Cement and Concrete Research 58 (2014) 169–178

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

A DEM hard-core soft-shell model for the simulation of concrete flow

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ARTICLE INFO

Article history:
Received 6 June 2013
Accepted 24 January 2014

Keywords:
Rheology (A)
Fresh concrete (A)
Modelling (E)
DEM

ABSTRACT

A new DEM model for the simulation of concrete flow is presented. Fresh concrete is described as an assembly of composite particles made of spherical hard grains representing coarse aggregates surrounded by concentric spherical layers representing mortar. Two kinds of simulations are carried out: rheological simulations performed in a Couette geometry and slump test simulations. Rheological simulations show that the rheological behaviour of simulated concretes can be approximated with the Bingham model. The force model used allows for a direct relation between rheological characteristics of the mortar and rheological characteristics of the simulated concrete. Slump test simulations show that the model is able to describe the shape of concrete during the flow. The yield stresses and viscosities of numerical concretes are then calculated from the slump values and slump times with equations of the literature.

1. Introduction

The use of Self Compacting Concrete (SCC) has considerably increased in the past decade. Characterised by its ability to spread into formworks under its own weight without vibration, this concrete has both to be very fluid and to present a high resistance to segregation. In order to meet these hard to please requirements, SCC incorporates large amounts of mineral and chemical admixtures, which complicates its mixture proportioning. Numerical simulation could complete the experimental characterization, providing potential tools for understanding the behaviour of fresh concrete and for its design and mixture proportioning, thereby allowing decreasing the number of tests necessary to achieve the final composition.

Roussel et al. [1] have defined three kinds of numerical method families for the modelling of concrete flow: single fluid simulations, modelling of discrete particle flow, and modelling of particles suspended in a fluid. They give a detailed review of these methods with their respective advantages and drawbacks. Single fluid modelling can be used to simulate the full-scale casting of a concrete of known rheological characteristics [2,3]. It could therefore be employed in order to define the specifications of fresh concrete for a given application by varying the rheological characteristics of the fluid and studying the efficiency for filling the formwork. However, it does not allow representing particles, and can therefore not simulate neither the heterogeneous nature of concrete nor the blocking or segregation that can occur during the flow. Also, it cannot be used to connect the composition of the mix (water to cement ratio, volume of paste…) to its rheological behaviour because rheological characteristics are entry data for the simulation, and consequently it cannot be used directly as a tool for helping mixture proportioning.

The two other numerical method families involve the explicit description of particles. Thus, they could be used to describe blocking [4,5] and segregation of particles [6] which are of great importance in the design of SCC. Dissipative Particle Dynamics (DPD) [7] and Finite Element Method with Lagrangian integration points [8] both allow for the description of particles suspended in a fluid phase. However, these methods are computationally expensive and do not allow for the description of a large number of particles.

One of the usual methods used for particle flow simulation is the Distinct (or Discrete) Element Method (DEM), initially developed by Cundall and Stack [9]. Since this seminal work, it has considerably developed and it is now widely used for the simulation of granular materials in various fields, in particular in geomechanics [10]. Several studies have been carried out to simulate concrete flow with the DEM [11–16]. Chu and Machida [11] developed in particular a modified 2D DEM model, describing concrete as composite particles (spherical aggregate surrounded by an outer binding layer of mortar). These studies have shown that DEM was suitable to reproduce qualitatively the behaviour of concrete flow in different tests such as slump flow, L-box, J-ring… However, it is generally very difficult to connect the force model used

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http://dx.doi.org/10.1016/j.cemconres.2014.01.022
0008-8846

in the DEM to the physical characteristics of the concrete compounds [17,18]. In particular, the force models generally take into account an attractive component for the normal force between particles, whereas for concrete flow, energy dissipation is essentially governed by shear of fluid between particles.

The aim of this study is to develop a DEM approach allowing to simulate concrete flow and to connect the main parameters of the force model used to the macroscopic rheological characteristics of the numerical concrete. A composite DEM model is proposed similarly to [11] but with different force models and in 3D. Hard grains representing aggregates are surrounded by soft shells representing fluid mortar. Soft shell interactions represent the shear of mortar between aggregates, and hard core interactions eventually represent the repulsion and friction forces between contacting aggregates. The force models used are presented in details in Section 2. Then two kinds of tests are simulated with varying parameters: rheological tests in a Couette geometry and slump flow tests. These two kinds of simulations are respectively presented in Sections 3 and 4. Finally in Section 5, the results obtained in both cases are compared to experimental and theoretical results found in the literature.

2. Presentation of the DEM hard-core soft-shell model

2.1. Principle

Concrete is described as an assembly of composite particles made of spherical hard grains of radius R_i representing coarse aggregates surrounded by concentric spherical layers of width w_m representing mortar (Fig. 1). The basic assumption of the model is that this layer of mortar is dragged by the aggregates. This hypothesis is very strong and does not correspond to the reality of the complex flow in a concentrated suspension. However, it allows simplifying considerably the computation of fluid–particle interactions, and allows therefore taking into account a reasonable number of particles without needing unreasonable computing times. Rheological characteristics are attributed to the layer of mortar, which is very deformable and can exhibit large overlaps with other layers of mortar of surrounding particles. On the contrary, spherical particles representing coarse aggregates are given micromechanical characteristics of a solid material. They can also overlap but these overlaps are very limited given the modulus of elasticity used in the computations. Composite particles can therefore be considered as hard-cores surrounded by soft-shells of mortar. This principle of hard-core soft-shell model has already been used by Bentz et al. [19] for the geometrical description of Interfacial Transition Zone percolation in concrete.

Interactions between two composite particles are made of two members: the "fluid" interaction between two overlapping soft-shells and eventually (if the particles are close enough) the solid interaction between the two hard-cores.

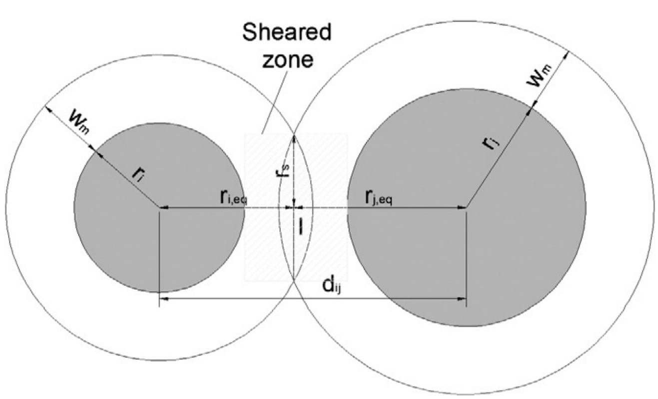

Fig. 1. Schematic representation of two soft-shells being in interaction.

2.2. DEM description and presentation of hard-core interactions

The DEM model used in our study is similar to that presented by Yang et al. [20] and Remond [5]. The displacements of particles are computed according to Newton's law of motion. The translational and rotational displacements of a particle P_i are given by Eqs. (1) and (2):

$$m_i \frac{dV_i}{dt} = m_i\ g + \sum_{j=1}^{n_c}\left(F_{hc,ij} + F_{ss,ij}\right) \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_c}\left(T_{hc,ij} + T_{ss,ij}\right) \tag{2}$$

where m_i and I_i are respectively the mass and moment of inertia of the particle P_i, V_i and ω_i are its linear and angular velocities, n_c is the number of particles that are in interaction with particle P_i, $F_{hc,ij}$ is the contact force exerted by particle P_j on particle P_i and $T_{hc,ij}$ its resulting torque (hard-core interactions), $F_{ss,ij}$ is the fluid force exerted by particle P_j on particle P_i and $T_{ss,ij}$ its resulting torque (soft-shell interactions described in Section 2.3).

$F_{hc,ij}$ is decomposed into a normal ($F^n_{hc,ij}$) and a tangential ($F^t_{hc,ij}$) component. The normal component of contact force $F_{hc,ij}$ involved in Eq. (1) is computed with the nonlinear Hertz model [21] (Eq. (3)):

$$F^n_{hc,ij} = -\left[\frac{2}{3}\ E\ \sqrt{\bar{R}}\ \xi_n^{3/2}\ +\ \gamma_n\ E\ \sqrt{\bar{R}}\ \sqrt{\xi_n}\ \dot{\xi}_n\right]\ n_{ij} \tag{3}$$

where ξ_n is the overlap between solid particles P_i and P_j ($\xi_n = max(R_i + R_j - d_{ij}, 0)$), $\bar{R} = R_iR_j/\left(R_i + R_j\right)$ is the effective radius, γ_n is the normal damping coefficient, $E = Y / (1 - \nu^2)$, Y being the Young modulus and ν the Poisson's ratio.

The tangential force exerted on particle P_i by particle P_j is computed according to the Mindlin–Deresiewicz theory [22,23] (Eq. (4)):

$$F^t_{hc,ij} = \mu\ \left|F^n_{hc,ij}\right|\ \left[1 - \left(1 - \frac{|\xi_t|}{\xi_{\max}}\right)^{3/2}\right]\ t_{ij} \tag{4}$$

where μ is the friction coefficient, ξ_t is the cumulated tangential displacement, and ξ_{max} is the maximal tangential displacement beyond which gross sliding occurs, given by:

$$\xi_{\max} = \xi_n\ \mu\ \frac{2-\nu}{2(1-\nu)}. \tag{5}$$

2.3. "Fluid" model — soft-shell interactions

The fluid interaction $F_{ss,ij}$ between two soft-shells surrounding particles P_i and P_j is decomposed into a normal and a tangential components (respectively $F^n_{ss,ij}$, and $F^t_{ss,ij}$).

The normal component of the fluid interaction $F^n_{ss,ij}$ consists only of a repulsive elastic force depending on the overlap intensity between the two soft shells (Eq. (6)). However, in order to maintain large overlaps between soft shells, the normal component of the force is activated only when the distance between the two hard-cores is lower than a given length h_{min}. Unless mentioned, this length has been fixed to $h_{min} = w_m / 2$ in all the simulations presented in this paper. No damping is taken into account for this normal force in order to avoid an additional parameter. Indeed, with the above definition, the overlaps between soft-shells are large enough