Simulation of SCC Flow

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Reprinted from First North American Conference on the Design and Use of Self-Consolidating Concrete. Proceedings. Chicago, IL, November 12-13, 2002, pp. 27-30, 2003.

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

SIMULATION OF SCC FLOW

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INTRODUCTION

In principle, self-consolidating concrete (SCC) should allow for the easy movement of concrete around flow obstructions under its own weight without the use of external vibration. The flow of concrete around barriers will depend on a variety of factors, including the concrete or mortar viscosity, the yield stress and the size distribution and shape of the coarse aggregate. Modeling the flow of complex fluids like concrete presents a great research challenge because of the necessity of accounting for the polydisperse motion of the aggregate, while, simultaneously solving the Navier-Stokes equations for the liquid phase in which they are immersed. Numerous schemes (1) have been developed using many standard computational approaches for solving the Navier-Stokes equations with moving rigid bodies. In general though, they are rather complicated and demand very large computational resources. Recently some novel approaches (2), based on cellular automata methods (lattice Boltzmann and dissipative particle dynamics (DPD)) have shown great promise for modeling a variety of complex flow problems. DPD has been shown to be particularly well suited for modeling complex systems like suspensions. This paper will give some highlights of the method and some examples of applications to SCC technology.

Fresh concrete is a complex fluid that necessitates the understanding of phenomena on many length scales. On one scale, one can think of concrete as a suspension composed of a fluid phase (mortar) and a solid phase (coarse aggregate). Similarly, for mortar the fluid phase is the cement paste and the sand (the aggregates) is the solid phase (3, 4). Also, in cement paste, the cement could be considered the particle and the water the matrix. When modeling suspensions using DPD at any scale, the fluid phase is represented by particles that correspond to mesoscopic regions of fluid. Interactions between the particles are incorporated so that their motion is consistent with the equations of hydrodynamics (Navier-Stokes equation and continuity equation). To model the motion of the solid bodies, a subset of the DPD fluid particles are "frozen" (1) together to present individual aggregates. Once the forces on each rigid body are determined, the particles move according to the Euler equations (5). Details of modeling suspensions with the DPD method are available in Ref.6, 7, 8.

Of course, this model needs to be validated before it can be used to predict concrete flow. At first, we chose some simple cases where results were clearly known from the literature or available data. The following cases were selected, each of which revealed excellent agreement between the DPD prediction and the experimental results:

- The Einstein prediction of intrinsic viscosity for dilute hard sphere suspensions.
- Simulations of ellipsoids under shear where the particles undergo a tumbling motion called Jefferies orbits.
- Viscosity of dense suspensions of silica particles.
- Flow of spherical beads in cement paste measured by a parallel plate rheometer.

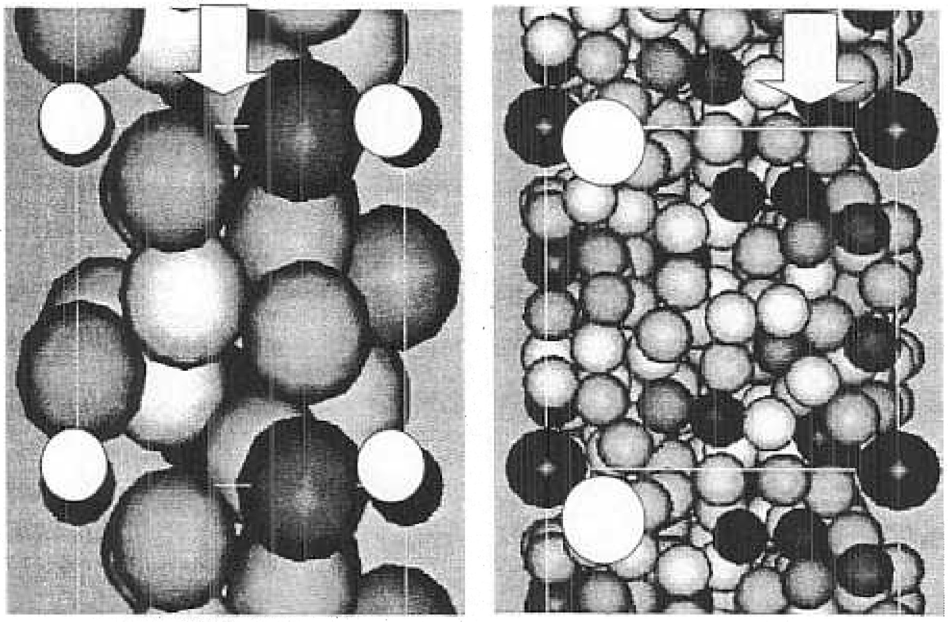
Although the validation of computational approaches can be a challenge because of the dearth of known analytical solutions for complex flow problems, it is believed that, based on these four comparisons, DPD produces reasonable results and can be used as a predictive tool when used carefully. Further, an advantage of DPD is that it naturally accommodates flow in many complex geometries like flow around rebars or various rheometers. Some examples of concrete flowing in complex geometries will be now shown.

EXAMPLE OF APPLICATIONS TO THE SCC TECHNOLOGY

We first examined the flow of a suspension of mono-disperse spherical aggregates between solid cylinders under unidirectional vertical body force, representing gravity. This scenario is a model for the flow of SCC between rebars under its own weight. The diameter of the coarse aggregates or spherical particles is either one fifth or one-half of the distance between the rebars (Figure 1). These two cases obviously represent the extremes and not the likely gradation of coarse aggregates, but it is a good way to test the prediction: the concrete with the large aggregate (diameter 1/2 of the distance between the rebars) had a tendency to jam or stop flowing while systems with small aggregates (diameter 1/5 of the distance between the rebars) would flow freely without stopping. Further studies will consider the simulation of concretes with a broader distribution of aggregate size and shapes that is more representative of a real SCC.

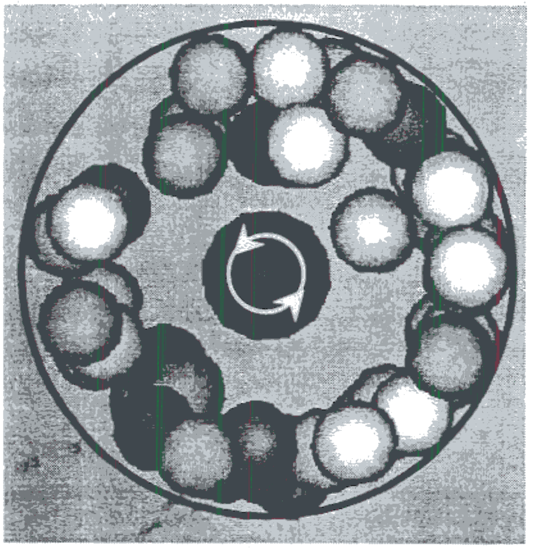
Another application of this model for the concrete industry is the simulation of flow in various concrete rheometers. These rheometers, as shown elsewhere (9, 10) have different geometries and flow patterns. It was also shown in ref. 6 that the rheological properties measured by different concrete rheometers cannot be compared directly. The reason for these discrepancies is not clear at this time, although some hypotheses have been advanced (10). Better understanding of the flow in rheometers is necessary to test these hypotheses in a meaningful way, and this model provides a means to develop that understanding. At this point, two types of rheometer were simulated: parallel plate, such as the BTRHEOM, and coaxial (Figure 2), such as the BML or CEMAGREF. The descriptions of these rheometers are given in ref. 10. Some preliminary results showed that if the inner cylinder of the coaxial rheometer does not have fins or serrations, the coarse aggregates have a tendency to move outward as a result of the presence of shear gradients. This implies that the torque measured is really the torque generated by a coupling of the rotor to the mortar phase and not to the concrete. This result is in agree-

Figure 1.



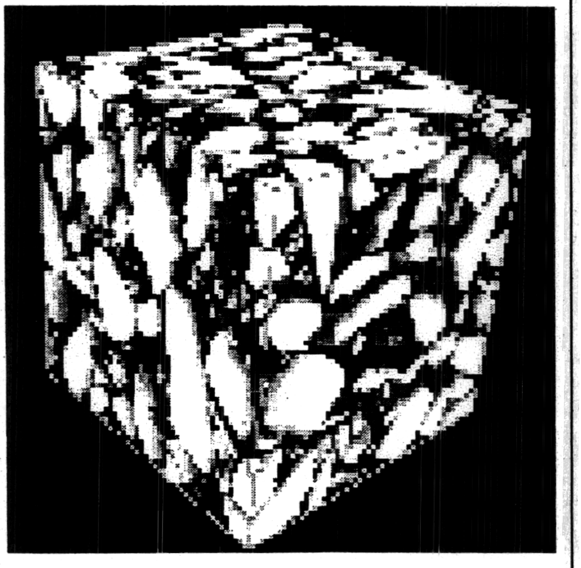
Simulation of SCC flow between two rebars: A) aggregate diameter is ½ and B) aggregate diameter is 1/5 of the distance between the rebars. The rebars (white circles) are pointing into the figure and the flow is in the direction of the arrow.

Figure 2.



Simulation of a coaxial rheometer. The inner cylinder is rotating while the outer cylinder is fixed.

Figure 3.



Reconstructed X-ray computed tomograph of a concrete specimen (270x270x270 pixels) (about 108 mm x 108 mm x 108 mm). This cube has been "cut" from a larger image, so that the flat faces of the aggregates at the surface are artificial.

ment with the general knowledge that the rotating cylinder needs to be strongly coupled with the concrete and therefore it should not be smooth but have fins.

Obviously, a more realistic simulation of a concrete needs to take into account that the aggregates are not spheres or ellipsoids. Collaboration with the Federal Highway Association (11) allowed us to obtain X-Ray tomography-based images of aggregates (Figure 3). These images were incorporated into the code and can now replace the spheres in our simulation.

CONCLUSION

In conclusion, DPD is potentially a powerful tool for the simulation of complex flow problems that are of interest to the cement and concrete industry. We have found favorable agreement between simulation results and theoretical and experimental data. Furthermore, we plan further comparisons with experimental devices used to characterize the flow of SCC concrete. Such studies should help provide better interpretation of measurements and to improve or develop new measurement methods. For instance, we can now measure the plastic viscosity of a mortar, then virtually add coarse aggregates of various gradation and obtain the plastic viscosity of the concrete (12). To avoid repetitive simulations a database is being created under the VCCTL consortium (13) that allows the user to search for the aggregate gradation desired and obtain the relative plastic viscosity of the concrete at various concentrations of aggregates. The relative plastic viscosity is the ratio of the plastic viscosity of the concrete to the plastic viscosity of the mortar. Knowing the plastic viscosity of the mortar, the VCCTL software predicts the plastic viscosity of the concrete. It was also shown that the relative plastic viscosity determined from DPD simulations is comparable with the relative plastic viscosity measured using various concrete rheometers (6) even when the results from the concrete rheometers are not expressed in fundamental units.

It is possible to imagine the time when a SCC composition could be determined by simply measuring the rheological property of a mortar or cement paste, the measuring the coarse aggregates shape and size, and then virtually testing the concrete for flow in a structure of rebars representing the structure to be built.

The step of measuring the cement paste or mortar is unavoidable until a better understanding is obtained of the interaction between the cement, chemical admixtures, air content, and supplementary cementitious materials.

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