2009 BFRL Project Description

Project Title: Rheology-Based Processing of Concrete

September 12, 2008

Principal Investigators: Chiara F. Ferraris, x6711 and Nicos Martys, x5915

BFRL Program: HYPERCON: Prediction and Optimization of Concrete Performance

Objective: To provide the concrete industry with measurement techniques of the rheological properties of fresh concrete using calibrated concrete rheometers since empirical measurements of concrete flow properties hinder the optimization of concrete composition for ease of placement, pumpability and behavior under vibration.

Problem:

What is the problem? **Efficient flow and placement of fresh concrete is crucial for its economical use and application; however, no calibrated rheological measurement tools or standard tests to characterize concrete flow properties exist that are based on fundamental rheological science**. Concrete rheometers are commercially available but cannot be widely adopted because the results obtained are dependent on the rheometer used, i.e., an engineer cannot specify rheological parameters without also specifying which exact rheometer to use. This prevents the industry from being able to write specifications that use rheological parameters instead of slump tests or other empirical methods. A collaborative survey[1] by the National Ready-Mixed Concrete Association and NIST indicated that the major problems of concrete placement are associated with its flow. A white paper sponsored by ACBM (The Center for Advanced Cement Based Materials) on Self Compacting Concrete (February 2007[2]) states that "A good test method that can help to quantitatively determine the viscosity and the yield stress of self-compacting concrete (SCC) in the field is urgently needed." The American Concrete Institute (ACI, 304-2R-96[3]) states that "pumping may be used for most concrete construction". About 25 % to 40 % (87 million m^3/year) of all concrete is pumped[4]. Nevertheless, no measurement techniques are available that optimize the pumpability of a concrete/grout.

Why is it hard to solve? The concrete rheometers commercially available provide data that cannot be compared because the results[5] cannot be analytically resolved to extract the rheological parameters such as yield stress and plastic viscosity. Only a combination of a

[1] C. F. Ferraris, C. Lobo, "Processing of HPC" Concrete international, vol. 20 #4, 1998 p. 61-64
[2] http://www.selfconsolidatingconcrete.org/ACBM%20White%20Paper.PDF
[3] ACI 304.2R-96 reapproved 2008, "Placing Concrete by Pumping Methods"
[4] Private communication from Mr. Tom O'Malley, Schwing America
[5] C. Ferraris, L. Brower editors, "Comparison of concrete rheometers: International tests at LCPC (Nantes, France) in October 2000", NISTIR 6819, September 2001 and C. Ferraris, L. Brower editors, "Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May 2003", NISTIR 7154, September 2004

reference material and intensive computational simulation could allow the development of correlation or calibration methodologies for concrete rheometers. The reference material should ideally have stable properties independent of the shear rates, be a granular material such as concrete, and inexpensive, while most standard material for rheometers are oils and Newtonian fluids. In order to relate concrete rheometer measurements to fundamental material properties, detailed modeling of suspension flow composed of a wide range of particles size requires large scale simulation and innovative development of simulation codes.

How is it solved today, and by whom? Today, chemical admixture and concrete mixture design are only mapped out by trial and error using empirical tests. This is time consuming and costly. In special cases, concrete rheometers are used in the field but only by researchers. Some discussions on how to improve the measurements and to related them to rheological properties was initiated by ACI by forming in 2006 a new committee 238 dedicated to "Workability of Fresh Concrete". The prediction of viscosity of a granular material such as concrete from its matrix viscosity can be simulated by NIST models. Indeed, NIST has the most sophisticated approach for modeling realistic suspensions.

Why NIST? NIST has the unique capability to combine modeling with experimental measurements. Instrumentally, NIST has a concrete rheometer, is building an instrumented pumping station, and has extended knowledge in paste rheological measurements. NIST has developed the world's most sophisticated models of the flow of suspensions, which can simulate the viscosity of a material with particles of any shape. This project will enhance the measurement capability and the performance-based standards of the building industry by providing standard reference material and technologies to characterize critical properties of the concrete. This project is aligned with the BFRL strategic goal of "Measurement Science for Sustainable Infrastructural Materials."

Approach:

What is the new technical idea? The new technical idea is based on a multiscale approach to concrete. Concrete consists of cement in water (cement paste, 100 nm – 40 μm), sand in cement paste (mortar, 0.1 – 1 mm), and coarse aggregates in mortar (concrete, 1 mm – 20 mm). This composition requires the development of measurement science tools at each level that can be linked from the microscale to the macroscale, by pursuing two linked avenues of research: 1) calibration of concrete rheometers by development of a standard reference material in combination with the computer simulation of flow in a rheometer; and 2) use of a calibrated rheometer and an instrumented pumping station to correlate concrete material properties to the behavior of the pumped material in combination with computer simulation. This is an Integrated Computational Materials Engineering (ICME)[6] approach. Reference material candidates have been identified, but extensive rheological testing needs to be performed to ensure that they can be used as paste, mortar, and concrete substitutes. The computer simulation will predict the plastic viscosity of the simulated mortar from the paste and then scale to the concrete level by the model addition of coarse aggregates. Also, the computer simulation will be used to determine

[6] Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security (National Research Council, National Academies Press, in press, 2008)

the flow inside a rheometer and extract the viscosity of the material depending on the geometry – this cannot be done analytically for any suspension of particles. The building of a unique instrumented pumping station will allow the measurements of critical parameters of the flow of grouts through the pipes. Using a rheometer and simulation, the grout rheological properties will be linked to the grout behavior in the pipes. The knowledge acquired will enable the construction industry to select better materials based on measured performance specification.

Why can we succeed now? The basic ground work has been performed at NIST in the past 10 years by developing a state of the art rheological laboratory for cementitious materials, successful computer algorithms to predict 3-D concrete flow, and new computational capabilities (BFRL's Hercules computer, access to National Aeronautics and Space Administration (NASA) and Department of Energy (DOE) supercomputers). The Virtual Cement and Concrete Testing Laboratory (VCCTL) consortium provides collaboration with the ready-mixed concrete industry and in the construction chemical admixtures industry. NIST is building a fully instrumented pumping station, initially for grout, combined with cement paste, mortar, and concrete rheometers. Potential candidates for reference materials have been identified based on the fundamental rheological parameters required. The multi-scale research plan is close to being fully operational, and the flow models are very close to being able to simulate the flow in concrete rheometers.

What is the research plan? To replace empirical standard tests with performance based tests based on fundamental rheological properties of fresh concrete that allow for performance prediction, it is necessary to develop measurement science and calibration protocols for concrete rheometers. Since the amount of concrete delivered by pumping is increasing, we also need to examine how pumpability is related to fundamental rheological parameters, for which we need calibrated concrete rheometers that can deliver results in fundamental units.

The calibration of concrete rheometers is not trivial as the flow pattern for a suspension is not analytically known and therefore measured results cannot be expressed in fundamental material properties and are in fact device-sensitive. The methodology to resolve the issue is to combine measurements with simulation and standard reference materials (SRMs) whose properties, unlike concrete, do not change with time. The simulation will determine the flow patterns in the rheometers and interpret the results obtained in the experimental data obtained on the SRMs.

First, a coaxial rheometer geometry will be studied using a detailed simulation of suspension flow and simulations using a representative continuum non-Newtonian fluid, both with smooth particle hydrodynamics and with lattice Boltzmann techniques. This will allow us to test the multiscale hypothesis that we can take detailed simulation results from one scale and coarse grain them to describe a continuum fluid at larger scales. Then a similar study will be carried out for the commonly used vane rheometer design. Linking results from the coaxial simulation results and the vane rheometer will be important to help validate the concept of using a standard reference material for different rheometers in that the constitutive relation for the fluids should be the same for both rheometers. So the experimental work and the simulation work will be mutually supportive, and will result in SRMs that are certified through a

combination of experiment and simulation (computational materials engineering, in the ICME approach). Concrete rheometers will then be calibrated using the SRMs. This calibration protocol will be offered for standardization. The computer simulation will not need to be run by every user, but will be available publically to interpret and calibrate experimental results.

In parallel, a unique instrumented pumping station will be built for grouts, as a first step towards pumping concrete. This will provide a practical application of the use of the calibrated rheological measurements. A protocol to predict the pumpability of a grout will be established. Collaboration with the industry will be sought to identify chemical admixtures and supplementary cementitious materials that affect the pumpability of grouts and determine how these materials affect the rheological properties of the material. Using calibrated rheometers, we will develop correlations between fundamental material properties and pumpability. The suspension rheology model will be extended to the pipe flow geometry to help interpret experimental results from the pumping experiments and "complete the loop" by relating all results back to fundamental rheological parameters. Detailed knowledge of the suspension flow in pipes is crucial for understanding how to optimize flow in pipes, and to deliver to industry an instrumented grout pumping station that is based on fundamental rheological parameters.

Recent Results:

- **Outcome**: Established NIST as the recognized world leader in combining computer simulation and experimental rheological measurements.
- Preliminary simulation of coaxial and vane rheometers have been performed, demonstrating the feasibility of the idea of combining simulation and experiment to quantitatively calibrate concrete rheometers.
    - **Output**: Zhu H., Martys N., Ferraris C.F., De Kee D." A numerical study for the flow of Bingham-like fluids in two dimensional vane and coaxial cylinders using a Smoothed Particle Hydrodynamic (SPH) based method" Accepted to J. of Non-Newtonian Fluid Mechanics**,** January 2008
    - **Output:** Martys N. S., Ferraris C.F., Gupta V., Cheung J.H., Hagedorn J. G., Peskin A. P., Garboczi E. J., "Computational model predictions of suspension rheology: comparison to experiment", 12th Int. Congress of the Chemistry of Cement, Montreal (Canada) paper # W6-06.3, July 2007
- Calibration using oil of non-traditional rheometer geometries successfully performed
    - **Output**: Ferraris C.F, Geiker M., Martys N. S. and Muzzatti N., "Parallel-plate Rheometer Calibration Using Oil and Lattice Boltzmann simulation", J. of Advanced Concrete Technology, vol. 5 #3, October 2007, pp. 363-371
- Techniques to measure cement paste (containing fly ash) rheological properties with various composition and temperatures and to correlate the results with concrete behavior were developed in collaboration with industry (Boral Technologies) and government agencies responsible for infrastructure (FHWA). ASTM is now considering the standardization of these test methods.
    - **Output**: Taylor P.C., Johansen V.C., Graf L. A., Kozikowski R. L., Zemajtis J. Z., Ferraris C. F., "Identifying Incompatible Combinations of Concrete Materials;

Volume I & II" FHWA report # FHWA-HRT-06-080, 2006 (http://www.fhwa.dot.gov/pavement/concrete/pubs/06079/ and http://www.fhwa.dot.gov/pavement/concrete/pubs/06080/index.cfm)

- Outcome: Award of 1.2M and 750,000 hours, respectively, on two of the nations supercomputers (NASA Columbia and DOE Argonne Blue Gene)
    - **Output**: N. S. Martys', D. Lootens , W. L. George, S.G. Satterfield, P. Hebraud "Spatial-Temporal Correlations at the Onset of Flow in Concentrated Suspensions", The XVth Inter. Cong. On Rheology, Ed. A. Co, L. G. Leal, R. H. Colby, A. J. Giacomin, AIP Conf Proc. vol 1027, Monterey, CA, pp. 207-209, 2008
    - **Output**: D. Lootens, N. S. Martys, W. George, S. Satterfield, P. Hebraud, "Stress Chains Formation under Shear of Concentrated Suspension" The XVth Inter. Cong. On Rheology, Ed. A. Co, L. G. Leal, R. H. Colby, A. J. Giacomin, AIP Conf Proc. vol 1027, Monterey, CA, pp. 677-679, 2008.

Standards and Codes: Chiara Ferraris is the chair of both ACI 238 "Workability of Fresh concrete" and of ASTM C01.22 (Workability). The ASTM C01.22 subcommittee is sponsoring a test to measure cement paste rheological properties using a rheometer, which is the first step toward standardizing the NIST multi-scale approach. This standard alone can be used to predict qualitative incompatibilities between cement and chemical admixtures and fly ash at the cement paste level, avoiding the full concrete level.