A NEW, PORTABLE RHEOMETER FOR FRESH SELF-CONSOLIDATING CONCRETE

by Eric P. Koehler, David W. Fowler, Chiara F. Ferraris, and Sofiane Amziane

Published by: American Concrete Institute, 2006, in "Workability of SCC: Roles of Its Constituents and Measurement Techniques (SP233CD)" *Proceedings of a Special Session of the American Concrete Institute Spring 2005 Convention*.

Note: This article refers to the first-generation prototype of the ICAR rheometer. A second-generation prototype, which is smaller and easier to use, has been developed and tested extensively.

A NEW, PORTABLE RHEOMETER FOR FRESH SELF-CONSOLIDATING CONCRETE

by Eric P. Koehler, David W. Fowler, Chiara F. Ferraris, and Sofiane Amziane

Synopsis: The accurate determination of fresh concrete rheology is key to ensuring the successful production of self-consolidating concrete (SCC). Rheometers, however, are used infrequently in the field. Empirical test methods are most commonly used to determine SCC workability despite measuring quantities that are related to rheological parameters only in an indirect way, if at all. Instead of using multiple empirical test methods to measure the workability of SCC, it is desirable to use a rheometer in both the laboratory and field to determine the flow properties of SCC quickly. Existing rheometers are generally unsuitable for routine field use due to their large size, high cost, or both. This paper describes the use of the International Center for Aggregates Research (ICAR) rheometer, a low-cost, fully portable device that can measure concrete mixtures ranging in workability from approximately 50 mm in slump to SCC. Laboratory test results of SCC mixtures and field testing experience are presented to demonstrate the validity and practicality of the ICAR rheometer.

Keywords: self-consolidating concrete; rheology; workability; field testing; slump flow; stability; mixture proportioning.

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.

Dr. Chiara F. Ferraris has been a physicist in the Materials and Construction Research Division of the NIST Building and Fire Research Laboratory since 1994. The main emphasis of her research is on the rheology of cement paste, mortar, and concrete. She has been an active member of ACI since 1990. Presently, she is the Chair of ACI 236 "Material Science of Concrete" and of ACI 236A "Workability of Fresh Concrete."

Dr. Sofiane Amziane is an Associate Professor of Civil Engineering at the University of South Brittany at Lorient, France. He is a member of ACI committee 236. His research interests include cement based material behavior, rheology, and setting.

INTRODUCTION

Since the introduction of self-consolidating concrete (SCC) in the 1980s, a profusion of test methods has been proposed for measuring SCC workability (1, 2). Most of these new tests are empirical; that is, they generally are used to simulate a field condition and to measure a quantity related to an aspect of workability, such as the ability of concrete to fill formwork, pass through reinforcing bars, or resist segregation. In contrast, rheology—or the scientific study of the flow and deformation of matter—has been applied on a limited basis to concrete in order to measure fundamental flow parameters. Although the application of rheology has proven promising, important challenges must be addressed to apply rheology to concrete on a wider basis in the field. This paper describes a new, low-cost, portable rheometer for fresh concrete, presents rheometer test results for SCC mixtures, and discusses how the rheometer can be used on a routine basis in the field.

RESEARCH SIGNIFICANCE

The characterization and control of fresh concrete properties are often more critical for SCC than for conventional concrete. The flow properties of SCC can be strongly influenced by construction conditions and changes in material properties and mixture proportions. Rheology represents a direct, scientific approach to monitoring and controlling SCC properties. The use of a low-cost, portable rheometer to develop mixture proportions and to monitor and control SCC in the field can improve SCC quality control and enhance the efficiency of SCC production.

BACKGROUND

Rheology is a well-established, widely used science (3, 4). Although rheology is used in many industries, the application of rheology to concrete has been limited historically. Rotational rheometers are typically used to measure flow curves, which relate shear stress (τ) to shear rate ($\dot{\gamma}$) in order to describe fundamental flow properties. The most common constitutive relationship used to characterize concrete flow is the Bingham model, which requires the determination of yield stress (τ_0) and plastic viscosity (μ) as shown in Eq. 1.

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

In simple terms, yield stress is the amount of stress needed to initiate flow while plastic viscosity is the amount of resistance to flow once the yield stress has been exceeded. In some cases, the Herschel-Bulkley model, which is shown in Eq. 2, is more appropriate for concrete because it utilizes empirical constants *a* and *b* to represent a nonlinear flow curve.

$$\tau = \tau_0 + a\dot{\gamma}^b \tag{2}$$

In addition to indirect measurements of yield stress accomplished by measuring a flow curve, yield stress can also be measured directly, such as with a stress growth test. In a stress growth test performed in a rotational rheometer, the material is sheared at a constant, low shear rate to allow an elastic build-up of stress in the specimen. Eventually, a peak torque is reached, after which viscous flow occurs. The peak torque is used to determine yield stress. The yield stress measured from the stress growth test is a static measurement of yield stress—that is, it is made without any breakdown of thixotropy—and is typically not equal to the yield stress determined from a flow curve measurement (4, 5). Thixotropy, which is common in SCC mixtures, is a reversible, time-dependent decrease in viscosity that occurs when a material is subjected to constant shearing.

A variety of obstacles have limited the use of rheology in the concrete industry. The fact that concrete is a complex material with time-dependent properties and a wide range of particle sizes presents unique challenges in designing a rheometer appropriate for concrete. Existing concrete rheometers are generally too large for routine use on a jobsite. The price of these existing rheometers is prohibitive for a substantial portion of the concrete industry, especially when compared to the widely used slump test. The variability between different rheometers reduces confidence in test results and increases the difficulty of comparing results from different rheometers. (An ACI-sponsored international test program has initiated research to address this problem (6, 7)). Finally, rheology, due to its limited use, is an unfamiliar topic to a concrete industry that has specified concrete in terms of slump for more than eight decades. Consequently, the industry must overcome an initial learning curve to apply rheology to concrete construction.

Despite the present limited use of rheometers, the application of rheology to concrete can accelerate the use of new and underutilized materials, enhance the mixture proportioning process, and improve field quality control. A study facilitated by the Strategic Development Council of the American Concrete Institute identified the development of portable testing technologies for use in the field as a high priority research need and specifically cited the need for field test methods for rheology (8). A simple, portable rheometer is clearly needed to enable routine measurements of rheology in the field and to improve the characterization and control of concrete in general and SCC in particular.

A NEW PORTABLE RHEOMETER

A new rheometer was developed at the International Center for Aggregates Research (ICAR)[1] at the University of Texas at Austin to address both the needs of the concrete industry and the limitations of existing rheometers (9). The ICAR rheometer is a low-cost, fully portable rheometer for measuring concrete with workability ranging from a slump of approximately 50 mm to SCC.

The first generation prototype of the ICAR rheometer, which was developed with off-the-shelf components, is shown in Fig. 1. It is approximately the size of a portable, hand-held drill and utilizes a four-bladed vane that is immersed into concrete and rotated at a range of fixed angular velocities (controlled-rate rheometer). The vane is attached to the rheometer with a keyless chuck. The rheometer can be quickly mounted in a frame and positioned over a standard container, which facilitates test operation and ensures consistent test geometry. The device is lightweight and can be easily moved around on a jobsite by one person. Power can be supplied from an 18- or 24-volt battery or a standard alternating current source. The operation of the device is fully automated and does not require advanced training. In fact, the use of two parameters, which can be quickly compared to a specification, makes the interpretation of test results simpler than relying on multiple empirical tests or qualitative observations. Computer software controls the operation of the test and the computation of test results. In later versions of the device, it is envisioned that smaller components designed specifically for the ICAR rheometer will be housed in a plastic protective case.

The ICAR rheometer can be used to measure a flow curve, perform a stress growth test for yield stress, and characterize thixotropy. In a flow curve test, the vane is rotated at a range of fixed angular velocities while the torque acting on the vane is recorded. The range of angular velocities, number of different angular velocities, and whether the angular velocities are measured in ascending or descending order can be selected by the user. The vane acts in a manner analogous to the inner cylinder in a coaxial cylinders rheometer and is advantageous because of its compact design and the elimination of

---

[1] Commercial equipment, instruments, and materials mentioned in this paper are identified to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

slippage resulting from wall effect (10, 11, 12). In fact, vanes have been used to measure a wide range of concentrated suspensions, especially for direct yield stress measurements (12, 13, 14, 15).

The torque versus angular velocity data measured in a flow curve test are analyzed to determine rheological parameters. Due to end effects and the fact that not all of the material in the annulus region of the rheometer container flows in all cases, it is not possible to use traditional equations—such as the Reiner-Riwlin equation for Bingham materials—to relate the torque and angular velocity measurements from the ICAR rheometer to yield stress and plastic viscosity in fundamental SI units of Pa and Pa·s. Multiple approaches for computing test results in fundamental units are available (4, 16, 17, 18). Ongoing research at NIST into the use of simulation models such as dissipative particle dynamics (19) may provide a means for computing results in fundamental units. The approach used in this paper is to fit a straight line to the torque (*T*) versus angular velocity (*N*) data, as indicated in Eq. (3). For this paper, the slope of the line is denoted as the V-value (N·m·s), which is related to plastic viscosity, while the intercept of the line with the torque axis is denoted as the Y-value (N·m), which is related to yield stress.

$$T = Y + VN \tag{3}$$

The ICAR rheometer can be used to measure concrete with a maximum aggregate size of up to 25 mm and can be adapted to measure mortar by using a smaller vane and container. Previous testing (9) conducted with the ICAR rheometer showed that the device was capable of measuring a wide range of concrete mixtures with different materials and mixture proportions. Although the ICAR rheometer is capable of measuring a broad range of workability, the repeatability of test results is best for highly fluid mixtures such as SCC. In fact, the concepts of fluid rheology are better suited for SCC and other highly flowable concrete than for conventional concrete because highly fluid materials behave more like homogenous fluids.

Unlike existing rheometers that are used mainly in a laboratory setting, the ICAR rheometer was designed to be accurate enough to be used in the laboratory for research or mixture proportioning and rugged enough to be used in the field for verification of rheological parameters. The first generation prototype of the ICAR rheometer was constructed at a low cost. It is envisioned that a mass production version of the ICAR rheometer could be economically viable for routine measurements.

TESTING PROGRAM

A series of SCC mixtures covering a range of rheological properties were tested to demonstrate the validity and use of the ICAR rheometer.

Materials and Mixture Proportions

Three aggregate fractions—coarse and intermediate-sized crushed limestone aggregates and a natural sand—were used in all mixtures. The particle size distributions of these aggregates are shown in Table 1. The cementitious materials consisted of an

ASTM C 150 Type I portland cement and an ASTM C 618 Class F fly ash. The high-range water-reducing admixture (HRWRA) was a polycarboxylate-based admixture intended for the production of SCC in precast applications. All mixtures incorporated a water reducing and retarding admixture at a constant dosage of 130 mL per 100 kg of cement. Additional details on the materials are provided in ref. (9).

Nine concrete mixtures were prepared, as indicated in Table 2, to examine the effects of cement paste content, water-cementitious materials ratio (*w/cm*), fly ash replacement rate, and HRWRA dosage on SCC rheology. The HRWRA dosage, expressed in L/m^3, was varied for each of the nine mixtures to produce a range of rheological properties for a given mixture. Any loss of workability occurring as the HRWRA dosage was varied and the concrete was retested was not quantified independently.

Test Methods

Rheological measurements were made with both the ICAR rheometer and the BTRHEOM rheometer, a parallel plate rheometer for testing concretes with slumps greater than approximately 100 mm (20). This latter rheometer was selected due to its availability to the authors and because its use would allow the study results to be correlated with the results of other rheometers from the international comparisons of concrete rheometers sponsored by ACI (6, 7).

The dimensions of the ICAR rheometer used for the testing are shown in Fig. 2. Concrete was discharged directly from the mixer into the ICAR rheometer container. The vane was inserted into the concrete and rotated at a angular velocity of 6.3 rad/s (1.0 rev/s) for a breakdown period of 25 s. Seven flow curve points were then measured at descending angular velocities from 6.3 rad/s (1.0 rev/s) to 0.31 rad/s (0.05 rev/s). A straight line was fit to the torque versus angular velocity data to determine Y-value and V-value as indicated in Eq. 3. Although it is possible to compute negative Y-values with this method (21), such negative values do not represent physical entities but, rather, are the result of a mathematically convenient method of interpreting results.

The parallel plate rheometer (Fig. 3) was loaded with concrete using a scoop. After a standard breakdown time of 15 s, five flow curve points were measured at descending angular velocity from 6.3 rad/s (1.0 rev/s) to 1.3 rad/s (0.2 rev/s). The test results were computed in fundamental units based on the Bingham model.

In addition, the slump flow test was performed by filling concrete into a standard slump cone (ASTM C 143) that was centered on a level plastic plate. The slump cone was lifted and three measurements were made: the time for the concrete to spread to a horizontal diameter of 500 mm (T_{50}), the final horizontal spread diameter, and the visual stability index (VSI). The VSI ratings, which were determined based on the definitions of Daczko (22), were made on a scale of 0 to 3, with 0 exhibiting excellent stability and 3 exhibiting poor stability. All fresh concrete tests were started simultaneously to ensure consistency.

RESULTS

The test data showed clear trends for each change to the mixture proportions. For a given dosage of HRWRA, increasing the cement paste content reduced both Y-value (Fig. 4) and V-value (Fig. 5). This result was expected because the increased cement paste content reduced the aggregate concentration. For concentrated suspensions, it is well known that reducing the solid volume concentration results in a reduction in suspension viscosity (3). The change in Y-value at a constant HRWRA dosage was much more significant when the cement content (with constant *w/cm*) was increased from 386 kg/m^3 to 445 kg/m^3 than when the cement content was further increased to 504 kg/m^3. Increasing the HRWRA dosage had little incremental effect on Y-value at the higher two cement contents of 445 kg/m^3 and 504 kg/m^3. The V-value, however, decreased sharply with increasing HRWRA dosage at all three cement paste contents, which demonstrated the effect of the HRWRA in de-agglomerating cement particles.

Increasing the *w/cm* generally reduced the Y-value although the results were variable (Fig. 6). This variability in the Y-value results reflected the fact that the Y-values were all relatively low for the range of HRWRA dosages considered and that further increases in HRWRA dosage had little effect on Y-value. It is possible that this variability could have been reduced by increasing the precision of the ICAR rheometer. Therefore, the more important variable in terms of predicting material performance for SCC was the V-value. The trends for V-value (Fig. 7) were much clearer, with higher *w/cm* resulting in lower V-values. The reductions in Y-value and V-value with increasing *w/cm* can be attributed to the reduced contacts between cement particles and the resulting reduction in inter-particle friction. The potency of incremental HRWRA dosages in terms of V-value was diminished for higher *w/cm* because the particles were already significantly separated at higher *w/cm* values, which minimized the effect of the HRWRA in de-agglomerating cement particles.

The use of fly ash generally reduced the Y-value for a given HRWRA dosage (Fig. 8). Just as was the case for the *w/cm* tests, the V-value became more important than the Y-value for predicting material performance once the Y-value was reduced to a sufficiently low level. Indeed, the use of fly ash significantly reduced the V-value (Fig. 9). In order to ensure stability, the *w/cm* for the 20 % fly ash replacement mixture was reduced to 0.32 from 0.35. Relative to the cement-only control mixture, this decrease in *w/cm* and use of fly ash resulted in an increase in the V-value but a reduction in the Y-value. This result suggested that fly ash can be used to reduce yield stress without resulting in undesirably large decreases in plastic viscosity and the attendant stability problems that increasing *w/cm* could cause. The reductions in Y-value and V-value could be attributable to the spherical shape of the fly ash particles, which acted as ball bearings to reduce the friction between particles (23, 24). The fineness of the fly ash offset this ball bearing effect and was probably partly responsible for the increase in V-value when comparing the cement-only mixture to the mixture with 20 % fly ash and a lower *w/cm*.

The test data from the ICAR rheometer can be used to consider the tradeoffs between changing cement paste content, water-cementitious materials ratio, fly ash replacement rate, and HRWRA dosage in order to achieve proper SCC flow properties. For instance, increasing cement paste content, *w/cm*, fly ash replacement rate, and HRWRA dosage all resulted in decreases in Y-value and V-value; however, the magnitudes of the changes in rheological properties varied widely depending on the mixture proportions. Each change in mixture proportions has different implications in terms of cost and hardened properties. All of this data can be used to optimize mixture proportions and to adjust mixture proportions effectively to account for construction variables.

For the ICAR rheometer to be used on a widespread basis in the field, the parameters measured by the ICAR rheometer must be related not only to fundamental units but also to practical field requirements. In general, the yield stress must be kept to a sufficiently low level to ensure that the material will flow under its own weight. Meanwhile, the plastic viscosity must be kept within a certain range in order to avoid segregation and to ensure that the concrete will flow at a sufficient speed.

The results of the empirical tests can be compared to the Y-values and V-values measured by the ICAR rheometer. Figure 10 shows that the Y-value from the ICAR rheometer was related to slump flow. The concrete in the slump flow test continues to flow as long as the stress induced by gravity exceeds the yield stress. Therefore, both the ICAR rheometer and the slump flow test measure an entity related to the stress needed to cause flow. Figure 11 indicates that the V-value from the ICAR rheometer was related to T_{50} measurements. When concrete flows quickly, the resistance to flow—and, thus the viscosity—is low. The relationship between T_{50} and V-value exhibited more variability than the relationship between slump flow and Y-value, in part, because of the difficulty in determining the precise start and stop times for T_{50}. More fundamentally, viscosity, which is closely related to V-value, is a measurement of just one entity—the rate of change between shear stress and shear rate—while T_{50} is the result of various forces acting over the duration of flow.

One approach to specifying SCC in terms of rheology is to use a workability box, which stipulates acceptable ranges of yield stress and plastic viscosity for a particular application (24). Figure 12 shows a workability box based on the results from the ICAR rheometer. A concrete mixture was considered to be SCC if the slump flow was greater than 610 mm and the VSI was 1 or less. Mixtures denoted "under" SCC had slump flows less than 610 mm while mixtures indicated as "over" SCC had slump flows greater than 610 mm but exhibited VSI values greater than 1. The workability box was not rectangular, like those discussed in previous publications (21, 24, 25). In general, the workability box indicated that the Y-value needed to be sufficiently low for the concrete to exhibit the requisite slump flow. As the Y-value was decreased below a certain point, the V-value had to be increased in order to ensure stability.

Figures 13 and 14 compare the data from the two rheometers. The correlation coefficients (R^2) were 0.87 for both yield stress and plastic viscosity measurements. This degree of correlation is comparable to the results obtained in two international comparisons of concrete rheometers held in France (6) and the United States (7) and coordinated by ACI subcommittee 236A on workability. It should be noted that the

BTRHEOM exhibited an offset error, which reduced the precision of the zero offset and the yield stress measurements. Improved precision in measuring yield stress for both the ICAR rheometer and BTRHEOM rheometer would make these devices more valuable.

FIELD TESTING

Field testing was conducted to demonstrate the portability of the ICAR rheometer. The testing, which is described in further detail in ref. (26), involved materials and mixture proportions known to perform well in general ready-mix applications. As shown in Fig. 15, the concrete could be sampled directly from the discharge chute on a mixing truck and tested immediately. Because a single test takes only 30 s to 60 s, the use of the ICAR rheometer to verify mixture properties creates minimal disruption to a construction operation. The ability of the ICAR rheometer to characterize rheology quickly in the field can enable the mixture proportions to be adjusted precisely and a higher level of quality to be achieved.

CONCLUSIONS

The ICAR rheometer was able to distinguish successfully the effects of cement paste content, water-to-cementitious materials ratio, fly ash replacement rate, and high-range water-reducing admixture dosage. The effects of each of these changes to mixture proportions can be used to proportion mixtures and control quality in the field by considering the tradeoffs in flow properties, cost, strength, and durability. To achieve SCC flow properties, it was generally necessary to reduce yield stress to a sufficiently low value and to control plastic viscosity to a proper range of values to achieve stability while ensuring sufficient fluidity. The results from the ICAR rheometer were well correlated to the results of the BTRHEOM rheometer—an outcome that was expected based on the results of the two earlier ACI-sponsored rheometer comparisons (6, 7). Additional work is needed to relate results from the ICAR rheometer to fundamental units. Research sponsored by ACI to develop a standard reference material will enable results from different rheometers to be compared directly. The operation of the ICAR rheometer was simple, fast, and well suited for use in the field. The low cost and portable form factor of the ICAR rheometer can potentially make the routine field measurement of fresh SCC rheology a viable option.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Aggregates Foundation for Technology, Research, and Education (AFTRE) for funding the research described in this paper. The field testing could not have being performed without access to the facilities of Aggregate Industries, the materials of Sika Corporation, and the laboratory skills of Max Peltz (NIST). The support by the NIST Hypercon program and the VCCTL Consortium is greatly appreciated. Edward Garboczi (NIST), Nicos Martys (NIST), and Kevin Folliard (University of Texas at Austin) are also thanked for their constructive comments on this paper.

REFERENCES

1. Koehler, E.P., Fowler, D.W., “Summary of Concrete Workability Test Methods,” ICAR Report 105.1, International Center for Aggregates Research, August 2003, 92 pp.

2. Bartos, P.J.M., Sonebi, M., Tamimi, A.K. (Eds.), “Workability and Rheology of Fresh Concrete: Compendium of Tests,” RILEM, Cachan Cedex, France, 2002, 154 pp.

3. Barnes, H.A., Hutton, J.F., Walters, K., “An Introduction to Rheology,” Elsevier, New York, 1989, 199 pp.

4. Whorlow, R.W., “Rheological Techniques,” Ellis Horwood, London, 1992, 460 pp.

5. Amziane, S., Ferraris, C.F., “Monitoring of Setting Evolution of Cementitious Materials by Measurements of Rheological Properties and Pore Water Pressure,” to be submitted to *Advances in Cement Research*, 2004.

6. Ferraris, C.F., Brower, L.E. (Eds.), “Comparison of concrete rheometers: International tests at LCPC (Nantes, France) in October 2000,” NISTIR 6819, National Institute of Standards and Technology, Gaithersburg, MD, 2001, 157 pp.

7. Ferraris, C.F., Brower, L.E. (Eds.), “Comparison of concrete rheometers: International tests at MB (Cleveland, OH, USA) in May 2003,” NISTIR 7154, National Institute of Standards and Technology, Gaithersburg, MD, 2004, 116 pp.

8. Strategic Development Council, “Roadmap 2030: The U.S. Concrete Industry Technology Roadmap,” American Concrete Institute, Farmington Hills, MI, 2002, 44 pp.

9. Koehler, E.P., “Development of a Portable Rheometer for Fresh Portland Cement Concrete,” MS Thesis, University of Texas at Austin, August 2004, 419 pp.

10. Yan, J., James, A.E., “The yield surface of viscoelastic and plastic fluids in a vane rheometer,” *Journal of Non-Newtonian Fluid Mechanics*, V. 70, No. 3, 1997, pp. 237-253.

11. Keentok, M., Milthorpe J.F., O’Donovan, E., “On the shearing zone around rotating vanes in plastic liquids: theory and experiment,” *Journal of Non-Newtonian Fluid Mechanics*, V. 17, No. 1, 1985, pp. 23-35.

12. Barnes, H.A., Nguyen, Q.D., “Rotating vane rheometry-a review,” *Journal of Non-Newtonian Fluid Mechanics*, V. 98, No. 1, 2001, pp. 1-14.

13. Nguyen, Q.D, Boger, D.V., “Direct Yield Stress Measurement with the Vane Method,” *Journal of Rheology*, V. 29, No. 3, 1985, pp. 335-347.

14. Barnes, H.A., Carnali, J.O., “The vane-in-cup as a novel rheometer geometry for shear thinning and thixotropic materials,” *Journal of Rheology*, V. 34, No. 6, 1991, pp. 841-866.

15. Liddell, P.V., Borger, D.V., “Yield stress measurement with the vane,” *Journal of Non-Newtonian Fluid Mechanics*, V. 63, No. 2-3, 1996, pp. 235-261.

16 Nguyen, Q.D., Boger, D.V., “Measuring the Flow Properties of Yield Stress Fluids,” *Annual Review of Fluid Mechanics*, V. 24, 1992, pp. 47-88.

17 Ferraris, C.F., Martys, N.S., “Relating Fresh Concrete Viscosity Measurements from Different Rheometers,” *Journal of Research of the National Institute of Standards and Technology*, V. 108, No. 3, May-June 2003, pp. 229-234.

18 Tattersall, G.H., Banfill, P.F.G., “The Rheology of Fresh Concrete,” Pitman Publishing, Marshfield, MA, 1983, 356 pp.

19 Martys, N., Ferraris, C.F., “Simulation of SCC Flow,” Conference Proceedings, *First North American Conference on the Design and Use of Self-Consolidating Concrete*, November 12-13, 2003, Chicago, IL.

20. de Larrard, F., Hu, C., Sedran, T., Szitkar, J. C., Joly, M., Claux, F., Derkx, F., “A New Rheometer for Soft-to-Fluid Fresh Concrete,” *ACI Materials Journal*, V. 94, No. 3, 1997, pp. 234-243.

21. Ferraris, C., Brower, L., Ozyildirim, C., Daczko, J., “Workability of Self-Compacting Concrete”, Symposium Proceedings, *PCI/FHWA/FIB International Symposium on High Performance Concrete*, September 25-27, 2000, Orlando, FL.

22. Daczko, J.A., “Stability of Self-Consolidating Concrete – Assumed or Ensured?,” Conference Proceedings, *First North American Conference on the Design and Use of Self-Consolidating Concrete*, November 12-13, 2003, Chicago, IL.

23. Ferraris, C., Obla, K., Hill, R., “The influence of mineral admixtures on the rheology of cement paste and concrete”, *Cement and Concrete Research*, V. 31, No. 2, 2001, pp. 245-255.

24. Beaupré, D., “Rheology of High Performance Shotcrete,” Ph.D. Thesis, University of British Columbia (Canada), 1994.

25. de Larrard, F., “Why Rheology Matters,” *Concrete International*, V. 21, No. 8, 1999, pp. 79-81.

26. Amziane, S., Ferraris, C.F., Koehler, E.P., “Measurement of Rheological Properties of Fresh Concrete Using a Mixing Truck,” *Journal of Research of the National Institute of Standards and Technology*, Vol. 110, No. 1, 2005, pp. 55-66.

TABLES

Table 1: Aggregate particle size distributions

US Standard Sieve	**Mesh Size (mm)**	**Percent Passing**		
		Coarse	**Int.**	**Sand**
1 in.	25.0	100.0		
¾ in.	19.0	82.4		
½ in.	12.5	10.7	99.9	
3/8 in	9.5	0.6	81.3	
#4	4.75	0.3	11.9	97.3
#8	2.36		1.8	86.2
#16	1.18		1.2	70.5
#30	0.600			49.0
#50	0.300			27.3
#100	0.150			6.8
#200	0.075			0.6

Table 2: Initial mixture proportions

Mix	**Change**	**Aggregate (SSD)**			**Cement**	**Fly Ash**	**w/cm**
		Coarse	**Int.**	**Fine**			
		kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	
1	Control	530.1	285.4	808.9	445.0		0.40
2	Reduce cement	564.2	303.8	861.0	385.6		0.40
3	Increase cement	495.9	267.0	756.8	504.3		0.40
4	w/cm = 0.43	523.3	281.8	798.6	439.3		0.43
5	w/cm = 0.37	537.3	289.3	819.8	451.0		0.37
6	w/cm = 0.35	542.1	291.9	827.3	455.1		0.35
7	20 % fly ash	530.1	285.4	808.9	356.0	89.0	0.40
8	40 % fly ash	530.1	285.4	808.9	267.0	178.0	0.40
9	20 % fly ash, w/cm = 0.32	542.8	292.3	828.3	364.5	91.1	0.32

FIGURES

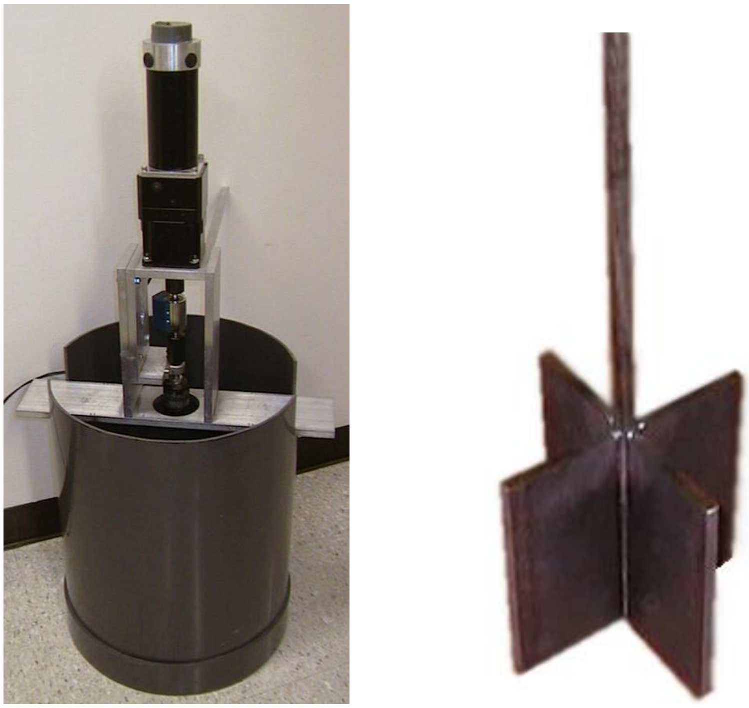

Figure 1: First generation prototype of the ICAR rheometer and vane

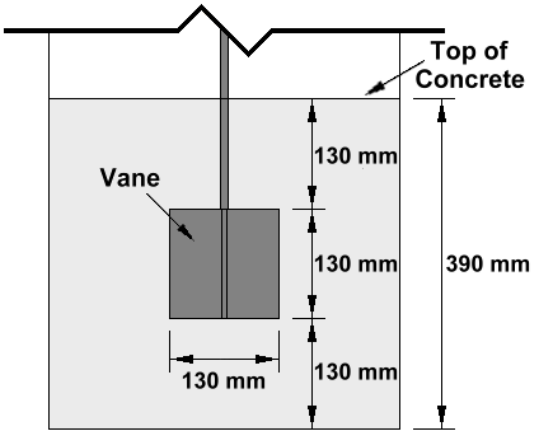

Figure 2: Dimensions of the ICAR rheometer

Figure 3: BTRHEOM rheometer

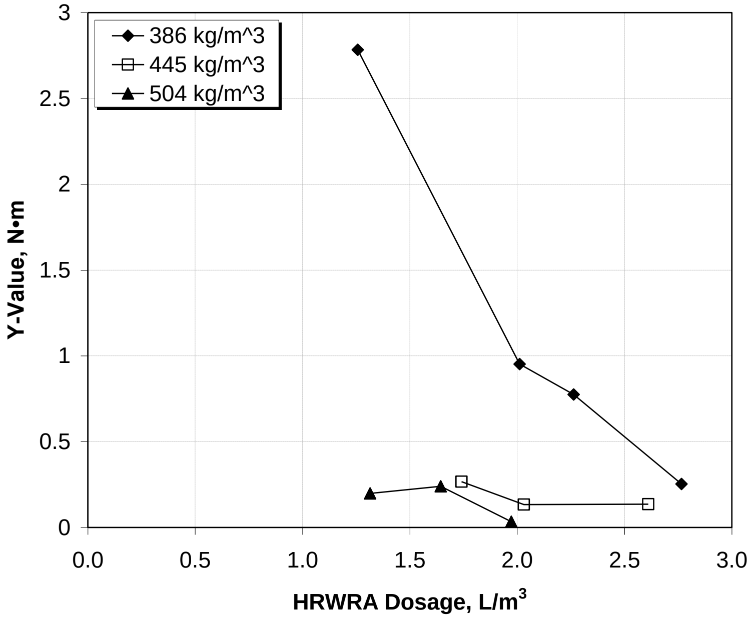

Figure 4: Effect of cement paste content on Y-value from ICAR rheometer (constant *w/cm*)

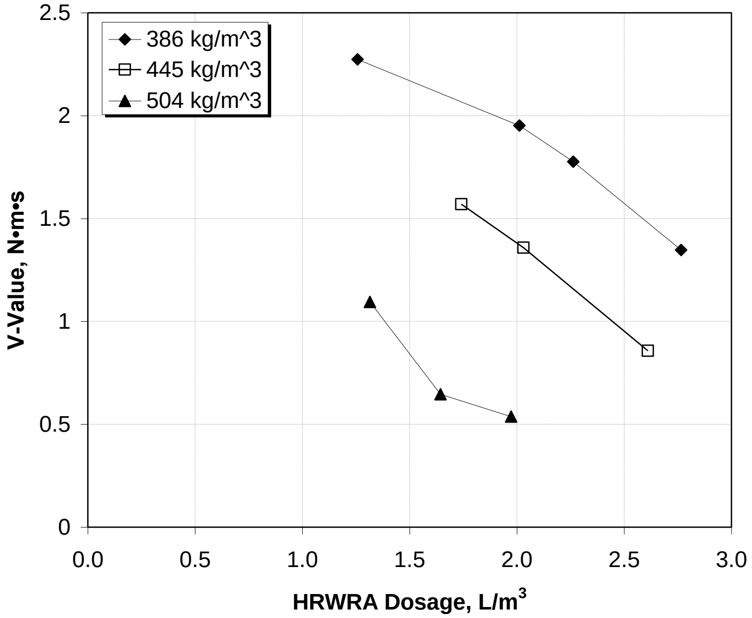

Figure 5: Effect of cement paste content on V-value from ICAR rheometer (constant *w/cm*)

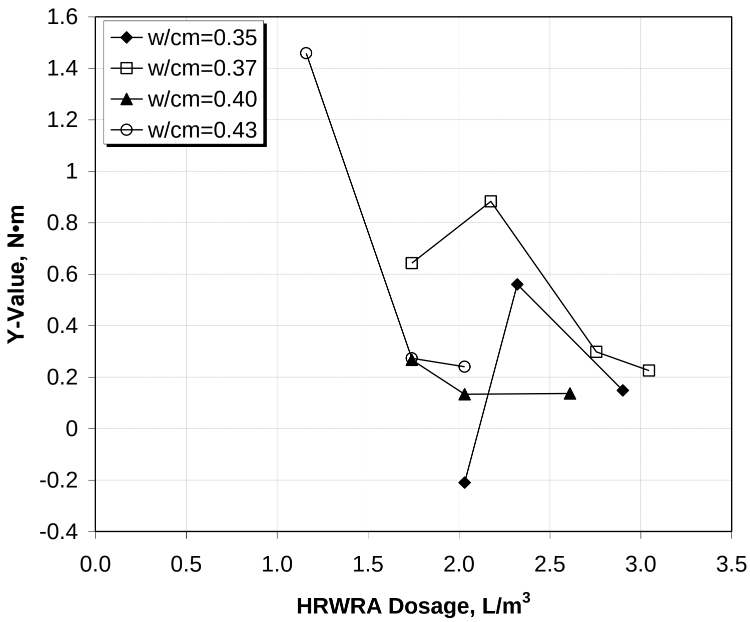

Figure 6: Effect of water-cementitious materials ratio on Y-value from ICAR rheometer

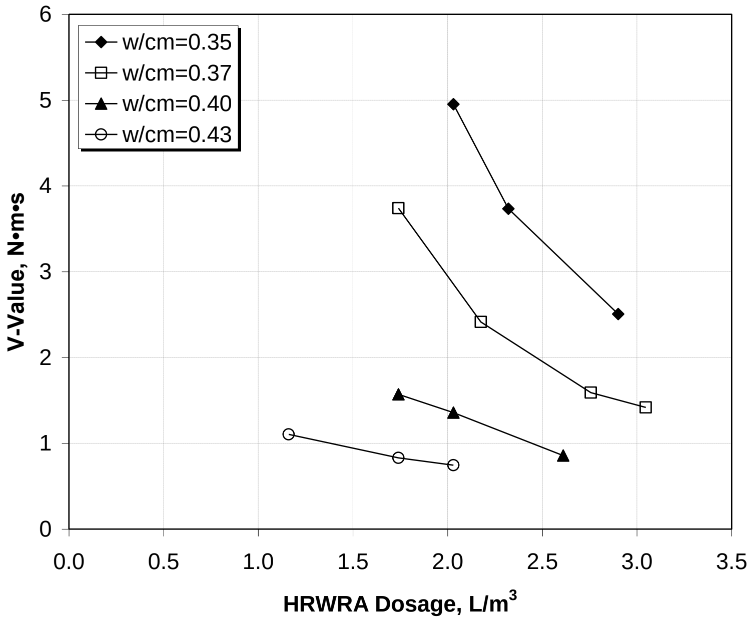

Figure 7: Effect of water-cementitious materials ratio on V-value from ICAR rheometer

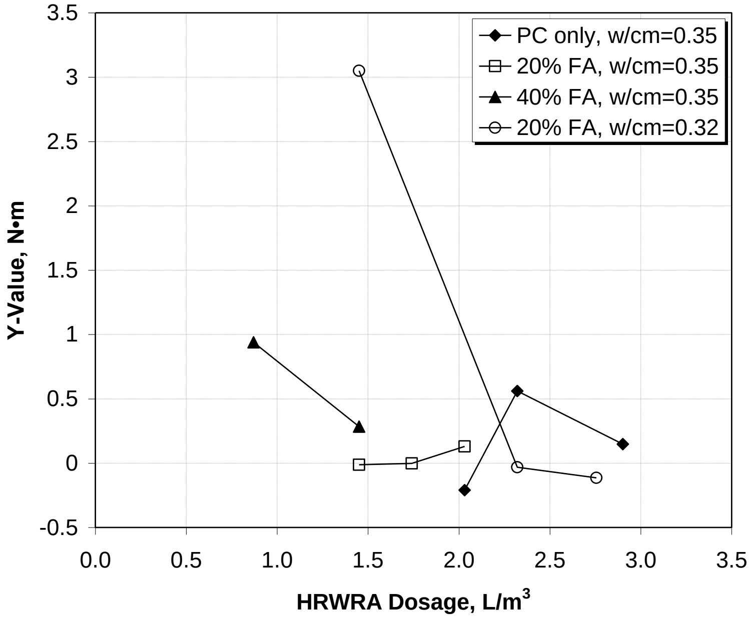

Figure 8: Effect of fly ash (FA) replacement rate on Y-value from ICAR rheometer

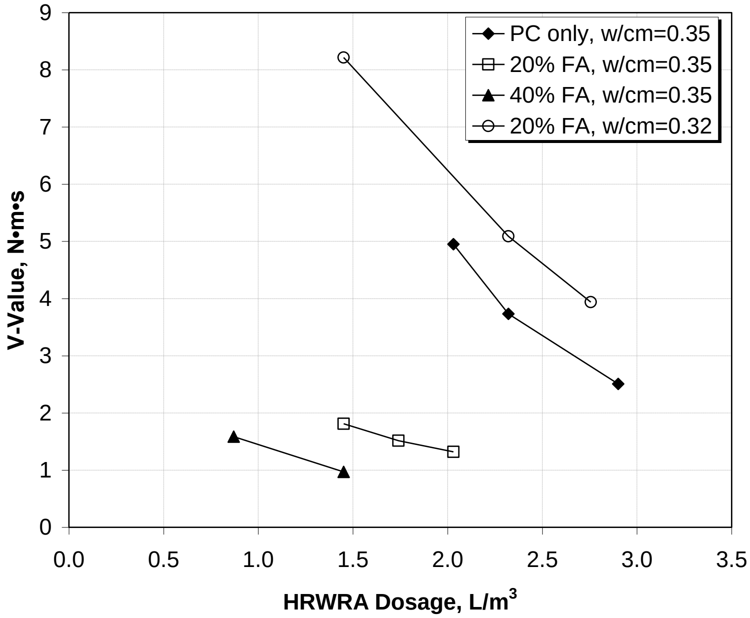

Figure 9: Effect of fly ash (FA) replacement rate on V-value from ICAR rheometer

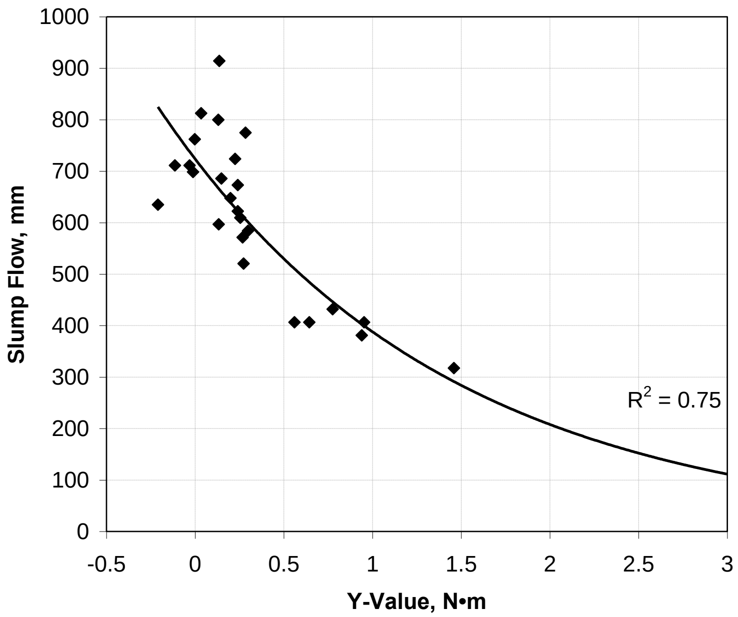

Figure 10: Relationship between ICAR rheometer Y-value and slump flow

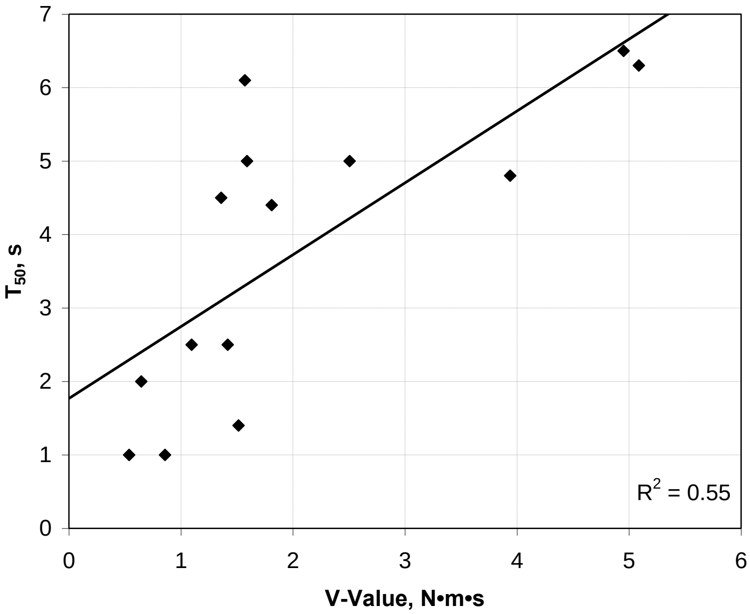

Figure 11: Relationship between ICAR rheometer V-value and T_{50}

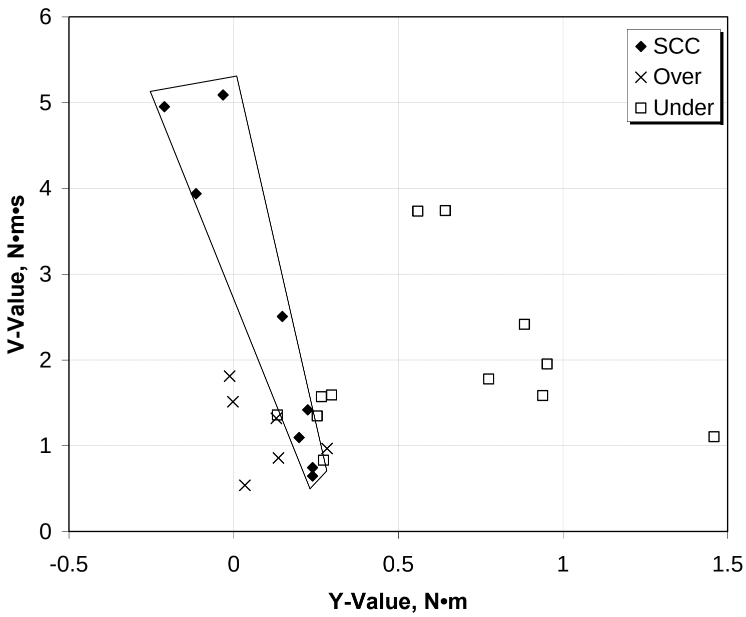

Figure 12: Workability box

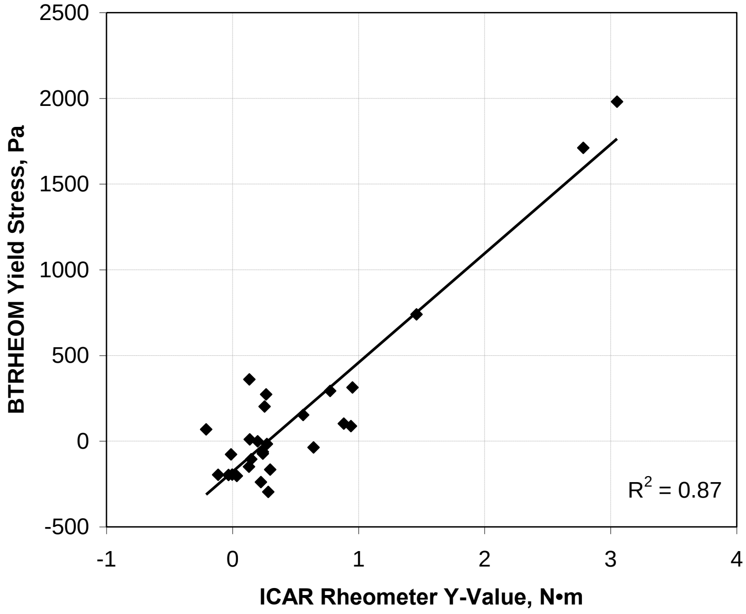

Figure 13: Correlation between values of yield stress measured by the two rheometers used in this study

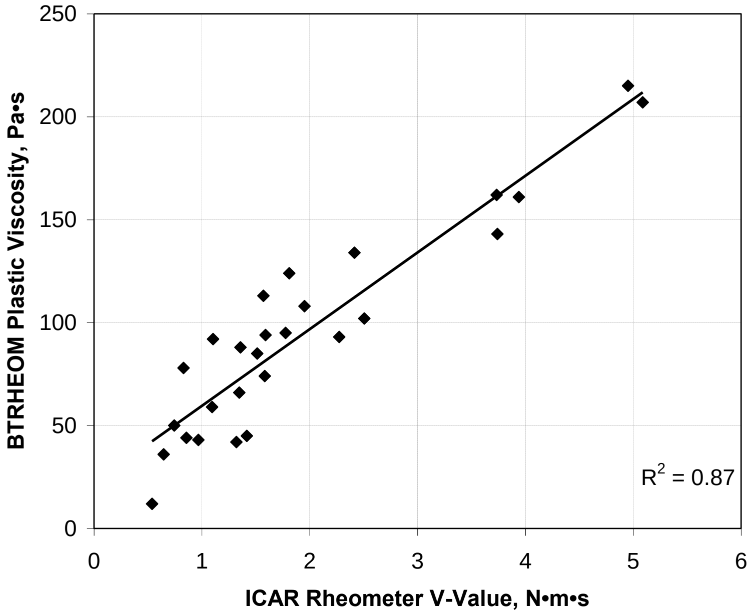

Figure 14: Correlation between values of plastic viscosity measured by the two rheometers used in this study

Concrete Truck **Sampling Concrete** **Testing Concrete**

Figure 15: Field testing