Research Article

Calibration of Contact Parameters for Moist Bulk of Shotcrete Based on EDEM

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To obtain the contact parameters of the moist bulk of shotcrete accurately and quickly, this study calibrated the contact parameters of the moist bulk of shotcrete by physical stacking test and simulation method. Based on the Hertz–Mindlin with JKR (Johnson–Kendall–Roberts) model, the discrete element simulation is carried out. Using P-BD to screen seven initial parameters, it is found that JKR surface energy, rolling friction coefficient between particles and restitution coefficient of particle impact have significant effects on the angle of repose of the moist bulk of shotcrete. According to B-BD, the second-order regression model of angle of repose and significance parameters was established. Three significant parameters were obtained: JKR surface energy 0.418 J/m², rolling friction coefficient 0.06 and static friction coefficient 1. The angle of repose obtained by simulation is compared with the physical test value, and the relative error is 1.88%. The results show that the calibration method proposed in this study can accurately simulate the physical stacking test, and can provide a reference for the calibration of contact parameters of the moist bulk of shotcrete.

1. Introduction

As an advanced geotechnical engineering construction technology, shotcrete is widely used in mine roadway, railway tunnel, subway, underground engineering and municipal construction for surrounding rock control and roadway closure [1–6]. The traditional dry shotcreting process produces high concentration dust (hundreds of times higher than the industry standard) [7–10], which poses a great threat to the working environment and physical and mental health of shotcreting workers. Moist shotcrete (water cement ratio < 0.4) is a feasible way to solve the problem of dust, but the existing research mainly focuses on equipment research, process optimization and material preparation [11–13], and the research on physical contact characteristics of moist bulk of shotcrete is relatively less. Especially for the study of contact characteristic parameters of mechanical operation such as mixing and pneumatic conveying of moist bulk of shotcrete. Accurate material contact characteristic parameters are the key to revealing the motion characteristics of moist bulk of shotcrete through simulation experiments. However, the main components of moist bulk of shotcrete are coarse aggregates, fine aggregates and partially hydrated cement aggregates with multiscale particle sizes. Therefore, the relevant contact parameters are difficult to obtain timely and accurately by conventional measurement methods.

To effectively solve the problem of contact parameter calibration of wet materials, a method of virtual calibration of material parameters by using discrete element method is proposed. At present, the use of discrete element method to calibrate particle parameters has been applied in many areas,
such as rock, soil and agriculture, and has been verified in some fields [14, 15]. In agriculture, Horabik [16] used DEM to model plant roots and determined the coefficient of restitution and viscoelastic contact model. Coetzee and Els [17] used the discrete element method to calibrate the parameters of granular material through the interaction between blade and granular material, and the simulation results are verified by experiments. Caiwang and Limming et al. [18, 19] calibrated the contact parameters of pig manure by simulation method and physical stacking test. Using the Hertz–Mindlin with JKR model, the simulation experiment is carried out. In rock, Xia et al. [20] proposed the important parameters affecting the angle of repose of loose coal, obtained the contact parameters of loose coal, and verified the accuracy of discrete element parameters through relevant experiments. Barrios et al. [21] approximate the shape of iron ore pellets and estimate the material and contact parameters by single event experiments. The results show that only when the DEM particles have realistic shape, the contact parameters are physically reasonable. Zhang et al. [22] established the rock aggregate shape database by using the DEM, and studied the influence of particle shape on the shear behavior of particles, which accurately revealed the potential mechanism to explain the macro mechanical behavior dominated by the shape of rock particles. Zhang et al. [23] proposed a new discrete modeling framework for large-scale triaxial tests of crushed stone considering the realistic particle shape and real flexible boundary conditions. Xie et al. [24] proposed a polyhedral spherical contact model based on the deepest point method. The experiment and simulation research were carried out by the method of over discrete element to test the accuracy of the model in the laboratory scale horizontal drum with elevator. In soil, Wei et al. [25] based on soil accumulation test, the soil discrete element simulation model is constructed. The experiment shows that the method of the system calibration of the simulation parameters of clay loam is accurate and feasible, and the accurate discrete element simulation model of clay loam is constructed. Marczewska et al. [26] studied the macroscopic effective elastic parameters of soil granular materials by using the DEM, reproduced the behavior of the materials with spherical particles, and calculated the relationship between the contact parameters and the elastic modulus. Uçgul et al. [27] proposed that the appropriate DEM parameters of soil particles were determined by linear plastic contact model and the angle of repose and penetration test with disk and cone, and the soil tool interaction in noncohesive soil was modeled. Based on the assumption of initial bonding state, Liu et al. [28] established a new variable constitutive law and obtained a high-precision DEM model of lunar soil. In addition, in contact mechanics, Korayem et al. [29–32] conducted a simulation study based on nanomanipulation with atomic force microscopy, using the JKR impact theory, developed the concurrent study of adhesion and impact.

From the current point of view, most academic scholars have realized the parameter calibration of crops, rocks, soil and other materials by means of simulation, but few researchers have reported on the material parameter calibration of moist bulk of shotcrete [33, 34], especially for moist materials (water cement ratio <0.4). Due to a small amount of moisture (to reduce the dust production during transportation), there are great differences in flow, friction and other characteristics between the wet material and fresh concrete (water cement ratio >0.4). Scholars at home and abroad have tried many methods to calibrate the contact parameters of DEM, but there is no standardized calibration method at present. The common research method is to measure the macro characteristic parameters of a large number of particles, and then carry out the reverse calibration. In the process of reverse calibration, the test is usually repeated, which is very time-consuming and random. In order to improve this shortcoming, researchers have proposed some methods, such as experimental design, artificial neural network [35, 36], etc. Among these methods, the experimental design based on response surface has been widely used [37]. Compared with other methods, test design based on response surface theory has unique advantages in establishing regression model and analyzing influence factors.

Therefore, this study carries out the simulation test based on DEM, and establishes the contact parameters and angle of repose model of moist bulk of shotcrete through Plackett–Burman design (P-BD) test, climbing test and response surface design (B-BD) test. Finally, the angle of repose obtained from the simulation is compared with the physical test value. In order to provide timely and effective material contact parameters for moist bulk of shotcrete mixing, pneumatic conveying and other mechanized operations at different stages.

2 Materials and Methods

2.1 Test Materials and Devices. Moist bulk of shotcrete is premixed with coarse aggregate, fine aggregate, cement and part of water. The standard P. O 42.5 cement produced by China United Cement Group Co. Ltd. was used in the experiment, and the quality met the requirements of GB 175-2020 Common portland cement [38]. The fine aggregate is sand with a fineness modulus of 2.89, the water content of sand about 4.5%, apparent density of 2500 kg/m³ and good durability. The coarse aggregate is gravel with good durability, and the particle size is 5–10 mm, which meets the requirements of Technical code for engineering of ground anchorages and shotcrete support [39]. The grading curves of coarse and fine aggregates used are shown in Figure 1.

The test device for measuring stacking angle is shown in Figure 2. The angle of repose of moist bulk of shotcrete is measured by funnel method. The onsite test device is shown in Figure 2(a). The blanking height of the test is set as 130 mm, and the pipe length and diameter of the funnel blanking port are 50 mm. After the test, Matlab is used to read the image of one side of the moist bulk of shotcrete, and the image is denoised, grayed and binarized respectively. Finally, the boundary points of the image are extracted, and the boundary points are fitted linearly. The slope of the fitting line is the tangent value of the angle of repose of the moist bulk of shotcrete.
The measurement formula of angle of repose [40] is as follows:

$$\theta = \arctan[k] \times 180^\circ / \pi, \quad (1)$$

where $\theta$ is the angle of repose; $k$ is the slope.

Figure 2(b) shows the simulation test device of moist bulk of shotcrete. When the funnel is filled with moist bulk of shotcrete, the moist bulk of shotcrete are likely to be blocked near the outlet of the funnel due to the friction between the moist bulk of shotcrete. Therefore, in the simulation test, the outlet of the funnel is always in the open state. With the continuous generation of the simulated moist bulk of shotcrete, the outlet of the funnel is always blanking until all the moist bulk of shotcrete stop moving. In order to ensure that the results obtained by the simulation without influence of subjective selection, a new algorithm developed based on Python [41] is used to automatically measure the angle of repose of the moist bulk of shotcrete. The data processing process is shown in Figure 3.

In the data processing process, first of all, the same parameters to complete multiple groups of experiments. Secondly, in the self-developed program, read the simulation results and find the key. H file. In the data file, the domain is divided into multiple bins, the center of bin is found, and the particle with the highest point in bin is determined. Finally, the angle of repose of all tests is obtained.

2.2. DEM Simulation

2.2.1. JKR Model. In this study, EDEM 2020 is used to simulate the angle of repose test of shotcrete. The JKR contact theory is the extension of the Hertz contact theory; it assumes that the adhesion effect only occurs on the contact surface, as shown in Figure 4. When two particles do not adhere to each other, their contact radius $a$ is expressed with the Hertz contact theory; otherwise, the external load is $N$, and the contact surface radius is $a > a_c$.

In order to determine the effect of adhesion on contact characteristics, Johnson [43] applied the Griffith energy method to determine the surface energy $U_s = -\pi a_c^2 \Delta \gamma$, where the total energy $U_T$ of the system is a function of the contact area $A$.

When $dU_T / dA = 0$, $U_T$ is in the equilibrium state. The equivalent load force $N_t$ of the two particles affected by the external load $N$ and surface adhesion can be determined as follows:

$$N_t = N + 3\pi R' \Delta \gamma + \sqrt{(3\pi R' \Delta \gamma)^2 + 6\pi R' \Delta \gamma N}. \quad (2)$$

The corresponding contact surface radius is as follows:

$$a^3 = \frac{3R'}{4E_s} \left[ N + 3\pi R' \Delta \gamma + \sqrt{(3\pi R' \Delta \gamma)^2 + 6\pi R' \Delta \gamma N} \right]. \quad (3)$$

The amount of overlap $\alpha$ of the two particles can be calculated with (3):

$$\alpha = \frac{a^2}{R^2} - \left(\frac{2\pi \Delta \gamma}{E_s}\right)^{1/2}. \quad (4)$$

The increase in the normal force $\Delta N$ with respect to the increase in the amount of overlap $\Delta \alpha$ can be written as follows:

$$\Delta N = 2a E_s \Delta \alpha \left(3\sqrt{N} - 3\sqrt{N_c}/3\sqrt{N} - \sqrt{N_c}\right). \quad (5)$$

Based on (4), there are two conditions:

For $\Delta \gamma = 0$, (4) can be simplified to the Hertz contact force $a^3 = 3R^* N/4E_s$ without considering the adhesion of the particles.

For $N = 0$, the two particles adhere to each other, and the radius of the contact surface can be expressed as follows:

$$a^* = \frac{9\pi \Delta \gamma (R^*)^2}{2E_s} \quad (6)$$

When $(3\pi R^* \Delta \gamma)^2 + 6\pi R^* \Delta \gamma N \geq 0$, (1) can be solved. The result is presented in (7):

$$N \geq -\frac{3\pi R^* \Delta \gamma}{2}. \quad (7)$$

Thus, when the external load $N$ is negative (the two particles attract each other), the radius of the contact surface decreases; for $N \geq -3\pi R^* \Delta \gamma/2$, the particle adhesion is in a critical state, and when the pull force increases again, the two particles separate. The maximal pull force $N_c$ required for separating the two particles is expressed as follows:

$$N_c = \frac{3\pi R^* \Delta \gamma}{2}. \quad (8)$$

The corresponding contact radius is

$$a^c_3 = \frac{3R^* N_c}{4E_s} = \frac{9\pi \gamma (R^*)^2}{8E_s}. \quad (9)$$

The relationship between $N_c$ and $a_c$ is

$$\left(\frac{N}{N_c} - a^c_3 \right)^2 = 4 \left(\frac{a}{a_c}\right)^3. \quad (10)$$

The contact radius $a/a_c$ changes with $N/N_c$, as shown in Figure 4.
In Figure 5, it can be seen that when the external pressure load is gradually reduced, the radius of the contact surface is gradually reduced, until the external pressure is reduced to 0, the surfaces between particles are still adhered together, corresponding to point A (when $a_0 = 0$):

$$
\left( \frac{a}{a_0} \right) = \sqrt{4}.
$$

(11)

When the tensile load is applied, the radius of contact surface further shrinks, and the tensile force reaches the maximum at point $B$: $N = -N_c$, $a = a_c$, the contact between particles begins to be unstable, but the surface is still adhered together. If the tension of $N_c$ is maintained, the particles will be pulled away immediately. If the tension is gradually reduced at this time, the radius of the contact surface will be steadily reduced until it is completely separated.

2.2.2. Particle Model. Different from other grains with a specific shape, concrete damp material has many sizes of particles, and the shape of coarse aggregate is different, which has a significant impact on the test results. However, the high computational cost greatly limits the simulation time, the complexity of particle shape, and the number of particles, and the simplification and assumption of diversified and multiscale particles are inevitable. Therefore, the moist bulk of shotcrete is simplified: the typical shape is selected for particle modeling, and based on the sphere model, five kinds of nonspherical coarse aggregate particles are established by using multi sphere combination method, as shown in Figure 6. Through Leica DVM50C digital microscope observation, it is found that there are a large number of cement aggregates with the particle size of 2 mm after partial hydration and fine aggregate wrapped with cement slurry, and the shape is relatively smooth, as shown...
Figure 4: Contact between particles of JKR model [42].

Figure 5: Variation of contact radius with load in JKR model.

in Figure 7. Therefore, it is simplified into spherical particles with a certain viscosity and a diameter of 2 mm.

Nonspherical particles are formed by the accumulation of many spherical particles. Sphericity is the ratio of the area of the sphere of the same volume as the particle to the area of the particle, expressed as follows [44]:

\[
S = \pi^{1/3} \left( \frac{6V_p}{A_p} \right)^{2/3},
\]

where \( V_p \) is the particle volume, \( A_p \) is the surface area of particles.

2.3. Classification of Parameters. Based on the JKR model, three kinds of parameters are proposed:

(1) Material intrinsic parameters: this is the characteristic parameter of the material itself, which has nothing to do with the outside world. Generally speaking, it can be relatively fixed. It can be found in some physical property manuals or literature, and it can also be measured by relatively mature experimental methods.

(2) The basic contact parameters: this is a physical property parameter that only works when two objects come into contact. It has something to do with both objects that come into contact. These three parameters vary greatly. For example, the friction coefficient of steel balls with different polishing degrees will vary greatly, so it is impossible to make a physical property manual or database for reference. Usually, it needs to use experimental measurement or “virtual experiment” calibration.

(3) Contact model parameters: some special contact models also need additional model parameters. For example, JKR needs a “surface energy” to characterize the contact viscosity of particles. Because this parameter is modeled, it is difficult to directly convert it to the actual material characteristics, so it must be calibrated by “virtual experiment.”

2.4. Parameter Calibration Method

2.4.1. Field Test Determination

(1). The Coefficient of Restitution. The principle of determining the coefficient of restitution [45] is the law of collision:

\[
e = \frac{v_2 - v_1}{v_{10} - v_{20}}.
\]

In order to measure the restitution coefficient of impact between the moist bulk of shotcrete (aggregate) and funnel (stainless steel), physical experiments were carried out. In order to meet the actual collision situation, the moist bulk of shotcrete material is taken to fall from the specified height and collide with the steel plate to measure the rebound height of the moist bulk of shotcrete. Therefore, it is necessary to simplify the formula of the collision law:

\[
e = \frac{h}{H}.
\]

where \( h \) and \( H \) are the initial and vertical positions of the particles respectively.

Under the action of gravity, the rebound process of particles is very fast, and it is difficult to accurately determine the rebound height of particles. In order to ensure the measurement accuracy of coefficient of restitution, a set of measuring device is designed in this experiment, as shown in Figure 8. High speed camera and image processing technology are used to constitute the measuring device system. A measuring ruler is used to calibrate the actual rebound height in the measuring background to record the movement process of particles. The image processing method is used to record and analyze the rebound process of particles.

(2). Rolling Friction Coefficient. The rolling friction coefficient between particles and steel plate, as well as between particles, is measured by inclinometer method [40], as shown in Figure 9. The measured slope angle is \( \phi \). Then, the rolling friction coefficient is

\[
f_s = \tan \phi.
\]

2.4.2. Simulation Test Calibration. The discrete element parameters of shotcrete are less studied, and the GEMM database of EDEM software does not recommend the
simulation parameters of materials based on the exact values of different types and different physical characteristics. Considering that the physical properties of the particles are close to those of clay, grain and organic fertilizer, it is necessary to accurately calibrate and optimize the simulation parameters of shotcrete based on the recommended range.

(1) Plackett–Burman test was designed by using design expert software, and the significant physical parameters were selected by taking the angle of repose of shotcrete as the response value. There are 11 parameters $T_1$~$T_{11}$ in the simulation test, and each parameter takes two levels of low and high according to the recommended range value. Among them, $T_8$~$T_{11}$ are virtual parameters, which are represented by code $-1$ and $+1$ respectively, as shown in Table 1. Each group of simulation tests were repeated 4 times, and the
average value was recorded as the angle of repose of a single group of tests.

(2) Based on the significance parameters selected from Plackett–Burman test, the steepest climbing test is designed to further narrow the range of significance parameters to accurately enter the area near the optimal value. In the simulation test, the nonsignificant parameters are selected from the recommended values of GEMM database. The basic contact parameters of the material are determined by the test, and the significant parameters are gradually increased according to the designed step size. The angle of repose of the simulation test is recorded and analyzed, and the relative errors between the simulation test results and the measured test results are calculated respectively.

(3) Based on the steepest climbing test results, according to the Box Behnken test design, three levels of significance parameters were selected to design the test, which were expressed in the form of code +1, 0 and −1, respectively. The angle of repose of each group of simulation test was recorded. In addition, a total of 17 groups of tests were carried out, and each group of simulation tests were repeated four times. The average value was recorded as the numerical result of a single group of simulation tests.

3. Results and Analysis

3.1. Simulation Parameter Calibration Results

3.1.1. Results of the Plackett–Burman Test. In Table 2, the results of Plackett–Burman test are shown. It can be seen from Table 2 that the influence of some simulation parameters on the angle of repose is extremely significant, and the maximum and minimum values of the angle of repose are 43.92° and 10.3°, respectively. Therefore, it is necessary to analyze the influence of various simulation parameters on the angle of repose.

As shown in Table 3, the influence of simulation parameters is obtained. The $R^2$ of the model was 0.9978 and the $R^2_{\text{adj}}$ was 0.99920, respectively. The results show that the model can be used to explain the influence of factors on response value. The CV of model was 3.36%, which indicates that the model was selected correctly. The Adeq Precision was 41.488. In conclusion, the experimental results have higher reliability.

Through further analysis of the model data, a Pareto chart was obtained (Figure 10). The significant ranking of factors can be seen intuitively: P-P static friction coefficient > JKR surface energy > P-S static friction coefficient > P-S collision restitution coefficient > P-S rolling friction coefficient > P-P rolling friction coefficient > P-P restitution coefficient, in addition, each factor can also be seen positive and negative effects.

It can be seen from Table 3 and Figure 10 that the surface energy, the P-P static friction coefficient and P-P rolling friction coefficient of particles have significant effects on the angle of repose of moist bulk of shotcrete, while other contact parameters have little effect. The influence order of significant factors on angle of repose is: P-P static friction coefficient > JKR surface energy > P-S static friction coefficient > P-S rolling friction coefficient. The effect of friction coefficient between particles on stacking angle is greater than that of P-S friction coefficient. The effect of P-P static friction coefficient on angle of repose is greater than that of P-S rolling friction coefficient, which is consistent with Yan et al. [46] results. However, in the study of Zhou et al. [47], the rolling friction coefficient between particles has a great influence on the angle of repose, because they ignored the shape of particles in their study and only used spherical particles for simulation experiment. Compared with the irregular particles in this study, spherical particles are easier to roll. In addition, due to less interaction between particles and geometry, the effect of S-S rolling friction coefficient on angle of repose is very small.

3.1.2. Determination of Other Parameters. As the following contact parameters have no significant effect on the angle of repose of moist bulk of shotcrete, the contact parameters in Table 4 are determined by combining the

Figure 9: Rolling friction coefficient measuring device.
recommended parameter range of GEMM material library of EDEM soft and field test measurement.

3.1.3. Analysis of Steepest Climbing Test Results. The design scheme and results of the steepest climbing test are shown in Table 5. The results show that with the increase of \( T_2, T_7 \) and \( T_3 \) values, the angle of repose obtained from the simulation test increases gradually, while the relative error between the angle of repose obtained from the simulation test and the measured test decreases first and then increases. The relative error of angle of repose reaches the minimum value at NO. 5 test level, so the optimal range of test variables is near No. 5 test level. Therefore, we choose the No. 5 level as the center point and set it to the middle level, choose level 4 and 6 for low level and high level respectively, and carry out subsequent B-BD test and regression model analysis. The low, medium and high levels of physical parameters \( T_2, T_7 \) and \( T_3 \) were 0.6, 0.8, 1, 0.3 J/m², 0.4 J/m², 0.5 J/m² and 0.06, 0.08, 0.1, respectively.

3.1.4. Results of the BBD Simulation. In Table 6, there are shown the results of the Box–Behnken simulation test. By analyzing the data in Table 6, a quadratic regression model for the repose angle and the test variables is established using Design Expert 10, given as

\[
\theta = 35.03 + 0.76 \cdot T_2 + 2.55 \cdot T_3 - 1.65 \cdot T_7 - 0.94 \cdot T_2T_3 \\
- 0.26 \cdot T_2T_7 + 0.18 \cdot T_3T_7 + 2.36 \cdot T_2T_2 + 0.77 \cdot T_3T_3 \\
+ 0.94 \cdot T_7T_7 - 1.80 \cdot T_2T_2T_3 + 1.48 \cdot T_2T_7T_7 - 0.53 \cdot T_2T_3T_3.
\] (16)

The analysis of variance of the regression model is shown in Table 7. P-P static friction coefficient, JKR surface energy and P-P rolling friction coefficient have extremely significant effects on the angle of repose of shotcrete: \( P < 0.0001 \) of the regression model means that the relationship between the dependent variables and all independent variables of the model is extremely significant. The coefficient of determination \( R^2 = 0.9973 \) and the corrected coefficient of determination \( R^2 \text{adj} = 0.9891 \) are close to 1, so the regression equation obtained has high reliability. Adeq precision = 41.693, means that the regression model has good accuracy.
3.1.5. Regression Model Interaction Effect Analysis. In this experiment, the angle of repose of moist bulk of shotcrete is used as the evaluation indicator of simulation model, and the quadratic multiple regression fitting is carried out on the model data by using Design Expert 10 software. The response surface and contour distribution diagram of the interaction between the parameters affecting the angle of repose of the objective function in Figures 11 and 12 are respectively JKR surface energy and P-P static friction coefficient interaction P-P static friction coefficient and P-P static friction coefficient interact.

By analyzing the variance of the model in Table 7, the effect of T2T7 on the angle of repose was significant ($P = 0.0013$). When the P-P rolling friction coefficient is 0.08, the response surface and contour map of the interaction between the P-P static friction coefficient and the JKR surface energy are found.

The elliptical contour line indicates that the interaction between the two factors is significant, and the circle indicates that the interaction between the two factors is extremely insignificant. In the contour map shown in Figure 11(a), it can be considered that there is an interaction relationship between the surface energy and the static friction coefficient between particles.

As shown in Figure 11(b), the repose angle of moist bulk of shotcrete increases with the increase of JKR surface energy of particle-particle. This is because the increase of JKR surface energy will lead to the increase of particle-particle cohesion, making some particles adhere together to form new aggregates, which will lead to the stability of the whole material after

### Table 3: Analysis of significance of parameters in PB test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect</th>
<th>Sum of squares</th>
<th>Contribution</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>$-0.74$</td>
<td>1.66</td>
<td>0.14%</td>
<td>7</td>
</tr>
<tr>
<td>$T_2$</td>
<td>15.27</td>
<td>699.82</td>
<td>58.75%</td>
<td>1</td>
</tr>
<tr>
<td>$T_3$</td>
<td>3.20</td>
<td>30.66</td>
<td>2.57%</td>
<td>3</td>
</tr>
<tr>
<td>$T_4$</td>
<td>1.40</td>
<td>5.91</td>
<td>0.50%</td>
<td>6</td>
</tr>
<tr>
<td>$T_5$</td>
<td>$-2.04$</td>
<td>12.48</td>
<td>1.05%</td>
<td>4</td>
</tr>
<tr>
<td>$T_6$</td>
<td>1.57</td>
<td>7.36</td>
<td>0.62%</td>
<td>5</td>
</tr>
<tr>
<td>$T_7$</td>
<td>10.51</td>
<td>331.17</td>
<td>27.80%</td>
<td>2</td>
</tr>
</tbody>
</table>

$R^2 = 0.9978$, $R^2_{adj} = 0.9920$, $CV = 3.36\%$, $adeq$ precision = 41.488. Note. The variables $T_1$–$T_7$ are equal to those in Table 1.

### Table 4: Nonsignificantly affected parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-P restitution coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>P-S restitution coefficient</td>
<td>0.5</td>
</tr>
<tr>
<td>P-S static friction coefficient</td>
<td>0.5</td>
</tr>
<tr>
<td>P-S rolling friction coefficient</td>
<td>0.2</td>
</tr>
</tbody>
</table>

3.1.5. Regression Model Interaction Effect Analysis. In this experiment, the angle of repose of moist bulk of shotcrete is used as the evaluation indicator of simulation model, and the quadratic multiple regression fitting is carried out on the model data by using Design Expert 10 software. The response surface and contour distribution diagram of the interaction between the parameters affecting the angle of repose of the objective function in Figures 11 and 12 are respectively JKR surface energy and P-P static friction coefficient interaction P-P static friction coefficient and P-P static friction coefficient interact.
accumulation, the surface particles are difficult to slide, and the top particle group is not easy to collapse, thus forming a large angle of repose. However, the repose angle first decreases and then increases with the increase of P-P static friction coefficient, and the trend is less and less obvious with the increase of JKR surface energy of particle-particle.

By analyzing the variance of the model in Table 7, the effect of T2T3 on the angle of repose was significant ($P < 0.05$). When the JKR surface energy is 0.4, the response surface and contour map of the interaction between P-P rolling friction coefficient and P-P static friction coefficient are found.

The elliptical contour line indicates that the interaction between the two factors is significant, and the circle indicates that the interaction between the two factors is extremely insignificant. In the contour map shown in Figure 12(a), it

<table>
<thead>
<tr>
<th>No.</th>
<th>T2</th>
<th>T7 (J/m²)</th>
<th>T3</th>
<th>Repose angle (°)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
<td>0.3</td>
<td>0.08</td>
<td>36.25</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.3</td>
<td>0.08</td>
<td>38.57</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
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<td>0.08</td>
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Note: The variables T2, T3 and T7 are equal to those in Table 1.
can be considered that there is an interaction relationship between the rolling friction coefficient and the static friction coefficient between particles.

As shown in Figure 12(b), the repose angle of moist bulk of shotcrete decreases with the increase of particle rolling friction coefficient. This is because when the JKR surface energy and P-P static friction coefficient are certain, the increase of rolling friction coefficient leads to the decrease of particle-particle cohesion, which makes the particles on the surface of the particle pile easy to slide and disperse, and then leads to the collapse of the particles at the top of the particle pile, thus forming a small stacking angle. However, the angle of repose decreases first and then increases with the increase of P-P static friction coefficient.
3.2. Determination of Optimal Parameter Combination. The angle of repose of the moist bulk of shotcrete measured by field test is 39.80°. Taking the actual angle of repose as the response value, using the optimization function of design expert 10, the best combination of contact parameters is as follows:

1. The rolling friction coefficient between particles is 0.06
2. The JKR surface energy is 0.418 J/m²
3. The static friction coefficient between particles is 1

Three repeated simulation tests were carried out under the combined optimization parameters, and the average stacking angle was 39.05°. The relative error is 1.88% compared with the actual physical test. As shown in Figure 13. The comparison between simulation test and physical test is obtained. The test results indicate that the shape and angle of the stacking angle obtained by the simulation test under the optimized parameters are similar to those obtained by the physical test, which indicates that the parameters can be used as a reference for the characteristics of the moist bulk of shotcrete particles.

4. Conclusions

In this paper, based on the accumulation test of the moist bulk of shotcrete, the simulation parameters of moist bulk of shotcrete are calibrated and optimized by using the method of combination of measured test and discrete element simulation, combined with EDEM software. Taking the angle of repose as response value, with the help of design expert software, the significance analysis and response surface method are applied to optimize the simulation parameters. The physical parameters that affect the angle of repose significantly are selected, and the interaction between the parameters that affect the angle of repose is analyzed to determine the optimal parameters. The conclusions are as follows:

1. The results of Plackett–Burman test and variance is analyzed. According to the significance of each factor, the order is: P-P static friction coefficient > JKR surface energy > P-P rolling friction coefficient.
2. The results of Box–Behnken response surface test are analyzed. The regression model of significant factors and angle of repose was established. The analysis of variance shows that the angle of repose is significantly affected by JKR surface energy, P-P static friction coefficient and P-P rolling friction coefficient.
3. The results show that when JKR surface energy is 0.418 J/m², P-P static friction coefficient is 1 and P-P rolling friction coefficient is 0.06, the simulation results are consistent with the field test results, and the relative error is 1.88%.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Guanguo Ma wrote the original draft and conceptualized the study. Zhenjiao Sun investigated and validated the study. Hui Ma supervised the study. Pengcheng Li took part in data curation.

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References


