THREE DIMENSIONAL DISCRETE ELEMENT SIMULATION OF SLUMP FLOW FOR SELF COMPACTING CONCRETE
3次元個別要素法による自己充填コンクリートのスランプフロー解析

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1. INTRODUCTION

The slump flow test is one of the most popular methods of evaluating the consistency of concrete, both in the laboratory and construction sites due to its ease of operation and the portability, where the slump is greater than 24-cm [1]. The slump flow test, specified by the Japan Society of Civil Engineers (JSCE), judges the capability of concrete to deform under its own weight against the friction of the surface with no other external restraint present.

2. MODEL USED

It is considered that single-phase model is sufficient for the flow simulation of granular material. It was shown, however, that fresh concrete cannot be modeled as single-phase and must be modeled as multi-phase material [2]. 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 by 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 [3].

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 insitu 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. However,

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in present research complete process was simulated according to Newtonian mechanics with particle interactions 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 particle has 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 the compaction process the amount of element of each mortar and aggregate have been calculated using mix proportion given in Table 1. Also, the equivalent density of mortar and aggregate [3] has been calculated using the mix proportion shown in Table 1. To see the effect of overlap on the porosity of compacted state of slump flow simulation, porosity has been calculated for different overlap with same ball diameter and same volume. It is found that porosity decreases as the overlap increases. So, by changing the percent overlap initial porosity can be changed.

Table 1 Basic mix proportion of concrete.

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

4. PARAMETER SELECTION PROCEDURE FOR FLOW BEHAVIOR

In Noor and Uomoto [4], they proposed DEM parameters suitable for fresh concrete simulation (Table 2) by conducting extensive simulation on lifting sphere viscometer test. Authors of this paper first tried to use their proposed parameters for simulating slump flow. These parameters have found to simulate the lifting sphere viscometer test very well. With these parameters the authors did their first slump flow test, but slump flow has not been observed, instead normal slump has been observed. It is, therefore, needed to find out the parameters, which would produce flow behavior in the slump simulation. To do this, sensitivity analysis is needed to see the effect of individual parameters towards flow behavior. The effect of mortar element normal stiffness, ball diameter, ratio of normal to shear stiffness, bond have been selected for sensitivity analysis. Therefore, several runs were conducted to observe the behavior of mortar element spring, which is shown in Fig. 1. It can be observed from Fig. 1 that slump value

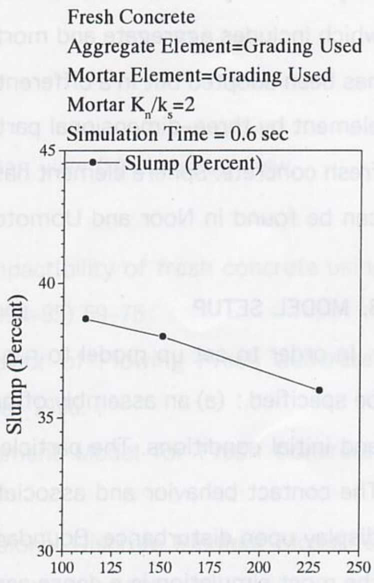


Fig. 1 Effect of normal stiffness on slump.

Table 2 Simulation parameter values.

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	6.00	0.0	0.01	0.01
Aggregate	1.0E+05	5.0E+04	0.1	0.0	0.0

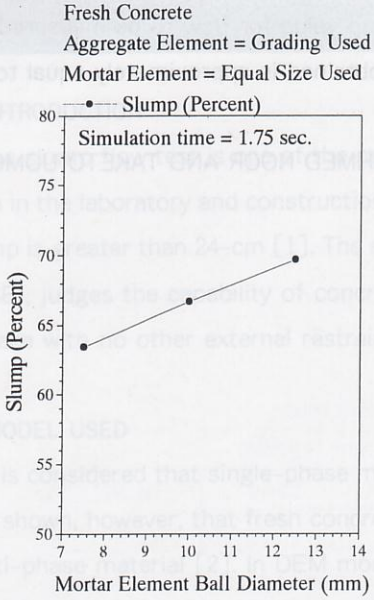


Fig. 2 Effect of Ball Diameter on slump.

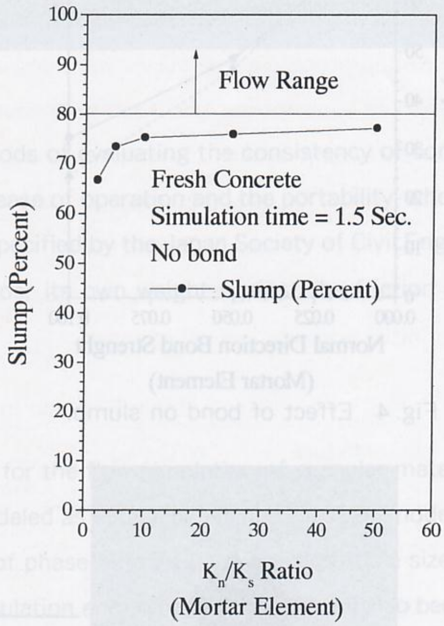


Fig. 3 Effect of shear stiffness on the slump.

increases with the decrease of the stiffness value of the mortar element but not sufficient slump has been observed. Then, instead of using equivalent grading for the mortar element, equal size mortar element has been introduced. Two runs were conducted and shown in Fig. 2. It is seen from Fig. 2 that as the ball diameter increases the slump value increases accordingly. This reveals the fact that the ratio of the particle surface to particle volume increases with the decrease of the ball diameter; and in this way increases the shear rate between the phases. By seeing this effect, the value of the ratio of the normal stiffness to shear stiffness has been increased to reduce the shear force between the particles. All the following runs were conducted using equal ball size for mortar element. The effect of the normal stiffness to the shear stiffness has been shown in Fig. 3. It is observed from Fig. 3 that the slump value is near the flow range. All this runs were conducted without the bond value for both the normal direction and shear direction. To observe the effect of bond on the slump flow value several analyses were conducted for a particular grading, mortar element size and mortar element stiffness (shear) value, and the calculated result is shown in Fig. 4. It can be said from Fig. 4 that by controlling the bond one could achieve different slump flow or different slump value.

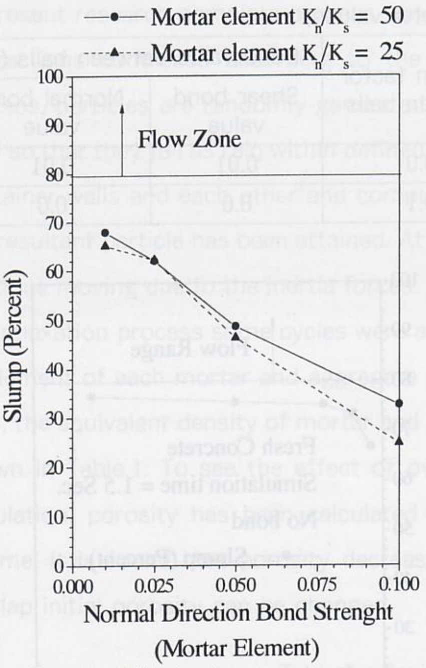
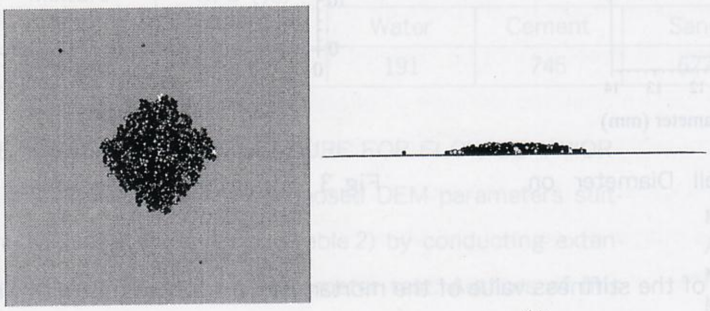


Fig. 4 Effect of bond on slump.



(a) (b)

Fig. 5 Slump flow simulation. Simulation time 7.5 sec. (a) plan view (b) elevation view.

5. SIMULATION RESULTS AND CONCLUSIONS

After all these detailed analysis, one final run was conducted for longer time. The simulation time was more than 6 sec. and the slump flow was achieved, which is shown in Fig. 5. The value of the percent slump achieved is 90 percent, which is above than required slump value for flow to be measured and slump flow obtained is approximately equal to the 60 cm.

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