研 究 速 報

Numerical Simulation of Fresh Concrete (4)

Three-Dimensional Discrete Element Simulation of U-Box Boxed and V-Funnel Test for Self-Compacting Concrete

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1. INTRODUCTION

Self-compacting concrete, requiring no consolidation work in site, has been developed in Japan to improve the reliability of concrete, and concrete structures. The establishment of methods for the quantitative evaluation of the degree of self-compactibility is a key issue in establishing the mix design system. In the system currently proposed, the Boxed test, U-box test and V-funnel test are utilized as the means of evaluation. In this paper, the numerical simulation of these test methods has been described. The Boxed and U-box filling tests are another type of test to evaluate the ability of concrete to pass through reinforcing bars under its own weight. This evaluates self-compactability in terms of the concrete height after passing through parallel bars. The advantage of this test is the ease of measurement. The detailed dimensions of the Boxed and U-box test, used in the present simulation, are shown in Fig. 1. As a method of evaluating the self-compactibility of concrete, a technique has been proposed for measuring deformation rate. Conventional funnel tests are used to measure the apparent viscosity of paste and grout. A funnel test is a simple mean of evaluating the ability of concrete to pass through spaces. In other words, the funnel tests measured different relationships between solid particle size and funnel size in the case of concrete when compared with conventional relationships between powder particle and funnel size.

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 [1, 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 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 [3, 4]. In this paper, at first qualitative 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. The constitutive model used here is same as the constitutive model used in paper Noor and Uomoto [3, 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,

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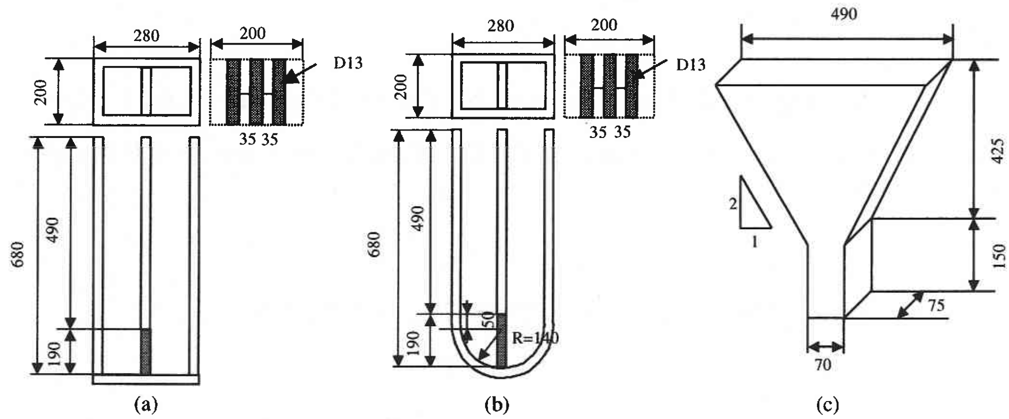


Fig. 1 The detailed actual dimensions of (a) Boxed, and (b) U-Box and (c) V-funnel. Simulation size is half of this size. (Dimensions in mm).

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 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 collided with the container walls and each other and computations were 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 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 [3] of mortar and aggregate has been calculated using the mix proportion shown in Table 1. To observe the effect of stiffness ratio towards the porosity of compacted state of Boxed test simulation, porosity has been calculated (Fig. 2) for different stiffness ratio. It is seen from the Fig. 2 porosity decreases as the stiffness ratio increases. So, by changing the stiffness ratio 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

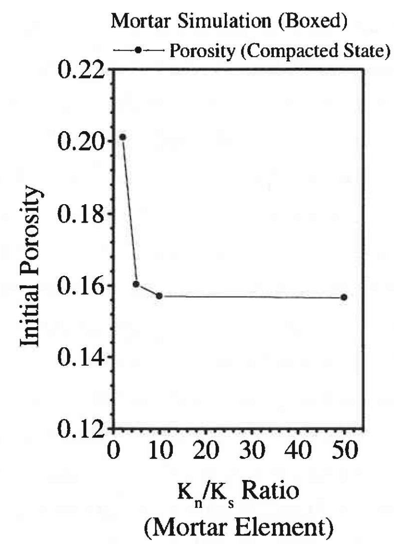


Fig. 2 Effect of mortar element stiffness ratio on porosity Boxed test.

4. BOXED AND U-BOX TEST

The one DEM parameter value selected for one simulation does not give guarantee that it will work for another simulation. For this reason the parameters that work for the slump flow simulation [5] may not work for the Boxed or U-box simulation. Detailed parametric study, which has been done to simulate slump, gives the guideline for any flow simulation. Boxed or U-box test is a kind of test, which also depends on the concrete flow. Before the final Boxed and U-box simulation only two parametric study have been conducted. In slump flow simulation the effect of the stiffness value of the aggregate element has not been looked into. One thing should be noted here that both the normal and shear stiffness of the aggregate element can be increased or decreased proportionately but the ratio of the normal stiffness to shear stiffness must be kept between 2/3 to 1. Because this has been proposed by previous researchers [6], for gravel like elements. Two runs were conducted to observe the effect of the stiffness of the aggregate element, which is shown in Fig. 3.

One thing that has been learned from the slump flow simulation is the effect of the ratio of the normal stiffness to the shear stiffness. To obtain this, normal stiffness has been kept constant and the shear stiffness has been decreased. To observe the effect of this ratio on the Boxed flow several simulation were conducted. The reason that Boxed has been chosen for this purpose is it is difficult for concrete to flow in Boxed test rather than U-box test. The result of this simulated value has been shown in Fig. 4. It can be said from Fig. 4 that this ratio has some influence on the flow of the concrete and larger the ratio larger was the rising height in the right side of the box of the Boxed test simulation. Again all this simulations were conducted with out any shear and normal direction bond.

From the above analysis the ratio of the normal stiffness to shear stiffness has been chosen as 50, and the normal stiffness value of the aggregate has been chosen 1E+05. With these selected parameters two final simulation one for Boxed and another for U-box have been conducted and their final simulation stage have been shown in Fig. 5 and Fig. 6, respectively. The value of the rising height for the Boxed is 11.5 cm and for the U-box is 12.1 cm. in simulation, which are approximately equal to 23 cm and 24.2 cm for real cases. In simulation, actual value does not have much importance but the qualitative result is important to analyze the internal behavior such as blocking of aggregate at the reinforcement etc. This confirms that flow also can be simulated using DEM model.

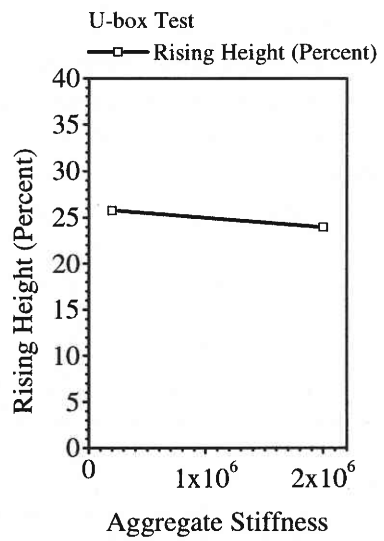


Fig. 3 Effect of aggregate stiffness on rising height of U-box test.

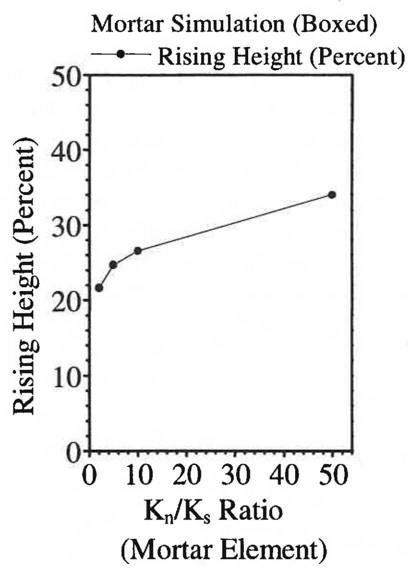
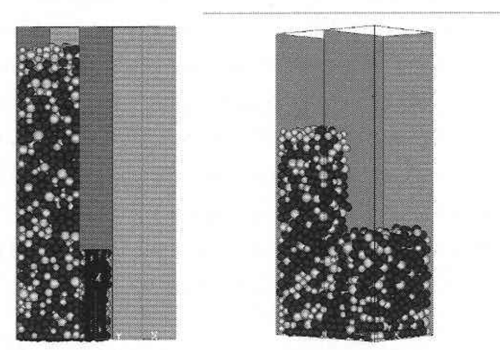
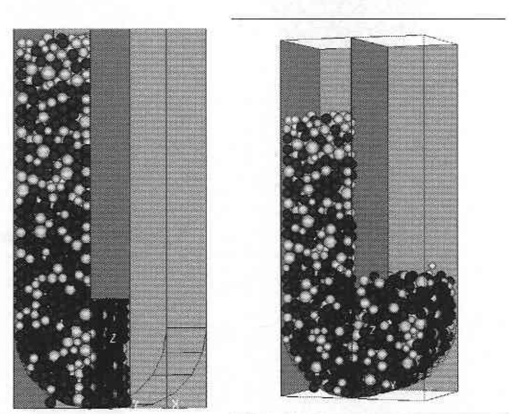


Fig. 4 Effect of mortar element stiffness ratio on the rising height of Boxed test.



(a) Start (b) Final

Fig. 5 Boxed Test simulation



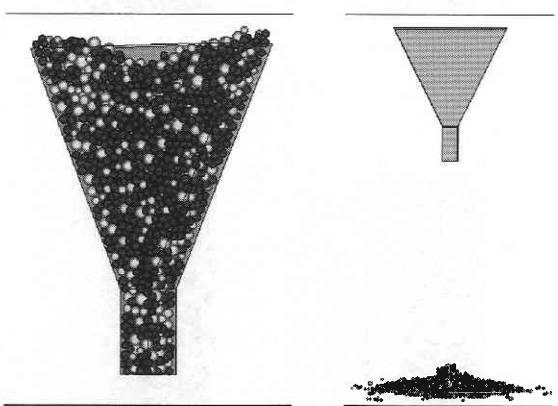
(a) Start (b) Final

Fig. 6 U-box test simulation.

5. V-FUNNEL TEST

As a method of evaluating the self-compactibility of concrete, a technique has been proposed for measuring deformation rate. Conventional funnel tests are used to measure the apparent viscosity of paste and grout. A funnel test is a simple mean of evaluating the ability of concrete to pass through spaces. In other words, the funnel tests measured different relationships between solid particle size and funnel size in the case of concrete when compared with conventional relationships between powder particle and funnel size.

Conventional funnels for concrete testing have a circular cross-section through which concrete undergoes a 3-D deformation. In actual formwork, however, concrete, deforms two-dimensionally when passing through such obstacle as reinforcing bars. Therefor, the funnel, which is shown in Fig. 1 (c), has been used for the current simulation, as funnel forces concrete to deform two dimensionally. After filling the funnel with concrete to its top edge the discharge port was opened and the time required for the concrete to flow out is measured. One simulation has been conducted using the DEM parameter selected in the previous analyses. For funnel simulation bond has been provided and the value selected for the bond is 0.025 N for both normal and shear direction. The time required to flow out all the concrete from the V-funnel has been found out equal to 9.5 sec., which is closed to the actual value, measured in experiment. The start and final stages of the V-funnel test are shown in Fig. 7.



(a) Start (b) Final

Fig. 7 V-funnel test.

6. CONCLUSIONS

In this paper, several consistency and flow test methods have been successfully simulated. The objective of the ongoing research is to find out the relationship between rheological constants and DEM parameters used in these tests. But the simulation of these three test methods warrants consideration before studying the relationship between rheological constants and DEM simulation values. Authors wish to produce the work on the relationship of DEM parameters and actual rheology in future publication. Initial results obtained from numerical experiment show that the discrete element simulation reproduces the qualitative behavior observed in fresh concrete. These preliminary results regarding flow simulation indicate that discrete element modeling approach may lead to a powerful modeling tool for simulating the behavior of fresh concrete. As the flow in concrete is confirmed in these simulations, then other flow related parametric study should be done very easily.

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