論文 Three-Dimensional Discrete Element Simulation of Lifting Sphere Viscometer Test for Fresh Concrete

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ABSTRCT: In this paper Lifting sphere viscometer test was simulated, to provide guidelines for choosing parameters appropriate for fresh concrete, by three-dimensional discrete element method. Initial results obtained from numerical experiment show that the discrete element simulation reproduces the qualitative behavior seen in fresh concrete.

KEY WORDS: Discrete Element Method, Self-compacting Concrete, Fresh Concrete, Lifting Sphere Viscometer, Three-Dimension, Simulation.

1. INTRODUCTION

The discrete element method (hereafter, DEM), which models a problem as a discrete assemblage of particles, has features that make it attractive for modeling large deformation problems in fresh concrete engineering. Before such modeling can be attempted on large-scale problem, however, several issues must be resolved, such as choosing appropriate model parameters and reducing the enormous number of particles required for a realistic model. In this research guidelines have been provided for choosing the DEM model parameters necessary for obtaining realistic aggregate and mortar behavior. In this study, three dimensional particle flow code (hereafter, PFC^{3D}) program has been used, as a tool, to simulate behaviors of fresh concrete; and lifting sphere viscometer test was selected as test method to compare numerical simulation. Sphere element has been used to model the mortar and aggregate.

2. JUSTIFICATION OF USING DEM

The following are the justifications for the use of DEM instead of a continuum approach to simulate fresh concrete. The difficulty of continuum modeling approach, such as finite element method, for concrete is due to its inability to explain the considerable movement and rotation of granular particles. Traditional theoretical (continuum models) and experimental investigations of the behavior of particulate systems are restricted by the limited quantitative information about what actually happens inside particulate assemblies. In addition, what is not well understood is the way in which the inter-particle behavior is affected by the spatial and size distributions of the constituent particles. The concrete material is discrete at some level. The heterogeneous property of the concrete makes it an unrealistic trade-off to assume the homogeneity within samples or elements. The microscopic model, PFC^{3D}, was used because (a) it has the criteria of DEM that allows finite displacements and rotation of discrete bodies and recognizing new contacts automatically and (b) it uses an explicit time marching method to solve the equations of motions directly.

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3. JUSTIFICATION OF SELECTING LIFTING SPHERE VISCOMETER TEST

To see the qualitative behavior of fresh concrete, lifting sphere viscometer test has been selected. Lifting sphere viscometer is one of the popular devices to investigate the rheological properties of fresh concrete recommended by JCI [1, 2]. In this research, the lifting sphere viscometer test was chosen because it can provide the possibility of direct comparison of the experimental results, obtained from the test, with the simulated results. The type of lifting sphere viscometer device used is shown in Fig 1. It is quite similar to that devised in the literature [3]. However, the size (Fig. 1) is the half of the original size used in the simulation to reduce the number of sphere elements and simulation time.

4. DEM MODEL FOR FRESH CONCRETE

DEM is originally proposed for rock and granular flow simulation. It is considered that single-phase model is enough for the flow simulation of granular material. However, it was shown that fresh concrete can not be modeled as single-phase and must be modeled as multi-phase material [4, 5]. In DEM model, the increase of phase numbers and small particle sizes like that of cement and sand extremely complicates the simulation and the calculation speed also becomes very slow. All previous models known to the authors used either one-phase model or two-phase model, which includes aggregate and mortar property in the same element. In this research two-phase model has been adopted but in a different way. Here, aggregate and mortar have been modeled using separate element shown in Fig. 2. Nevertheless, DEM model can be composed of cement paste, fine aggregate and coarse aggregate element separately. However, the huge number of fine aggregate would make the numerical simulation time consuming. Thus two-phase model, one mortar element and one coarse aggregate element were used in this study. The major parameters used in this simulation are contact stiffness and bond strength both for shear and tangential direction and friction factor between two elements at each contact point. To get successful model for concrete simulation the constituent model, i.e., mortar model and aggregate model should be verified before hand.

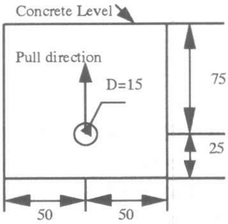


Fig. 1 Geometry of the container of lifting sphere viscometer test (Unit: mm).

4.1 CONTACT CONSTITUTIVE MODELS

The overall constitutive behavior of a material was simulated in PFC^{3D} by associating a simple constitutive model with each contact. The constitutive model acting at a particular contact consists of three parts: a stiffness model, a slip model, and a bonding model. PFC^{3D} provides two contact stiffness models: a linear model, and a simplified Herz-Mindlin [6] model. In this paper, linear model has been used. The slip model is an intrinsic property of the two entities (ball-ball or ball-wall) in contact. It provides no normal strength in tension and allows slip to occur by limiting the shear force. In this research this model was always kept active, unless a contact bond was present — in which case, the contact bond model behavior supersedes the slip model behavior. PFC^{3D} allows particles to be bonded together at contacts. Two bonding models are supported: a contact bond model and a parallel bond model. However, the presence of a contact

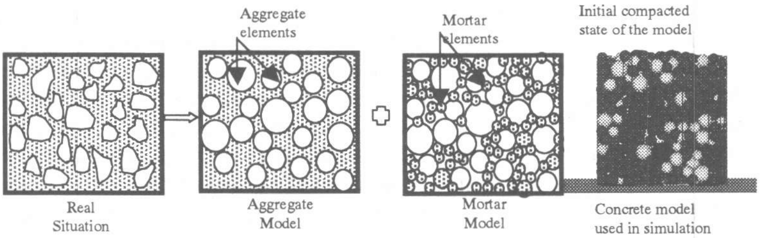


Fig. 2 Two-phase concrete model adopted in the present study.

bond inactivates the slip model. Once a bond is formed at a contact between two particles, that contact continues to exist until the bond is broken. Here, only contact bond model has been used not the parallel bond model. A contact bond can be envisioned as a pair of elastic springs (or a point of glue) with constant normal and shear stiffness acting at the contact point. These two springs have specified shear and tensile normal strength. Contact bonds allow tensile forces to develop at a contact. The magnitude of the tensile normal contact force is limited by the normal contact bond strength. If the magnitude of the tensile normal contact force equals or exceeds the normal contact bond strength, the bond breaks, and both the normal and shear contact forces are set to zero. If the magnitude of the shear contact force equals or exceeds the contact bond strength, the bond breaks, but the contact forces are not altered. The constitutive behavior relating the normal and shear components of contact force and relative displacement for particle contact occurring at a point is shown in Fig. 3. As parallel bond model has not been used in this research, it is not described.

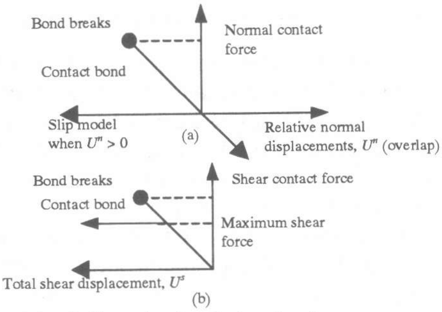


Fig. 3 Constitutive behavior for contacts occurring at a point, (a) Normal component of contact force, (b) shear component of contact force.

4.2 EQUIVALENT DENSITY CONCEPT

Mortar, more or less, can fill every part of a volume. If we want to model the mortar with element and give the same density then, for the same volume, mass will be less. At the same time it is very difficult to determine the equivalent density before final particle compaction. And it also depends on the stiffness, which cannot be changed after compaction without changing the volume of the initial compacted state. Then, particle number in a given volume and porosity will be changed again. Thus, it requires trial and error procedure, which is not feasible at present time. This has been understood during sensitivity analysis of parameters. During parameter selection procedure the trial and error method has been used with one trial. An alternative approximate method based on solid crystal structure has been adopted. To calculate the equivalent density face centered solid crystal structure unit cell has been used. This unit cell uses 14 lattice points eight of which are corner atoms (forming the cube) with other six in the center of each of the faces. Since two cubes share the face atoms they only contribute three atoms to the unit cells. These three atoms plus one from the corners yield the four net atoms in unit cells. Now the unit cell was considered as real mortar and the four net atoms as DEM mortar element. Equivalent density is that density, which equates both the masses. This equivalent density is independent of ball size but depends on the unit cell porosity. This method approximately conserves the mass, if the porosity of the final compacted state does not become too low; this independence on ball size makes it suitable for simulation, which has several ball sizes.

4.3 MORTAR , AGGREGATE AND CONCRETE MODEL

Mortar element is a hypothetical element in the simulation. It is difficult to determine any entity such as grading of mortar element, parameter values etc. This is due to the fact that there is no definite rule to determine fresh mortar stiffness. To calculate the stiffness of mortar a new approach has been adopted. Stiffness has been calculated by fixing the amount of overlap between the two-mortar element. In this study the largest ball size and smallest ball size have been averaged to calculate the mortar stiffness, for a specified grading curve. For a fixed equivalent density, the value of stiffness, which gives the fixed overlap, has been chosen as mortar element stiffness. In this study one-percent overlap has been fixed. For mortar element contact bond between the elements has been used, and friction value has been kept zero. Bond value was selected using trial and error method. The value, which gives the qualitative behavior of mortar, has been selected for the analysis.

To model the aggregate, actual grading curve has not been used. If the actual grading curve had been used it would have taken large computing time. So, for the present research different grading curve has been proposed, which will be discussed later. As for the parameter value, Ting [7] assumed elastic granite cylinders to have normal stiffness ranged from 10^8 to 10^{10} pa. Mindlin [8] assumed the elastic bodies in contact with elliptical contact areas to have the ratio of shear stiffness to normal stiffness to be between 2/3 to 1, the estimations for normal shear stiffness pairs for gravel-gravel contacts should be kept within the above range. In present study to observe the qualitative behavior of aggregate model normal and shear stiffness have kept equal to 1.0E+05 (N/m) and 5.0E+04 (N/m), respectively. For aggregate element no inter-particle bond has been selected, only friction value has been taken. To model concrete, the separate model for mortar and aggregate has been combined. For concrete model an extra bond property has been introduced between mortar and aggregate.

5. MODEL SETUP

In order to set up model to run a simulation, three fundamental components of the problem must be specified: (a) assembly of particle, (b) contact behavior and material properties and (c) boundary and initial conditions. The starting point of the most simulation is a dense assembly of particles that are contained within a given region of space and are in equilibrium. Unfortunately, there is no unique way to fill a polyhedral space with sphere to a given porosity unless regular packing are required—for example, face centered cubic arrays. All published works known to the authors on computer simulations of the particle-packing problem have employed arbitrary, non-physical rules to decide upon the final particle positions. However, in present research complete process was simulated according to Newtonian mechanics with particle interactions controlled according to the theoretical contact mechanics. To simulate the particle deposition process, particles are randomly generated within a prescribed region and then subjected to a gravity field so that they fall as rain within defined container walls. As a consequence, particles collide with the container walls and each other and computations are continued until an equilibrium configuration of the resultant particle has been attained. At the end of the process before the particles settle down they continue moving due to inertia forces. Cycles of relaxation are needed to settle down the particles. For relaxation process some cycles were applied.

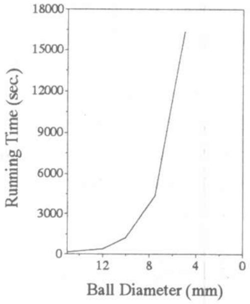
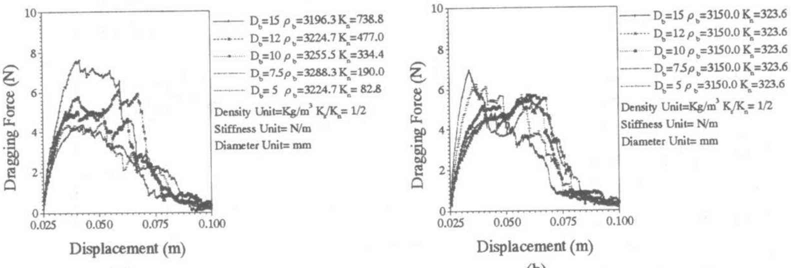


Fig. 4 Running time vs. Ball Diameter.

6. PARAMETER SELECTION PROCEDURE

To select the qualitative value of the parameters like friction, contact stiffness, bond value and aggregate grading, sensitivity analysis is required. This selection procedure has nothing to do with mortar or aggregate model. This is just getting the idea of behavior of each parameter. Running time is very important in this regard. To perform detail parametric study the ball size has to be selected in such a way that the running time can be reduced significantly. For this purpose several analysis were conducted with different ball sizes (Fig 4). It is clear from Fig. 4 that time required increases very rapidly, as ball size becomes less than 7.5 mm. Now for the same parameters, Fig. 5 shows the force-displacement relationship. Two cases have been shown: one with equivalent density (calculated using one trial method) and the other with constant normal density. As ball size increases (Fig. 5(a)) the force displacement curve shifts upward. This is because as the ball size increases the equivalent density of the ball decreases (except for 5 mm ball) and the stiffness of the mortar spring increases. Due to the increase of spring constant the lifting force increases. But for actual case density should decrease as the ball size decreases, due to the decrease in porosity. This may be due to the fact that only one trial has been performed to calculate equivalent density for these analyses. In Fig. 5(b) as ball size increases the force displacement curve shifts downward. This is due to the fact that for same density, stiffness is the same for fixed overlap and for smaller ball co-ordination number with lifting sphere increased. The simulation, which has been done using equivalent grading curve, described later, second case has been adopted and approximate equivalent density has been calculated using the method described in article 4.2.



(a) (b)

Fig. 5 Lifting sphere viscometer simulation with different ball size for (a) equivalent density and (b) normal density.

6.1 BOND EFFECT

From contact constitutive model it is understood that if the normal bond breaks then the contact force resets, but if the shear bond breaks the contact forces don not reset. It goes up to the normal bond strength of the ball. During this phase slip model remains activated according to friction factor. This has been verified by giving the different bond values to the program. Several analysis have been conducted considering two different cases: (a) keeping the normal bond strength larger than the shear bond strength and (b) keeping the shear bond strength larger than the normal bond. For the first case a large value for the normal bond has been kept constant and the value of the shear bond is increased from very small value. The opposite has been done for the second case. In the first case, it has been found out that all force displacement value more or less the equivalent. For the second case, as the normal bond value increases the force displacement value increases and finally obtains the first case value. From this, it can be understood that shear bond value would dictate the selection of normal bond value. Once it is selected the same value can be provided to the normal bond. It has been found from the analysis that shear and bond strength equal to 0.01 (N) gives good qualitative result.

6.2 GRADING CURVE SELECTION

Mortar element simulates the effect of combined sand and cement in simulation. No particular grading curve can be applied. Use of actual grading to get the compacted assembly, may not be judicious enough. So, a method has been proposed. The actual grading curve has been shifted to the right (Fig. 6(a)). Lowest part has been kept equal to 7.5 mm. Percent finer has been kept equal. Because it should give the same fineness modulus (FM) if the original sieve size is changed to equivalent selected size of the ball. The same has been done for coarse aggregate. Coarse aggregate element size should not be greater than lifting sphere diameter (15mm) and also should not be less than 7.5 mm as described earlier. Grading curve selected for both the elements are shown in Fig. 6. After selecting the grading curve, two cases have been analyzed for mortar simulation, with (a) grading curve generated from large particle to small particle, (b) grading curve generated from small particle to large particle. The effect of this to the numerical simulation is shown in Fig 7(a). In the present case, grading curve generated from large particle to small particle, due to the easiness of filling a volume with random particle generator, has been adopted.

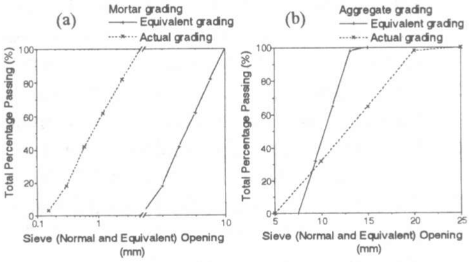
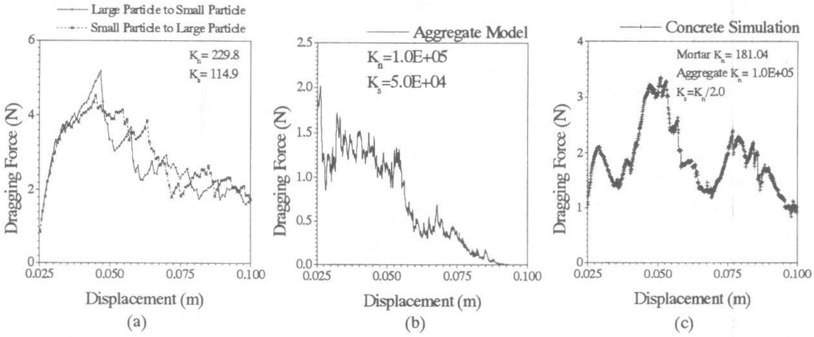


Fig. 6 Grading curve diagram (a) for mortar element (b) for concrete element.

7. SIMULATION RESULTS AND DISCUSSION



(a) (b) (c)

Fig. 7 Numerical simulations of lifting sphere viscometer test for (a) mortar (b) coarse aggregate and (c) concrete. (Stiffness Unit: N/m)

From above discussion for mortar model and aggregate model the selected parameter values are: (a) normal bond strength is 0.01 (N) and shear bond strength is 0.01 (N) for mortar, and no normal and shear bond strength for aggregate, (b) no friction factor for mortar but for aggregate, it has been chosen equal to 0.1, (c) normal and shear bond strength between aggregate and mortar for concrete has been kept same as mortar, and (d) the grading curve used for mortar and aggregate (Fig 6). Considering all this parameters mortar and concrete simulation has been done separately. It is observed that, both the simulation qualitatively simulate the force-displacement curve for mortar and aggregate, respectively. Then one final analysis has been conducted combining these two models to simulate the behavior of fresh concrete (Fig. 7(c)). For concrete simulation, mix proportion of powder type self-compacting concrete has been used. Water cement ratio was 0.83 percent by volume. The weight of water, cement, sand and gravel in 1 m^3 were 191 kg, 746 kg, 677 kg, and 791 kg, respectively. It can be observed from these Figures that this two-phase model can simulate the qualitative behavior seen in lifting sphere viscometer test [9]. Thus, it can be said, from initial numerical results obtained, DEM is powerful numerical tool to simulate the behavior of fresh concrete.

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