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**DEVELOPMENT AND USE OF A PORTABLE  
RHEOMETER FOR CONCRETE**

by

Eric P. Koehler and David W. Fowler  
The University of Texas at Austin  
10100 Burnet Road, Building 18B  
Austin, TX 78758

Tel: 512-471-1630

Fax: 512-471-4555

E-mail: [ekoehler@mail.utexas.edu](mailto:ekoehler@mail.utexas.edu), [dwf@mail.utexas.edu](mailto:dwf@mail.utexas.edu)

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# DEVELOPMENT AND USE OF A PORTABLE RHEOMETER FOR CONCRETE

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**Synopsis:** Although workability is a crucial property for the successful production of concrete, it is commonly measured with inadequate, empirical test methods such as the slump test. In contrast, the measurement of rheology provides an improved, scientific means of characterizing concrete flow properties. Existing rheometers, however, are not well-suited for routine jobsite measurements. This paper describes a new, portable, and low-cost rheometer developed at the International Center for Aggregate Research (ICAR). The ICAR rheometer can be used to measure a flow curve, perform a stress growth test, characterize thixotropy, and monitor workability retention. It is capable of measuring a wide range of concrete workability, from a slump of approximately 50 mm to self-consolidating concrete. The ICAR rheometer can potentially make the routine measurement of concrete rheology on jobsites technically and economically viable.

**Keywords:** field testing, mixture proportioning, rheology, self-consolidating concrete, slump, workability

*Eric P. Koehler is a graduate student at the University of Texas at Austin, where he received his MS degree in 2004. He is a member of ACI committees 236 “Material Science of Concrete” and 236A “Workability of Fresh Concrete.”*

*Dr. David W. Fowler holds the Joe J. King Chair in Engineering No. 2 at the University of Texas at Austin and is the director of the International Center for Aggregates Research. He is an ACI Fellow and a member of The Concrete Research Council and ACI committees 224, 236, and 548.*

## INTRODUCTION

For more than eighty years, the workability of freshly mixed concrete has been evaluated predominately throughout the world with one test method: the slump test. Although workability is a broadly defined term, the slump test measures only one aspect of workability, namely, consistency. Other aspects of workability are commonly described in subjective, qualitative terms. Whereas the cost of the slump test is essentially inconsequential relative to the value of concrete tested, the direct and indirect costs of poor concrete workability can be significant. Certain concrete mixtures—such as those containing aggregate microfines smaller than  $75\ \mu\text{m}^1$  or fiber reinforcement<sup>2</sup>—cannot be characterized adequately with the slump test. Numerous test methods have been introduced to provide an improved description of workability<sup>3,4</sup>; however, the vast majority of these test methods have found little use. A simple, relevant, and accurate field test for concrete workability is clearly needed<sup>5</sup>.

The concrete industry has made strides in applying rheology—that is, the scientific study of the flow and deformation of matter—to the workability of concrete<sup>6,7</sup>. By providing a scientific description of fundamental flow properties, rheology represents a useful method of characterizing workability. A new, portable rheometer was developed at the International Center for Aggregates Research (ICAR) for making routine jobsite measurements of concrete rheology<sup>8</sup>. This paper provides a background on the development of the ICAR rheometer and presents test results from a range of concrete mixtures. By providing a simple and reliable means of characterizing workability, the ICAR rheometer can improve the mixture proportioning process, enhance field quality control, and enable the expanded use of new and underutilized materials.

## BACKGROUND

### Fluid Rheology

Freshly mixed concrete can be considered a concentrated suspension of aggregates in cement paste. The characterization of concrete rheology is complicated by the fact that concrete is a complex material with time-dependent properties and a wide range of particle sizes. Measurements of fluid rheology are based on the relationship between shear stress ( $\tau$ ) and shear rate ( $\dot{\gamma}$ ), as expressed in a flow curve. Concrete flow properties are most commonly characterized based on the Bingham constitutive model, which describes concrete flow in terms of yield stress ( $\tau_0$ ) and plastic viscosity ( $\mu$ ), as indicated in Eq. 1.

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

In practical terms, yield stress represents the stress necessary to initiate or maintain flow while plastic viscosity expresses the increase in shear stress with increasing shear rate once the yield stress has been exceeded. Other models, such as the Herschel-Bulkley model, can also be used to represent concrete flow<sup>9</sup>.

### Concrete Rheometers

Multiple rheometers have been developed for concrete<sup>3,4</sup>. Results from different concrete rheometers can vary widely even for identical concrete mixtures due, in part, to device artifacts and assumptions made in the determination of results<sup>6,7</sup>. Concrete rheometers typically feature one of three geometrical configurations—parallel plate, impeller, or wide-gap coaxial cylinders. Parallel plate rheometers, which consist of two horizontal plates with one plate rotating relative to the other, permit a small specimen size and the direct analytical calculation of rheological parameters in fundamental units. The unknown degree of slippage that occurs at the vertical side-walls, which must be provided to confine the specimen, complicates the computation of rheological parameters<sup>6</sup>.

Impeller rheometers, which consist of an impeller that is rotated in a concrete specimen, can be simple to use; however, the shear rate and shear stress in the material around the impeller is unknown and the direct analytical calculation of fundamental rheological parameters is not possible. Although calibration procedures have been suggested<sup>10,11</sup> to relate the intercept and slope of the torque versus rotation speed plot to yield stress and plastic viscosity, the accuracy of such procedures is debatable<sup>9,12</sup>.

Wide-gap coaxial cylinders rheometers, which consist of two cylinders with one cylinder rotating relative to the other, are applicable to many materials—including concrete. The gap between outer and inner cylinders must be set to a sufficient multiple of the maximum aggregate size. Depending on the range of rotation speeds, material rheological properties, and ratio of outer to inner cylinder radii, a certain portion of the material in the annulus of a coaxial cylinders rheometer may be subjected to stress below the yield stress and not flow. The result is the presence of a dead zone, which is depicted in Fig. 1. Several techniques are available to compute rheological parameters analytically given the presence of a dead zone<sup>6,12,13,14</sup>. It is important to consider the size of the flowing region relative to the maximum aggregate size to ensure the flowing region is representative of the bulk concrete properties. End effects, which are due to shear stress acting on the ends of the inner cylinder and to the fact that the direction of maximum shear stress is not radially outward near the ends of the inner cylinder—must be minimized or taken into account analytically<sup>12</sup>. Secondary flows, which are in a direction different from what is intended, and sedimentation, which is possible during extended periods of shearing, must be minimized. Although the actual distributions of shear rate and shear stress in a concrete rheometer are complex and cannot be determined precisely by analytical means, reasonable approximations can be made to provide accurate and useful information.

### Yield Stress Measurement

Although it has been suggested that yield stress does not technically exist because all materials flow if given sufficient time<sup>15</sup>, yield stress is a practical material parameter that should be measured for concrete. The question, then, concerns how yield stress is defined and measured. Indirect methods of determining yield stress

involve measuring a flow curve and extrapolating the curve to determine the shear stress at zero shear rate based on a known constitutive model or fitted curve. The accuracy of such an indirect measurement depends on the appropriateness of the constitutive model or fitted curve, the accuracy and the range of the experimental flow data, and the characteristics of the instrument used<sup>16</sup>. In contrast, direct methods measure only yield stress<sup>17,18</sup>. For instance, a rate-controlled stress growth test consists of applying shear stress to a specimen at a low, constant shear rate until the yield stress is reached and the material begins to flow. Such a test has been used for cement paste<sup>19,20</sup>.

Yield stress measurements can depend to a significant degree on whether the test represents a static or dynamic measurement. In a static test, such as the stress growth test, the stress required to initiate flow in an at-rest material is measured. In contrast, a dynamic test measures the stress required to maintain flow, such as in a flow curve test. The yield stress is typically higher when measured with a static test rather than a dynamic test because the static measurement must overcome any effects of thixotropy and the non-preferential orientation of particles<sup>12</sup>.

#### Use of Vane Geometry

Instead of using a traditional coaxial cylinders rheometer with smooth or roughened walls, the inner cylinder can be replaced with a vane, such as the one shown in Fig. 2. As it turns, the vane cuts a cylindrical volume, much like a traditional inner cylinder. Slippage due to wall effect is mitigated because yielding occurs within the material along a cylindrical surface defined by the tips of the blade rather than at the boundary of a cylinder. Further, the action of inserting the vane into the specimen creates minimal disruption to the specimen. Vanes have been used widely for yield stress measurements of concentrated suspensions<sup>21</sup>.

It is generally assumed that the yield surface occurs along an imaginary cylinder defined by the tips of the vane<sup>17</sup>. The total torque is attributable to the torque acting on the side and ends of the vane, as indicated in Eq. 2:

$$T = \left( \frac{\pi}{2} D^2 H \right) \tau_s + 2 \left( 2\pi \int_0^{D/2} \tau_e(r) r^2 dr \right) \quad (2)$$

where  $D$  = vane diameter,  $H$  = vane height,  $\tau_s$  = shear stress on vane side,  $\tau_e(r)$  = function expressing distribution of shear stress on vane ends, and  $r$  = radius. If the shear stress is assumed to be constant across the vane surface and equal to the yield stress ( $\tau_o$ ), the total torque can be expressed as shown in Eq. 3:

$$T = \frac{\pi D^3}{2} \left( \frac{H}{D} + \frac{1}{3} \right) \tau_o \quad (3)$$

The rotation speed used in a rate-controlled stress growth test can influence the yield stress significantly<sup>22</sup>. If the rotation speed is too high, viscous resistance of the fluid and instrument inertia can lead to errors<sup>16</sup>. If the rotation speed is too low, the reformation of network bonds and reorientation of particles can increase the measured yield stress<sup>22</sup>.

Given the successful use of the vane for determining yield stress, the vane has been extended to measurements of flow curves<sup>21</sup>. If the material within the vane moves

with the vane, then a vane-in-cup rheometer should be equivalent to a coaxial cylinders rheometer, with the exception that slip is reduced or eliminated.

#### Requirements for Measuring Concrete Rheology

While concrete rheometers provide useful information about workability, several significant factors have stymied the adoption of rheometers on a more widespread basis. First, the complexity of concrete—in particular, the large aggregate size, time-dependence of flow properties, and sensitivity to small changes in mixture proportions or material properties—makes the development of a rheometer for concrete difficult. It has been shown that a rheometer's geometry, gap size, and surface texture can have a significant influence on the measurement of the rheological properties of cement paste<sup>23</sup>. Adding fine and coarse aggregate further complicates the determination of rheological parameters<sup>24</sup>. Second, rheology is still largely an unfamiliar topic for the concrete industry. Third, rheometers are not capable of measuring low-slump concrete (less than approximately 50 mm) and generally work best for fluid concretes. While it is technically possible to build a rheometer with a sufficiently large motor and to analytically account for a potential dead zone, the concepts of fluid rheology used for moderate- and high-slump concretes are not appropriate for low-slump concretes. A different approach that takes into account parameters relevant to low-slump concrete is needed<sup>25</sup>. Fourth, the cost of concrete rheometers has traditionally been prohibitive for many applications, especially for the field. Finally, rheological parameters must be related to practical field applications so that field personnel understand the relevance test results.

Any workability test method must meet a series of minimum requirements to ensure practicality and viability. First, the test method should determine fundamental rheological parameters or closely related values. It should measure the widest possible range of concrete mixtures in terms of both workability range and aggregate size. It should be compact, lightweight, and rugged for field use. The specimen size should be kept to a minimum. The operation of the test should be fast so that the test does not interrupt construction operations and simple so that minimal training is required. Any data processing should be automated so that test results are available immediately. Finally, the device should be sufficiently low in cost so that routine field measurements are economically viable.

### **THE ICAR RHEOMETER**

The ICAR rheometer is a portable, controlled-rate rheometer capable of measuring concretes with workability ranging from a slump of approximately 50 mm to self-consolidating concrete<sup>8</sup>. The device is about the size of a portable, hand-held drill and includes a four-bladed vane that is immersed into concrete. In developing the rheometer, the vane was found to be the preferable geometry<sup>8</sup>. The dimensions and overall configuration of the first generation prototype, which was developed with off-the-shelf components, are depicted in Fig. 3. The vane can be rotated at a series of specified fixed speeds while the resulting torque is measured. The rheometer can be secured quickly into a frame and positioned above a container. The use of this frame simplifies test operation and ensures consistent geometry. The entire rheometer set-up—including the frame and container—is lightweight and can be easily moved by one person on a jobsite. The vane is attached with a keyless chuck. The vane size can be selected to measure concrete, mortar, or other coarse-grained suspensions.

The operation of the test and computation of results are automated by a software program. Once the test is started, the software controls the test, computes and displays test results, and stores test data to a file. In the first generation prototype, the software is operated from a laptop computer; however, it could also be operated by a handheld computer or similar embedded electronics.

The ICAR rheometer is capable of performing a stress growth test and measuring a flow curve. In the stress growth test, the vane is rotated at a constant speed while the increase in torque is monitored. The stress growth test is complete once the peak torque, which indicates the yield stress, is identified. A typical stress growth test plot, as shown in Fig. 4, consists of three portions: an initial linear region followed by a curved region and then a peak<sup>17,19,22,26,27</sup>. In the flow curve test, the vane is first rotated at a constant speed to achieve structural breakdown of the concrete. Then, the speed is varied in distinct steps in ascending or descending order and the torque at each step is measured. Results can be expressed in terms of torque versus speed or can be computed in fundamental units of pascals (yield stress) and pascal-seconds (plastic viscosity) based on one of the methods referenced earlier<sup>6,12,13,14</sup>. In addition, the ICAR rheometer is capable of characterizing thixotropy and monitoring workability retention. An external or internal vibrator can be used to consolidate concrete or to measure rheological properties under vibration.

It is envisioned that in future versions of the ICAR rheometer, all components will be made smaller and lighter and housed in protective case. The first generation prototype was constructed at a significantly lower cost than other existing rheometers. The ICAR rheometer, with its low cost and portable form factor, can permit laboratory measurements to be made in the field.

## EXPERIMENTAL TESTING

A series of concrete mixtures was tested to demonstrate the ability of the ICAR rheometer to detect changes in rheology<sup>8</sup>. A portion of those tests is presented herein.

### Materials and Mixture Proportions

Two control concrete mixtures, indicated in Table 1, were systematically altered by incorporating—one at a time—fly ash (ASTM C 618 Class F), ground granulated blast furnace slag (GGBFS), silica fume, polycarboxylate-based high-range water-reducing admixture (HRWRA), and air-entraining admixture, and by changing the water content. The water contents shown in Table 1 correspond to slumps of 100 mm. Based on anticipated changes in workability, the water contents were adjusted for the control mixtures in each mixture series so that the range of slumps would be between 75 and 175 mm for all mixtures in the series. The three aggregates—a crushed limestone coarse aggregate, a river gravel, and a natural sand—are described in Table 2. All mixtures incorporated an ASTM C 150 Type I portland cement.

### Test Procedures

All fresh concrete tests were performed at consistent times after a standard mixing procedure in a rotating drum mixer. The ICAR rheometer was used to perform a stress growth test and measure a flow curve. For the stress growth test, the vane was rotated at a constant speed of 0.025 rev/s and the stress growth yield stress was computed based on Eq. 3. Once the maximum torque had been reached, the flow curve test was started. First, the vane was rotated at a speed of 1.0 rev/s for 25

seconds to ensure the breakdown of any effects of thixotropy. Five flow curve points were then measured in descending order from 1.0 rev/s to 0.2 rev/s. Yield stress and plastic viscosity were computed in fundamental units based on the procedure described in Reference 8, which involved determining the radius to the dead zone for each flow curve point and calculating the Bingham parameters based on the calculated distribution of shear in the flowing regions. In addition, slump (ASTM C 143) and air content (ASTM C 231) were measured.

## EXPERIMENTAL RESULTS AND DISCUSSION

The use of fly ash at mass replacement levels ranging from 10 to 55% generally decreased yield stress but either increased or decreased plastic viscosity depending on the dosage, as indicated in Fig. 5. It is generally known that the spherical shape of fly ash particles should reduce yield stress and plastic viscosity; however, the small size of the fly ash particles relative to the cement grains they replace partially offsets the positive effects of the spherical shape<sup>28</sup>.

The use of GGBFS, shown in Fig. 6, increased the yield stress from the flow curve test when used at a replacement rate of 20% but resulted in incremental decreases in the yield stress from the flow curve test when used at higher replacement rates of 35 and 50%. The plastic viscosity was generally reduced with increasing replacement levels of GGBFS. The effect of GGBFS on the yield stress measured from the stress growth test was similar to that on the yield stress measured from the flow curve tests for Mixture 1 but was muted for Mixture 2. Elsewhere, the use of slag has been shown to be variable depending on the type of slag and the mixture proportions<sup>28</sup>.

The effects of replacing cement with silica fume depended on the composition of the original control mixture, as indicated in Fig. 7. The yield stress increased for Mixture 1 but remained approximately unchanged for Mixture 2 as the mass replacement rate of silica fume was increased to 8%. The plastic viscosity was reduced at low replacement levels, but it increased at the 8% replacement rate. In general, it is known that the use of silica fume increases yield stress and plastic viscosity, except at low replacement levels where the workability may be improved depending on other mixture properties<sup>11,28,29</sup>. Although the spherical shape of silica fume particles may improve workability, the fineness of silica fume particles is dominant in its effects on workability.

The use of HRWRA resulted in nearly linear decreases in yield stress but mixed changes in plastic viscosity, as indicated in Fig 8. In general, HRWRAs, which deflocculate cement grains, are known to mainly decrease yield stress while the plastic viscosity may increase, decrease, or remain approximately the same<sup>28,30</sup>.

Fig. 9 indicates that increasing the water-to-cementitious materials ratio resulted in decreases in yield stress and plastic viscosity. This trend was expected because it is generally known that increased water content results in reduced solids volume concentration and reduced interparticle friction<sup>11,28</sup>.

The effect of entrained air content depended on the control concrete mixture, as indicated in Fig. 10. The use of air-entraining admixture caused the yield stress measured from the flow curve to increase for Mixture 1 but decrease for Mixture 2. The yield stress measured from the stress growth test decreased in both mixtures,

although the reduction in Mixture 2 was much greater. The air entraining admixture generally reduced plastic viscosity in both mixtures. Elsewhere, it has been shown that the spherical shape of entrained air bubbles can reduce plastic viscosity; however, the possible formation of bubble bridges between cement grains can increase yield stress<sup>31</sup>.

The test results presented for each mixture proportion change exhibited variability due, in part, to the fact that each point was measured on a separate batch of concrete (unintentional material variance), possible sampling errors, and variance in shear history for each specimen. Fluid rheology measurements are generally best for highly fluid mixtures, which behave more like homogenous fluids. In general, however, the trends for each change in mixture proportions were consistent with expectations. In developing mixture proportions or evaluating the properties of a concrete mixture, the type of data presented in Figs. 5 to 10 can be used to consider tradeoffs between factors such as cost, strength, and durability.

The flow curve and stress growth tests each gave different indications of yield stress, as indicated in Fig. 11. The lack of agreement between the two measurements indicates that the tests measure different properties. The stress growth test, which is performed before any structural breakdown and is influenced by thixotropy, measures the concrete in a static, unsheared condition. The flow curve measurement is performed after the breakdown of any effects due to thixotropy and provides a dynamic indication of yield stress. Though different, both tests are useful. The stress growth test indicates the amount of stress needed to initiate flow from rest while the flow curve test indicates the stress needed to maintain flow.

## CONCLUSIONS

Numerous test methods exist for measuring concrete workability, yet few are used on a widespread basis. The ICAR rheometer was developed to address the needs of the concrete industry and the shortcomings of existing concrete workability test methods. It is a low-cost, portable rheometer capable of measuring nearly the full range of workability from a slump of approximately 50 mm to self-consolidating concrete. It can be used to measure a flow curve, perform a stress growth test, characterize thixotropy, and monitor workability retention. The test procedure is comprehensible and requires no advanced training. The test can be performed quickly—a single flow curve test can be completed in less than 60 seconds. The rheometer can be used for research and development, mixture proportioning, and field testing. The ICAR rheometer was able to detect changes in workability due to the use of fly ash, GGBFS, silica fume, HRWRA, and air-entraining admixture and changes in water content. The ICAR rheometer provides information the slump test cannot provide. The low cost and portable form factor of the ICAR rheometer can make the routine field measurement of rheology a viable option.

## ACKNOWLEDGMENTS

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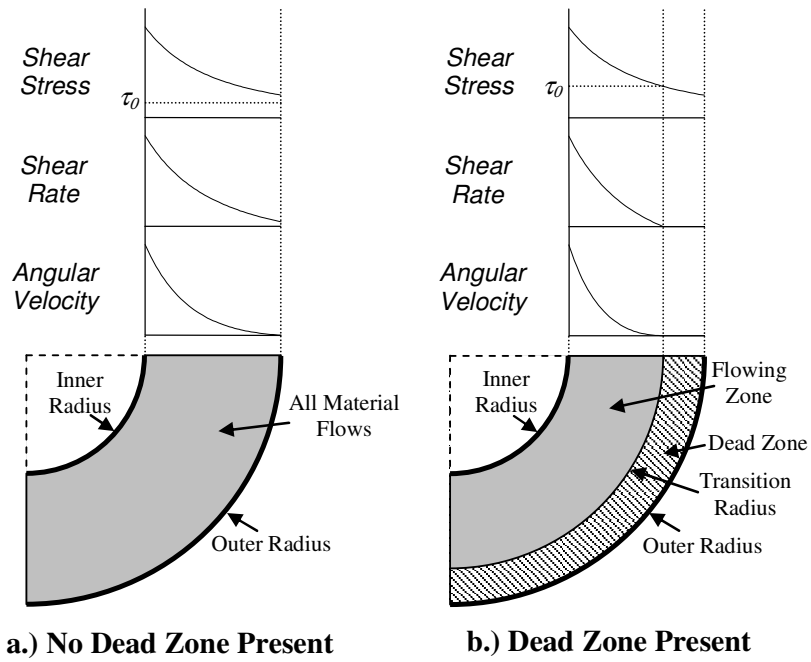
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**Table 1 – Control Concrete Mixture Proportions (for 100-mm Slump)**

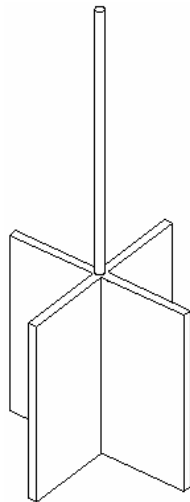
Mixture ID	Mass, kg/m <sup>3</sup>				
	River Gravel (SSD)	Crushed Limestone (SSD)	Natural Sand (SSD)	Cement	Water
Mixture 1	1114.4		687.7	365.0	173.4
Mixture 2		1023.4	696.2	388.2	174.7

**Table 2 – Aggregate Particle Size Distributions**

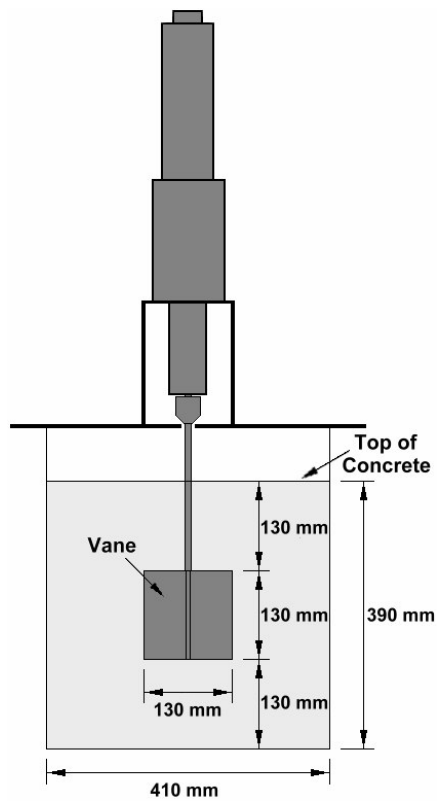
US Standard Sieve	Mesh Size (mm)	Percent Passing		
		Crushed Limestone	River Gravel	Natural Sand
1 ¼ in.	31.5	100.0	99.6	
1 in.	25.0	100.0	83.4	
¾ in.	19.0	82.4	44.1	
½ in.	12.5	10.7	17.0	
⅜ in.	9.5	0.6	5.1	
#4	4.75	0.3	0.5	97.3
#8	2.36			86.2
#16	1.18			70.5
#30	0.600			49.0
#50	0.300			27.3
#100	0.150			6.8
#200	0.075			0.6
Fineness Modulus		--	--	2.63



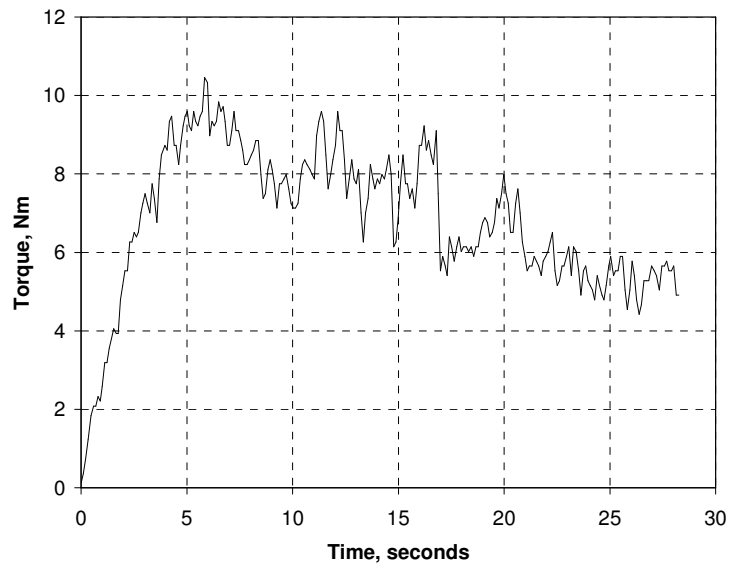
**Fig. 1 – Flow of a Bingham Material in a Coaxial Cylinders Rheometer where the Inner Cylinder Rotates and Outer Cylinder Remains Fixed (One-Quarter of Rheometer Shown)**



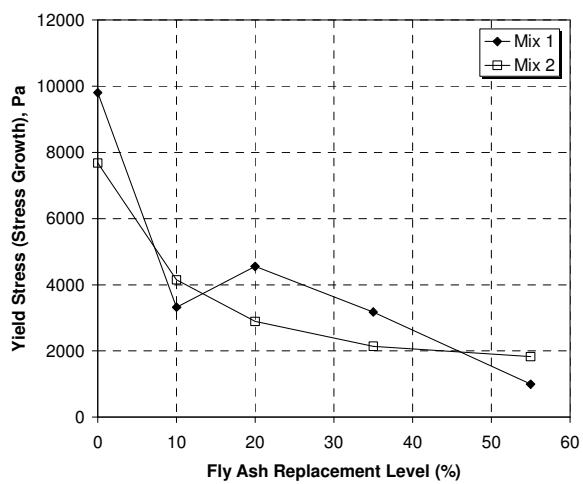
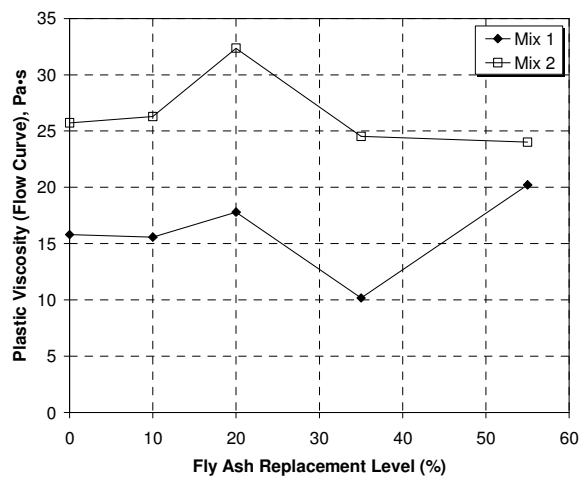
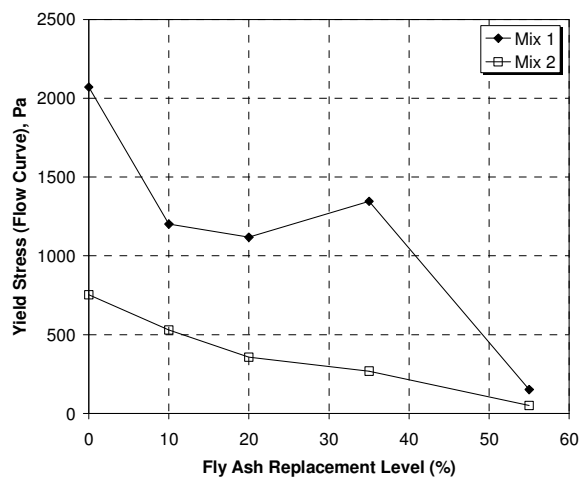
**Fig. 2 – Typical Vane for Yield Stress Measurement**



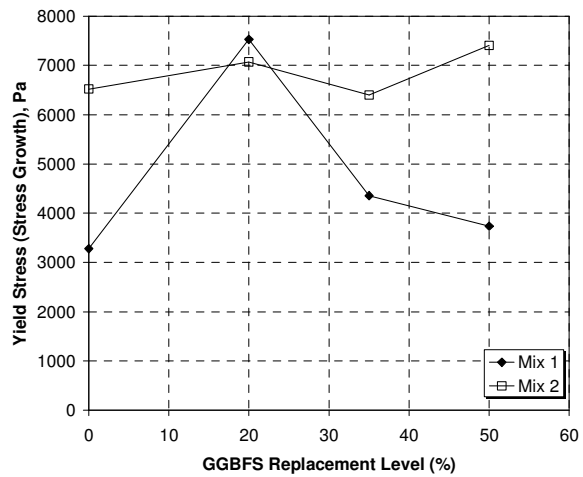
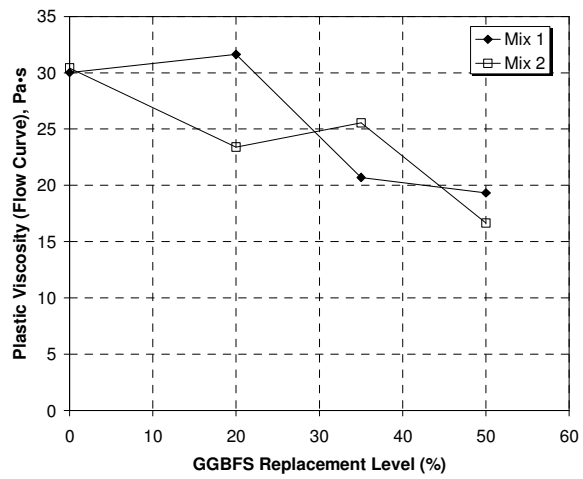
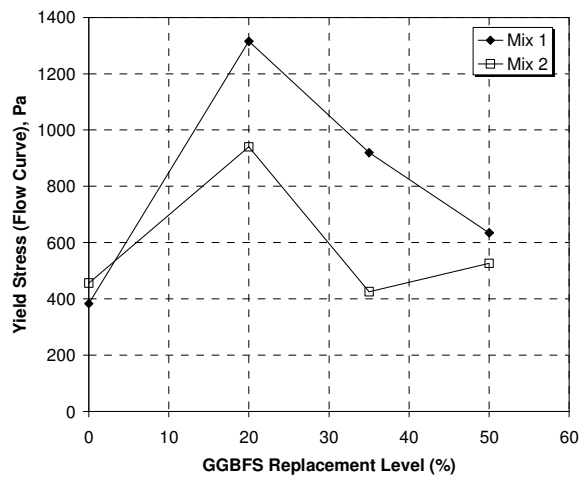
**Fig. 3 – Dimensions of ICAR Rheometer First-Generation Prototype (Control Electronics Not Shown)**



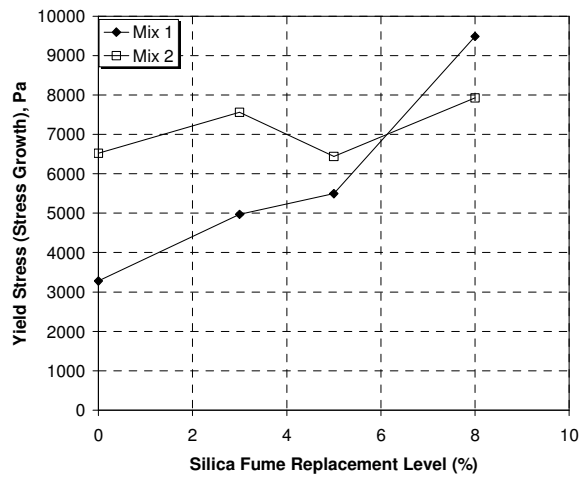
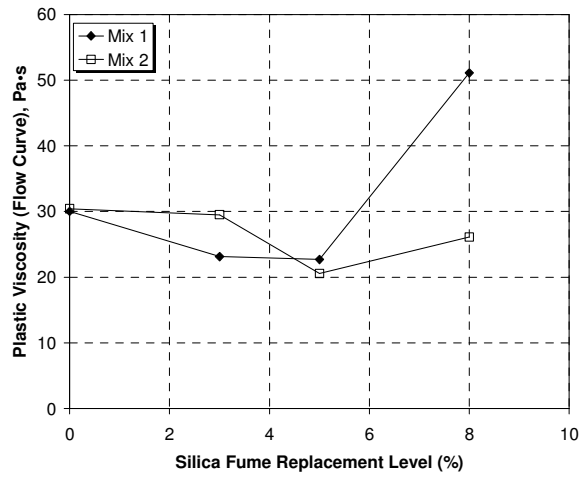
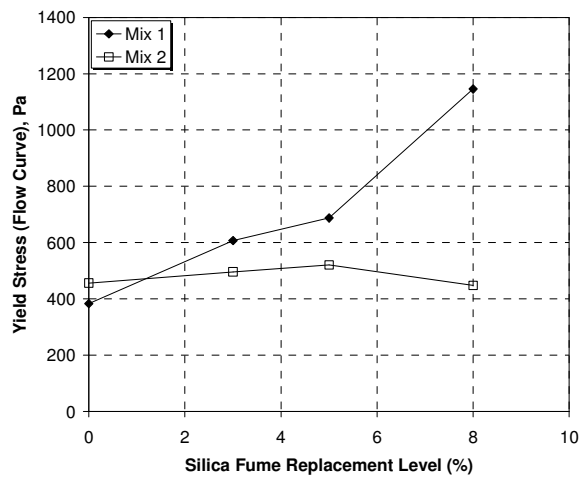
**Fig. 4 – Typical Stress Growth Test Plot**



**Fig. 5 – Effects of Fly Ash on ICAR Rheometer Results**



**Fig. 6 – Effects of GGBFS on ICAR Rheometer Results**



**Fig. 7 – Effects of Silica Fume on ICAR Rheometer Results**

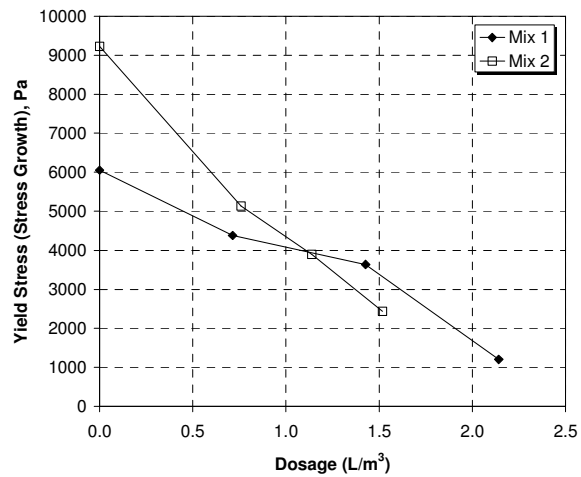
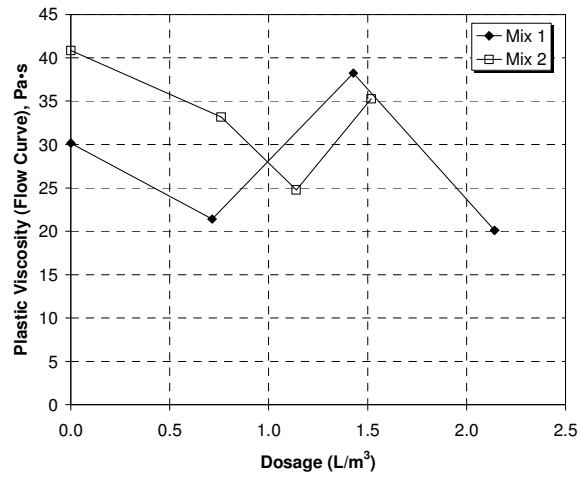
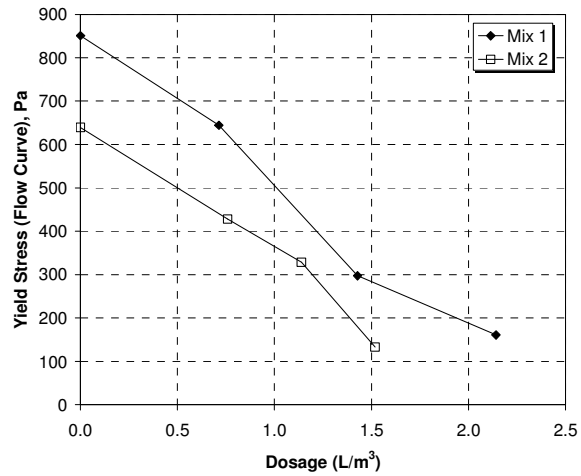
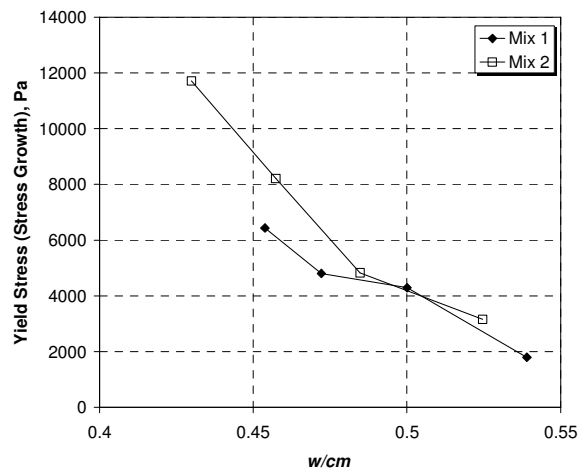
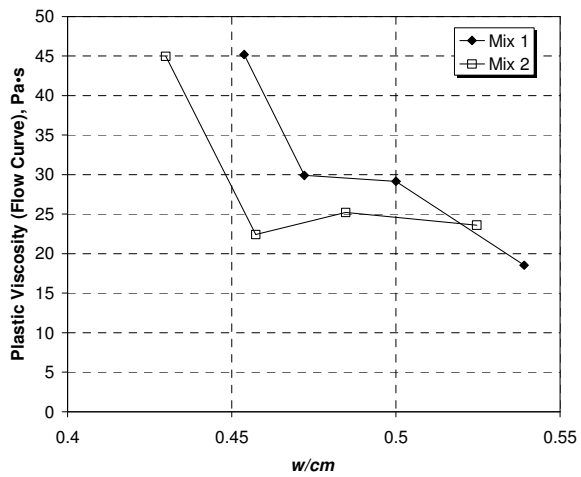
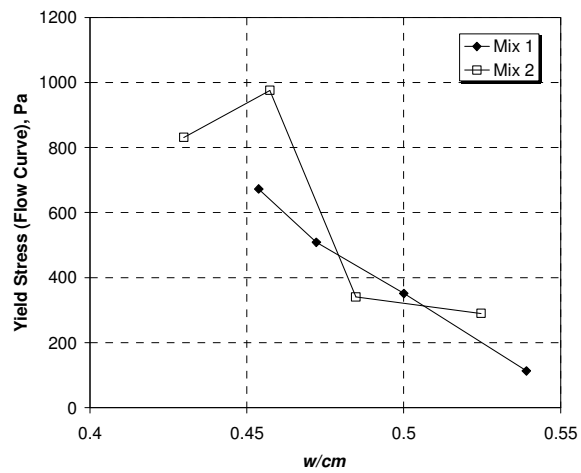
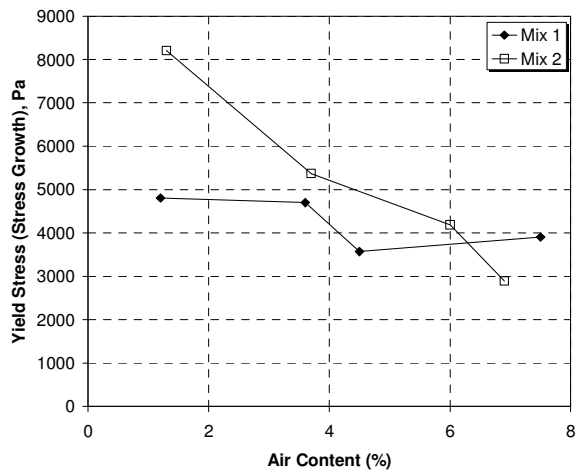
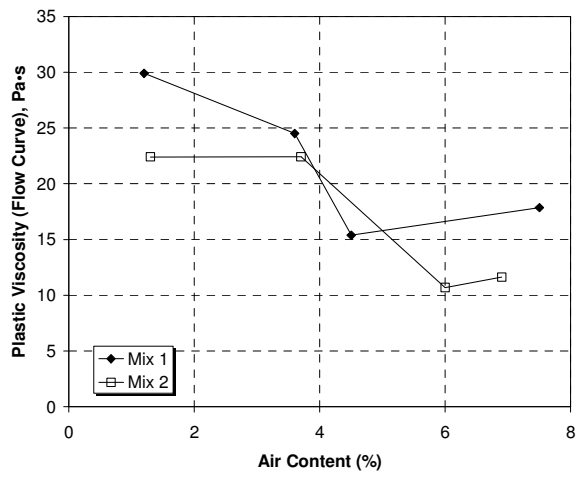
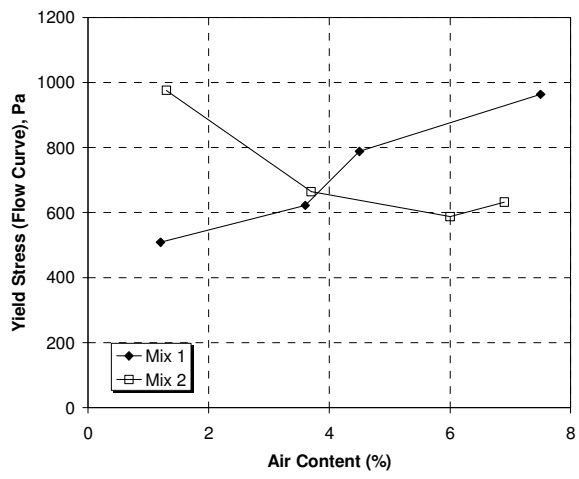


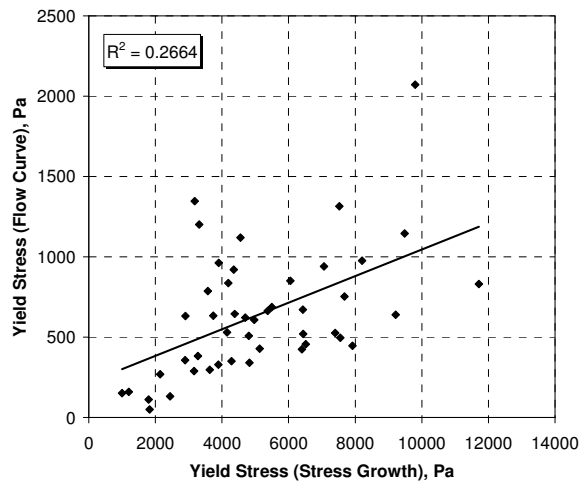
Fig. 8 – Effects of HRWRA on ICAR Rheometer Results



**Fig. 9 – Effects of  $w/cm$  on ICAR Rheometer Results**



**Fig. 10 – Effects of Air Content on ICAR Rheometer Results**



**Fig. 11 – Yield Stress Measurements from Flow Curve and Stress Growth Tests**