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# A PORTABLE RHEOMETER FOR SELF-CONSOLIDATING CONCRETE

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## INTRODUCTION

Self-consolidating concrete (SCC) is a material that is defined, in large measure, by its workability. Therefore, the characterization and control of workability are critical to ensuring the successful performance of SCC. Although numerous empirical workability test methods have been proposed for SCC, no single empirical test is capable of providing a complete description of workability. Instead, a series of empirical tests must be selected to provide a more comprehensive characterization of SCC flow properties. The use of rheology, or the scientific study of the flow and deformation of matter, provides a direct and efficient means for characterizing the fundamental flow properties of concrete. The application of rheology, however, has been limited due, in part, to the cost and size of existing rheometers. A new rheometer was developed at the International Center for Aggregates Research (ICAR) with the objective of making the routine measurement of concrete rheology technically and economically viable (1). The ICAR rheometer is a low-cost, portable concrete rheometer for use in the laboratory and field. This paper describes the ICAR rheometer and its application to SCC.

## RHEOLOGY OF SCC

Rheological measurements are used widely in many industries (2, 3) and have been applied to concrete for over three decades (4). In characterizing rheology, concrete is considered a fluid, namely, a concentrated suspension of aggregate particles in cement paste. The cement paste itself is a concentrated suspension of cement grains in water (5). Rheological measurements involve determining the relationship between shear stress ($\tau$) and shear rate ($\dot{\gamma}$), as expressed in a flow curve. The constitutive relationship most commonly used for concrete is the Bingham model, which is defined by yield stress ($\tau_0$) and plastic viscosity ($\mu$) as given in Equation 1:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

In practical terms, yield stress is the amount of stress needed to initiate or maintain flow while plastic viscosity describes the resistance to flow once the yield stress has been exceeded. SCC must have a yield stress near zero to ensure that it will flow under its own mass and a moderate viscosity to resist segregation. These two terms, which are measured simultaneously, provide a standard, scientific means of quantifying concrete flow properties. They can be used to model concrete flow and to compare one concrete mixture to another. In addition, other important rheological considerations are thixotropy and workability retention. Thixotropy—which is the reversible, time-dependent reduction in viscosity when a material is subjected to constant shearing—results from the breakdown of the at-rest structure of the concrete and has implications for properties such as segregation resistance and formwork pressures. It should not be confused with shear-thinning behavior, which describes the decrease in viscosity as a function of increasing shear rate, not time. Workability retention, which is a separate property from setting time, is influenced by variables such as cement hydration and admixture performance.

Although direct rheological measurements provide an efficient means for characterizing flow properties, empirical tests are most commonly used for conventional concrete and SCC (1). Empirical tests simulate a field condition and measure a quantity, such as a distance or time, that is related to an aspect of workability. Though appealing for their simplicity and practicality, empirical tests measure values that are related to fundamental rheological properties only indirectly. It is the rheological properties of the concrete that govern how SCC flows in the field—whether in the slump flow test, through a pump line, or around an intricate reinforcement arrangement, for example. In empirical tests, the geometry of the concrete and the stresses acting on it at any given time are changing and not fully known, making it difficult to isolate the effects of fundamental flow properties. Therefore, rheological parameters can be preferable to empirical parameters, provided they can be measured in a practical manner and related to field placement requirements.

Several obstacles have limited the use of rheology for SCC in the past. First, the high cost, large size, and limited availability of existing rheometers—especially compared to the inexpensive and widely available slump flow test—have made the application of rheology impractical in many cases. Due to differences in design and various artifacts, the absolute results from different rheometers are not standardized and can vary widely, even for identical concrete samples (6, 7). Finally, rheology is a new and unfamiliar subject in much of the concrete industry, resulting in further reluctance to use rheology.

Despite these drawbacks, rheology is well suited for concrete in general and SCC in particular. Highly fluid concrete mixtures, such as SCC, behave more like homogenous fluids than stiffer, less fluid concrete mixtures and, therefore, can be measured with greater accuracy and repeatability. The use of rheology, by providing a better description of workability, can accelerate the use of new and underutilized materials, enhance the mixture proportioning process, and improve field quality control. In fact, a study facilitated by the Strategic Development Council of the American Concrete Institute identified the creation of portable testing technologies as a high priority research need and specifically identified the desire for a field test method for rheology (8).

## ICAR RHEOMETER

### Objectives

The ICAR rheometer was developed to address the needs of the concrete industry and the limitations of existing rheometers. The development of a rheometer for concrete presents unique challenges because concrete is a highly complex material with time-dependent properties and a wide range of particle sizes. To be viable, a new rheometer should be lightweight and portable for easy use on a jobsite. It should be fast and simple to use while also providing accurate and reliable results. Finally, it must be low in cost.

## Description

The first-generation prototype of the ICAR rheometer, which is pictured in Figure 1, was developed with off-the-shelf components as a proof-of-concept device. It utilizes a four-bladed vane that is immersed into a concrete sample and rotated at various fixed speeds while the resisting torque acting on the vane is measured. The vane, which acts as the inner cylinder of a coaxial cylinders rheometer, is utilized because of its compact design and the elimination of slippage (9). The entire device is approximately the size of a portable, hand-held drill and can be quickly mounted in a fixed frame above a standard container. The use of the standard container simplifies the test process and ensures consistent test geometry. Computer software fully automates the operation of the test and computation of test results.

The ICAR rheometer is normally used to measure concretes with aggregate sizes up to 25 mm, but can be adapted to measure mortar by using a smaller container. The dimensions used for concrete measurements are shown in Figure 2. In later versions of the device, it is envisioned that all components will be simplified and stored in a protective, plastic case. The ICAR rheometer has been tested successfully on concrete mixtures with workability ranging from a slump of 50 mm to SCC (1).

**Figure 1. First Generation Prototype of the ICAR Rheometer and Vane (Inset)**

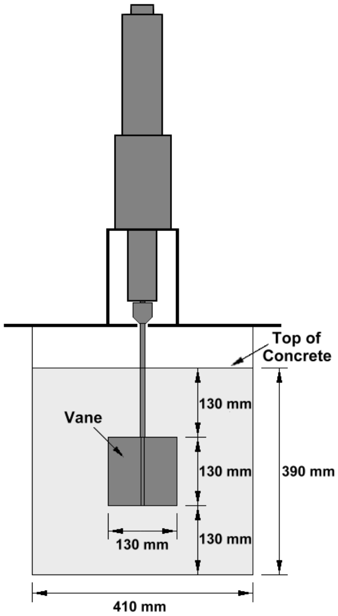

**Figure 2. Dimensions of the ICAR Rheometer for Concrete Measurements**

## Capabilities

The ICAR rheometer can be used to measure a flow curve, perform a stress-growth test, and characterize thixotropy and workability retention. In a flow curve test, which typically takes less than 60 seconds, the vane is first rotated at a fixed speed to minimize the effects of thixotropy. The speed is then decreased in a stepwise fashion, with the resisting torque acting on the vane measured at each speed point. The torque ($T$) and rotation speed ($N$) data can be used to compute results in relative or fundamental units. To compute relative units, a straight line is fit to the torque and rotation speed data, with the torque-axis intercept taken as the relative yield stress value (*Y*, N•m) and the slope taken as the relative plastic viscosity value (*V*, N•m•s):

$$T = Y + VN \tag{2}$$

Computation of results in fundamental units of yield stress (in Pa) and plastic viscosity (in Pa•s) requires calibration (4, 10) or certain assumptions about the distribution of shear stress and shear rate in the concrete sample (1, 3, 11). In the future, the development of standard reference calibration fluids could simplify the direct comparison of test results with other concrete rheometers.

Yield stress can be determined independently of the flow curve with a rate-controlled stress growth test. In this test, the vane is rotated at a constant, low speed and the gradual increase in torque is monitored. The maximum torque, which is not influenced by thixotropic breakdown, is used to compute the yield stress at rest (9). In addition to comparing the at-rest yield stress to the yield stress determined in a flow curve test, thixotropy can be further evaluated by monitoring the breakdown or build-up in torque over time at different speeds, among other methods (12). Workability retention can be evaluated by making periodic rheology measurements over time.

## EXPERIMENTAL TESTING

A series of SCC mixtures, shown in Table 1, was tested to evaluate the effects of fly ash and water content on workability (1). The mixtures included an ASTM C150 Type I portland cement and an ASTM C618 Class F fly ash. The dosage of a polycarboxylate high-range water-reducing admixture (HRWRA) was varied for each mixture. The aggregate consisted of natural sand (0-5 mm) and two sizes of crushed limestone aggregate (intermediate: 5-13 mm; coarse: 13-25 mm).

**Table 1. Mixture Proportions**

| Mix | Aggregates (SSD) | | | Cement | Fly Ash | w/cm |
|---|---|---|---|---|---|---|
| | Coarse | Int. | Fine | | | |
| | *kg/m³* | *kg/m³* | *kg/m³* | *kg/m³* | *kg/m³* | |
| 1 | 550.6 | 296.5 | 840.3 | 462.2 | 0.0 | 0.35 |
| 2 | 545.9 | 293.9 | 833.0 | 366.6 | 91.7 | 0.35 |
| 3 | 541.5 | 291.5 | 826.2 | 272.7 | 181.8 | 0.35 |
| 4 | 545.5 | 293.7 | 832.3 | 457.9 | 0.0 | 0.37 |
| 5 | 537.9 | 289.6 | 820.9 | 451.6 | 0.0 | 0.40 |
| 6 | 530.6 | 285.7 | 809.7 | 445.4 | 0.0 | 0.43 |

Each mixture was tested with the ICAR rheometer and the slump flow test. The ICAR rheometer was used to measure a flow curve based on seven speed points ranging in descending order from 1.0 rev/sec to 0.05 rev/sec. The results were computed in terms of yield stress value and plastic viscosity value as described in Equation 2. The slump flow test involved filling a standard slump cone, removing the cone, and determining the horizontal spread and the time for concrete to flow to a diameter of 500 mm ($T_{50}$).

The effects of using fly ash or increasing water content on yield stress value were minimal, as indicated in Figure 3, because all yield stress values were relatively low for the HRWRA dosages considered. Plastic viscosity was influenced to a much greater degree, as indicated in Figure 4. The effect of increasing the water-to-cementitious materials ratio (w/cm) to 0.40 from 0.35 was similar to using fly ash at a 20% mass replacement. Likewise, increasing the w/cm to 0.43 from 0.35 had a similar effect as using fly ash at a 40% mass replacement.

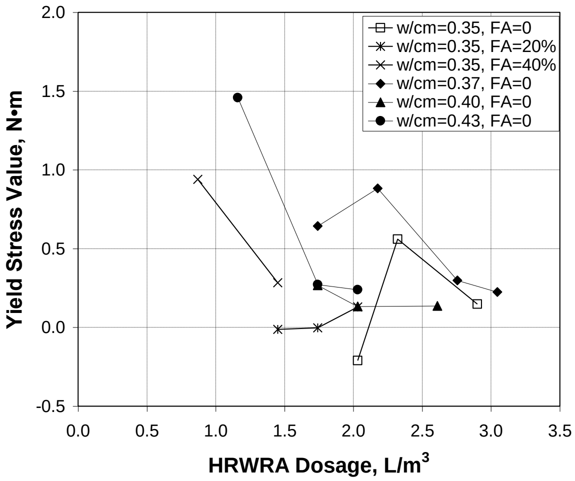

**Figure 3. Yield Stress Value Measurements**

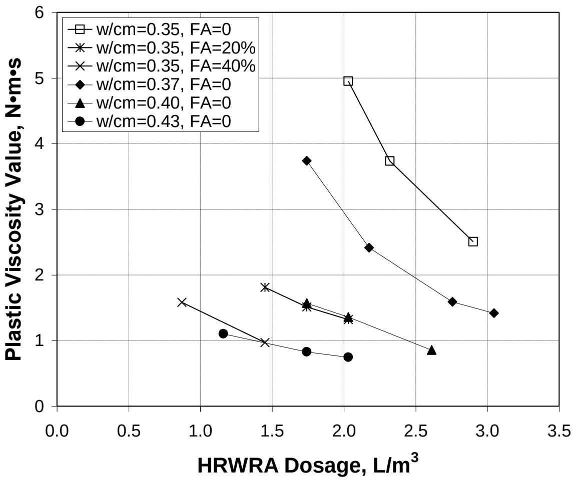

**Figure 4. Plastic Viscosity Value Measurements**

The yield stress values and plastic viscosity values measured by the ICAR rheometer were related indirectly to the slump flow and $T_{50}$ results, respectively, as indicated in Figures 5 and 6 for the full data set in Reference (1). The scatter in these plots reflects the fact that the results of the slump flow test were influenced not just by the rheological parameters, but also by other factors such as the changing and unknown stresses acting within the specimens during the tests.

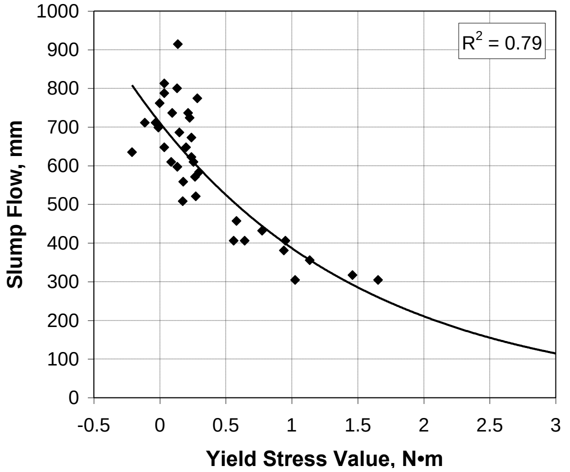

**Figure 5. Relationship between Slump Flow and Yield Stress Value**

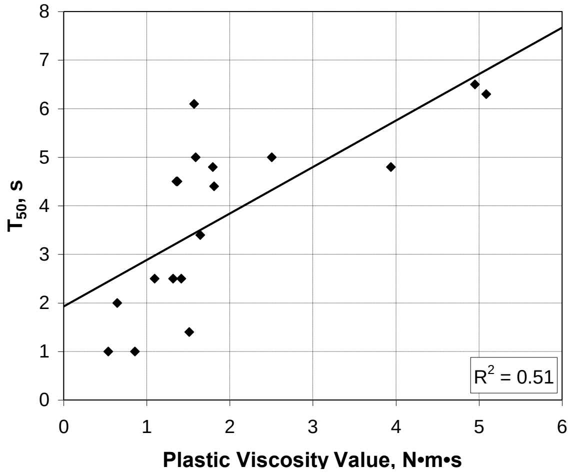

**Figure 6. Relationship between $T_{50}$ Measurement and Plastic Viscosity Value**

## CONCLUSIONS

The ICAR rheometer is a portable, practical, and low-cost concrete rheometer designed for research and mixture proportioning in the lab and routine quality control measurements in the field. In contrast to empirical tests, the ICAR rheometer provides a direct way to characterize the fundamental flow properties of SCC. In addition to measuring the Bingham model parameters, the ICAR rheometer can be used to characterize thixotropy and workability retention. Experimental testing was presented to demonstrate the ability of the ICAR rheometer to distinguish changes in water and fly ash contents. The use of rheology can enable more efficient mixture proportioning and more effective field quality control.

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