Research on Rebound Rate of Nano-Scale Admixture Wet-Mix Shotcrete

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Abstract. High rebound rate and low construction efficiency are outstanding problems for traditional shotcrete. To solve these problems, Nano-scale admixture (NSA) was used to prepare high performance wet-mix shotcrete. Tests of sidewall rebound rate and overall rebound rate were carried out to study the effect of NSA. A total of eight mixtures were measured to assess the effect of impact factors such as active admixture variety (silica fume and NSA), NSA content (7.5%, 10% and 12.5%) and NSA fineness (128nm, 137nm and 147nm) on rebound rate. The results indicated that the sidewall rebound rate and overall rebound rate of shotcrete were reduced by 17% and 25% respectively when NSA replaced silica fume at the same content, which was about 10% with respect to the total amount of cementing materials. Rebound rate decreased as NSA content increased from 7.5% to 12.5%. Rebound rate also could be reduced when particle size of NSA decreased from 147nm to 128nm. The results confirmed the role of NSA in reducing rebound rate of shotcrete. NSA could promote the adhesion between shotcrete and receiving surface, improve the cohesion in mixtures, which could keep such as coarse aggregate, synthetic fiber from being rebounded out of cementing paste. Therefore, the rebound rate was reduced.

1. Introduction

Shotcrete lining has become the main support structure in underground openings, which can reduce the risk of collapse and rock burst during construction. Especially in southwest of China shotcrete lining is widely used. In recent years with the advance of the great western development strategy, high ground stress and high external water pressure are prominent problems, which make it difficult to support and construct safely. The hydraulic tunnel at Jinping hydropower station can be taken as an example, of which the maximum depth is 2525m, of which the maximum external water pressure is 10.2MPa [1], of which the typical ground stress is 35.7MPa [2]. It is difficult for traditional shotcrete to satisfy the demand of fast supporting, and keep surrounding rock stable timely. That is a great challenge.

Corresponding measures must be done to ensure the normal construction in bad geological condition with high ground stress and high external water pressure. Rebound is a typical characteristic of shotcrete differing from normal concrete, which limits construction process of shotcrete lining especially. Therefore, rebound rate has become one of the most critical properties. Consequently, reducing rebound rate is an important measure to support rapidly and timely. One way to reduce rebound rate is to incorporate superfine cementing powder as fly ash, silica fume, metakaolin and ground granulated blast furnace slag [3,4]. In the superfine cementing powder, silica fume was the most effective component to reduce rebound rate. Maybe the fineness was a critical factor. Hence,
Nano-scale admixture (NSA) was introduced to shotcrete. NSA could reduce rebound rate [5,6] and promote compressive, tensile, flexural, bond strength [7,8]. A lot of attention has been paid to the influence of NSA on rebound rate [9,10]. NSA at the content of 10% could reduce rebound rate by about 52% to 72%. The time taken in each excavation and supporting cycle was reduced by 0.7 hours, which had been proved in Baihetan hydropower station, Guolangqiao hydropower station, Beijing-Zhangjiakou intercity railway and Chengdu Subway by application of in-situ spraying tests. However, NSA remains a new product for shotcrete. Little attention has been paid to analyze the distinction of silica fume and NSA in reducing rebound rate. In addition, the fineness and content of NSA also need to be optimized based on rebound rate. What is more important is that much further work about the mechanism that NSA reducing rebound rate needs to be done.

In this study, rebound rate of shotcrete was tested using wet sprayed machine. The different effects of NSA and silica fume on rebound rate were studied. The roles of NSA content and fineness in reducing rebound rate were also assessed. After that, the mechanism that NSA reducing rebound rate was discussed.

2. Materials and methods

2.1. Materials
Portland cement with a fineness of 340 m²/kg, a specific gravity of 3.11, and 28-d compressive strength of 53.0 MPa. Silica fume with a fineness of average particle diameter of 168 nm, a SiO₂ amount of 92%. Three NSA marked as N1, N2 and N3. The fineness of average particle diameter of N1, N2 and N3 were 128 nm, 137nm and 147nm, respectively. The SiO₂ content for these three NSAs are separately 82%, 84% and 84%. Manufactured sand of marble rocks crushed with a fineness modulus of 2.8, a stone powder content of 12.5%, a saturated surface-dry water absorption of 1.30%. Manufactured stone of marble rock crushed with a specific gravity of 2.67, a particle size between 5mm and 15mm. The water reducer was a powder of polycarboxylic acid with a water reducing rate of 26% when 0.1% was added. The alkali-free liquid accelerating agent with a compressive strength rate of 95%, an initial setting time of 3.3 minutes and final setting time of 8.5 minutes when 8% was added. Macro synthetic polypropylene fiber with a length of 30mm and equivalent diameter of 0.81mm, a tensile strength of 474 MPa, an elastic modulus of 6.0 GPa.

2.2. Mix compositions
The mix compositions of shotcrete were given in Table 1.

Table 1. Mix compositions of shotcrete (kg/m³).

| Mixture | Cement | Silica fume | NSA | Sand | Stone | Water | Steel fiber | synthetic fiber | Water reduce | Accele- rator |
|---------|--------|-------------|-----|------|-------|-------|-------------|----------------|--------------|-------------|
| S10F8   | 419    | 41.9        | 0   | 1006 | 670   | 201   | 0           | 8              | 0.46         | 36.9        |
| S10G40  | 419    | 41.9        | 0   | 1006 | 670   | 201   | 40          | 0              | 0.46         | 36.9        |
| N1-10F8 | 419    | 0           | 41.9| 1006 | 670   | 201   | 0           | 8              | 0.65         | 36.9        |
| N1-10G40| 419    | 0           | 41.9| 1006 | 670   | 201   | 40          | 0              | 0.65         | 36.9        |
| N2-10F8 | 419    | 0           | 41.9| 1006 | 670   | 201   | 0           | 8              | 0.55         | 36.9        |
| N3-10F8 | 419    | 0           | 41.9| 1006 | 670   | 201   | 0           | 8              | 0.55         | 36.9        |
| N1-07F8 | 419    | 0           | 41.9| 1006 | 670   | 201   | 0           | 8              | 0.46         | 36.9        |
| N1-12F8 | 419    | 0           | 41.9| 1006 | 670   | 201   | 0           | 8              | 0.69         | 36.9        |
In the shotcrete mixtures, Portland cement was replaced with silica fume or NSA by 10%. Concrete mixture was replaced with steel fiber or synthetic fibers in a volume percentage of 0.5% and 0.9%, respectively. The slump up of mixtures varied between 190mm and 210mm. N1, N2, N3 represented three kinds of NSA. Therefore, N1-10F8, N2-10F8 and N3-10F8 illustrated three shotcretes with different NSA varieties.

2.3. Procedures of mixture made
The wet-mix shotcrete was mixed as follows.

Firstly, the powder of water reducer was poured into water and then mixed to be uniform.

Secondly, coarse aggregate and silica fume or NSA were put into the mixer, then mixed about thirty seconds. After that three-fourths of mixed water prepared was poured into the mixer again, and thirty seconds were taken to continue mixing.

The last, cement, fine aggregate, the other one-fourth mixed water were put into the mixer. Three minutes were taken to continue mixing, and in the last thirty seconds, steel fiber or synthetic fiber were added in a uniform speed to keep fiber well diverse.

After procedures above, the mixture was finished.

2.4. Rebound rate
Rebound rate is a term that expresses the characteristics of adhesion and cohesion of shotcrete, which could be calculated as Eq.1. It presented mass percentages of rebound materials in total materials during a shooting process.

\[
R = \frac{W_R}{W_T} \times 100\% 
\]

In which, \(R\) is the rebound rate (%); \(W_R\) is the weight of rebound materials (kg); \(W_T\) is the weight of total materials shot in the experiment (kg).

(1) Sidewall rebound rate. A sidewall rebound rate meant that the rebound rate was tested while concrete sprayed onto sidewall as a receiving surface.

Experiments were carried out in laboratory. The rebound rate was evaluated by spraying concrete onto steel moulds located at an 85-degree angle to the ground plane with a wet sprayed machine as Figure 1, of which the air pressure was 0.5MPa, of which the productivity was 6m³/h. Every test of sidewall rebound rate consumed concrete about 200 liters to 400 liters.

(2) Overall rebound rate. An overall rebound rate meant that the rebound rate was evaluated when concrete sprayed onto sidewalls and crown uniformly at the same time.

Tests of overall rebound rate were carried out in a hydraulic tunnel in southwest of China as Figure 2.
Figure 2 presented a schematic representation of cross-section in the hydraulic tunnel. Concrete was sprayed onto surrounding rock of tunnel bodies with a wet sprayed machine, of which the air pressure was 0.7MPa, of which the productivity was 20m$^3$/h. Every test approximately consumed 8m$^3$ concrete.

3. Results and discussion

Comparison between silica fume and NSA based on rebound rate. Sidewall rebound rate and overall rebound rate of silica fume shotcrete and NSA shotcrete were shown as Figure 3. Steel fiber or synthetic fiber were also used in the mixture. And N1 was applied as representative of NSA. Figure 3 showed that no matter which fiber was used, NSA shotcrete (N1-10F8 and N1-10G40) had a rebound rate about 4.5% for sidewalls and 8.0% for overall cross-sections. Silica fume shotcrete (S10F8 and S10G40) had a rebound rate about 5.4% for sidewalls and 11.0% for overall cross-sections. The results indicated that rebound rates of shotcrete could be reduced by 17% for sidewalls and 25% for overall cross-sections when NSA were applied to replace silica fume. In other words, NSA could obviously reduce the rebound rate of shotcrete. It was prior to silica fume, which was considered to be the most effective cementing materials in reducing rebound rate before.

![Figure 3](image_url)

**Figure 3.** Rebound rates of NSA shotcrete and silica fume shotcrete.

![Figure 4](image_url)

**Figure 4.** Rebound rates of shotcrete with different NSA contents.
3.1. Influence of NSA content on rebound rate

Sidewall rebound rate and overall rebound rate of three NSA shotcretes were shown in Figure 4, in which the mass percentages of NSA were 7.5%, 10% and 12.5% (N1-07F8, N1-10F8 and N1-12F8), respectively.

The sidewall rebound rates were 5.0%, 4.4% and 4.0%, overall rebound rates were 9.0%, 8.3% and 7.8% for these three NSA shotcretes, in which NSA replaced Portland cement respectively by 7.5%, 10% and 12.5%. The results indicated that rebound rate could be reduced by increasing NSA content. For example, compared with shotcrete with 7.5% NSA replacement, rebound rate of shotcretes with 10% and 12.5% NSA were reduced by 12% and 20% for sidewalls, 8% and 13% for overall cross-sections. However, it might increase the crack risk as NSA content was increased. And crack went against durability of concrete, and safety of supporting structure. In addition, increasing NSA content could add the flow resistance of shotcrete, which might lead to a blockage in the pipe, which also needed to be concerned closely.

3.2. Influence of NSA fineness on rebound rate

Rebound rates of shotcretes with NSA in three different varieties of fineness were given in Figure 5, in which the average particle diameters of NSA were 128nm, 137nm and 147nm (N1-10F8, N2-10F8 and N3-10F8), respectively. Figure 5 showed that when chemical composition of NSA was similar to each other, the finer NSA was, and the lower rebound rate of shotcrete was no matter sidewall rebound rate or overall rebound rate. Due to the distinction of average particle diameter among three NSA were just for 10nm, which slightly affected the rebound rate. However, the tendency behavior above was obvious.

On basis of the results of rebound rates of eight shotcretes, it was found that sidewall rebound rates were all lower than overall rebound rates, which could contribute to two main reasons. On one hand, overall rebound rate included rebound rates in sidewalls and crown. While sidewall rebound rate was just for sidewalls and rebound rate in crown was higher than that in sidewalls. On the other hand, build-up thickness of shotcrete in sidewalls was higher than that in crown, which was beneficial for reducing rebound rate [11].

![Figure 5. Rebound rates of shotcretes with three fineness of NSA.](image)

**Mechanism for NSA in reducing rebound rate.** Rebounding is a normal phenomenon when concrete is sprayed onto the receiving surface. Increasing the amount of concrete in-place is equal to reduce rebound rate. There were two methods to raise the amount of shotcrete to stay in-place. Firstly, promoting the adhesion between concrete mixtures and receiving surface which could help concrete adhere to the objects such as surrounding rock or old concrete. NSA could be used to improve the...
bond strength, increase concrete in-place, and reduce rebound rate. Secondly, adding the cohesion of concrete mixture which could increase the bond strength among components in the plastic concrete. The cohesion was closely related to torque viscosity of mixtures [12]. That was, with the increment of torque viscosity, the cohesion of mixtures rose, which was beneficial for reducing rebound rate. NSA replacing silica fume, decreasing particle size of NSA, and raising the content of NSA were all able to add the cohesion of mixtures, which was the major cause of reducing rebound rate. As was proved in some researches [13], when Portland cement was replaced by cementing materials such as fly ash, silica fume, metakaolin and ground granulated blast furnace slag, the torque viscosity of shotcrete mixtures would be raised in various degrees. And the rebound rate was reduced in corresponding order, which indicated that torque viscosity would be related closely to rebound rate.

Another analysis was based on energy transforming in the shooting process. When materials were impacted to receiving surface, if there was no energy loss, the components of concrete would be rebounded to move in inverse direction at the same velocity. However, due to some components could be compressed to compaction. That was, kinetic energy was partly transformed to deformation energy. Furthermore, each component in the rebounding process was resisted by other components in the mixture. A little thermal energy would be also produced because of the role of frictional resistance. Therefore, the torque viscosity was increased when NSA was incorporated to the concrete mixtures. The energy transformed to deformation energy and thermal energy was raised. Then kinetic energy or velocity of the rebound materials was reduced. Hence, the amount of rebound materials decreased and the rebound rate was reduced. The view that increasing adhesion could reduce rebound rate has been widely accepted. While the effect of cohesion on rebound rate still should be further investigated. Figure 6 and Figure 7 gave a representation of how to reduce rebound rate by increasing cohesion in the mixtures. Increasing cohesion mainly reduced the rebounding of components that was easily rebounded such as coarse aggregate and synthetic fiber. In the schematic representation, coarse aggregate was taken as a component easily to be rebounded. If the torque viscosity or frictional resistance was in a relatively low level, the coarse aggregate impacted to the receiving surface would be easily rebounded out of cementing paste as Figure 6. Whereas if frictional resistance that representing cohesion was high enough, the coarse aggregate would be dragged by other components in shotcrete mixtures during the rebounding process. Therefore, it was prevented from being rebounded out of the cementing paste. After that, it still stayed in-place just as Figure 7.

![Figure 6. Coarse aggregate being rebounded out.](image)

![Figure 7. Coarse aggregate staying in-place.](image)
4. Conclusions

Rebound rates of eight shotcrete mixtures were tested. Comparison between silica fume and Nano-scale admixture was done. The impact factors such as fineness and content of Nano-scale admixture were also investigated. On basis of rebounding tests, the mechanism that Nano-scale admixture reducing rebound rate was discussed. The conclusions were obtained as follows:

Nano-scale admixture shotcrete had lower rebound rate than shotcrete with the same content of silica fume. Sidewall rebound rate and overall rebound rate of shotcrete were reduced by 17% and 25% respectively when silica fume was totally replaced by Nano-scale admixture.

Rebound rates of Nano-scale admixture shotcrete decreased as particle size of Nano-scale admixture decreasing from 147nm to 128nm or Nano-scale admixture content increasing from 7.5% to 12.5%.

Nano-scale admixture could improve adhesion between shotcrete and receiving surface, and raise cohesion of mixtures. Increasing cohesion in mixtures would keep components easily to be rebounded such as coarse aggregate and synthetic fiber from being rebounded out of cementing paste. Hence, the rebound rate was reduced.

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