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Research Article

Analysis of Rebound Rate of Wet Shotcrete Based on Experiment and Discrete Element Method

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Wet shotcrete support is the main support method for underground engineering construction at present. The rebound rate is one of the indicators to evaluate the support effect, and a lower rebound rate will improve the construction effect of wet shotcrete. The concrete aggregates available in different regions of China have different particle sizes. To achieve better supporting effect, the discrete element method is used to simulate the spraying process of wet shotcrete. By constructing the nozzle structure and simplifying the concrete structure, the paper establishes the discrete element model of wet shotcrete. Using the above model, the paper analyzes the effects of injection distance and shrinkage angle on the injection rebound rate of concrete with three aggregate sizes of 5~11 mm, 11~17 mm, and 17~25 mm. The optimal construction parameters of concrete with different aggregate particle size ratios were obtained through simulation experiments. The simulation results are highly consistent with the field experimental structure. It is feasible to simulate wet shotcrete spraying process by the discrete element method.

1. Introduction

At present, wet shotcrete support is the main support method in mine roadway. Wet shotcrete technology began to appear in the mid-1960s, and it was introduced to China after 1970, and gradually, it attracted the attention of the construction industry [1]. The rebound rate is one of the indexes to evaluate the support effect [2]. Reducing the rebound rate can effectively save resources, protect the health of construction personnel, and improve work efficiency.

Researchers have conducted many studies on the rebound rate of shotcrete. Chen et al. [3] studied the injection characteristics of different air pressure and injection distance and analyzed the relationship between the initial injection time and the rebound rate. The results show that the rebound rate decreases exponentially with the increase of spray time, and it is relatively small when the air pressure is small. The best initial spray time is 9 s, which can effectively reduce the rebound rate. Gang et al. [4] have studied the relationship between the resilience of wet-sprayed concrete and the rheological properties of fresh concrete (slump, yield stress, plastic viscosity, etc.), the influence of the rheological property of fresh concrete on the rebound property of shotcrete is revealed, and the influence of additives on the rebound rate of shotcrete is studied by adding different types and dosages of additives. Armengaud et al. [5, 6] and others studied the influence of auxiliary cementitious materials (SCMS) on the resilience of wet-sprayed concrete and analyzed the influence of aggregate size on the working efficiency of auxiliary cementitious materials. The results show that the cementitious material is effective to reduce the rebound rate. Through theoretical analysis, Armelin and Banthia [7] established the rebound theory. The theory can predict the aggregate rebound of shotcrete. The experimental results show that the theoretical analysis is in good agreement with the experimental results. Bindiganavile and Banthia [8, 9] have studied the influence of aggregate density and concrete admixture on the rebound rate of wet-sprayed concrete and established the theory of coarse aggregate rebound.

There are many pieces of research on wet shotcrete based on the experimental platform, however, there are some disadvantages, such as high cost, labor, and material resources. The development of computer technology promotes the application of the numerical simulation method in the study of wet shotcrete. A spiral nozzle of wet sprayer was designed by SU [10]. The air phase and the concrete phase of the nozzle flow field were simulated by the CFD method, and the velocity of each phase and the volume fraction of each phase in the exit section of the spiral nozzle and common nozzle were analyzed. The simulation results show that the performance of the spiral nozzle is better than that of the common nozzle. Alexandrian and Michael [11] and Bunch and Thomas [12] studied the working performance of the nozzle and analyzed the influence of the velocity slip rate between the two-phase fluid in the nozzle on the delivery efficiency. Wet shotcreting includes two processes of shotcreting and pumping [13]. Concrete particles are divided into mortar and aggregate by Cao et al. [14], and a local pipe model of pumping concrete is established by the discrete element method. The effect of aggregate volume fraction on the flow behavior of fresh concrete was studied. The results show that with the increase of coarse aggregate volume fraction, the pumping pressure increases and the pipeline wear increases. The flow behavior of aggregate in the pipe was studied by the discrete element method (DEM), and the influence of aggregate on the pumping performance of the concrete was analyzed by Zhan et al. [15] and Hao et al. [16]. The discrete element method (DEM) can directly describe the aggregate in concrete.

According to the literature review, the research of rebound rate is still based on experiment. The numerical simulation based on the discrete element method can make up for the existing research methods and observe the movement behavior of aggregate in concrete. In this paper, the discrete element method is used to study the rebound rate of wet shotcrete, and the discrete element model of shotcrete is established to analyze the influence of the shrinkage angle and the distance of shotcrete on the rebound rate under different particle sizes, and the relationship among rebound rate, particle radius, jet distance, and nozzle shrinkage angle was investigated.

2. Experiment

2.1. Experimental Design. Field experiments were carried out on wet shotcrete [17, 18]. The concrete used in the experiment is the same batch of C30 concrete in a certain place, and the content of each component is shown in Table 1. The experimental device includes an experimental platform, a signal acquisition device, and a recorder. The experimental platform is used to conduct concrete jet impact experiments. The signal acquisition device is used to collect the concrete spraying force data of the experimental platform and transmit it to the recorder. This experimental device can measure the impact force, spray range, and rebound rate of the concrete shot by the concrete sprayer, as shown in Figure 1.

As the most important component of wet spraying machine, nozzle determines the quality and rebound rate of shotcrete. The research and exploration of its structure have become the focus of many scholars. The constriction angle is located in the constriction section of the nozzle and plays a crucial role in the performance of the nozzle. The changes in the shrinkage angle can affect the speed and spread of the concrete outlet, which, in turn, affects the rebound of the concrete, and it may even cause nozzle wear and pipe blockage. Figure 2 is a schematic diagram of the nozzle structure, and θ is the convergence angle.

In this experiment, the aggregate diameter, jet distance, and nozzle shrinkage angle are independent variables, whereas jet angle and wind pressure are constant values, as shown in Table 2.

The preprepared sand, cement, water, gravel, etc., are placed in the ready-mix concrete, and the concrete is pumped to the nozzle after it is well-mixed. The concrete is mixed with the accelerator at the nozzle. The high-pressure air gives the concrete ultra-high kinetic energy, causes the concrete to spray fast on the hitting plate. At the end of the experiment, the rebound concrete is collected, weighed, and analyzed to determine the rebound rate, as in equation (1).

$$n = \frac{W_1}{(W_1 + W_2)} \times 100\%, \quad (1)$$

where n is the rebound rate, W_1 is the amount of scattered concrete collected, and $(W_1 + W_2)$ is the total amount of concrete used.

2.2. Experimental Results and Analysis. The purpose of the experiment is to verify the feasibility of the discrete element model to simulate the concrete spraying process without extensive experiments. In the experiment, the spray angle was fixed at 90 degrees, the wind pressure was fixed at 0.1 MPa, the particle size was 5 mm and 15 mm, the spray distance was 0.6 m and 1.0 m, and the shrinkage angles were 6°and 8°. There were eight groups of experiments. Each group was tested 10 times, and the average value of the spray range and rebound rate was recorded, as shown in Table 3.

Figure 3 shows the curve of the injection range and the rebound rate of the experiment. It can be seen from Figure 3 that when the particle size is 15 mm, the spray distance is 1.0 m, and the shrinkage angle is 8°. The rebound rate is low, and the spray range is small.

3. Discrete Element Model of Shotcrete

3.1. Fundamentals of Particle Discrete Elements. The concept of the discrete element method was proposed by Cundall [19]. This method uses the force-displacement law and Newton's second theorem cyclically to update the contact force and position between the contacting elements and construct new element contacts, thereby simulating the motion and interaction process of granular media. This method is a numerical method for analyzing the mechanical behavior of discontinuous media, as shown in Figure 4.

The particles in PFC are rigid entities, and the mechanical relationship between the particles can produce overlapping effects to simulate the contact force between the particles. Contact forces appear in pairs between particles and particles and between particles and walls. They are dynamically generated and disappear thus. In the PFC model, the interaction

Table 1: Content of each component of C30 concrete (kg).

Concrete grade	Water	Cement	Sand	Aggregate	Water reducing agent	Fly ash	Water binder ratio	Wet bulk density
C30	175	461	512	1252	3.2	90	0.42	2290

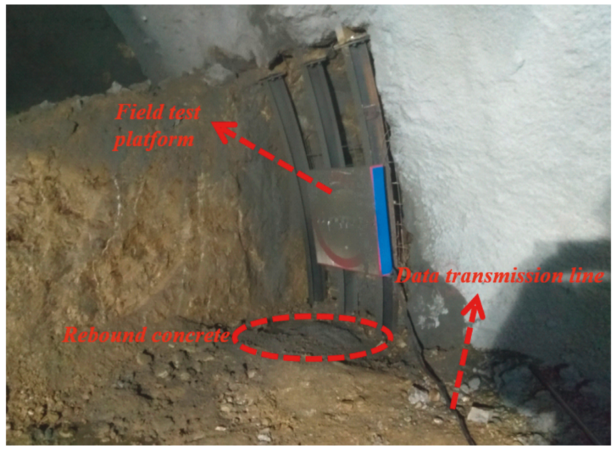

Figure 1: Field test platform.

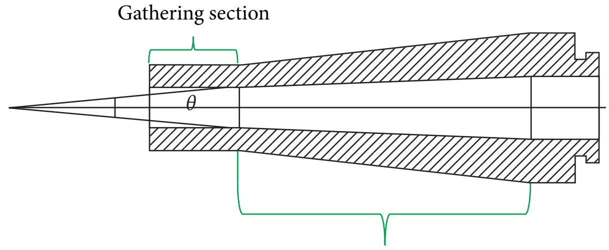

Figure 2: Nozzle diagram.

Table 2: Experimental parameters.

Parameters	Spray angle	Wind pressure (MPa)	Constriction angle	Aggregate particle size	Spray distance
Value	90°	0.1	4°~8°	5~25 mm	0.6~1.2 m

Table 3: Field test record sheet.

Experimental group	Aggregate (mm)	Jet distance (m)	Angle of contraction (°)	Spray range (mm)	Rebound rate (%)
1	15	0.6	6	225	12.52
2	15	0.6	8	231	11.41
3	15	1.0	6	213	9.63
4	15	1.0	8	205	9.12
5	5	0.6	6	256	15.26
6	5	0.6	8	271	14.89
7	5	1.0	6	240	11.23
8	5	1.0	8	223	10.56

between particles is reflected at the point of contact through internal forces, and the deformation of particles only occurs at the point of contact. Each contact needs to be assigned a contact model. These models are, in a broad sense, between particles' law of interaction.

Figure 5 is a schematic diagram of the overlap between particles, and particles A and B are in contact and overlap. The overlapping amount is represented by $U^{(A-B)}$, x_A and x_B are the position vectors of the sphere centers of the two particles, R_A and R_B are the radii of the two particles, d represents the

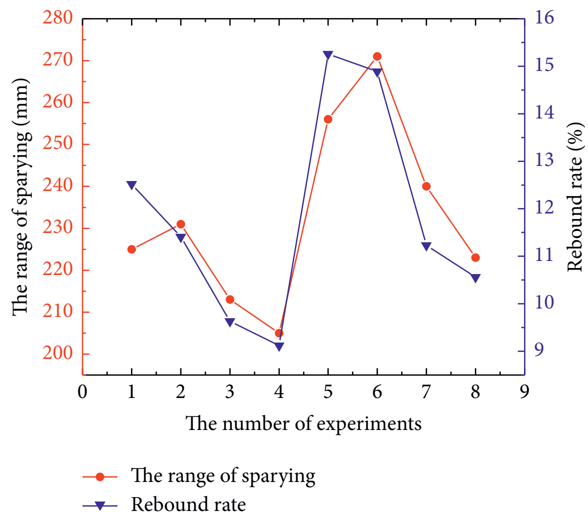

FIGURE 3: Spray range and rebound rate.

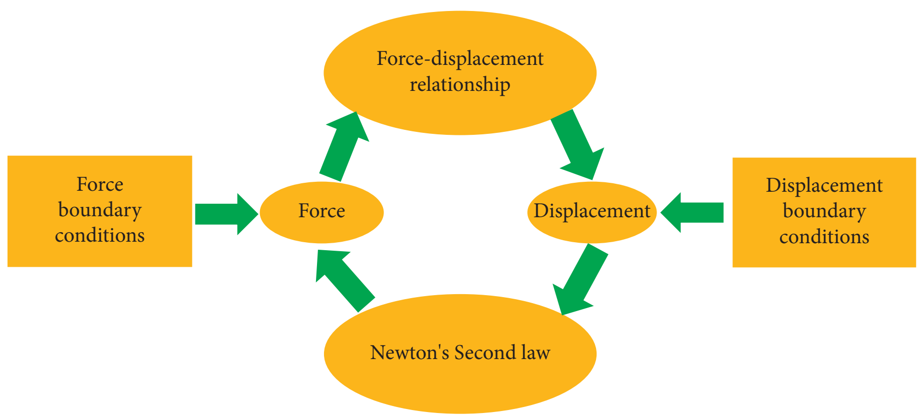

FIGURE 4: Mechanical principle diagram.

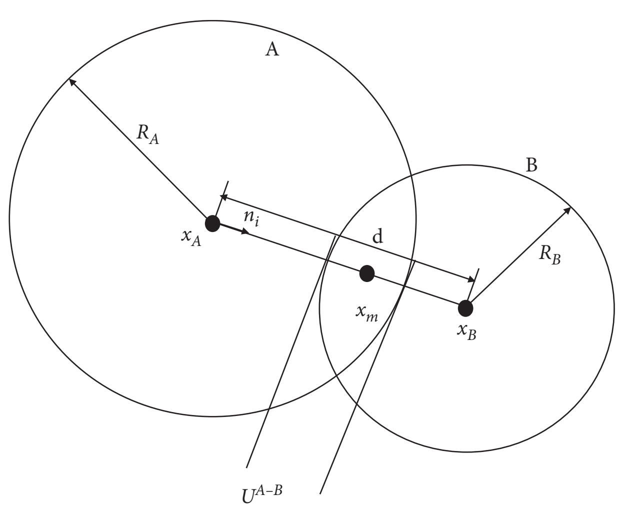

FIGURE 5: Particles contact overlay.

distance between the centers of mass of the two particles, and x_m represents the contact point between the particles.

$$n_i = \frac{(x_A - x_B)}{d}, \tag{2}$$

$$d = |x_B - x_A| = \sqrt{(x_B - x_A)(x_B - x_A)}, \tag{3}$$

$$U^{(A-B)} = (R_A + R_B) - d. \tag{4}$$

Equation (2) is the unit normal vector between the two particles. Equation (3) is the distance between the centroids of the two particles. Equation (4) represents the contact overlap between the two particles.

3.2. Particles Model. In this study, the method of particle grading is used to generate large particles and small particles. The model uses a large number of small particles to simulate slurry and large particles to simulate aggregate [20]. The small particles generated by particle grading have a radius of 2-3 mm, a volume fraction of 0.4, a large particle with a radius of 5–25 mm, and a volume fraction of 0.6. The overall particle porosity is 0.2. Finally, the simulation test established particle models with an aggregate particle size of 5 mm and 15 mm, as shown in Figure 6.

After the modeling is completed, the researchers assign solid properties to the particles and check the microscopic contact parameters between particles and particles and between particles and walls. The specific assignment parameters are shown in Table 4.

3.3. Contact Model. In this study, the linear model [21] was used to simulate the interaction between aggregates, and the linear parallel bond model [22] was used to simulate the interaction between mortars and between aggregates and mortar [23]. In the linear model, the contact forces are the linear force F^l and the damping force F^d, respectively, and each force contains two components, normal and tangential. The linear force is provided by two springs with constant normal phase stiffness k_n and tangential stiffness k_s. The damping force is provided by the damper, including normal phase damping β_n and tangential damping β_s, where μ is the friction coefficient and g_s is the surface clearance. The spring and damper are in a parallel relationship. The linear parallel bond model adds parallel bonds to the linear model. A parallel bond is viewed as a set of elastic springs with constant normal stiffnesses $\overline{k}_n$ and shear stiffnesses $\overline{k}_s$. In the linear parallel bond model, the contact force adds to the parallel bond force $\overline{F}$ and the parallel bond moment $\overline{M}$. The parallel bonding force includes normal and tangential components, and the moment includes torque and bending moment. When the normal or shear stress on the contact bond is greater than its maximum normal or shear strength, the parallel bond will break. Linear parallel bond model reverts to linear model. All contact force-displacement relationships in the

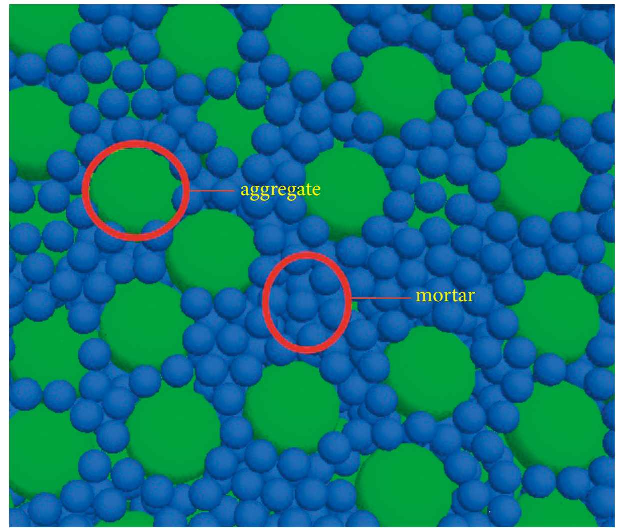

Figure 6: Schematic diagram of particles model.

model follow the force-displacement law. The model is shown in Figure 7.

4. Numerical Simulation

4.1. 3D Model. In this study, the PFC3D software was used to numerically simulate the injection process. The particles and walls generated by the software are all three-dimensional. As shown in Figure 8, the distance from the nozzle outlet to the wall is the spray distance. Aggregates are produced using particle grading. When aggregates are generated, there is overlap between the particles. Particles are rigid bodies. If there is no restriction at the beginning of the calculation, the rebound force generated by the overlapping particles will cause them to fly around with great kinetic energy. Before the software calculation starts, the author sets the program loop to about 2000 steps, and it clears the particle state every 5 steps.

4.2. Parameter Calibration. By adjusting the experimental parameters, 8 groups of orthogonal experiments were carried out on different particle sizes, different shrinkage angles, and different spray distances. The relevant parameters set in the numerical simulation are consistent with the field experiments. The process of calibrating model parameters is the process of continuously updating relevant parameters and performing numerical simulation calculations. In the early stage, the contact parameters were continuously adjusted to make the results as consistent as possible with the experiment. We refer to parameter values in references [14, 15] and calibrate according to the experimental results. It is a process of trial and error. We adjust some parameters until the simulation results are close to the experimental results. The numerical simulation process is shown in Figure 9. Each particle in the nozzle has an initial velocity. The particles are ejected from the nozzle and then collide with the wall. Some particles cling to the walls, while others bounce off. Table 5 shows the results of the simulated injection range and rebound rate, and Figure 10 shows the

Table 4: Particles property assignment table.

Particles type	Density (kg/m^3)	Damping	Gravitational acceleration (m/s^2)	Initial velocity (m/s)
Large particles	2500	0.7	9.8	20
Small particles	1500	0.7	9.8	20

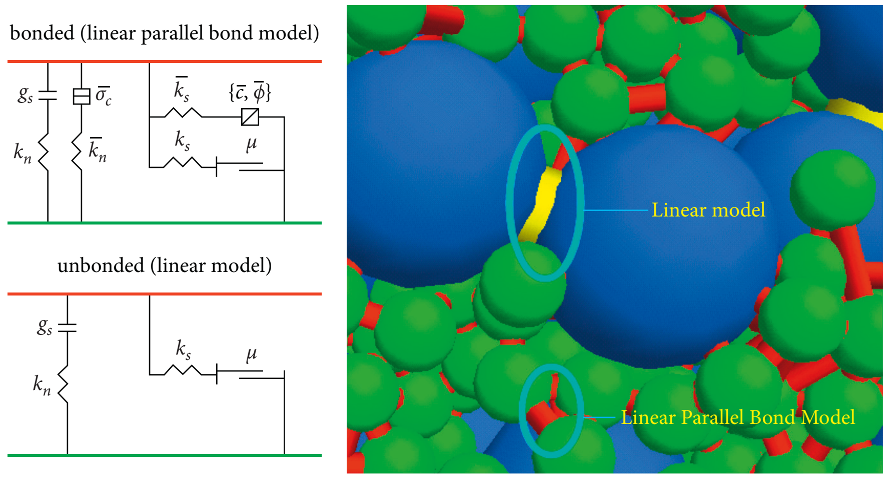

Figure 7: Contact model

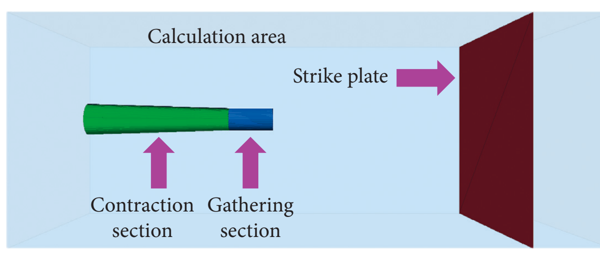

Figure 8: Geometric model

Figure 9: Numerical simulation experiment process.

Table 5: Numerical simulation experimental results.

Experimental group	1	2	3	4	5	6	7	8
Spray range (mm)	215	225	232	215	248	259	256	237
Rebound rate (%)	12.16	11.13	9.78	9.89	15.56	14.59	11.44	10.78

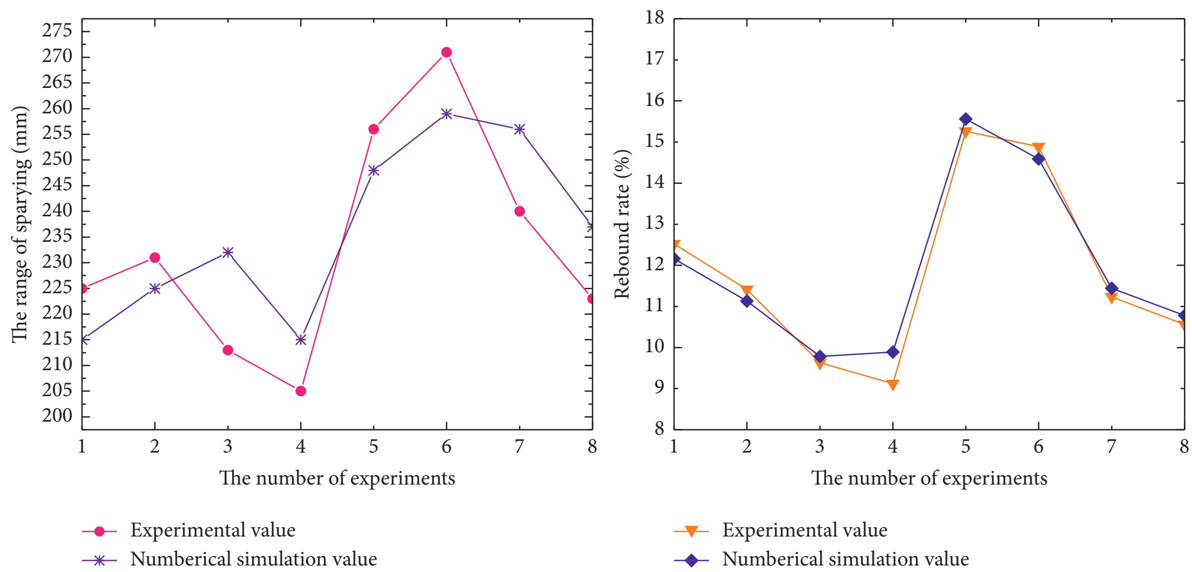

FIGURE 10: Curve of spray range and rebound rate.

comparison between the numerical simulation experimental values and the field experimental values.

As shown in Figure 10, the numerical simulation results are consistent with the results of the field experiments. The comparison results show the feasibility of PFC3D software to simulate concrete spraying, and the relevant parameter values are shown in Table 6. These parameters can provide reference for similar research.

5. Analysis and Discussion of Numerical Simulation Test Results

The discrete element model suitable for shotcrete is obtained by calibrating the mesoparameters through experiments. The model was used to numerically simulate the rebound rate under different particle sizes, spray distances, and shrinkage angles. Through the analysis and processing of the test data, the value ranges of the spray distance and the shrinkage angle when the rebound rate is the smallest under different particle sizes are obtained.

5.1. Influence of Spray Distance on Rebound Rate. The concrete spray distance is the vertical distance from the nozzle to the spray surface when supporting the construction surface. Technically, to meet the injection situation, the concentration of the material bundle does not disperse, the rebound rate is small. The shotcreting distance of concrete should be determined according to the concrete conditions of site construction. Generally, the spray distance within 0.6~1.2 m is the best, and the particle diameter is divided into three groups: 5~11 mm, 11~17 mm, and 17~25 mm. Seven different spray distances are selected, which are 0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.0 m, 1.1 m, and 1.2 m, respectively, and the other parameters are set values, as shown in Table 7.

Analyzing the results of numerical simulation, the rebound rate varies with the injection distance, and there is a linear relationship between the rebound rate and the injection distance in the case of different aggregate particle sizes. The simulation results are shown in Figure 11.

It can be seen from Figure 11 that with the increase of spraying distance, the rebound of concrete first decreases and then increases. No matter which interval the particle diameter is located in, when the spray distance is about 0.8~1.1 m, the rebound rate is better, because the experiment is carried out at a fixed outlet velocity. When the wall is close to the nozzle, the particles will collide with the wall at a higher speed, and the kinetic energy of the particles will be greater. When the viscosity between the particles on the wall is not enough to dissipate the energy of the particles, the particles will have a rebound effect and even return to their original shape. When the wall is far away from the nozzle, the kinetic energy of the particles will be consumed during the air movement, resulting in insufficient impact on the wall, so that the concrete layer cannot be compacted, thereby causing rebound.

5.2. Influence of Shrinkage Angle on Rebound Rate. The constriction angle is very important to nozzle performance. Changes in the shrinkage angle can affect the velocity and spread of the concrete outlet, which, in turn, affects the concrete's rebound, and it may even cause nozzle wear and pipe blockage. Change the constriction angle of the nozzle. Other parameters are fixed values, and the specific parameter settings are shown in Table 8.

The discrete element models with the shrinkage angles of 4°, 5°, 6°, 7°, and 8° were established. The rebound rates of particles with different shrinkage angles of 5~11 mm, 11~17 mm, and 17~25 mm were simulated, respectively, and the effect of shrinkage angle on the rebound rate was analyzed. The results are shown in Figure 12.

Table 6: Contact parameter table.

Name	Linear contact normal stiffness	Linear contact shear stiffness	Linear contact friction coefficient	Parallel bond normal stiffness	Parallel bond shear stiffness	Parallel bond tensile strength	Parallel bond cohesion	Critical damping ratio	Contact radius
Aggregate-aggregate	$1e^4$	$1e^3$	0.3					0.3	
Aggregate-mortar	$1e^3$	$1e^2$	0.2	$1e^3$	$5e^3$	$6e^3$	$6e^3$	0.5	0.5
Aggregate-wall	$1e^4$	$1e^3$	0.3					0.3	
Mortar-mortar	$1e^3$	$1e^2$	0.1	$2e^4$	$1e^4$	$6e^4$	$3e^4$	0.5	0.5
Mortar-wall	$1e^3$	$1e^2$	0.1	$2e^3$	$1e^3$	$6e^3$	$6e^3$	0.5	

Table 7: Parameter setting table.

Parameters	Spray angle	Initial speed	Constriction angle	Particle size	Spraying distance
Value	90°	20 m/s	6°	5~25 mm	0.6~1.2 m

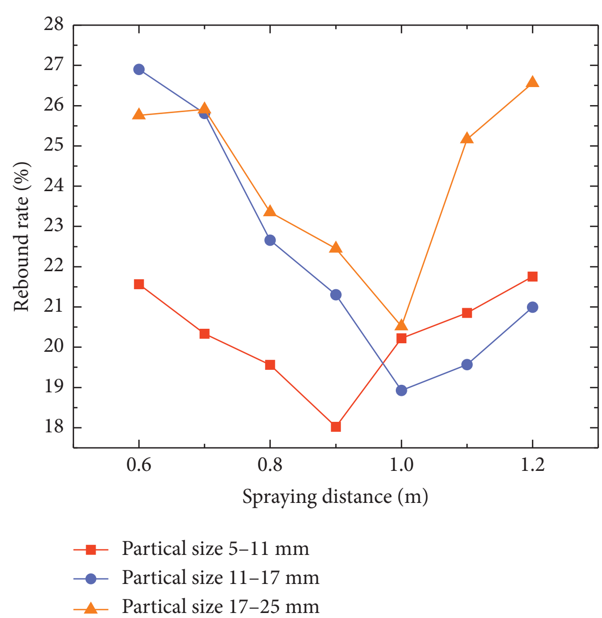

Figure 11: Relationship between rebound rate and spray distance.

Table 8: Parameter setting table.

Parameters	Spray angle	Initial speed	Constriction angle	Particle size	Spraying distance (m)
Value	90°	20 m/s	4°~8°	5~25 mm	1.0

It can be seen from the figure that when the aggregate particle size is in the range of 5~11 mm, the rebound rate is the best when the shrinkage angle is 7°. When the particle size is in the range of 11~17 mm, the rebound rate is the best when the shrinkage angle is also about 7°. When the particle size is 17~25 mm, the rebound rate is the best when the shrinkage angle is 5°. It is because when the particle size is larger, i.e., the particle volume is larger, the increase of the shrinkage angle will have a greater impact on the velocity of the large particle. The rebound rate is the ratio of mass, and

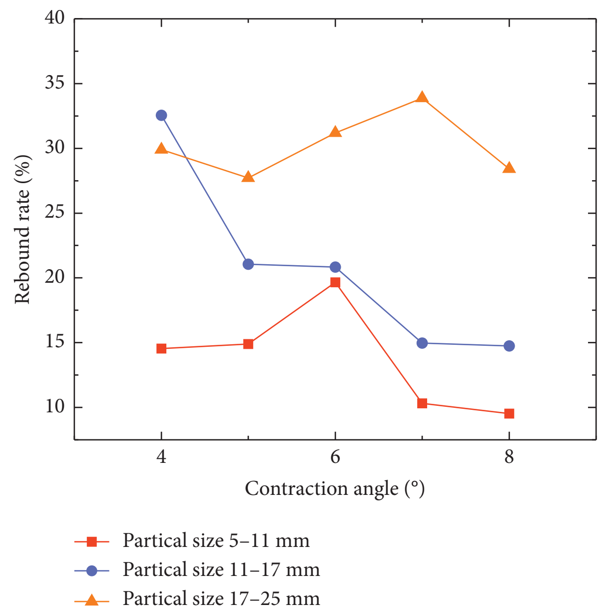

Figure 12: Relationship between shrinkage angle and rebound rate.

the density and volume of the large particle are greater than the small particles of the slurry, and hence, the rebound rate increases.

6. Conclusion

In this paper, a discrete element model of wet shotcrete is established to simulate the movement behavior of concrete. The effects of spray distance and shrinkage angle on the rebound rate in three particle size ranges of 5~11 mm, 11~17 mm, and 17~25 mm were analyzed.

(1) When the spraying distance is 0.9 m, the rebound rate of the particles of 5~11 mm is the smallest, and when the spraying distance is 1 m, the rebound rate of the particles of 11~17 mm and 17~25 mm is the smallest.

(2) The 5~11 mm and 11~17 mm particles have the smallest rebound rate when the shrinkage angle is 8°, and the 17~25 mm particles have the smallest rebound rate when the shrinkage angle is 5°.

The discrete element model of shotcrete not only helps us to better observe the motion behavior of aggregates but also provides a new idea for the numerical simulation of wet shotcrete.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Acknowledgments

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