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SIMULATION OF SELF-COMPACTING CONCRETE IN V-FUNNEL TEST BY SPH

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ABSTRACT

Computational modelling of the flow for a viscous fluid such as self-compacting concrete (SCC) is a potential tool for understanding its rheological behaviour and for mix proportioning as well. The present paper describes a simple approach to simulate the flow of SCC mixes of different strengths and performances containing aggregate particles of various sizes in the V-funnel test using 3-dimensional mesh-less smooth particle hydrodynamics (SPH) computational technique. A comparison between the results of the numerical simulation with the corresponding experimental observations has revealed the flow characteristics of SCC mixes and confirmed the capability of SPH and the rheological model to predict SCC flow and mould filling behaviour.

Keywords: *Self-compacting concrete; V-funnel; SPH; Bingham parameters; plastic viscosity; yield stress.*

1. Introduction

In concrete construction, massive problems arise from the insufficient filling of formwork, inadequate de-airing and concrete segregation. The impact of such problems has increased year after year since the formwork is becoming continuously more complex and reinforcement is becoming denser. Self-compacting concrete (SCC) has been developed to solve these engineering issues. It is a concrete that flows under its own weight, without external vibration, while maintaining homogeneity. This ensures proper filling of formwork and produces high quality finish in restricted areas and heavily reinforced structural members. Various tests are implemented to evaluate the characteristics of SCC, including its filling ability, passing ability, and segregation resistance [1].These tests can be avoided by using the most cost-effective computational modelling to save time, effort and materials. Such modelling can also provide an understanding of the SCC flow behaviour, which is crucial to achieving high quality. Indeed, the employment of the modelling has brought insight into the significance of the rheology as a tool for the optimization of mix composition, and the processing techniques to fulfil the levels of engineering properties required for the intended civil applications.

The V-funnel test, which is one of the standard SCC tests, is designed to determine the filling ability of SCC in which shorter flow time indicates greater flowability. The V- shape restricts the flow, and prolonged flow times may give some indication of the susceptibility of the mix to blocking.The actual time ($t_{v\text{-}funnel}$) taken (the discharge time) when it is possible to see vertically through the V-funnel into the container below is measured. A time delay of 10 ± 2 s from filling the V-funnel to the release of the gate at the bottom of the V-funnel is permissible. In this paper, SCC flow during the V-funnel test of SCC mixes of various strengths and performances is modelled using the SPH method and the concrete discharge time is determined. This will provide a tool for simulating the discharge time and its comparison with the EFNARC guidelines.

2. Numerical simulation

Since SCC flow during the V-funnel test is typically a free surface flow with large deformations, the Lagrangian mesh-less SPH numerical method is preferred to solve the governing SCC flow equations. It is also able to treat naturally highly-varying density, deformable boundaries, propagation of discontinuities, multi-phase flows and other physically complex flow situations. The SPH is a mesh-less particle numerical approach based on an interpolation theory, in which the partial differential equations of motion of continuum fluid dynamics are transformed into integral equations by using an interpolation function.

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This interpolation is carried out by ‘‘kernel estimate’’ of the field variable at any point. The basic equations solved in the SPH are the incompressible mass and momentum conservation equations [2], together with the Bingham-type constitutive relation. In this approach, the flow continuum is discretized into a limited number of particles, *N*. The particles, which behave as Lagrangian fluid elements, carry all the necessary information needed about the flow variables; this feature is the principal strength of the method. The field variables and their gradients are approximately calculated and interpolated from values at a discrete set of particles in a domain of influence. All randomly generated particles, which represent the paste and the large aggregates, form a homogeneous mass with the same properties as the continuum except their assigned volumes.

3. Governing equations

Given its shear rate-dependent response, SCC can be regarded as a non-Newtonian incompressible fluid. Its rheology is best described by a Bingham-type model which contains two material properties, the yield stress, τ_y and the plastic viscosity, η. From a computational perspective, it is expedient to approximate the bi-linear Bingham constitutive model with a kink at $\dot{\gamma}= 0$ by a continuous function:

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

in which *m* is a very large number, $m = 10^5$. Suitable numerical schemes, which integrate the Lagrangian SPH approximations of the governing equations (i.e. mass and momentum conservation equations) with the rheological Bingham type model for SCC, have been developed. These schemes have been exploited to understand the flow behaviour of SCC containing coarse aggregate particles of various sizes. The isothermal, Lagrangian form of mass and momentum conservation equations are:

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

where ρ, t, $\boldsymbol{v}$, P, $\boldsymbol{\tau}$ and g represent the fluid particle density, time, particle velocity, pressure, shear stress tensor and gravitational acceleration, respectively. The first term in Eq.(2) vanishes since the density is constant due to the incompressible flow assumption. A projection method based on the predictor-corrector time stepping scheme has been adopted to implement the incompressible SPH approach. The prediction step is an explicit integration in time without enforcing incompressibility. Only the viscous and gravity terms (second and third terms, respectively) in Eq. 3 are initially considered to obtain temporal velocity for particles (v^*_{n+1}). Then, the correction step is performed by considering the pressure term (first term) in Eq.3, which will be obtained by imposing the incompressibility condition using Eq.2. Once the pressure is obtained from Poisson’s Equation, the particle velocity and position are updated by the computed pressure gradient. Figure 1 illustrates the time stepping scheme [3].

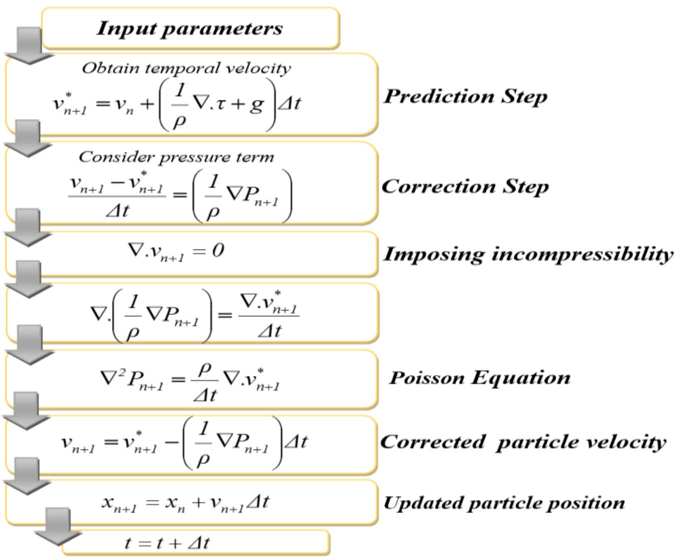

Figure 1: The predictor-corrector time stepping scheme of the incompressible SCC flow [3]

4. Initial configuration and treatment of large aggregates

It is necessary to impose appropriate initial boundary conditions to solve the mass and momentum conservation equations. Three sorts of boundary conditions have been applied in the modelling of the V-funnel test: zero pressure condition on the free surface ($P=0$), Dirichlet boundary condition at the walls of the V-funnel ($v_n = 0$), and Neumann conditions on the pressure gradient ($\partial P/\partial n = 0$) (zero pressure gradient is used only for solving the Poisson equation to find the pressure), as illustrated in Figure 2, where the geometry of the V-funnel apparatus is also shown. Rigid dummy particles of four arrays placed outside the walls of the V-funnel were used to implement the wall boundary conditions. To reveal the positions and velocity vectors of aggregates of various sizes, and those of the fluid particles representing the paste, the particles are represented by distinct colours and generated randomly. In order to get reliable simulation results, the kinematic coefficient of friction (c_f) between the V-funnel wall and the SCC mix has been altered to get the best fit between the experiment and simulated results for one mix. The same coefficient was then used for all other mixes.

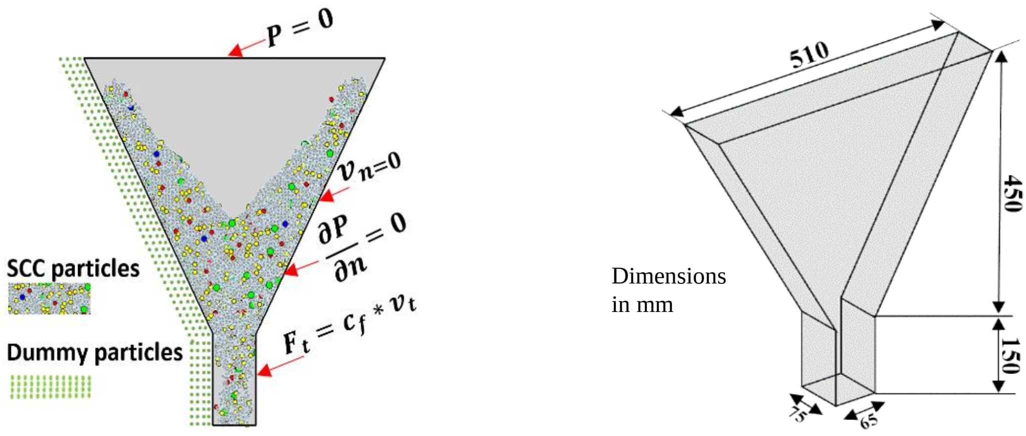

Figure 2: Boundary conditions and geometry of the V-funnel apparatus

5. Preliminary simulation results

A range of SCC mixes with 28-day cube compressive strength between 30 and 80 MPa has been developed following the rational mix design procedure described in [4].The plastic viscosities of these mixes were estimated following the micromechanical procedure described in [5]. This procedure is based on the rheology of concentrated suspensions, and it can predict accurately in a stepwise way the plastic viscosity of heterogeneous SCC mixtures beginning with the plastic viscosity of the homogeneous paste. On the other hand, the yield stress of a mix was estimated in an inverse manner from the measured time, t_{500} to reach 500 mm spread of the SCC mixes in a cone flow test using the three-dimensional SPH [6]. Details of the SCC mixes and their plastic viscosities are given in [7].The 3D numerical simulation of the V-funnel test for a typical SCC mix (Mix 50B) has been represented by 53,846 particles to investigate its flow characteristics and compare with the corresponding experimental results. The simulation has revealed the distribution of the large aggregates in the SCC mix (coarse aggregate size (g) ≥8 mm) to check whether these heavier aggregates remain homogenously distributed in the viscous mix during the flow.

It can be noticed from Figure 3 that the flow patterns obtained from the numerical simulation at various time step are very similar to those observed in the laboratory test. The slight difference in the discharge time, $t_{v\text{-}funnel}$ may be due to two possible reasons: firstly, the assumption that the SCC particles are spherical in shape and secondly, the slight time delay in opening the bottom gate. Importantly however, it can be observed from the simulated flow illustrated in Figure 3 that the larger aggregates (g) do indeed stay homogeneously distributed in the mix at various times during the flow.

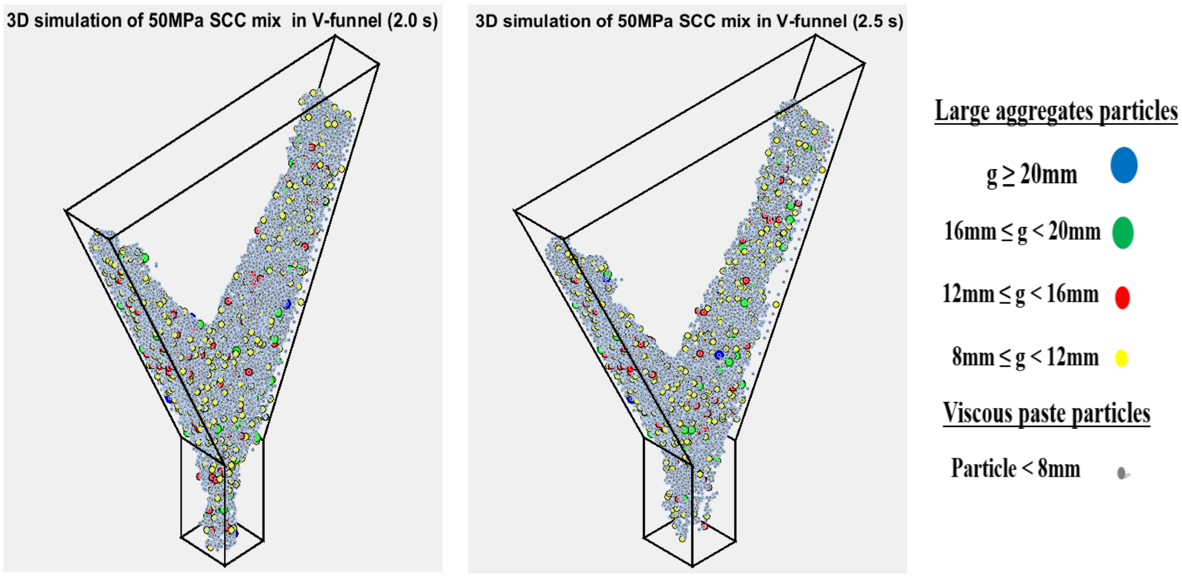

Figure 3: 3D simulation of 50MPa SCC mix in V-funnel after 2.0 s and 2.5 s showing the larger aggregates (g)

6. Conclusions

A 3D Lagrangian SPH numerical model has been developed to simulate the flow of SCC mixes of varying strengths and performances and to estimate the discharge time in the V-funnel test. Concrete is assumed as a heterogeneous, non-Newtonian fluid whose relation between shear stress and strain rate is of the Bingham type. This relation has been coupled with the Lagrangian mass and momentum conservation equations to simulate the SCC mixes of different viscosities and yield stresses in the V-funnel test after determining the proper number of particles for simulations. The predicted discharge time result is generally in good agreement with the test data. The numerical methodology also shows that it can conceptualise the flow behaviour of SCC mixes and provide insight into the distribution of larger aggregates during the flow. It can be concluded that without performing the V-funnel test, concrete discharge time, and consequently its suitability for application as SCC can be established when the plastic viscosity and yield stress are known.

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