work very well. Fly ash particles are spherical and can be easily dispersed in oil. Figure 2 shows an example of data obtained by varying the concentration of fly ash in two different oils A and B. The fly ash used had a nominal mean particle size of 25 μm. The viscosity of the oils was 0.08 Pa·s ± 0.05 Pa·s for oil A and 1.03 Pa·s ± 0.05 Pa·s for oil B. In Figure 2, the Y-axis is the relative viscosity of the mixture defined as the viscosity of the mixture divided by the oil viscosity [18]. The relative viscosity is plotted versus the mixture concentration. The oil viscosity does not change the influence of the concentration of fly ash on the plastic viscosity. This was expected, as the relative viscosity should be influenced only by the type and concentration of the particles. The data labeled "Simulation model" are from Ref. [15]. The simulation model was run at a shear rate of 10^{-4} s^{-1} instead of 10 s^{-1} used for the experimental test. While data from the simulation model are lower than the experimental data, the agreement is not too bad. Clearly we are not comparing the same suspension and various physical considerations may play a role at the different shear rates, such as agglomeration and interparticle interaction. As these factors can be incorporated into the model, we are encouraged by this approach. More research needs to be performed to select the most practical reference material for cement paste that can then be scaled up to mortar and concrete by addition of sand and coarse aggregates.

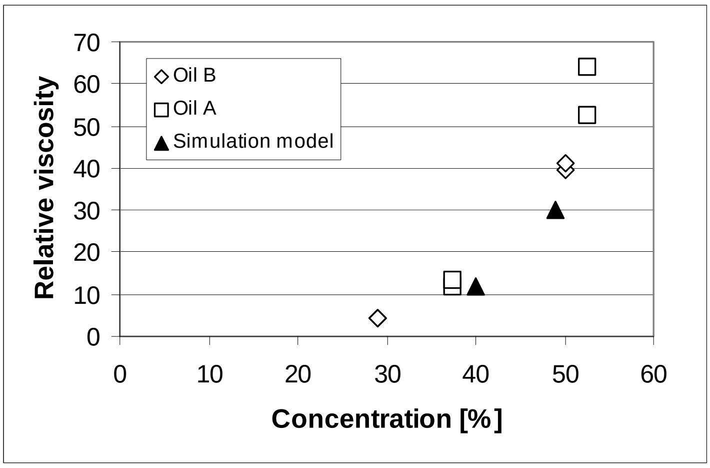

Figure 2: Relative viscosity of oil with various concentration of fly ash. The uncertainty of the measurement is estimate to be about ± 10 % in the relative viscosity.

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 empirical 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.

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 simulation model as shown in Figure 2. Nevertheless, 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 identify the fundamental factors that affect the yield stress. The particle concentration and shape must play a role, but with 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. A clear definition of experimental data that will give the intrinsic material yield stress is needed. As stated above, the measurement of the yield stress by a stress controlled experiment is not easy even for cement paste and no current concrete rheometer is stress controlled. Therefore, other methods need to be used to approximate the yield stress. The Bingham method is an extrapolation that could lead to underestimated yield stress, while a promising method is the stress growth. These two methods are also distinguished by the fact that the Bingham yield stress is a *dynamic* yield stress, while the stress growth is a *static* yield stress. Another issue is that both measurements are dependent on the lowest shear rate achievable with the instrument used in the test. Which one provides a better approximation for the intrinsic yield stress of the material? Should other methods be designed specifically to measure the yield stress?

5. WHAT'S NEXT?

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 where it is 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 not the case?

It is not the case because there are still many 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 the non-knowledge of the flow patterns in a rheometer. Perhaps we should think *outside the box* to design <u>*the*</u> *concrete/mortar rheometer* of the future. Prediction models are germinating but they are not fully operational as yet.

Another issue that could partially explain the difference between the various rheometers is that the measurements are not done at the same shear rates. This fact, linked with the shear rate dependence of the viscosity of cement paste, leads to data that are not comparable. Simulation might help to better determine the shear rates actually experienced by concrete in various rheometers, which might allow a correlation between the results.

Therefore, research is needed in numerous areas, such as the development of a granular reference material that could be used as a concrete, mortar and even a cement paste replacement to calibrate all rheometers. The development of a proper reference material cannot be achieved without the combination of experimentation and computer modeling. This combination 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, since we will better know what a given instrument is actually measuring.

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