論文 Findings of the Effects of Nozzle Orientation on Shotcrete from Numerical Analysis

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ABSTRACT: Shooting of equal consistency of concrete from vertical to overhead does not turn out the differences in rebound loss and its mechanism. Careful examination of the mechanics of an aggregate particle rebounding from a fresh shotcrete substrate reveals that the accelerations involved in the process are hundreds of times greater than that of gravity, indicating that gravity has little effect on rebound mechanism of aggregates. Also, in shotcreting it is a good way to shoot always perpendicular to the target wall with a view of minimal rebound loss and dense shotcrete. In this research, author presents analytical findings on nozzle orientation it by using Distinct Element Method (DEM) [1].
KEYWORDS: shotcrete, DEM, nozzle orientations, law of reflection of light

1. INTRODUCTION

Shotcrete has been referred to by such terms as gunite, pneumatically applied mortar or concrete, sprayed concrete, spraycrete, in general. Shotcrete has been a very potential repair material for the deteriorated concrete structures such as reservoir linings, dams, tunnel, shafts elevator, repair of earthquake and fire damages to masonry and concrete structures in these days around the world. However, the rebound during shotcrete is an inevitable phenomena. Excessive rebound not only increases the material cost in the beginning but also it hampers the durability of shotcrete in the long run. 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]. Due to this fact, author's concern directed toward the estimation of rebound loss and its mechanism from the analytical way.

The analytical flow simulation of fresh concrete is a recent challenge to the researchers. Due to the heterogeneity of the concrete mix, it shows neither a perfect viscous or particulate behavior. However, by grasping the particulate behavior of flow of fresh concrete like arching and blocking in pipes and in complex boundary conditions which is further magnified when it is exerted with high pressure as in the case of shotcreting, authors for the first time in the shotcrete research, proposes the application of Distinct Element Method to predict particle behavior and amount of rebound in shotcrete

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considering the influence of real size particle grading in a theoretical way. In this research, the shotcreting condition with different nozzle configurations (from vertical to overhead) and its consequent effects on rebound mechanism while shooting of concrete of equal consistency have been elucidated clearly. Shooting thickness should be properly selected both in vertical and overhead shotcreting to avoid sagging and sloughing due to excess shooting. Also, average acceleration involved in the penetration and reaction phases is hundreds of times greater than that of gravity indicating that gravity has little effect on the rebound mechanism of aggregates. The fluctuation in rapid hardening effects of accelerating agents gives a major difference in shooting for different nozzle configurations. Otherwise, the position of shooting is independent of rebound mechanism unless shooting is in angle.

2. PRINCIPLE OF SIMULATION

DEM is a very powerful tool for the flow simulation of granular media. However, in this research, the author extended 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*). The elements in DEM follow the practical real size of coarse aggregate particles as defined by the Fineness Modulus (FM) based on random variable generator.

As the fresh concrete is modeled as two phased materials, 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 while that of mortar is obtained from some trial simulations of consistency test for fresh concrete. Authors are working for the correlation of DEM parameters with mix proportion of concrete. The detail 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 these forces and moments 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

$$F = \sum f_e + \sum f_m + f_g = m\ddot{u} \tag{1}$$

$$M = \sum M_e + \sum M_m = I\ddot{\phi} \tag{2}$$

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. I is the moment of inertia. $\ddot{u}$ and $\ddot{\phi}$ are linear and rotational accelerations. The rheological property 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 hereafter. R_d is the percentage of allowable elongation of mortar spring before it fails which is a strain-controlled failure criteria for ease in understanding despite for stress-controlled failure criteria specified before [3]. 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 the author improved the efficiencies of the simulation by dropping this coefficient [3]. The new failure criteria of mortar spring in tension is illustrated in Fig. 2.

Here, it should be noted that 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 predominates more if it is in between the closely spaced particles than that of widely spaced. When an assembly of elements hits 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 particles than the bigger particles, which is the observed reality in shotcrete experiment. The simulation condition was prepared by random packing of random particle radius generated based on practical FM in the hopper shape device with the L-shape at the base enclosed by a rectangular boundary and then the situation is subjected to DEM simulation [3].

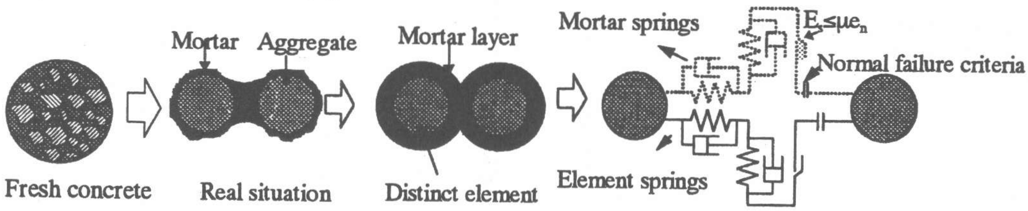

Fig.1 DEM modeling of shooting material (concrete)

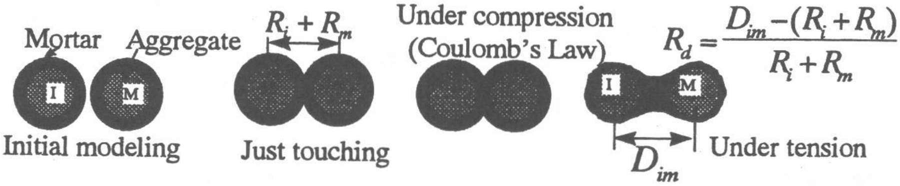

Fig.2 Criteria for failure of mortar spring in tension

3. SHOTRETE SIMULATION FOR DIFFERENT CONFIGURATIONS OF NOZZLE

In this simulation, the principle concern is directed toward getting the fact hidden on only the effects of nozzle orientation on rebound loss and the mechanism at shooting of same consistency of concrete at different nozzle positions. So, the properties of mortar and target wall (DEM spring parameters) were not changed in the entire simulation to indicate the more specific concrete modelling at certain mix proportion of concrete and shooting condition in real situation and then, DEM simulation was done for different nozzle orientations as shown in the following figures.

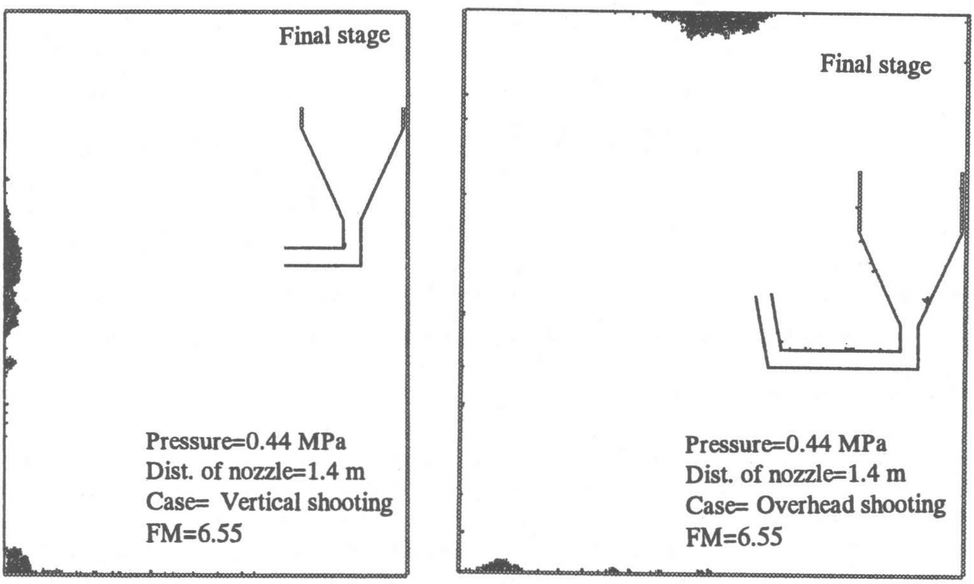

Fig. 3 Shotcrete simulation for vertical and overhead shooting (5 sec simulation)

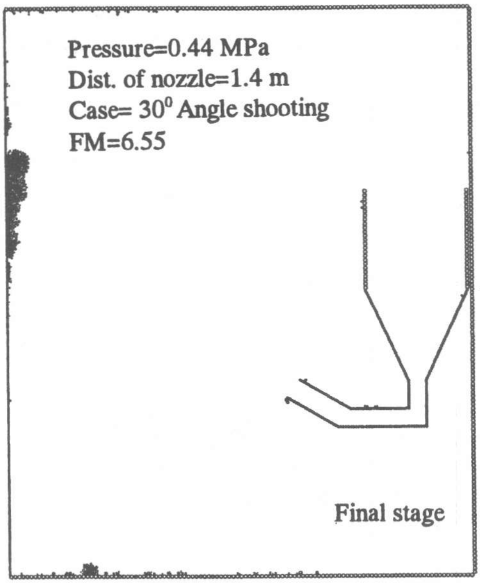

Fig. 4 Shotcrete simulation for 30° angle shooting (5 sec simulation)

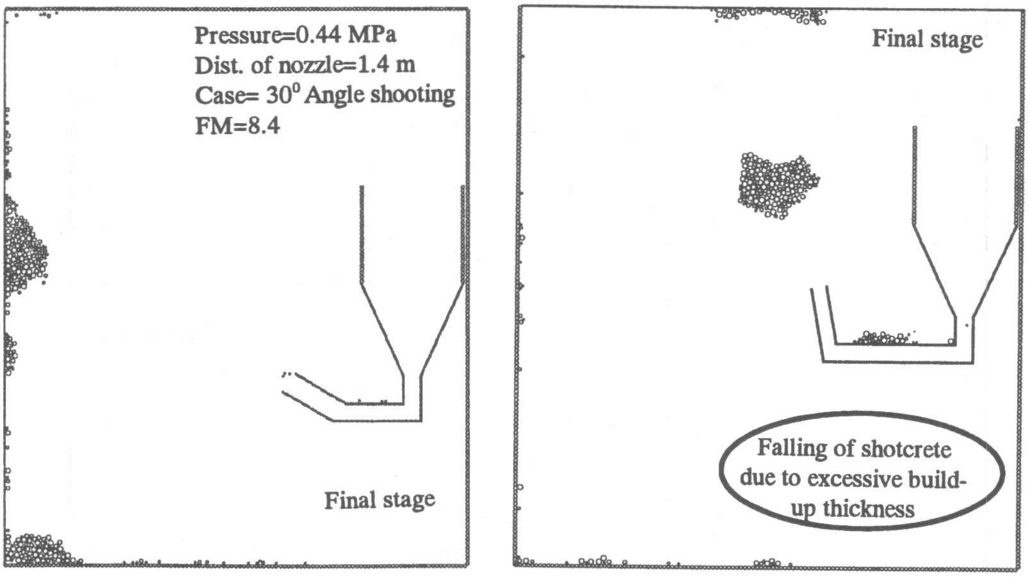

Fig. 5 Shotcrete simulation for 30^0 angle and overhead shooting (5 sec simulation)

4. DISCUSSION ON THE RESULTS

From above simulation, it is clear that, shooting of equal consistency of concrete from vertical to overhead does not turn out the differences in rebound loss and its mechanism (Figs. 3, 4 and Table 1). Although this is somewhat contrary to intuition, similar conclusion has also been drawn from the experimental result [4]. Careful examination of the mechanics of an aggregate particle rebounding from a fresh shotcrete substrate reveals that the acceleration involved in the process are hundreds of times (for short time instant while particle just hits and rebounds, fraction of millisecond) greater than that of gravity: for a 9.5 mm aggregate the average acceleration during the penetration and reaction phases are, respectively, 50,000 and 2,000 m/s^2 indicating that gravity has little effect on rebound mechanism of aggregates [4]. Therefore, it is not surprising that shooting conditions of equal shotcrete consistency, the position of shooting does not play major role in the rebound process. But the position of shooting might affect if shooting is done with very dry, wet consistency, less hardening effect of accelerating agent and shot for excessive thickness. This makes ultimate weakening of proper adhesion of shotcrete and is vulnerable to the position of shooting.

A 30^0 angle shooting is presented in Fig. 4 with FM equal to 6.55. For the small sizes of particles shooting spreads in a wider space over the target wall and less shooting thickness, so less rebound. To make clear the effect of the inclination angle of nozzle, shooting simulation with a little bigger size (FM=8.4, Sp. Gr.=2.68) is presented in Fig. 5. Simulation showed that the nozzle inclination gives more scatter of hitting particles and a growth in material loss. A major conclusion drawn from this research is that the inclination angle of nozzle is a principle factor to determine the rebound loss irregardless of the position of the nozzle. Thus, in shotcrete it is more appropriate to shoot always perpendicular to the target wall with a view of minimal rebound loss and dense shotcrete. However, in case of shooting over reinforcing bar and overhead shooting, nozzle inclination is inevitable for both good and safety in shotcreting at which the material loss must be sacrificed. In this research, it is clarified that the shotcreting is not much different, provided that shooting is done perpendicular to the target wall no matter whether vertical or overhead shooting. This explains the insignificance of the effect of acceleration due to gravity in attaching mechanism in shotcrete. However, the incident angle in shooting, if it is more than 30° the shooting phenomenon is quite different in term of rebound loss and quality assurance.

Table 1 Rebound loss and shooting profile

Shooting profile	Vertical	Overhead	Angle-1	Angle-2
Rebound % wt	32.28	28.45	25.42	38.26
Initial FM	6.55	6.55	6.55	8.40
FM of Rebound	6.61	6.62	6.60	8.64

Analogy between Particle Rebound and Law of Reflection of Light

The particle rebound in shotcrete is partially analogous to the law of reflection of light well established in physics which states as follows: (subjected to the surface condition of a target wall)

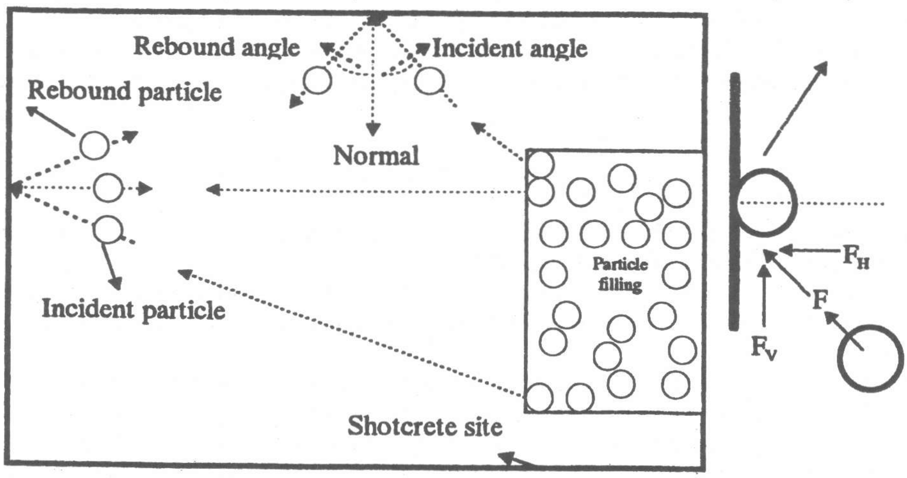

Fig.6 Analogy between particle rebound and law of reflection of light

- Particles hitting normally (incident particle) on the target wall are apt to rebound normally.
- Incident angle is likely equal to the rebound angle.

Particles hitting normal to the target wall are likely to rebound normally if the adhesive force between wall and particles is not sufficient enough to hold it on. In addition, if the particle hits on the target wall with some angle to the perpendicular on the target wall (incident angle), the particle rebounds with the equal angle (rebound angle). After rebound the trace of particle is little affected by gravity provided that the acceleration is minimum but this phenomenon is very analogous to the law of reflection of light and is illustrated in Fig. 6. At angle shooting, vertical resolved component (F_V) of resultant approaching force (F) of hitting particle, forces the particles to roll or slide over the target wall and increases rebound loss while that will be nil in vertical shooting with zero incident angle.

Due to the particles hitting normally on the target wall will rebound normally, they are again shot back by the incoming particle in perpendicular shooting (continuous shooting), so those particles instead of rebounding again shot over the target wall, ultimately the rebound will decrease. Contrary to perpendicular shooting, if particles are shot at some angle, the rebound will no more be back shot by incoming particles as in the case of perpendicular shooting which results in high rebound loss and less compaction in angle shooting. It is very important to note that shotcreting should always be done perpendicular to the target wall and angle shotcreting should be avoided what so far possible (for eg., in the case of reinforced shotcrete where shooting must be done in angle).

5. CONCLUSIONS

1) DEM proves to be a very potential tool for the different phenomenal simulation of shotcrete.
2) It is clarified that the shotcreting in term of rebound loss is not much different provided that shooting is done perpendicular to the target wall no matter whether vertical or overhead shooting.
3) Acceleration due to gravity is insignificant to the attaching mechanism in shotcrete. However, the incident angle in shooting, if it is more than 30° the shooting phenomenon is quite different in term of rebound loss and quality assurance.
4) It is recommended to all practical workers that shotcreting should always be done perpendicular to the target wall and angle shotcreting should be avoided what so far possible except for reinforced shotcreting where angle shooting must be for perfect encasement of reinforcing bars.
5) The particle rebound has been analogized with the theory of reflection of light in physics. The rebound mechanism of particles in shotcreting is very analogous to the theory of light reflection.

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