研 究 速 報

Numerical Simulation of Fresh Concrete (3)

Three-Dimensional Discrete Element Simulation of Slump Flow for Self-Compacting Concrete

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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 (Fig. 1) 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. This is a conventional method widely used for evaluating the flowability of concrete. This test, however, cannot evaluate concrete's passage through reinforcement bars because this is determined by deformability under limited external restraint due to the large free surface. Even concrete with the same slump flow can have different behavior when passing trough such obstacle as reinforcing bars, depending on their mix proportion.

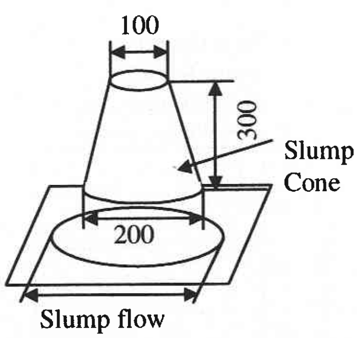

Fig. 1 Slump flow Test. Simulation sizes is half of this. (Dimensions in mm)

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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, 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 [4]. In the paper [4], first qualitative value of different parameter was calculated, and then mortar and aggregate simulations were conducted separately. Finally, concrete simulation was performed using those values, selected during mortar and aggregate simulation. The constitutive model used in this paper is same as the constitutive model used in paper by Noor and Uomoto [4].

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. In present research, however, complete process was simulated according to Newtonian mechanics with particle interactions controlled according to the contact mechanics. To simulate the particle deposition process, particles were 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 collided with the container walls and each other and computations are continued until an equilibrium configuration of the resultant particle was attained. At the end of the process before the particles settle down they continue moving due to the inertia forces. Cycles of relaxation were 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 [4] of mortar and aggregate has been calculated using the mix proportion shown in Table 1. To observe the effect of overlap towards the porosity of compacted state of slump flow simulation, porosity has been calculated (Fig. 2) for different overlap with same ball diameter and same volume. It is seen from the Fig. 2 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 (%)	Unit weight (kg/m^3)			
		Water	Cement	Sand	Gravel
Powder	83	191	746	677	791

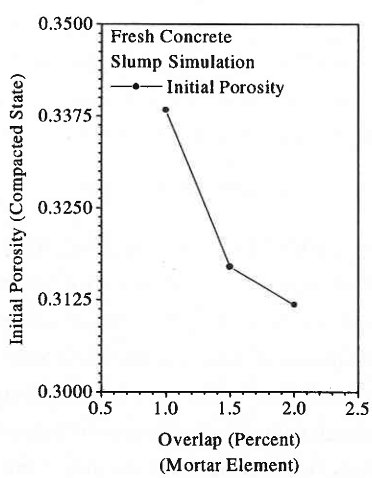

Fig. 2 Slump flow simulation.

4. MODEL SIMULATION TIME

The effect of simulation time has been observed by running same compacted state for different time (Fig. 3). Longer simulation produces higher percent slump (slump height/slump cone height) but it does not mean that continuously running would produce further slump flow. After some threshold time slump flow will be stopped. Basically it depends on the kinetic energy or the unbalanced force of the system. When these two become very low further flow will not be occurred. That is why in this paper final simulation has been continued for longer time greater than the threshold value. But for the sensitivity analysis shorter time has been used to save the running time. This explanation is given here because in parametric study in some cases the slump flow is not near the flow range, this is just due to shorter running time.

5. PARAMETER SELECTION PROCEDURE FOR FLOW BEHAVIOR

In Noor and Uomoto [5], they proposed DEM parameters suitable for fresh concrete simulation, after 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 were 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.

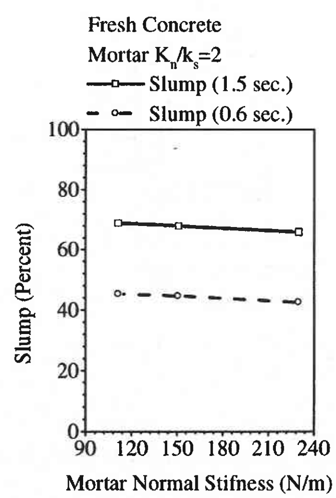

Fig. 3 Slump flow simulation.

It was, therefore, needed to find out the parameters, which would produce flow behavior in the slump simulation. Sensitivity analysis was needed to observe 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. 4. It can be observed from Fig. 4 that slump value 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. Several runs were conducted and shown in Fig. 5. It is seen from Fig. 5 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. The effect of the normal stiffness to the shear stiffness has been shown in Fig. 6. It is observed from Fig. 6 that the slump value is near the flow range. As the simulation time lower than the threshold value higher slump value was not observed. If the simulation were longer, then the slump flow could be achieved. 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. 7. It can be said from Fig. 7 that by controlling the bond one could achieve different slump flow or different slump value. After these sensitivity analyses, paramaters responsible in flow simulation in propused in Table. 2.

6. SIMULATION RESULTS AND CONCLUSIONS

After all these detailed analyses, one final run was conducted for longer time. Using the parameters shown in Table. 2. The simulation time was more than 6 sec. and the slump flow was achieved,

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	Noemal bond value
Mortar	229.8	6.00	0.0	0.01	0.01
Aggregate	1.0 E+05	5.0 E+04	0.1	0.0	0.0

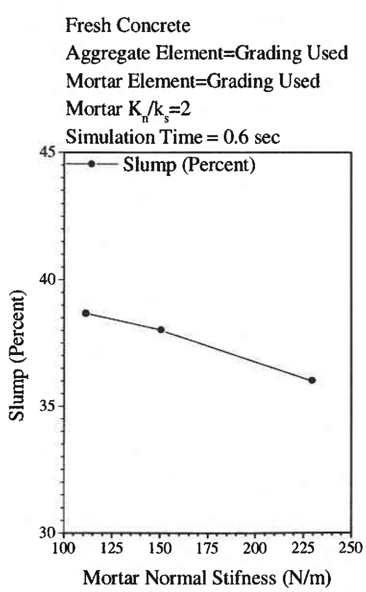

Fig. 4 Effect of mortar normal stiffness on slump value.

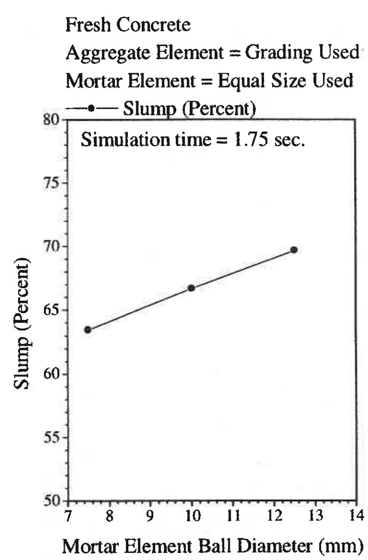

Fig. 5 Effect of mortar element ball diameter on slump value.

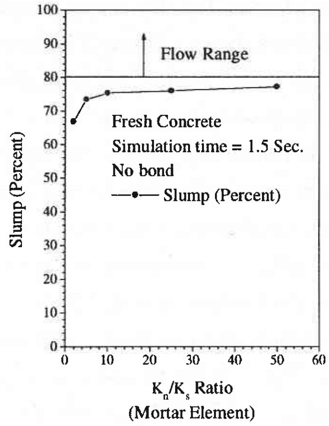

Fig. 6 Effect of stiffness ratio on the slump value.

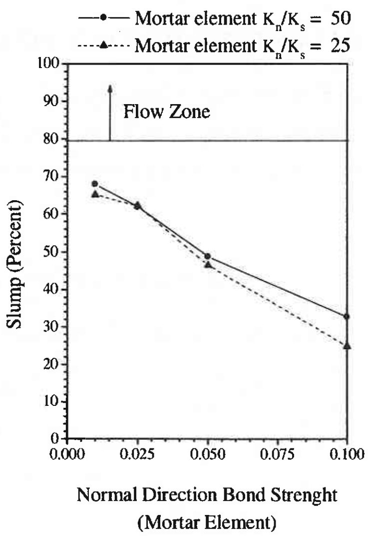

Fig. 7 Effect of bond on slump value.

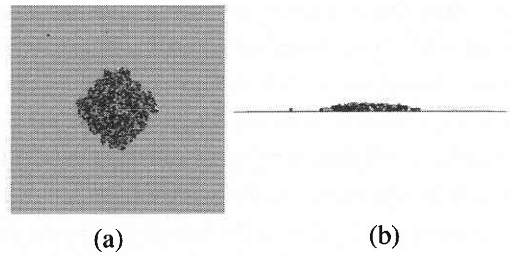

Fig. 8 Slump flow simulation. Simulation time 7.5 sec. (a) plan view (b) elevation view.

which is shown in Fig. 8. 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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REFERENCES

1) Ozawa, K., Sakata, N., and Okamura, H., "Evaluation of self-compactibility of fresh concrete using the funnel test", Transaction from the Proc. of JSCE, 90 (23) (1994–95) 59–75.
2) Nanayakkara, A.S.N. *et al.*, Deformation Field of Solid Phase within Tapered Pipe in Model Concrete Flow, The Second East Asia-Pacific Conference on Structural Engineering and Construction, Chiang Mai, 11–13 January 1989.
3) Pimanmas, A., Multiphase Model for Shear Constitutive behavior of Flowing Fresh Concrete, Master's Thesis Submitted to The University of Tokyo, September 1996.
4) Noor, M. A., and Uomoto, T. Three-Dimensional Discrete Element Model for Fresh Concrete, Journal of Institute of Industrial Science, Vol. 51 No. 4 1999.
5) Noor, M. A., and Uomoto, T. Verification Of The Three Dimensional Discrete Element Model For Fresh Concrete, Journal of Institute of Industrial Science, Vol. 51 No. 11 1999.