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A REVIEW OF DEM-BASED SIMULATION OF FRESH CONCRETE FLOW

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Recently, there has been growing research interest in simulation on the flow behaviors of fresh concrete, because these properties have significant effects on construction quality of casting and forming process, and also the properties of hardened concrete. The behaviors of fresh concrete are usually described by workability, consistency, flowability, mobility, pumpability, shootability, compactibility, and finishability. While various numerical simulations for concrete flow are available, District Element Method (DEM) has been applied widely due to its unique advantages of both macro and micro analysis i.e. the flow of the concrete mixture as a whole and particulate behavior of individual constituents in a mixture. This paper first presents a brief overview on the rheological models of fresh concrete, followed by a detailed review on simulating the fresh concrete flow using the DEM method. Moreover, recommendations for future work and directions will be provided.

Keywords: District element method, Rheology, Single-Phase Element Model, Separate Single-Phase Element Mode.

1 INTRODUCTION

Concrete plays a significant role in civil engineering materials all around the world. There has been a tremendous amount of research on hardened concrete, but only recently fresh concrete is drawing researchers' attention since the properties of fresh concrete have massive impacts on construction quality of casting and forming process, and the properties of hardened concrete as well (Jiao *et al.* 2017). Tattersall (1976) attempted to study flow behaviors of fresh concrete using a rheological method. The rheology is an effective tool to characterize the behaviors of fresh concrete, which are normally described as workability, consistency, flowability, mobility, pumpability, shootability, compactibility and finishability (Wallevik and Wallevik 2011). In this paper, various computational models of fresh concrete rheology will be overviewed first, followed by a detailed review on DEM simulation.

According to Roussel *et al.* (2007), there are mainly three kinds of computational modelling of concrete flow, which are *single fluid simulation*, *suspension flow simulation*, and *simulating of discrete particle flow.* Single fluid simulation is the most commonly used method in modelling fresh concrete flow. Mori and Tanigawa (1992) introduced Viscoplastic Finite Element Method (VFEM) and Viscoplastic Divided Element Method (VDEM) to model fresh concrete flow, assuming that fresh concrete was a homogeneous single fluid. Computational Fluid Dynamics (CFD) was also applied to simulate single fluid through the numerical solution of the governing partial differential equations or other mathematical equations of motion (Wesseling 2000).

Simulation of suspension flow models the particles suspended in a fluid. Visco-plastic suspension element method (VSEM) was derived from VFEM (Mori 1992) and used to predict the rheological properties of the concrete suspension from the rheological properties of the matrix and the coarse aggregate volume fraction.

Distinct element methods include standard discrete (distinct) method (DEM) and Dissipative Particle Dynamics method (DPD). DEM will be reviewed further in this paper. DPD has been presented by Martys (2005) in the field of cementitious material recently. In DPD, the chosen inter-particle interactions allow for much larger time steps. This makes it possible to study physical behavior on different levels of time scales.

2 DEM SIMULATION ON FRESH CONCRETE AND RHEOLOGICAL MODELS

DEM was initially developed by Cundall (1971) to analyze rock mechanics problems and then applied to soil problems and was introduced to analyse fresh concrete flow as a numerical method using the discontinuous body model (Petersson 2001).

The flow of fresh concrete should be defined as two parameters. One of them is the yield stress, since it shows an initial resistance to the flow, and the other is plastic viscosity, which governs the flow after it was initiated. Thus, fresh concrete and other cementitious suspensions are normally considered as a Bingham model material, a plastic material shows little or even no deformation up to a certain level of stress. Bingham model describes the rheological properties of fresh concrete with two parameters, yield stress and plastic viscosity.

The constitutive equation can be expressed as in Eq. (1) and Eq. (2):

$$\tau = G\gamma \quad \text{for } \tau < \tau_0 \tag{1}$$

$$\tau = \tau_0 + \mu\dot{\gamma} \quad \text{for } \tau \geq \tau_0 \tag{2}$$

where τ is shear stress; τ_0 is yield stress, which gives the maximum value for the static behavior of the material; γ is the shear deformation; $\dot{\gamma}$ is the shear rate; μ is a constant plastic viscosity, G is the spring constant.

When $\tau < \tau_0$, the mixture is in a solid state. When $\tau \geq \tau_0$, the mixture is yield to a liquid state and start to flow. Once the external force is reduced, and the condition is back to $\tau < \tau_0$, the concrete will stop flowing and reach a new solid state. Therefore, the yield stress is the most important parameter, which affects the shape and diameter of the flow spread.

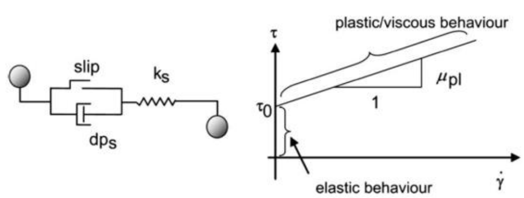

Figure 1. A Bingham material model (Mechtcherine *et al.* 2014).

One may note, there are many other yield-stress fluid methods commonly used in addition to the Bingham fluid model, for example, the Casson and the Herschel-Bulkley fluids (Mitsoulis 2007). However, the details of these models are not included in this paper.

3 DEM MODELS OF FRESH CONCRETE BEHAVIOR

The key point of simulating fresh concrete with DEM is to develop a reasonable DEM model. The available DEM for flow analysis of a concrete mixture can be divided into three main subgroups: single-phase element model, two-phase element model and multi-phase element model (Hoornahad and Koenders 2014, Quoc and Uomoto 2008). Because fresh concrete is made up of coarse aggregates and mortar with characteristics of a fluid, coarse aggregate can be described as discrete elements, and the assumption of mortar becomes the only difference in each model.

3.1 Single-Phase Element Model

According to Nabeta (1989), who was the first one to introduce DEM into fresh concrete simulation, the fresh concrete was considered as a single-phase material.

When developing a fresh concrete DEM model, Nabeta (1989) and Maki (1998) simplified the concrete mixture as follows: coarse aggregates are enclosed completely by a layer of mortar, but the mixture was considered as a single-phase material. In this case, contacts and collisions only take place between mortar cells (Figure 2). This model is quite similar to the traditional DEM model applied on fracture mechanics and granular systems for rock and soil (Quoc and Uomoto 2008).

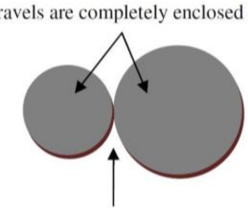

Figure 2. Single-phase model with gravel completely enclosed by mortar (Quoc and Uomoto 2008).

In this model, the motion of mortar can only take place with the movement of gravel but cannot move without gravel, and the interactions between coarse aggregates were ignored. Therefore, large deviations between the numerical and experimental results were usually observed. Although the single-phase model has significant drawbacks, it is a milestone in fresh concrete modeling, offering a possibility for the later research.

3.2 Two-Phase Element Model

In 1996, Chu developed a modified DEM model based on the work of Nabeta (1989). The mixture was divided into a mortar phase and a coarse aggregate phase, represented by an assembly of two-phase elements consisting of inner hard core coarse aggregates covered with a layer of the mortar which was very low in stiffness (Hoornahad and Koenders 2014). Although it was simplified that the coarse aggregates enclosed by mortar ring, which was similar to single-phase model, the aggregates could contact and collide with either mortar or aggregates based on the extent of overlapping. As shown in Figure 3, if the overlapping exceeds the thickness of mortar ring, contacts and collisions will take place between aggregates.

This two-phase assumption makes a step closer to the real situation, but it still considers mortar as a whole mixture with only mechanical behavior, but without specific geometrical characteristics (Quoc and Uomoto 2008). Besides, there are simplifications about the homogeneous distribution of mortar. This model was applied for simulation flow behavior and shootability of shotcrete (Puri *et al*. 2002).

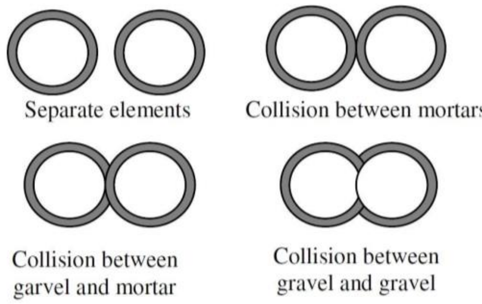

Figure 3. Illustration of different types of contact in two-phase modelling(Quoc and Uomoto 2008).

Two-phase element model is the most widely used DEM model for fresh concrete flow. For example, Hoornahad (2014) used a two-phase model to simulate the self-compacting mixture behaviors. Li *et al.* (2016) applied the two-phase model on the prediction of time-dependent flow behaviors of fresh concrete, and achieved a reasonable comparison between experimental and numerical result (see Figure 4).

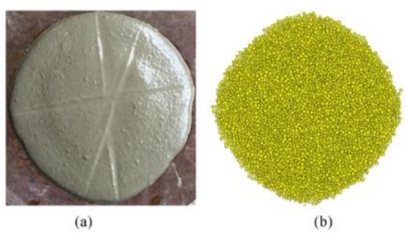

Figure 4. The final shape of the mortar on the flow table: (a) experiment (mean flow value: 210 mm), and (b) numerical simulation (mean flow value: 212mm) (Li *et al.* 2016).

3.3 Multi-Phase/ Separate Single-Phase Element Mode

In this model, the concrete mixture is divided into a mortar phase and a coarse aggregate phase, represented by a combination of separate-single phase elements including mortar and coarse aggregate (Hoornahad and Koenders 2014).

Noor (2000) adopted a new model in which aggregate and mortar elements had been modelled using separate elements as shown in Figure 5.

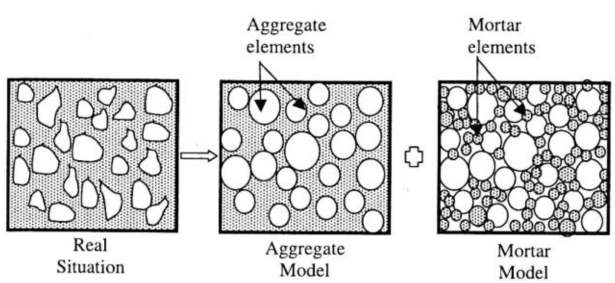

Figure 5. Model with separate single-phase particles for mortar and gravel (Noor 2000).

Since there were a vast number of fine aggregates, which would make the numerical simulation complicated and become time-consumed, the DEM parameters of mortar and aggregate elements were set and verified separately, for example, contact stiffness, bond strength for both shear and tangential direction, and friction factor between two elements at each contact point (Noor 2000). Noor (2000) gave a new method to choose appropriate simulation parameters and successfully reduced the element number. The numerical results using this new method was compared with experimental results and showed a good match. Therefore, the separate single-model can be applied to analyze the flow behaviors of fresh concrete and predict some common phenomenon such as the coarse aggregate blocking.

Taking all the advantages and disadvantages of existing DEM models into consideration, Quoc (2002) presented a new DEM model, in which the advantage of setting parameters of fine mortar and coarse aggregate element separately was adopted, while mortar element was divided into two parts, known as the spacing mortar and bonding mortar (as shown in Figure 6). Spacing mortar element was used to keep coarse aggregate element at a certain distance from each other, and bonding mortar was used to fill the space between space particles and coarse gravel. As the key point to the model, the parameters of these two mortar elements were required to be set up separately. Quoc (2002) introduced neural network to study the relationship between the rheological properties parameters and the numerical parameters of fresh concrete.

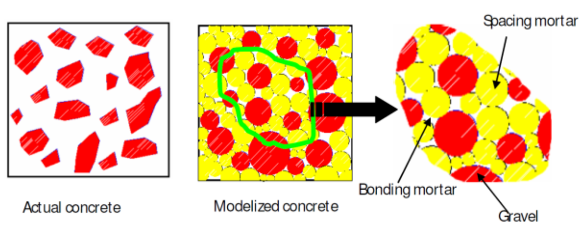

Figure 6. Modified model with two phases in separate particles (Quoc and Uomoto 2008).

4 CONCLUSIONS

In this paper, several numerical modelling methods of fresh concrete flow have been overviewed, including DEM. The paper focused on the rheological models and DEM models used in fresh concrete simulation.

The assumption of the rheology model is based on Bingham Model, however, De Larrard *et al.* (1998) pointed out that the relationship between torque and rotation speed was not exactly linear and even a negative yield stress countered with the Bingham model in their rheological tests. Thus, more research is required in the future to consider other rheology models such as Newtonian model (Mitsoulis 2007), Herschel- Bulkley (H-B) model (De Larrard *et al.* 1998), and modified Bingham model, etc.

Although DEM model has been successfully used to simulate the fresh concrete flow by many researchers, there are a lot more research could be done in the future. For example, the current model used only elastic component (spring), plastic component (slip/slider) and viscous component (dashpot) as particles' contact model. In reality, the interactions between mortar and coarse aggregates are much more complicated and the accuracy of the simple combination of the above contact model does not seem satisfactory. In the future research, other models such as liquid bridge model, hard-core soft-shell model will be studied and discussed.

Besides, there are some drawbacks of DEM modelling on fresh concrete, for example, it was not clear of how to determine DEM parameters used to simulate the fresh concrete flow. The parameters were fitted to obtain the best comparison between numerical predictions and experimental results.

In this paper, only a small section of DEM modelling is reviewed. There are several procedures of DEM modelling needs to be studied, for instance, constitutive relationships and parameter estimation.

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