研究速報

Properties of Shotcrete (10)

Nozzlings versus Rebound Loss in Shotcrete

吹付けコンクリートの特性に関する基礎的研究（10）
—吹付けコンクリートのリバウンドとノズル角度—

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1. INTRODUCTION

Shotcrete is an important component of modern underground construction and tunnelling activities. In tunnelling procedures employing the New Austrian Tunnelling Method (NATM), the tunnel walls are shotcreted immediately after excavation of the rock, with the concrete setting within a few seconds. Its main function is to preserve the stability of the rock until the final tunnel has been put in place and to protect the workers and machines operating at the site from danger of rockfall.

Proper nozzling in shotcrete depends on the skill of a nozzleman. It is recommended that, "to uniformly distribute the shotcrete and minimize the effect of slugging, the nozzle should be perpendicular to the surface and rotated steadily in a series of small oval or circular pattern. Waving the nozzle quickly back and forth changes the angle of impact, wastes material, increases overspray, and unnecessarily increases the rough texture of the surface"[1]. Here, the Distinct Element Modeling (DEM) of shotcrete[2] is shown for various nozzlings and qualitative conclusions are drawn. Nozzlings can be back and forward, angle, up and down. The nozzle position can be horizontal or vertical. Among many nozzlings, back and forward nozzling is a worst nozzling.

2. REBOUND IN SHOTCRETE

Rebound is aggregate and cement paste that ricochets off the surface during the application of shotcrete because of collision with hard surface, reinforcement, or with the aggregate themselves. Rebound is highly dependent on material quality, mix proportion and shooting condition. Mainly these factors are related to the constituent of concrete to be shot and application conditions. Factors related to the constituent of concrete to be shot are their quality and quantity. Factors related to application conditions are shooting pressure, angle in shooting and target wall characteristics, etc.

Initially the percentage of rebound is large but it becomes less after a plastic cushion has been built up. Rebound is much leaner and coarser than the original mix. Therefore, the cement content of the in place shotcrete is higher because of rebound. This increases the strength but on the contrary increases the tendency toward shrinkage cracking.

3. DIFFERENT NOZZLINGS IN SHOTCERETE

a) Back and forward nozzling

Pressurized consolidation is a very important fruit of shotcreting. However, a poor selection of shooting pressure has bad effects 2). Backward and forward nozzling produces a change in shooting pressure and causes a similar effect as the change of pressure results as shown in Fig. 1. In all simulations, the shooting situations are pressure = 0.44MPa, Dist. of nozzle = 1.4m and FM = 6.34.

b) Inclinations of nozzle

It is known that[3], shooting of equal consistency of concrete from horizontal to vertical does not turn out the differences in rebound loss and its mechanism. Although this is somewhat contrary to intuition, similar conclusion has also been drawn from the

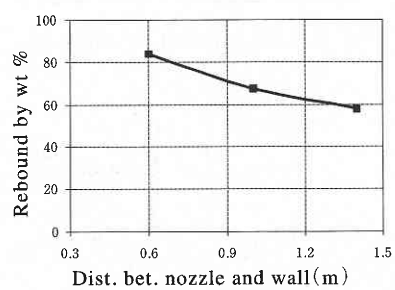

Fig. 1 Rebound by wt. % versus dist. between nozzle and wall

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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 greater than that of gravity. For a 9.5mm aggregate, the average acceleration during the penetration and reaction phases are 50,000 and 2,000 m/s2 respectively indicating that gravity has little effect on rebound mechanism of aggregate[5].

But the position of shooting might affect if shooting is done with dry or wet consistency, less hardening effect of accelerating agent and shot for excessive thickness. These make ultimate weakening of proper adhesion of shotcrete and are vulnerable to the position of shooting.

Angles in shotcrete impair shotcrete performances to a large extent[3]. Now, the principle concern is directed towards getting the hidden facts on only effects of nozzle orientation (as shown in Fig. 2, horizontal shooting, upper angle shooting and vertical shooting) on rebound loss and the mechanism. The properties of mortar and target wall (DEM parameters) are not changed in the entire simulation. This indicates certain mix proportion of concrete and shooting condition in real situation.

Extensive calculations are performed with upper angles 0°, 10° 30° 40° and lower angles. Simulation showed that the nozzle inclination gives more scatter of hitting particles and a growth in material loss. A major conclusion drawn from this study is that the inclination of nozzle is a principle factor to change in rebound loss independent of the position of the nozzle. If the angle of shooting is more than 10°, the shooting phenomenon is quite different in term of rebound loss and quality assurance as shown in Fig. 3. The upper angle shooting and the lower angle shooting gave similar effect[2]. Simulations for different angles are shown in Fig. 4. In horizontal shooting, the particles hitting normally on the target wall will rebound normally. Upon continuous shooting, they are again shot back by the incoming particle, so these particles will shot over the target wall instead of rebounding. Hence the rebound will decrease. Contrary to horizontal shooting, if particles are shot at some angle, the rebound particle will no more be back shot by incoming particles which results in high rebound loss and less compaction.

Thus, it is important to note that, shotcreting should always be done perpendicular to the target wall and angle shotcreting should be avoided as far as possible (for eg., in the case of reinforced shotcrete where shooting must be done in angle).

Warner[6] reports the nozzle should be directed toward the application surface at an angle as close possible to 90° and in no case less than 45°. However, in case of shooting over reinforcing bar and vertical shooting, nozzle inclination is inevitable for both good and safety in shotcreting at which the material loss must be sacrificed.

(c) Upward and downward nozzling

In the entire simulations presented here, the nozzle is always fixed at a certain position. Shooting thickness is not more than 60

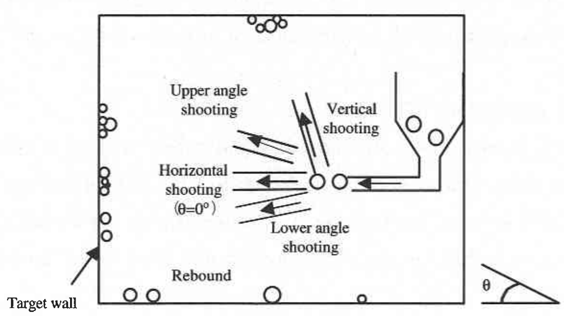

Fig. 2 Analyzed nozzle orientations

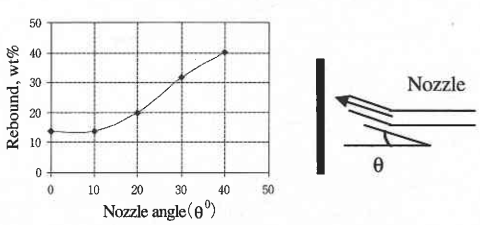

Fig. 3 Effect of angle in shotcrete

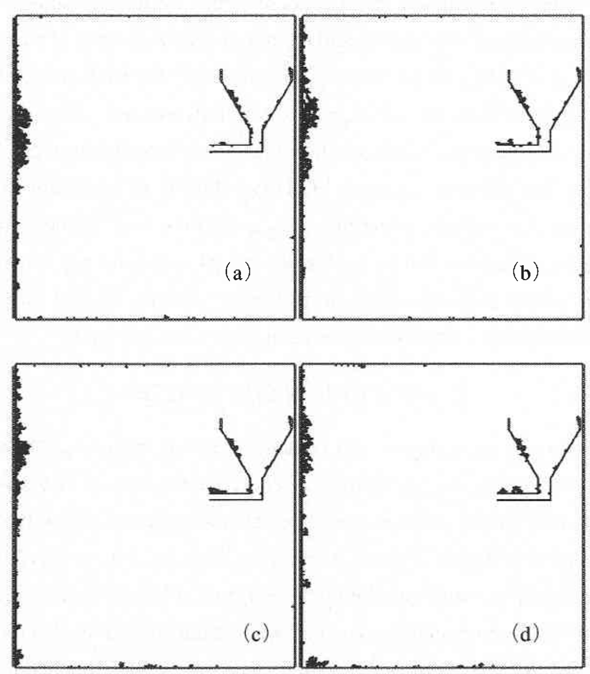

Fig. 4 Angle shootings with (a) 0° angle (b) upper 20° angle (c) upper 30° angle and (d) upper 40° angle

mm. So, excess shooting at same position produces the larger thickness. Because of this, the stress produced in the mass overcomes the adhesive stress, and slugging occurs. Slugging failure is shown in Fig. 5(b). The attached concrete supports itself till shooting only 220 particles as shown in Fig. 5(a) (thickness within 60mm), but the slugging failure occurs when it is increased to 304 particles (Fig. 5b).

Moving the nozzle vertically up and shooting all particles, the slugging failure does not occur as shown in Fig. 5(c). It is because shooting is distributed in wider spaces keeping thickness not more than 60mm. So, the thickness plays an important role in shotcrete and should be properly selected. Shotcrete can be done to a large thickness by making concrete more cohesive and adding more accelerating agent.

Thus, it is obtained that among different nozzlings, the angle nozzling and back and forward nozzling greatly hamper the shotcrete performances. In these two nozzlings, the angle nozzling is not devastating up to the permissible angle (in this calculation 10°), but back and forward nozzling shows a worst case.

4. REBOUND LOSS VERSUS TIME OF SHOOTING

In shotcrete, the particle rebound is highly affected by the paste (cement paste in case of mortar shotcrete and mortar in case of concrete shotcrete) either surrounding fine aggregates (or coarse aggregates) or appearing freely in the interstice of them[7]. It is because the attaching mechanism of large shot particles on the target wall is highly governed by the formation of thin cushion of paste mortar which is ultimately controlled by the mix proportion, shooting and target wall characteristics. A numerical simulation is presented capturing rebound at different interval of shooting time. It is seen that, first the smaller particles attach on the wall while bigger particles fall down and so the rebound mostly contains bigger particle sizes. The smaller particle hitting to the wall offers wider zone to catch the kinetic energy and attaches easily on the target wall. Once these smaller particles form a soft enough viscous platform on the target, it starts to catch the bigger particles into it (it is shown in Fig. 5(d) 1.5s after out of 6s shooting time). So at the later stage, the bigger particle sizes also get attached on the wall.

Due to this unavoidable phenomenon in shotcreting, the rebound of the particle goes on changing and is determined by the shooting time and shooting thickness as shown in Fig. 6. At the present stage, the experimental correlation of the DEM parameters for mortar is not yet defined. So, the quantitative comparison of results of DEM simulation and experiment can not be done. However, the qualitative comparison of the results is very useful.

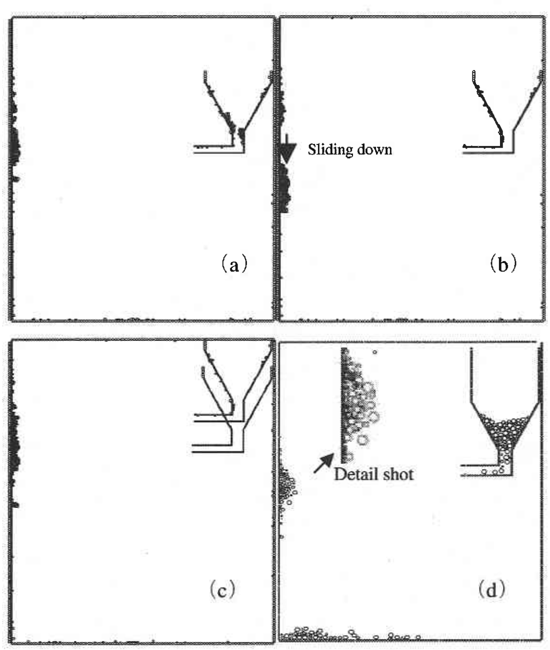

Fig. 5 (a) Shooting 220 particles (b) shooting 304 particles (c) nozzle moving vertically upward (d) shooting stopped at 1.5 s out of total 6 s (different element size)

5. CONCLUDING REMARKS

1. DEM proves to have great potential for different phenomenal simulations of shotcrete.

2. If the incident angle in shooting is more than 10°, the shooting phenomenon will be quite different in term of rebound loss and quality assurance.

3. It is recommended that shotcreting should always be done perpendicular to the target wall. Angle shooting should be avoided as far as possible except for reinforced shotcreting where angle shooting must be done for the perfect encasement of reinforcing bars.

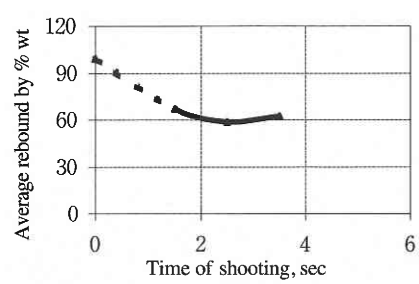

Fig. 6 Average rebound verses shooting time

4. Due to the time required to form a soft thin cushion of fines on the wall, particle rebound is highly dependent on the amount of shooting time and thickness.

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