研究速報

NUMERICAL SIMULATION OF FRESH CONCRETE (2) VERIFICATION OF THREE DIMENSIONAL DISCRETE ELEMENT MODEL FOR FRESH CONCRETE

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1. INTRODUCTION

In paper [1] authors gave detailed descriptions of three-dimensional discrete element model of the fresh concrete. Detailed description can also be found on (a) how to choose appropriate model parameter, and (b) how to reduce the enormous number of particle during any simulation. In this study, model proposed in the paper [1] has been verified. An experimental setup is needed to verify the model and lifting sphere viscometer test has been chosen for this purpose. Why this test method has been chosen is described in later section. It is considered that single-phase model is efficient for the flow simulation of granular material. It was shown, however, that fresh concrete can not be modeled as single-phase and must be modeled as multi-phase material [2, 3]. 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 using three dimensional particle flow code (hereafter, PFC^{3D}), as a tool, to simulate behaviors of fresh concrete. Sphere element has been used to model the mortar and aggregate. Detailed description can be found in Noor and Uomoto [1]. In this paper, at first quantitative value of different parameter has been calculated, then mortar and aggregate simulation have conducted separately. Finally, concrete simulation has been performed using those values, selected during mortar and aggregate simulation.

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2. JUSTIFICATION OF SELECTING LIFTING SPHERE VISCOMETER TEST

To see the qualitative behavior of fresh concrete, lifting sphere viscometer has been selected. Lifting sphere viscometer is one of the popular devices to investigate the rheological properties of fresh concrete recommended by JCI [4, 5]. In this research, the lifting sphere viscometer test has been 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 [6]. However, the size shown in the Fig. 1 is half of the original size used in the simulation to reduce the number of sphere elements and simulation time.

3. MODEL SETUP

In order to set up model to run a simulation, three fundamental components of the problem must be specified: (a) an assembly of particle, (b) contact behavior and material properties and (c) boundary and initial conditions. The particle assembly consists of the location and size distribution of particle. The contact behavior and associated material properties dictate the type of response the model will display upon disturbance. Boundary and initial conditions define the inisitu state. 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 interac-

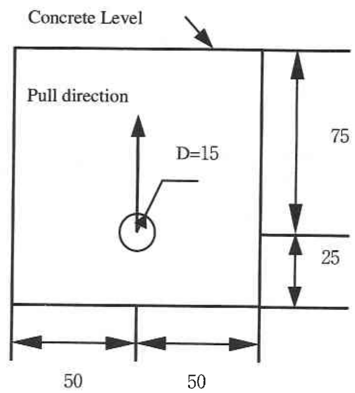

Fig. 1 Geometry of the container of lifting sphere viscometer test. (Unit: mm)

Table 1 Basic mixture proportion of concrete

Mixture type	W/C (%)	Unit weight (kg/m³)			
		Water	Cement	Sand	Gravel
Powder	83	191	746	677	791

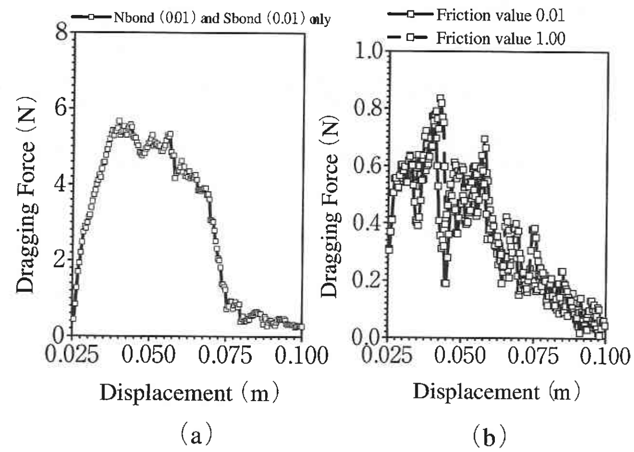

Fig. 2 Effect of (a) normal and shear bond, and (b) friction factor on the force-displacement curve. (Nbond / Sbond = Normal / Shear direction bond strength. K_n = 323.6 N / m K_s = 161.8 N /m)

tions controlled according to the 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 particles have been attained. At the end of the process before the particles settle down they continue moving due to the inertia forces. Cycles of relaxation are needed to settle down the particles. For relaxation process some cycles were applied. Before starting compaction process the amount of element of each mortar and aggregate have been calculated using the mix proportion given in Table 1. Also, the equivalent density of mortar and aggregate [1] has been calculated using the mix proportion shown in Table 1.

4. PARAMETER SELECTION PROCEDURE

To select the numeric value of the parameters like friction and bond value, sensitivity analysis is required. Numeric value for stiffness and grading curve has been proposed in Noor and Uomoto [1]. This selection procedure has nothing to do with mortar or aggregate model. This is just to get the idea of behavior of each parameter. Running time is very important in this regard. To perform detailed parametric study the ball size has to be selected in such a way that the running time can be reduced significantly. It is shown in Noor and Uomoto [1] that if size becomes less than 7.5 mm running time increases rapidly. For this reason during conducting sensitivity analysis 10-mm constant ball size has been selected. Before getting the actual value for the friction factor and bond value, in normal and shear direction, individual contribution of each parameter towards the force displacement curve has been observed. In this purpose two analyses have conducted once keeping the friction factor zero and another keeping the both bond values zero. These are shown in Fig. 2. Fig. 2 (a) shows the contribution of bond value. It can be said that by controlling the bond value for normal and shear direction we could control the force value of the simulation. The shape is smooth and resemblance the shape of the mortar simulation [7]. Fig. 2(b) shows the effect of friction to the force displacement curve. The contribution of friction factor towards the value of force is negligible but the shape is important, which resemblance the shape of the force displacement curve of aggregate in lifting sphere viscometer test [7]. Another important feature can be seen from the Fig. 2(b) that the increased friction factor does not have any effect on the amplitude of the force displacement curve. The effect of normal and shear bond value to the force displacement curve has been discussed in later section. Now the effect of ball size and the stiffness is shown in Fig. 3. Two cases have been examined: one with trial calculated density (calculated using trial and error method with one trial) and the other with constant normal density. In Fig. 3(a) as ball size increases 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 dragging force increases. But in 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

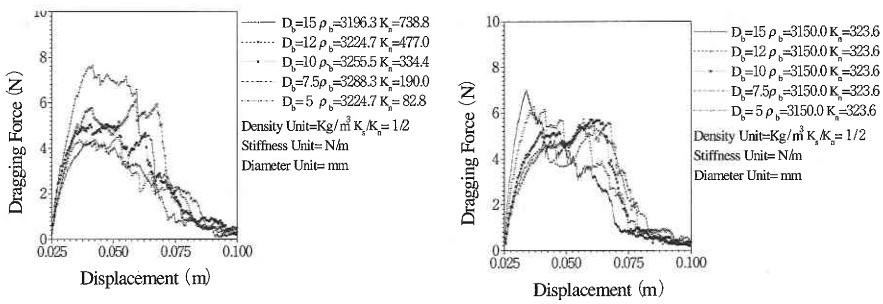

Fig. 3　Lifting sphere viscometer simulation with different ball size for (a) equivalent density and (b) normal density.

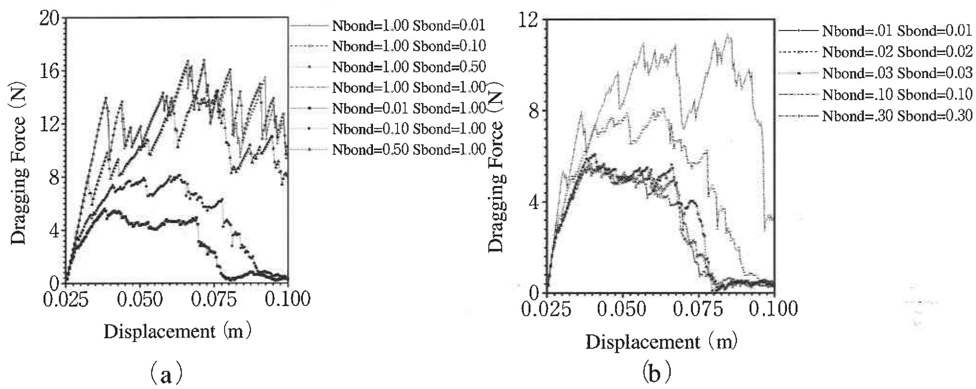

Fig. 4　Effect of normal and shear bond values to the force displacement curve of the lifting sphere viscometer test.

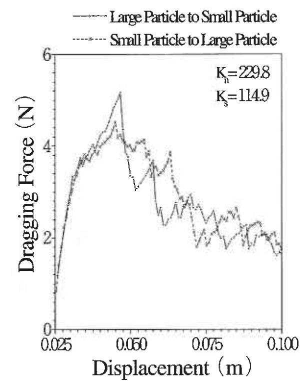

Fig. 5　Mortar Simulation

has been performed to calculate equivalent density for these analyses. In Fig. 3(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, in lifting sphere, increased. From above discussion it can be said that the effect of stiffness on the simulation is greater than the effect of ball size. In further simulations, using equivalent grading curve [1], second method has been adopted and approximate equivalent density has been calculated using the method described in paper Noor and Uomoto [1].

5. 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 do 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 bond behavior has been verified by giving the different bond values to the program. Several analysis have been conducted, which is show in Fig. 4, considering three different cases: (a) keeping the normal bond strength larger than the shear bond strength, (b) keeping the shear bond strength larger than the normal bond, and (c) keeping both normal and shear bond value same. For the first case a large value of 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. Both these cases are shown in Fig. 4(a) together. From this figure, 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, and the analysis conducted using this same bond value is shown in Fig. 4(b). It can be seen from the Fig. 4(b), that shear and bond strength equal to 0.01 (N) gives good qualitative result.

6. SIMULATION RESULTS AND CONCLUSIONS

Above discussions and analyses provide sufficient insight for selecting approximate values for each simulation. Individual simulation of mortar and aggregate has been done, before performing the final concrete simulation. Following sections describe the each simulation.

6.1 MORTAR SIMULATION

For mortar simulation the selected parameter values are shown in Table 2. Fig. 5 shows the mortar simulation with the selected parameter. Two cases have been analyzed for mortar simulation,

Table 2 Parameter values for Mortar and Aggregate Simulation.

Simulation	Normal Stiffness, K_n (N/m)	Shear Stiffness, K_s (N/m)	Friction factor between balls	Bond value between balls (N)	
				Shear bond value	Normal bond value
Mortar	229.8	114.9	0.0	0.01	0.01
Aggregate	1.0E+05	5.0E+04	0.1	0.0	0.0

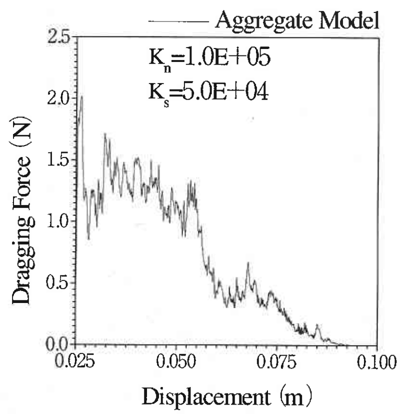

Fig. 6 Aggregate Simulation

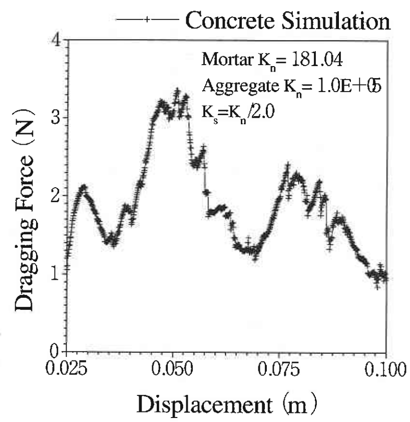

Fig. 7 Concrete Simulation

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 also shown in Fig 5. 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.

6.2 AGGREGATE SIMULATION

For aggregate simulation the selected parameter values are shown in Table 2. Fig. 6 shows the aggregate simulation with the selected parameters. The aggregate stiffness value, which has been suggested in Noor and Uomoto [1], has not been used here. Lower stiffness value than specified has been used here to keep time step within reasonable value.

6.3 CONCRETE SIMULATION

It can be said that, both the above simulations 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, which is shown in Fig 7. During the combination several things have been considered. The bond value between the mortar and aggregate element is introduced. The friction between aggregate and mortar is kept zero. It can be observed from the Fig. 5 to Fig. 7 that the two-phase model can simulate the qualitative behavior seen in lifting sphere viscometer test [7]. 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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