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SIMULATION OF SELF-COMPACTING CONCRETE FLOW IN J-RING USING SMOOTHED PARTICLE HYDRODYNAMICS

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ABSTRACT

In this study, an incompressible mesh-less smoothed particle hydrodynamics (SPH) methodology has been implemented to simulate the flow of self-compacting concrete (SCC) mixes in the J-ring test. A suitable Bingham constitutive model has been coupled with the Lagrangian momentum and continuity equations to model the flow. The capabilities of the SPH methodology are validated by comparing the simulation results with the actual J-ring tests carried out in the laboratory. The comparison shows that this methodology is efficient to predict precisely the behaviour of SCC in the sense that the simulated mixes meet the passing ability criterion and the shapes and diameters of the flow spread are nearly the same as observed in the laboratory test.

Keywords: *Self-compacting concrete (SCC); Smoothed particle hydrodynamics (SPH); Non-Newtonian fluid; J-ring test; plastic viscosity.*

1. Introduction

With the recent tendency towards the use of computer modelling in concrete technology, its application in self-compacting concrete (SCC) is in demand and increasingly becoming an important issue. In this regard, one of the important approaches offering considerable potential is the smoothed particle hydrodynamics (SPH). It is able to simulate flows that contain particles of different sizes. SPH is a particle-based method (it does not require re-meshing) to represent with an acceptable level of accuracy the rheological behaviour of heterogeneous flow. This method has been examined and proved to be efficient and accurate in modelling the flow of SCC in the cone slump flow and L-box tests [1, 2]. The goal of this paper is to extend its application to simulating the flow of SCC in the J-ring test. This methodology will provide a thorough understanding of whether or not an SCC mix can satisfy the self-compatibility criteria. For this purpose, a series of SCC mixes differing in target plastic viscosity and compressive strength were prepared in the laboratory. These mixes were designed according to the rational mix design method proposed in [3].

2. Numerical modelling

Fresh SCC is a non–Newtonian fluid best described by a Bingham–type constitutive model. From a practical computational perspective, it is expedient to approximate the bi-linear Bingham constitutive model, which has a kink at zero shear strain rate, by a smooth continuous function in which m is a very large number (e.g. $m = 10^5$).

$$\tau = \eta\dot{\gamma} + \tau_y\left(1 - e^{-m\dot{\gamma}}\right) \tag{1}$$

Here, τ, η, $\dot{\gamma}$ and τ_y represent shear stress tensor, mix plastic viscosity, shear strain rate and mix yield stress, respectively. The Bingham constitutive model of the mix is coupled with the Lagrangian continuity equation (Eq.2) and momentum conservation equation (Eq.3) to model the flow of the SCC mix:

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla.\mathbf{v} = 0 \quad , \quad \frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla.\boldsymbol{\tau} + \mathbf{g} \qquad (2), (3)$$

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where ρ, t, $\mathbf{v}$, P and g represent the fluid particle density, time, particle velocity, pressure and gravitational acceleration, respectively.

A projection method based on the predictor-corrector time stepping scheme has been adopted to track the Lagrangian non-Newtonian flow. The prediction step is an explicit integration of the momentum conservation equation (Eq.3) in time without enforcing incompressibility. Only the viscous stress and gravity terms are considered in Eq.3 and an intermediate particle velocity $\mathbf{v}^*_{n+1}$ is obtained as:

$$\mathbf{v}^*_{n+1} = \mathbf{v}_n + \left(\mathbf{g} + \frac{1}{\rho}\nabla.\boldsymbol{\tau}\right)\Delta t \tag{4}$$

Then the correction step is performed by considering the pressure term in Eq.3:

$$\frac{\mathbf{v}_{n+1} - \mathbf{v}^*_{n+1}}{\Delta t} = -\left(\frac{1}{\rho}\nabla P_{n+1}\right) \tag{5}$$

where $\mathbf{v}_{n+1}$ is the corrected particle velocity at the time step *n+1*. Computing Eq.5 requires the pressure P_{n+1}, which is obtained by enforcing the incompressibility condition from the continuity equation (Eq.2):

$$\nabla.\mathbf{v}_{n+1} = 0 \tag{6}$$

Hence the intermediate velocity can be projected on the divergence-free space by writing the divergence of Eq.5, using Eq.6, as:

$$\nabla.\left(\frac{1}{\rho}\nabla P_{n+1}\right) = \frac{\nabla.\mathbf{v}^*_{n+1}}{\Delta t} \tag{7}$$

As the density of particles remains constant in this simulations, Eq.7 can be rewritten as:

$$\nabla^2 P_{n+1} = \frac{\rho}{\Delta t}\nabla.\mathbf{v}^*_{n+1} \tag{8}$$

where ∇^2 is the Laplacian. Once the pressure is obtained from the Poisson equation (Eq.8), the particle velocity is updated by Eq.5. Finally, the instantaneous particle position is updated as:

$$\mathbf{x}_{n+1} = \mathbf{x}_n + \mathbf{v}_{n+1}\Delta t \tag{9}$$

3. Boundary conditions

Three types of boundary conditions need to be considered in the simulation of the J-ring test when solving the continuity and momentum conservation equations. These are: (1) a zero pressure condition on the free surface; (2) Dirichlet boundary condition at the wall of the cone, J-ring bars and the bottom plate, and (3) Neumann conditions on the pressure gradient (this zero pressure gradient is used only for solving the pressure Poisson equation), as shown in Figure 1A.

In this simulation, the technique based on arrays of rigid dummy particles was used to implement the cone wall, J-ring bars and base plate boundary conditions, as shown in Figure 1B. For realistic simulations, the friction between the SCC mix and the contacting surfaces should be taken into consideration. Here, the coefficient of kinematic friction (C_f) for the horizontal plate and J-ring bars is 0.55 and 0.48 N s/m, respectively. The former was determined previously by matching the t_{500} (the time when the mix spread reaches 500 mm) in slump cone test with the simulated results [2]. The latter was chosen by matching the t_{500J} in the J-ring test with the simulated results of Mix50 in the present study.

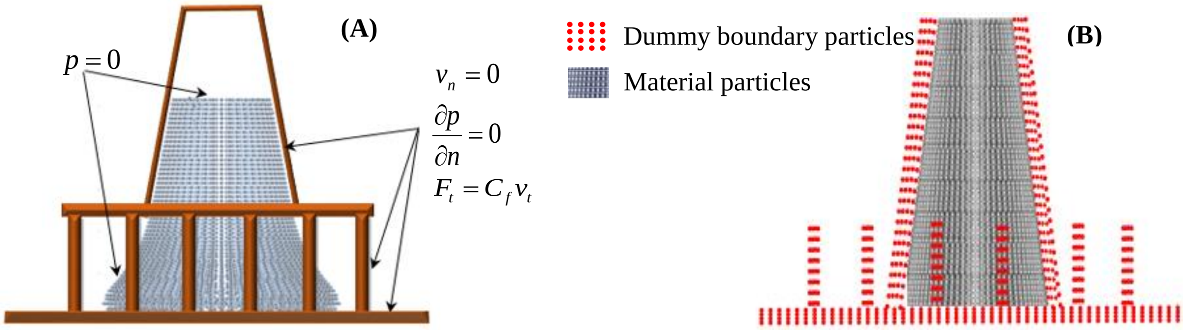

Figure 1: (A) boundary conditions, (B) Dummy particles for enforcing boundary conditions

4. Treatment of particles in the simulated mixes

In order to monitor the velocity vectors and positions of coarse aggregates of different representative sizes, as well as those of the fluid particles representing the mortar, the particles were represented by recognisable colours as shown in Figure 2. The volume of the mix in the cone was simulated by 23,581 particles. These particles were generated randomly in this simulation. Particles representing the mortar as well as the coarse aggregate form a homogeneous mass and possess the same continuum properties except for their assigned volumes. The masses of the SPH particles representing different coarse aggregate particles in the mix were calculated according to their respective volume fractions in the mix. Throughout the simulation, particles representing the coarse aggregates based on their assigned volumes were tagged (Figure 2) in order to monitor their velocity vectors and positions.

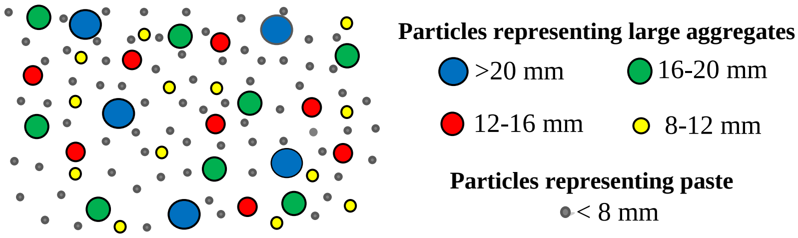

Figure 2: Schematic sketch of particle representation in the simulated mixes

5. Simulation results

To investigate how efficient the SPH is to predict the flow of SCC mixes through reinforcing bars, different SCC mixes were three-dimensionally simulated using the J-ring test. The fundamental parameters (plastic viscosity and yield stress) of these mixes have been determined to be used in the present simulation. The plastic viscosity was estimated by a micromechanical procedure from the known plastic viscosity of the paste and the SCC mix proportions [4] while the yield stress was predicted in an inverse manner using the SPH simulation of slump flow test [1].

The results of a typical SCC mix (Mix50) regarding its shape and spread as well as its blockage assessment are shown in Figures 3 and 4. From Figure 3A it can be noticed that the shape of the simulated spread looks smooth as a ‘pan cake’ identical to that in the laboratory test (Figure 3B). It can also be seen that the diameters of the flow spread of the simulated mix are nearly the same as that observed in the laboratory test.

With the reference to the passing ability criterion, SCC should have the ability to flow and pass through congested reinforcement and narrow openings while maintaining adequate suspension and distribution of coarse particles in the matrix. This means that arching near obstacles and blockage during flow have to be avoided. In this simulation, the SCC passing ability can be judged in terms of the height difference between the concrete inside and outside the steel bars of the J-ring using the following equation.

$$P_J = \frac{\Delta h_{x1} + \Delta h_{x2} + \Delta h_{y1} + \Delta h_{y2}}{4} - \Delta h_0 \tag{10}$$

Here, P_J is the blocking step, Δh_0 is the height measurement at the centre of flow and Δhx_1, Δhx_2, Δhy_1, Δhy_2 are the four measurement heights at positions just outside the J-ring. Taking the acceptance criterion of SCC passing ability as the blocking step (P_J) is no more than 10 mm [5], the simulated mix did flow homogeneously without blockage, as it is clearly observed in Figure 4.

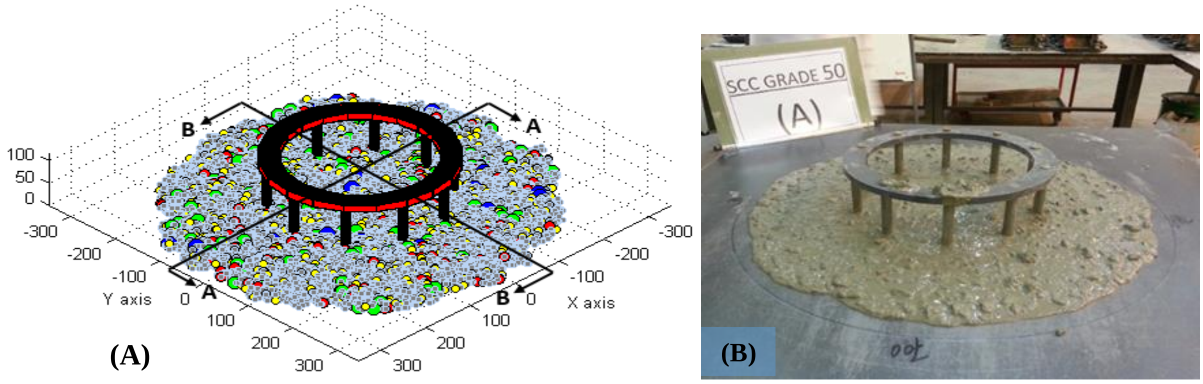

Figure 3: Flow pattern of SCC (Mix50) after final spread: (A) simulated mix, (B) experimental mix

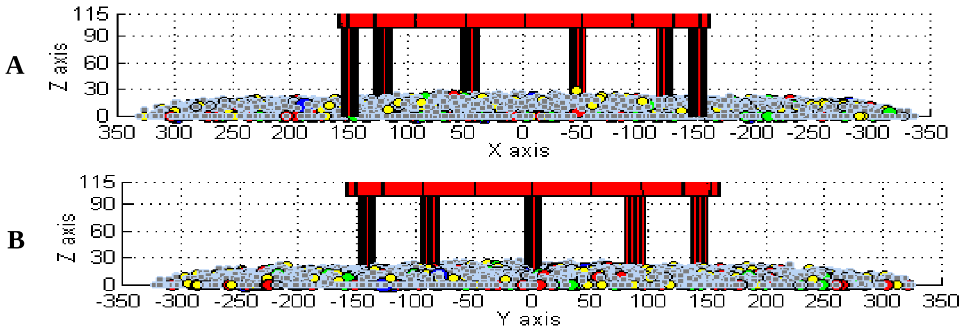

Figure 4: Diametrical cross-sections (A and B) of the simulated mix

6. Conclusions

This study reveals that the developed numerical methodology (SPH) is able to capture the flow behaviour of SCC mixes in the J-ring test. This has been validated by benchmarking the results of the numerical simulation against actual J-ring tests carried out in the laboratory. SPH simulation is therefore an indispensable and cost-effective tool for understanding the behaviour of fresh SCC replacing time-consuming laboratory tests, thereby saving time, effort and materials.

References

1. Badry F., Kulasegaram, S. and Karihaloo, B.L., Estimation of the yield stress and distribution of large aggregates from slump flow test of self-compacting concrete mixes using smooth particle hydrodynamics simulation. J Sustainable Cement-based Materials, doi:10.1080/21650373.2014.979266, 2016 (in press).

2. Deeb, R., Kulasegaram, S. and Karihaloo, B.L., 3D modelling of the flow of self-compacting concrete with or without steel fibres. Part II: L-box test and the assessment of fibre reorientation during the flow. Computational Particle Mechanics, 1, p. 391-408, 2014.

3. Abo Dhaheer, M.S., Al-Rubaya, M.M., Alyhya, W.S., Karihaloo, B.L. and Kulasegaram, S., Proportioning of self-compacting concrete mixes based on target plastic viscosity and compressive strength: mix design procedure. Journal of Sustainable Cement-Based Materials, doi: 10.1080/21650373.2015.1039625, 2016 (in press).

4. Ghanbari, A. and Karihaloo, B.L., Prediction of the plastic viscosity of self-compacting steel fibre reinforced concrete. Cement and Concrete Research, 39, p. 1209-1216, 2009.

5. BS EN 206-9, Concrete, Part 9: Additional rules for self-compacting concrete. British Standard Publications, 2010.