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SIMULATION OF THE FLOW OF SELF-COMPACTING CONCRETE IN THE L-BOX USING SMOOTHED PARTICLE HYDRODYNAMICS (SPH) METHOD

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ABSTRACT

Self-compacting concrete (SCC) has been widely used in structures around the world because of its ability to flow without external intervention. The ability of passing around and between obstacles and the filling of the formwork are important properties of SCC; they determine how well the SCC mix can flow through confined and limited zones. For this reason, it is essential to devise numerical tools aimed at the simulation of how SCC fills formwork as a homogeneous mass without the segregation of mix components. The present study reports a numerical investigation of the flow and the distribution of large coarse aggregates of SCC mixes in the L-box using the three-dimensional Lagrangian particle based smooth particle hydrodynamics (SPH) method.

Keywords: *Self-compacting concrete; Smooth particle hydrodynamics; yield stress; plastic viscosity and L-box.*

1. Introduction

Self-compacting concrete is described in its fresh state by high flow-ability, filling ability of the formwork, passing ability through restricted reinforcement bars and resistance to segregation without requiring any external vibration for compaction. The durability of concrete structures is affected by many problems of compactness; these problems result from incomplete filling of formworks and segregation of aggregates inside the structure. This problem is getting more acute as SCC is used in structures with complex shape and denser reinforcements. It is therefore important to have a tool for predicting the flow, filling and passing ability in order to save time, effort and materials. Computational simulation of SCC flow can be a helpful tool for understanding the rheological behaviour of SCC and can allow to identify a lower workability of fresh concrete that could ensure proper filling of formwork [1]. For this purpose, the three-dimensional Lagrangian particle based smoothed particle hydrodynamics (SPH) method is employed to simulate the flow of SCC in the L-box configuration and to reveal the distribution of coarse aggregate particles larger than or equal to 8 mm in the mix and then to compare the numerical results with the corresponding experimental data.

2. Numerical implementations

SCC is treated as a non-Newtonian fluid best described by a Bingham-type model that contains two material properties: the yield stress (τ_y) and the plastic viscosity (η) [2]. From a practical computational point of view, it is expedient to approximate the bi-linear Bingham constitutive model with a kink at by a smooth continuous function, where *m* is a very large number (m=10^5) [3].

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

There are two basic equations solved in the SPH method together with the constitutive relation; the incompressible mass and momentum conservation equations

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

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where ρ, t, $\mathbf{v}$, P, $\mathbf{g}$ and $\boldsymbol{\tau}$ represent the fluid particle density, time, particle velocity, pressure, gravitational acceleration, and shear stress tensor, respectively. Below we shall consider flows in which the density is constant, so that the first term in Equation (2) vanishes.
The solution procedure uses prediction-correction fractional steps with the temporal velocity field integrated forward in time without enforcing incompressibility in the prediction step. Only the viscous stress and gravity terms are considered in the momentum Equation (3) and an intermediate particle velocity $\mathbf{v}^*{}_{n+1}$ is obtained as:

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

Here, $\mathbf{v}_n$ and $\mathbf{v}^*{}_{n+1}$ are the particle velocity and intermediate particle velocity at time t_n and t_{n+1} respectively. Then the correction step is performed by considering the pressure term in Eq. (3):

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

Rearranging Equation (5) gives,

$$\mathbf{v}_{n+1} = \mathbf{v}^*{}_{n+1} - \left(\frac{1}{\rho} \nabla P_{n+1} \right) \Delta t \tag{6}$$

where $\mathbf{v}_{n+1}$ is the corrected particle velocity at the time step t_{n+1}. By imposing the incompressibility condition in the mass conservation Equation (2), the pressure P_{n+1} in equation (6) will be obtained. As the particle density remains constant during the flow, the velocity $\mathbf{v}_{n+1}$ is divergence-free. Enforcing the incompressibility condition as Equation (2) yields,

$$\nabla . \mathbf{v}_{n+1} = 0 \ , \quad \nabla . \left(\frac{1}{\rho} \nabla P_{n+1} \right) = \frac{\nabla . \mathbf{v}^*{}_{n+1}}{\Delta t} \qquad (7), (8)$$

Since the density of particles remains constant in the present simulations, Equation (8) can be rewritten as:

$$\nabla^2 P_{n+1} = \frac{\rho}{\Delta t} \nabla . \mathbf{v}^*{}_{n+1} \tag{9}$$

where ∇^2 is the Laplacian operator. Once the pressure is obtained from the Poisson Equation (9), the particle velocity is updated by the computed pressure gradient (see equation (6)). Finally, the instantaneous particle position is updated using the corrected velocity:

$$\mathbf{x}_{n+1} = \mathbf{x}_n + \mathbf{v}_{n+1} \Delta t \tag{10}$$

where $\mathbf{x}_{n+1}$ and $\mathbf{x}_n$ is the particle position at t_{n+1} and t_n respectively.

3. Modelling of the flow of SCC mix and the boundary conditions

The modelling of the flow of the SCC mix in the L-box has been done previously [4]. In the present study, three additional aspects are taken into consideration. These aspects include; friction on the sides of L-box and on the steel bars, the effect of the time delay in the lifting of the L-box gate manually on the simulated flow times and the comparison between the simulated distribution of larger coarse aggregates with the distribution in tests performed in the laboratory using colour coded aggregates. The distribution of the aggregate particles equal or larger than 8 mm in size have been modelled as separate particles suspended in the viscous paste containing the particles less than 8 mm in size. Four ranges of size of the coarse aggregates have been used during the numerical simulation size as follows; 8 ≤g≤ 12, 12 ≤g≤ 16, 16 ≤g≤ 20 and g≥20 mm with a total number of particles 59,568 and these particles were represented by distinct colours as shown in Figure 1(a). When solving the momentum and continuity equations, the boundary conditions need to be applied. Four arrays of rigid dummy particles placed outside the sides and the base of the L-box were used to implement the boundary conditions as illustrated in Figure 1(b). Dirichlet and Neumann boundary conditions were imposed on the sides and the base of the L-box. Friction between the boundaries and the SCC mix was imposed on the L-box sides and the base with a dynamic coefficient of friction between the SCC mix and steel equal to 0.55 Ns/m.

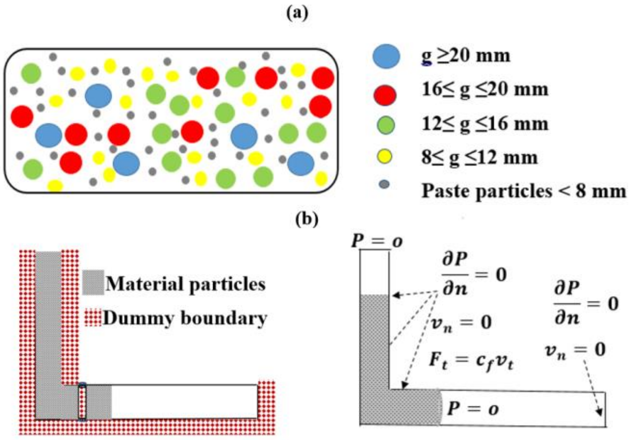

Figure 1 : (a) The aggregate particle representation (b) The boundary conditions of the L-box

4. Simulation results of the flow and the distribution of the coarse aggregates

The 3D simulation of the SCC flow and distribution of the large coarse aggregates has been performed on the mix of strength 60 MPa, which was developed according to the rational mix design method[5]. The results of the simulation when SCC mix reached 200 mm, 400 mm of horizontal section of the L-box are illustrated in Figure 2(a), (b). These flow times differ from the corresponding test results as a result to delay time in the lifting of the gate L-box manually. By cutting the simulated L-box specimen after the mix reached the end of horizontal section of the L-box and flow stopped by two longitudinal sections A-A and B-B Figure 2(c), it was found the modelled distribution patterns are agreed with the distribution of coarse aggregates in the experimental test results as illustrated in Figure 3.

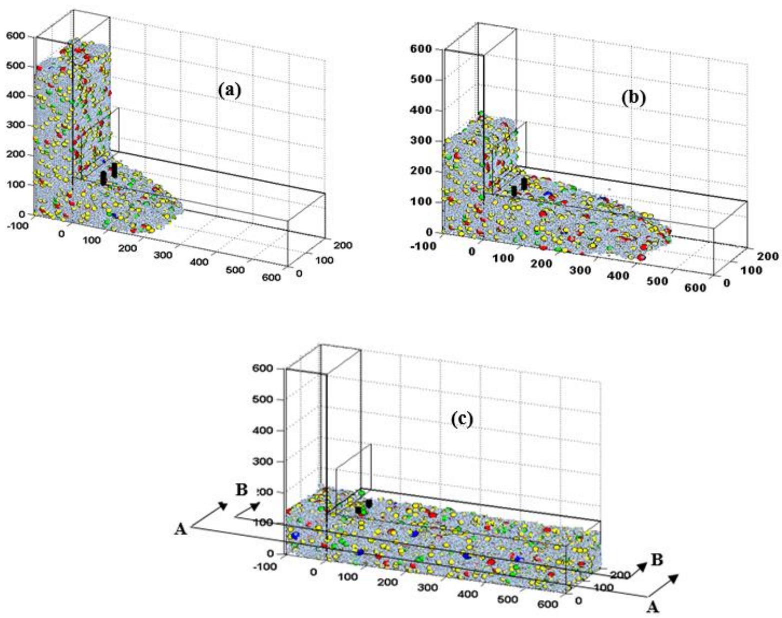

Figure 2 : The 3D simulation of the flow in the L-box after SCC mix reached (a) 200 mm (b) 400mm (c) the end of horizontal section of the L-box and the flow stopped

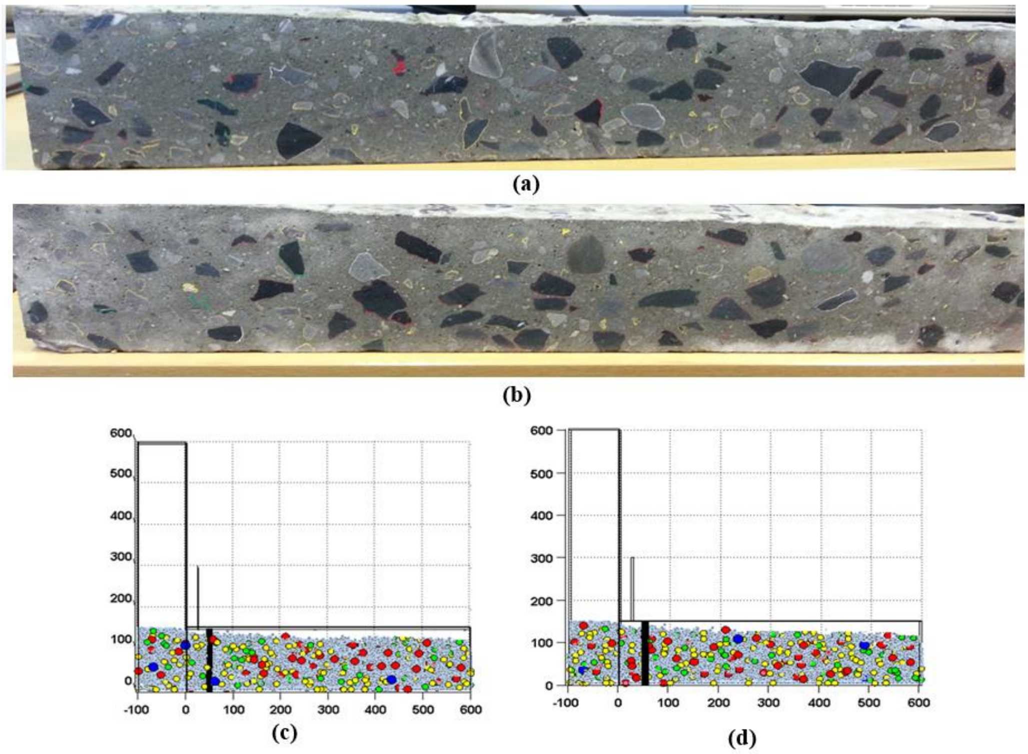

Figure 3: The distribution of the coarse aggregates in the experimental test (a) section A-A (b) section B-B and numerical simulation (c) section A-A (d) section B-B

5. Conclusions

The 3D simulation of the flow of the SCC mix in the L-box presents a prediction of the filling behaviour similar to that observed in the laboratory test. With regard to the flow times needed for the mix to reach 200 mm and 400 mm, there is a difference between the simulation flow times and that the corresponding experimental data due to the delay time in the lifting of the gate L-box manually. The 3D numerical simulations of the distribution of the coarse aggregates showed that the larger aggregates remained homogeneously distributed in the mix exactly as in the L-box test in the laboratory.

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