研究速報

吹付けコンクリートの特性に関する基礎的研究（3）

骨材の粒度分布を考慮した吹付けコンクリートのリバウンド性状に関する２次元個別要素法解析

Properties of Shotcrete (3)

Numerical Simulation of Shotcrete Rebound By 2D-DEM Considering Distinct Element Particle Grading

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1. INTRODUCTION

Shotcrete numerical simulation is a very difficult job because many conditions get involved in it resulting very troublesome to model it. So far, researchers. are concentrated on actual shotcrete experiment and later incorporating its idea back to material mix and shooting condition [1] to get more reliable shotcrete. Rebound is a very notorious behavior in shotcrete is affected by nozzle distance, nozzle orientation, particle size, shape and velocity, mix grading, cement content, water content, effects of admixtures and nature of the surface being sprayed [2]

ACI recommended practice for shotcreting mentions ASTM C33 grading must be satisfied for coarse aggregates. It is mentioned by Egger [3] that the maximum size of coarse aggregate should not exceed 10 mm. Otherwise, the diameter of hose pipe must be chosen four times the maximum size of coarse aggregate [3]. In this research, first time in the shotcrete research, the author propose the application of Distinct Element Method (DEM) to predict particle behavior and amount of rebound in shotcrete considering the influence of particle grading in a theoretical way. The element in DEM follows the practical real size of coarse aggregate particle as defined by the Fineness Modulus of its based on random variable generator.

2. IDEA OF SIMULATION

DEM is a very powerful tool for the flow simulation of granular media. However, in this research, the author extend this method to make it applicable to the flow modeling of granular-fluid mixture such as fresh concrete as the initial nature of shooting material in shotcrete. For the simplicity of the model, the interaction between fine aggregate and cement paste is neglected and mortar is considered by a constant thickness layer surrounding coarse aggregate modeled as a circular distinct element (*2-phase model*).

So, at the contact of two distinct particles, mortar layer comes first at the contact and once its deformation range is overcome, the inside element comes into play. DEM parameters of distinct element are obtained by wave propagation theory on objective media [4] while that of mortar is obtained from some trial simulations of consistency of fresh concrete. The more rigorous correlation between the DEM parameters of mortar and with the real design mix of concrete is still under author research concern. The details of the modeling idea is illustrated in Fig. 1. The principle roots in the calculation of total forces, moments acting on a particle in each small interval of time and later from this forces the instantaneous motion of the particle is calculated and the position of each particle is updated and preceded to the next time step. Total forces acting on an element are

$$F = \sum f_e + \sum f_m + f_g = m\ddot{u} \quad \cdots\cdots (1)$$

$$M = \sum M_e + \sum M_m = I\ddot{\phi} \quad \cdots\cdots (2)$$

where $f_e f_m$ and f_g are forces contributed by elements and mortar and gravity and M contributed by the same but moment, m is the mass of element $\ddot{u}$ and $\ddot{\phi}$ are the linear and angular accelerations respectively. I is the moment of inertia.

Criteria for failure mortar spring in tension

The rheological properties of mortar is mainly simulated in DEM by the thickness of its over the distinct element and the coefficient of allowable tension (R_d) in normal direction defined

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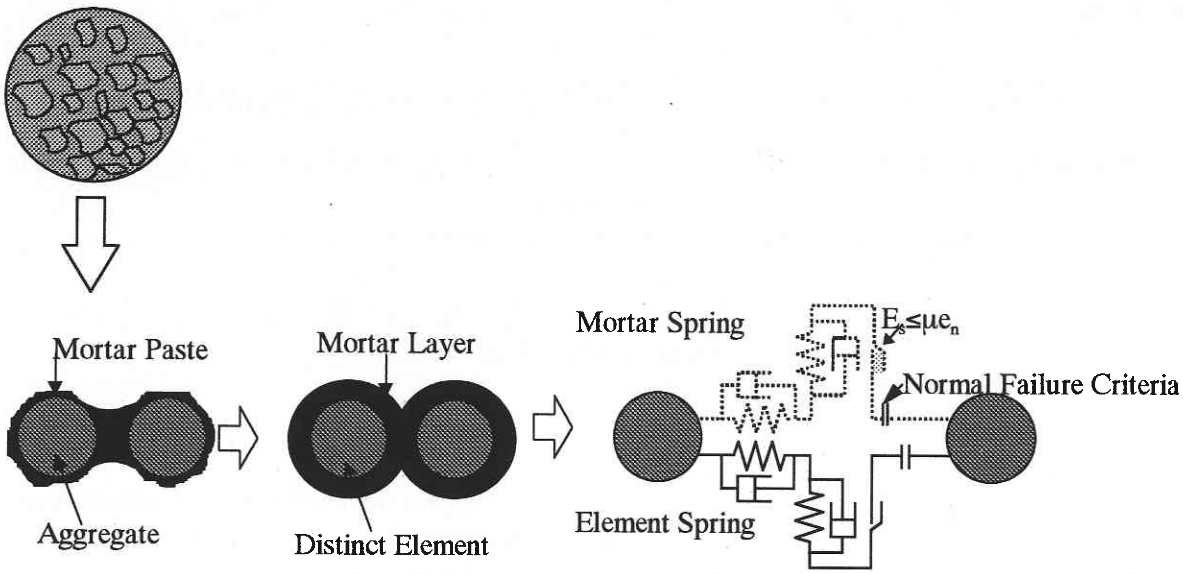

Fig. 1　DEM Modeling of Shooting Material (Concrete)

hereafter. In the beginning, allowable tension coefficient in shear direction has also been considered but from the many analysis of shotcrete phenomena, this coefficient was found to be insignificant, so author improved the efficiencies of the simulation by dropping this coefficient.

It should be noted that here the maximum deformation level that the mortar takes before breaking is made proportional to the particle radius to reflect the reality that role of mortar is predominate if it is in between the closely spaced particles than that of widely spaced. When an assembly of elements hit on the target wall, the failure criteria of preceding element was taken as that of the following one to offer the easiness on the attachment of smaller particle than the bigger particles, which is observed reality in shotcrete experiment.

3. SIMULATION SCHEME

A program based on random integer generator was developed to produce granular assemblages with required Fineness Modulus of coarse aggregate. This was done so as to incorporate the real size particle available in a typical mix proportion of concrete.

The particle assembly defined by three Fineness Module as seen in Table 1 was used and DEM simulation is done. In this analysis, the other properties of mortar and target wall and shooting condition were not changed. From the simulation, the effect of particle size distribution on rebound and attaching mechanism has been obtained clearly.

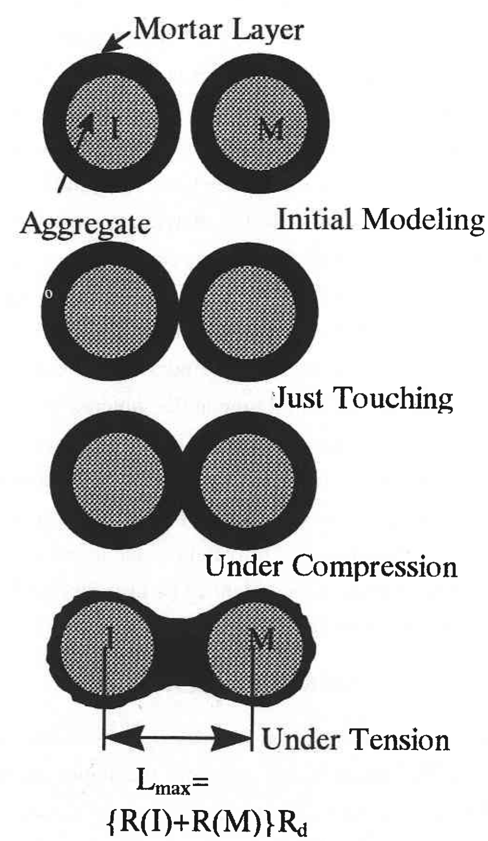

Fig. 2　Criteria for Failure Mortar Spring in Tension

4. DISCUSSION ON THE RESULTS

The properties of the springs and others of the model was kept same in the entire simulation to indicate the more specific concrete modeling at certain mix proportion of shooting concrete and shooting condition in real situation. The random particle radius based on above FM is generated and then assembled in the hopper shape device with the L-shape at the base enclosed by a rectangular boundary (*called shotcrete site*). The complexity in the shape of the device was incorporated to take into account the bends and kinks at the hose pipe of shotcrete to

Table 1　Coarse Aggregate Content

Analyzed Cases	Case-1	Case-2	Case-3
Fineness Modulus (FM)	6.91	7.70	8.40

Table 2　Rebound versus FM

Analyzed Cases	Case-1	Case-2	Case-3
Rebound % wt	19.60	50.68	58.75
Initial FM	6.91	7.70	8.40
FM of Rebound	7.39	7.94	8.64

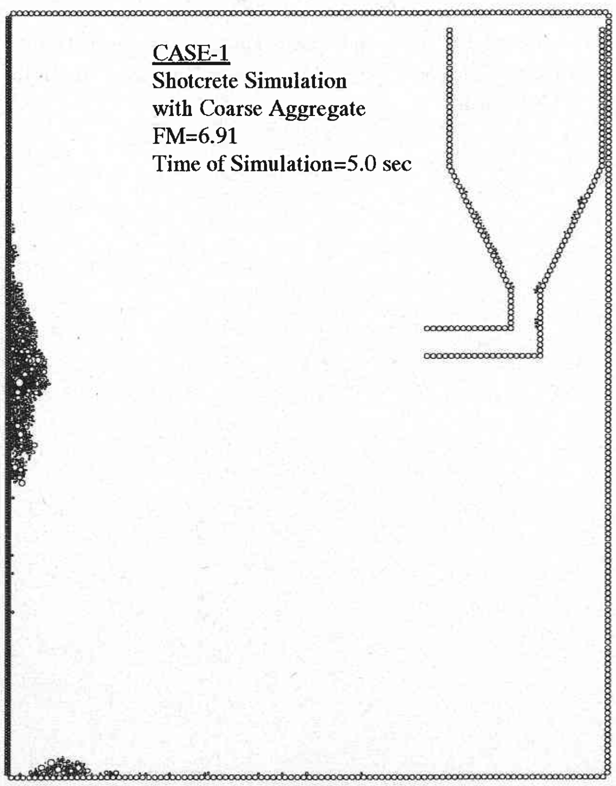

Fig. 3　Shooting Simulation with FM=6.91 at time 5.0 sec

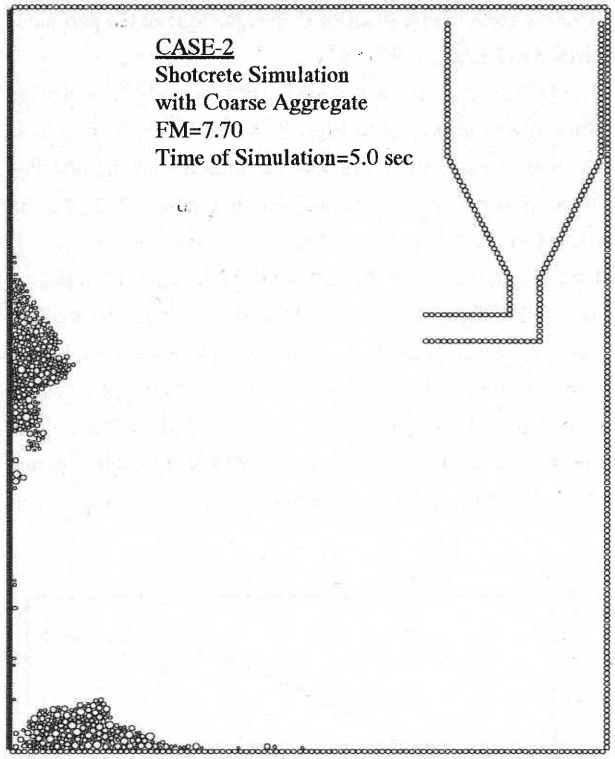

Fig. 4　Shooting Simulation with FM=7.70 at time 5.0 sec

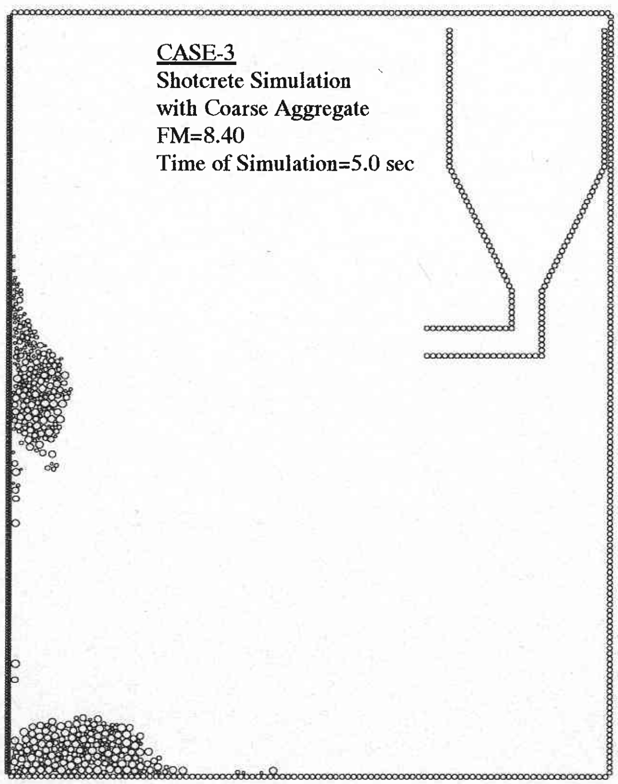

Fig. 5　Shooting Simulation with FM=8.40 at time 5.0 sec

deliver concrete in real situation. Then, the assembled particle is subjected to DEM simulation.

The DEM simulation was done for 5.0 sec and the final stage of shooting is indicated in Figs. 3, 4 and 5. From the visual inspection, it can be realized that the integrity of the attached concrete is highly affected by the particle grading. The effect of particle FM on the resulting rebound is shown in Fig. 6. It is reflected from this figure that rebound can be reduced greatly by incorporating finer particle in the mix. However, in this analysis for the given mix proportion, shooting condition and wall condition, smaller FM seems very much effective to reduce rebound than the bigger value. And also FM in the smaller range is more sensitive to make change in resulting rebound that in the larger range for the given material mix condition, shooting conditions. Table 2 shows the value of rebound measured and FM of the rebound.

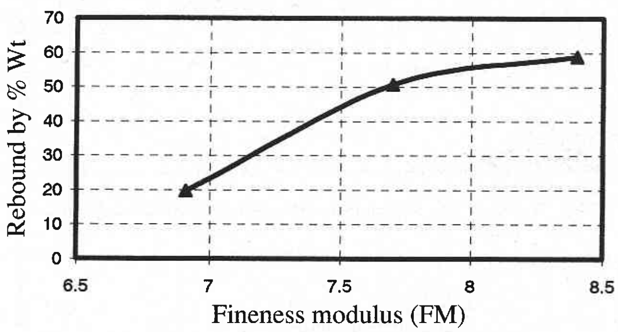

Fig. 6 Rebound by % Wt. versus FM

5. CONCLUDING REMARKS

1. The grading and FM of coarse aggregate greatly differed the shooting behavior and the amount of resulting rebound.

2. The smaller FM was more sensitive to the change in rebound than the larger FM for the given material mix condition, shooting conditions.

3. The FM of rebound collected was much higher than that of shooting material which verifies the rebound always comprises of mainly bigger size particles of the designed mix.

(manuscript resevied, August 11, 1997)

6. REFERENCE

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