Research Article

Size Effect on the Rheological Shear Mechanical Behaviors of Different Joints: A Numerical Study

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Under the condition of constant external stress, the displacement and stress of the joint will be adjusted continuously with time, resulting in the creep phenomenon, that is, the continuous increase of the strain with time, which further causes the damage of the jointed rock mass. In order to study the size effect of joint shear rheological mechanical properties, this paper conducted shear rheological numerical simulations on nonpenetrating and penetrating joint models established in Particle Flow Code (PFC) and analyzed the effect of specimen size on the rheological and shear mechanical behavior of the model. The results show the following: (1) For the rheological direct shear test, the instantaneous shear displacement of the joint increases continuously as the size increases, showing a significant positive size effect. (2) For through-type joints, only the cohesion shows a certain size effect, and the shear strength and friction angle have a nonobvious relation with specimen size. (3) For anchored through-type joints, the increase of the model size leads to a decrease in shear strength, while the friction angle-size effect of joints is not remarkable.

1. Introduction

Rock materials perform size effect, so the rock mechanical parameters obtained in the laboratory are actually different from those of engineering rock mass [1, 2]. In order to obtain more reliable parameters of engineering rock mass, it is of great engineering value to carry out research on size effect of rock materials [3, 4]. The mechanical properties of joints play an important role on the stability of rock mass engineering [5–7]. To obtain joint shear strength, carrying out laboratory direct shear test on rock joints is an important approach [8–10]. In the shear test of joint, according to the requirements of the testing machine or the specification of the mold, the size of the specimen is usually set to 70 mm × 70 mm, 100 mm × 100 mm, or 150 mm × 150 mm, which are far smaller than the actual engineering size. Based on this, some scholars have carried out related research on the size effect of rock material. Johansson [11] fabricated shear joint specimens of different sizes, obtained the shear stress-displacement curves of joints with different sizes, and established the relational model between shear joint strength and jointed specimen size, which was verified by experimental data. Up till now, there have been many related studies on the size effect of rock compressive properties, but there are still few studies on the size effect of rock rheological properties [12, 13], let alone the size effect of joint rheological properties. Under natural conditions, the failure of joints is often not caused by short-term loading, but after long-term loading [14–16]. Under the condition of constant external stress, the displacement and stress of the joints are continuously adjusted and reorganized with time, resulting in the creep phenomenon, that is, the continuous increase of the strain with time [17, 18], thereby causing the failure of the jointed rock mass [19, 20]. To prevent rock mass
failure caused by creep behavior, bolts are widely used as a more mature and effective reinforcement tool [21, 22]. Therefore, it is necessary to explore the size effect of the rheological shear mechanical properties of joints [23]. In this paper, the shear numerical models with through-type and nonpersistent joints are established by Particle Flow Code (PFC), which is widely used in geotechnical engineering modeling [24, 25]. Without changing the mesoscopic parameters of particles and contact, the influence of specimen size on the shear behavior of model is studied by carrying out rheological direct shear test on models of different sizes.

2. Modeling and Calculation Scheme

According to the division of different scales, six numerical models with sizes between 5 cm and 200 cm are established, as shown in Figure 1. The Flat-joint model is assigned to the rock particles of the model [26, 27], and the Burgers model is assigned to the joint. In this paper, the "trial and error" approach is used to calibrate rock mesoscopic parameters based on the consistency between the numerical simulation and the laboratory test results when the normal stress is 1 MPa [28]. Firstly, establishing the numerical model of the joint specimen, the shear stress-shear displacement curve of the joint is obtained by simulation, and finally, the mesoscopic parameters matching the actual situation are obtained by calibration [29]. The mesoscopic parameters selected in this study are shown in Table 1. According to the bolt parameters in the literature [30], the parallel bond model is used to simulate the bond between bolt particles. The friction coefficient is 0.5, which is less than the friction coefficient of the rock, the tensile strength of the bolt particles is 4.0 GPa, the cohesion is 0.9 GPa, and the friction angle is 20°. The bolt diameter is set to 2 mm, and the concrete parameters are shown in Table 2. Direct shear tests are performed on the generated numerical models, and the experimental results were recorded. As shown in Table 3, the side length of the model is between 5 cm and 200 cm, and the normal stress varies from 0.5 MPa to 2.5 MPa, with 0.5 MPa as the interval. The schematic diagrams of the through-type joint model, the nonpersistent joint model, and the anchored through-type joint model are shown in Figure 2.

3. Calculation Results and Analysis

3.1. Rheology-Size Effect of Through-Type Joint. The numerical simulation results are processed to obtain shear displacement-time curves of joints with different sizes, as shown in Figure 3. It can be seen from the figure that with the increase of the size, the instantaneous shear displacement continuously increases, showing a significant positive size effect. The rheological shear displacement corresponding to models of different sizes is roughly the same, which means the size effect of rheological shear displacement is nonobvious. By analyzing the elastic modulus of models
which means that the regular evolution law of shear strength with the increase of model size cannot be obtained, that is, the size effect is inconspicuous. This may be attributed to the fact that flat through-type joints rely on friction to provide shear strength when subjected to shear loads. When the joint undulation or roughness remains constant, the friction coefficient does not change with the joint length, resulting in nearly the same peak shear stress for models of different sizes, which may explain why the shear strength does not exhibit obvious size effect.

The shear strengths of models with different sizes subjected to normal stress at all levels are linearly fitted by the Mohr-Coulomb criterion, and the corresponding cohesion and friction angles are obtained to observe the overall variation trend. The relationships between the shear strength parameters and the model size are shown in Figures 7 and 8. It can be seen from Figure 7 that in the interval from 5 cm to 200 cm, the cohesion continuously decreases from the initial 0.602 MPa to the final 0.56 MPa, and the decrease range is 6.9%. The cohesion generally decreases with the increase of model size, but the relationship between the shear strength of the model and the size change is not obvious. This is mainly because the shear strength of the flat through-type joint is mainly provided by friction. As a result, the size effect of shear strength is inconspicuous. From Figure 8, the friction angle initially increases with the increase of model size, then decreases slightly with the size of the model after it reaches 50 cm, and finally fluctuates with the increase of model size. Generally, the friction angle increases from 43.94° when the model size is 5 cm to 44.58° when the model size is 200 cm. The amplification is not conspicuous, only 1.4%, indicating that the variation of model size performs a weak effect on the friction angle of the flat through-type joints, and the friction angle of flat through-type joints does not show obvious size effect.

Overall, for flat through-type joint, the cohesion generally decreases with the increase of model size, the change of the friction angle with the variation of model size has no regularity, and the parameter variation of models between different sizes is small, which does not show a significant size effect.

### Table 2: Mesoscopic parameters of bolt.

| Category               | Mesoscopic parameters | Value   |
|------------------------|-----------------------|---------|
| Density (kg/m^3)       |                       | 7850    |
| Radius (mm)            |                       | 0.18    |
| Normal stiffness kn    |                       | 8e9     |
| Shear stiffness ks     |                       | 2.286e9 |
| Tensile strength pb_ten (GPa) |               | 4.25    |
| Cohesion pb_coh (MPa)  |                       | 900     |
| Friction angle pb_fa (** ) |                 | 0       |
| Normal stiffness pb_kb |                       | 5.9e14  |
| Shear stiffness pb_kn  |                       | 5.9e14  |

### Table 3: The test scheme.

| Model size (cm) | The normal stress (MPa) |
|-----------------|-------------------------|
| 5               |                         |
| 10              |                         |
| 15              |                         |
| 20              | 0.5/1.0/1.5/2/2.5       |
| 50              |                         |
| 200             |                         |

with different sizes, the macroscopic shear stiffness corresponding to models with different size is obtained, as shown in Table 4. Adopting the nonlinear expression fit the data and the results are shown in equation (1). The fitting relation coefficient $R^2$ equals to 0.99, which shows that the equation can well predict the macroscopic shear stiffness of through-type joints with different sizes, indicating that there is a significant negative size effect on rheology for through-type joints, that is, the shear stiffness decreases nonlinearly with the increase of size.

$$G = 4.95 - 4.11(1 - \exp (-0.14x))$$  \(1\)

Under different normal stress levels, through-type joint models with different sizes are tested to obtain the relationship between shear strength and model size, as shown in Figures 4–6. From the figures, the average shear strength of models subjected to different normal stress fluctuates continuously with the increase of the model size. The ranges of shear strength are 0.012mpa, 0.042mpa, 0.071mpa, 0.053mpa, and 0.074mpa, respectively. It can be seen that the fluctuation range of shear strength caused by a size change less than 0.01 MPa, showing nonobvious size effect in the range of model size from 5 cm to 200 cm. When the model size increases from 5 cm to 20 cm, the shear strength decreases slightly. When the model size ranges from 20 cm to 200 cm, the variation amplitude of shear strength is relatively slightly.

3.2 Rheology-Size Effect of Nonpersistent Flat Joint. Figure 9 shows the shear strength of nonpersistent flat joint model with different sizes. It can be seen from the figure that the shear strength gradually decreases with the increase of the model size, the decreasing rate slows down significantly when the model size reaches 20 cm, and the shear strength no longer changes significantly when the model size reaches 200 cm. From Figure 9, the shear strength of the joint model under different normal stress decreases with the increase of model size, and the reduction ratio is 22.18%, 20.99%, 11.69%, 19.68%, and 18.22%, respectively. It can be seen that in the range of 10 cm to 200 cm, the descent range of shear strength generally decreases with the increase of normal stress, that is, the larger the normal stress, the smaller the descent range of shear strength.
The relationship between shear strength and model size is nonlinearly fitted using a power function equation:

\[ y = a + b x^c. \]  

In equation (2), \( y \) represents the shear strength, \( x \) represents the model size, \( a \) represents the curve intercept, the larger \( a \) is, the greater the strength is when the sample size approaches 0, and \( b \) represents the curvature of the curve.

The curve is fitted by equation (2), and the fitting results are shown in Table 5. It can be seen that the calculated results are in good agreement with the experimental results, and there is a significant relation of power function between the shear strength and model size. The fitting results mathematically prove the existence of the size effect. The fitting parameters \( a, b, \) and \( c \) are listed in Table 5. It can be seen that the variation law of parameter \( a \) is inconspicuous, but it generally increases with the increase of normal stress, from 73.65 when the normal stress is 0.5 MPa to 103.94 when the normal stress is 2.5 MPa. Parameter \( b \) generally decreases with the increase of normal stress, from -70.3 when the normal stress is 0.5 MPa to -97.47 when the normal stress is 2.5 MPa, and parameter \( c \) does not change significantly with the variation of normal stress. It shows that with the increase of normal stress, the size effect of model becomes more obvious, which is attributed to the friction factors being the main reason leading to the size effect, and as the normal stress increases, the friction leads to a more and more important weight in the shear strength.

Since five-level normal loads are applied to each model, the shear strength obtained in Figure 9 was linearly fitted.

The slope of the fitted curve is the friction angle and the intercept with the \( y \) axis represents the value of cohesion. Figures 10 and 11, respectively, demonstrate the relationship between cohesion, friction angle, and model size.

In Figure 10, the cohesion gradually decreases with the increase of model size, from the initial 2.113 MPa to 1.349 MPa, showing a decrease of 36.15%. When the model
Table 4: Relationship between model size and shear stiffness of through-type joint.

| Model size (cm) | Shear stiffness ($10^4$ kN/m) |
|-----------------|-------------------------------|
| 5               | 2.85996                       |
| 10              | 1.84801                       |
| 15              | 1.30353                       |
| 20              | 1.08759                       |
| 50              | 0.85285                       |
| 200             | 0.84925                       |

Figure 4: Relationship between model size and shear stiffness.

Figure 5: Relationship between shear strength and normal stress of joints with different sizes.

Figure 6: Relationship between shear strength and size of models subjected to different normal stress.

Figure 7: Relationship between the cohesion and model size.

size is less than 20 cm, the cohesion decreases rapidly, and then the decreasing rate slows down. From Figure 11, the variation trend of the friction angle with the model size is inconspicuous. Although the friction angle decreases from the initial 56.27° to 49.35°, showing a decrease of 12.2%, the variation trend fluctuates, which indicates that the friction angle has nonobvious size effect. Besides, the larger the model size, the lower the shear strength and cohesion. The decreasing rate of shear strength and cohesion gradually slows down, and the friction angle does not perform significant size effect. This indicates that for nonpersistent joint,
the size effect of cohesion is the main reason for the occurrence of the size effect of shear strength.

Table 5: Parameter fitting results of power function equation.

| Fitting parameters | $\sigma_N$/MPa |
|--------------------|---------------|
| $a$                | 73.65 45.74 102.4 117.9 103.9 |
| $b$                | -70.3 -41.74 -57.4 -112.2 -97.4 |
| $c$                | 0.004 0.007 0.03 0.003 0.15 |

3.3. Rheology-Size Effect of Anchored Through-Type Joint. The direct shear test of anchored through-type joint is simulated using PFC and the variation law of the shear strength of specimens with the model size can be obtained by calculation, as shown in Figure 12. Comparing to unanchored through-type joint, the shear strength of anchored through-type joint decreases gradually with the increase of model size, the decreasing rate slows down significantly when the model size reaches 50 cm. The shear strength no longer changes conspicuously when the model size increases to 20 cm. It can be seen that the shear strength of model under different normal stress decreases with the increase of model size. When the model size is between 10 cm and 200 cm, the descent range of the shear strength generally increases with the rise of normal stress, that is to say, the

![Figure 8](image_url)  
**Figure 8:** Relationship between the friction angle and model size.

![Figure 9](image_url)  
**Figure 9:** Relationship between model size and shear strength of models under different normal stress.

![Figure 10](image_url)  
**Figure 10:** Relationship between cohesion and model size.

![Figure 11](image_url)  
**Figure 11:** Relationship between friction angle and model size.
larger the normal stress, the larger the descent range of shear strength. Unanchored fl at through-type joint has no size effect, while anchored fl at through-type joint performs size effect. This is mainly because the existence of bolt improves the integrity of rock mass and increases friction near the bolt, and the frictional factor is an important reason for the size effect. Therefore, the addition of bolt leads to the size effect of through-type joint.

Adopting equation (2) to nonlinearly fit the relationship between shear strength and model size and the fitting results are shown in Figure 12. It can be seen in Figure 12 that the fitting results are good, indicating that there is a significant power function relationship between the shear strength and model size, and the fitting results mathematically prove the existence of size effect. The values of parameters $a$, $b$, and $c$ are listed in Table 6. It can be found that the parameters $a$ and $b$ increase with the increase of normal stress, parameter $c$ performs irregular variation. It demonstrates that with the increase of normal stress, the size effect of joint is continuously enhanced, which is due to the fact that the contribution ratio of friction to shear strength increases as the normal stress increases.

The shear strengths of anchored through-type joints are linearly fitted to obtain the cohesion and friction angle and their relationship with the model size, as shown in Figures 13 and 14. From Figure 13, the cohesion increases before the model size reaches 50 cm and then decreases, but the extreme value does not exceed 0.015 MPa in the whole process. The fluctuation range is very small, and there exists no significant size effect on cohesion. In Figure 14, the friction angle performs an obvious variation trend with the model size. The friction angle decreases with the model size, from the initial 48.71° to 45.22°, showing a decrease of 7.1%. The friction angle performs a significant negative size effect. Through the study on size effect of anchored flat through-type joints, it is found that the increase of model size has a relatively significant effect on the variation of shear strength and friction angle but has no obvious effect on the cohesion. This indicates that the size effect of friction angle is the main reason for the existence of the size effect of shear strength.
4. Conclusions

(1) For the rheological direct shear test, there exists a significant positive size effect on the instantaneous shear displacement of joint. The creep shear displacement corresponding to different model size is roughly the same, and the size effect of creep shear displacement is not obvious. The shear stiffness of joints decreases continuously with the increase of model size, and there is a conspicuous nonlinear relationship. When the model size increases to a certain value, the shear stiffness converges to a fixed value.

(2) For through-type joints, only the cohesion performs the size effect, the shear strength and friction angle do not show obvious size effect. For nonpersistent joints, an obvious law of size effect can be found, in which the shear strength and cohesion gradually decrease with the variation of model size, and the friction angle does not show conspicuous size effect. The size effect of cohesion is the main reason for the size effect of shear strength.

(3) For anchored flat through-type joints, the larger the model size, the lower the shear strength, while the size effect of the cohesion is inconspicuous. The size effect of the friction angle is the main reason for the existence of the size effect of shear strength.

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.

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