Research Article

Relationship between Mechanical Properties of Saturated Fissured Sandstone and Fissure Angle after Freeze-Thaw Cycles

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The change of mechanical properties of the surrounding rock of underground engineering in cold regions decreases engineering safety. In order to explore the influence of fissure angle on the mechanical properties of surrounding rocks, uniaxial compression and acoustic emission tests were carried out on the fissured sandstone in a saturated state. The results showed that the stress-strain curves of the fissured sandstone had “stress drop” phenomena, the acoustic emission ringing count rate and the cumulative ringing count versus time curve could describe the various stages of fissured sandstone failure, and the increase in the fissure angle made the acoustic emission activity more active. Fissures degraded the mechanical properties of sandstone. The peak strength and elastic modulus of the fissured sandstone increased with the increase of the fissure angle due to the large fissure width of the saturated sample and the freezing-thawing effect, and the peak strain and Poisson’s ratio had no obvious regularity. As the fissure angle increased, the dominant cracks in the failure mode changed from tensile cracks to shear cracks and then to tensile cracks, and the failure mode changed from splitting failure to shearing failure and then to splitting failure. This study can provide guidance and suggestions for the design of underground engineering in cold regions.

1. Introduction

Underground engineering in cold regions experiences freeze-thaw cycles, and water-ice phase changes occur in water to cause uneven expansion and contraction of minerals in the rock, leading to further development of primary fissures and pores inside the rock, which affects the stability of the surrounding rocks of underground works in cold regions [1].

As a composite brittle material, the study on the effect of internal fissures on the mechanical properties of rocks is more mature. Yang et al. [2–4] used an acoustic emission monitoring system to analyze the mechanical properties and deformation rupture process of fissured sandstone under uniaxial compression conditions and found that the fissure angle had a significant effect on the strength and deformation modulus of the specimen, and the change in acoustic emission was associated with the degree of damage inside the specimen. Li et al. [5] analyzed the crack development pattern of fissure rocks under uniaxial compression and observed two forms of crack emergence: internal tip cracking together with external tip cracking and external tip cracking only. Lee et al. [6] conducted numerical simulations on fissured specimens with three different arrangements under uniaxial compression conditions and investigated the effects of different angles of rock bridges on the emergence and extension of cracks and the damage pattern of specimens. Feng et al. [7] conducted a true triaxial unloading test and conducted an in-depth study on the relationship between the crack propagation process and the stress in three directions. Cheng et al. [8] carried out uniaxial compression tests on prefabricated fissure-like rock materials and found that the peak strength and residual strength decreased as the prefabricated fissure length increased and the failure mode changed from shear to tensile failure. Chen et al. [9] found that the inclination and length of the structural plane have important effects on the crack propagation behavior, failure mode, energy evolution, and displacement distribution of
surrounding rocks. Chen et al. [10] deduced the macroscopic damage variable formula of rock mass considering the crack propagation length and the friction effect of joint closure by combining the energy principle and the fracture damage theory and established a coupled damage variable considering macroscopic and microscopic defects.

In addition, underground engineering in cold regions suffers from freeze-thaw cycles for a long time, and the proportion of ice content inside the rock during freezing plays an important role in the mechanical properties of the rock. The ice content is governed by the initial water content. Boone [11, 12] et al. studied the effect of temperature change on the pattern of freezing swelling. Wang et al. [13] explored the mechanical properties of tuff rocks after freeze-thaw cycles at different temperatures and found that the uniaxial compressive strength and Young’s modulus of specimens decreased and structural face rupture increased after suffering freezing damage. Chen et al. [14, 15] proposed a shear creep intrinsic model considering the effects of freeze-thaw cycles and time-dependent damage based on NMR detection and shear creep tests. Mustafa Fener et al. [16] used polarized light microscopy to examine the structural changes in andesite after freeze-thaw cycles and determined the effect of the number of freeze-thaw cycles on the basic mechanical properties of the stone. Huang et al. [17] used the static elastic modulus to represent the freeze-thaw damage of rocks, established the damage principal structure model, and derived the final statistical damage principal structure equation. Liu et al. [18] proposed a new model for predicting freeze-thaw uniaxial compressive strength based on elastic-plasticity theory and fatigue damage mechanics, considering the actual state of rock stress distribution under freeze-thaw action. Based on the principle of static equilibrium, the law of conservation of energy, and the law of conservation of mass for rocks, Kang et al. [19] established a model undergoing controlling equations for the heat-water-force coupling of rocks undergoing freeze-thaw cycles.

In summary, current studies have focused on the mechanical properties of intact rocks in dry and saturated states [20] and ignored the fact that water-bearing rocks in nature have internal fractures and are often under freeze-thaw action. Fewer studies have been conducted on the mechanical properties of saturated water-bearing fractured rocks under freeze-thaw action. In view of this, the sandstone in this study was taken out during mine excavation as the background of the Jiangzhuang coal mine project in Jining City, Shandong Province. After the drilling, cutting, and grinding, the rock was made into a standard specimen of \( \Phi 50 \, \text{mm} \times 100 \, \text{mm} \) required for the test. A 25 mm long and 2 mm wide penetration fissure was cut in the center of the rock sample by using the SQ3020 CNC ultrahigh pressure water jet cutting machine (Figure 1(a)). The fissure dip angles were set at 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The specific distribution of specimen fissures was shown in Figure 1(b).

This test used the natural water-saturated method to produce sandstone specimens in a water-saturated state, and the specific operation steps were as follows: firstly, the specimens were put in a drying oven at 105°C for 24 hours. Second, we waited for them to cool to room temperature and weighed their dry mass. Then, we soaked the rock samples in water to absorb water, took out the specimens every 30 minutes at the beginning of the soaking process, wiped off the water on the surface of the specimens, and weighed their mass until saturation. Finally, we measured the saturation of the sandstone used in this test. The saturated water content was measured to be 1.18%.

The prepared fissured sandstones were wrapped tightly with cling film, and we placed them in a freeze-thaw cycle chamber for a freeze-thaw cycle test with a freezing temperature of \(-20^\circ\text{C}\) and a freezing time of 12 h. The dissolution temperature was set to \(20^\circ\text{C}\) and dissolution time to 12 h. In other words, each freeze-thaw cycle was 24 h. The number of freeze-thaw cycles was set to 20 times according to the corresponding test specification [21, 22]. The specimen numbers with different inclination angles under freeze-thaw action were shown in Table 1.

2.2. Test Equipment and Loading Procedure. Conventional uniaxial compression tests were performed on fissured sandstones under 20 freeze-thaw cycles using the STAC 600–50 multifunctional rock triaxial testing machine with stress-controlled axial loading. The axial loading rate was 0.05 MPa/s. During the loading process, it indicated that the sandstone lost its bearing capacity when the axial stress and hoop strain were greatly reduced, accompanied by a popping sound. The loading was stopped immediately. In addition, the acoustic emission signals were detected using an AE21C acoustic emission detector when the rock underwent uniaxial compression.

3. Mechanical Properties’ Analysis

3.1. Stress-Strain Curve Analysis. The fissured sandstone samples with a water content of 1.18% after 20 freeze-thaw cycles were subjected to conventional uniaxial compression tests, and the full stress-strain curves were obtained from the test results as shown in Figure 2, where \(\varepsilon_x\) was the axial strain, \(\varepsilon_\theta\) was the hoop strain, and \(\varepsilon_v\) was the volumetric strain.

The stress-strain curves of fissured sandstones were similar. They were up-concave and went through four stages: the compaction stage, elastic deformation stage, plastic deformation stage, and destruction stage. The weakening effect of water made it possible to compress the
microfractures inside the sandstone with relatively small load. In the elastic deformation stage, the phenomenon of “stress drop” appeared, and the full stress-strain curve showed “multiple peaks.” The number of “peak” increased compared with the intact sandstone specimen, and the curve fluctuations were more. The decrease in the proportion of linear elastic phase indicated that elastic deformation gradually decreased. This was because the sandstone used in the test had high brittleness and weak tensile capacity. The tensile deformation may have occurred during the compression process. During the plastic deformation stage, the circumferential and volumetric strains increased significantly. The internal cracks and newly generated cracks in the rock samples began to expand and penetrate, followed by macroscopic cracks. After reaching the peak strength, the stress decreased rapidly, indicating that the specimen lost its load-bearing capacity, and the rock samples showed brittle damage characteristics.

3.2. Acoustic Emission Characterization. Figure 3 showed the experimental results of the acoustic emission cumulative ringing count rate of the fissured sandstone.

At the beginning of the compression-density and elastic-deformation phases, the primary fissures within the sandstone were compacted, and the acoustic emission activity was minimal. The accumulated elastic energy started to be released, and new cracks were generated in the plastic deformation stage. The cumulative ringing count curve fluctuated frequently, and the "stress drop" phenomenon made the acoustic emission events reach a small peak. Then, the acoustic emission events entered a "silent period," the ringing count rate weakened, and the cumulative ringing count rate curve tended to be flat in this phase. After the "silent period," the fissured sandstone entered the damage stage. The stress reached its peak, and a large number of new cracks were generated, expanded, and penetrated, at which time the acoustic emission event was extremely active. The ringing count rate appeared to peak, and the cumulative ringing count rose sharply. After the stress peak, the rock sample had been damaged, and the sandstone was in the residual damage stage.

With the increased fissured dip angle, the acoustic emission ringing count rate and cumulative ringing count rates of the sandstone showed an increasing trend. At the same time, the cumulative ringing count rate-time curve could be divided into stable periods and unstable periods. In the stable period, the cumulative ringing count was growing at a low rate, and the cracks were developed and expanded steadily. In the unstable period, the cumulative ringing count was growing at a high rate, and the rock samples produced irreversible damage cracks. The duration of the stable period

**Table 1: Sample number.**

<table>
<thead>
<tr>
<th>Number of freeze-thaw cycles</th>
<th>Water content (%)</th>
<th>Fissure angle (°)</th>
<th>Specimen number</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.18</td>
<td>Intact</td>
<td>A-intact</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>A-0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>A-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>A-30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>A-45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>A-60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75</td>
<td>A-75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>A-90</td>
</tr>
</tbody>
</table>
of the cumulative ring count rate curve became longer with the increase of the dip angle, which indicated that the larger the angle was, the stronger the resistance of the sandstone to deformation.

3.3. Peak Strength Analysis. Figure 4(a) reflected the relationship between compressive strength of the water-saturated fissured sandstone and the fissure dip angle after freeze-thaw action. Figure 4(b) reflected the relationship between the effective bearing area of the fissured sandstone and the fissure dip angle.

As could be seen from the figures, the peak strengths of the fissured sandstone were smaller than those of the intact sandstone, which indicated that the presence of fissure had a weakening effect on the sandstone. The fissure opens up to form a larger sliding fault during fissured sandstone destruction, resulting in the weakening of strength. The lowest peak strength of the fissured sandstone was 11.16 MPa at a 15° fissure angle, and the highest peak strength of the fissured sandstone was 31.21 MPa at a 90° fissure angle. The peak strength increased with the increase in the fissure angle, but it was lower than that of the intact specimen. According to the literature, the test results of some scholars showed that the peak strength of the rock tended to decrease and then increase with the increase of the fissure angle. However, this phenomenon was not obvious in this paper, which was caused by the different fissure widths used in the specimens, and the fissure width in this study was 2 mm. The experimental results of Shen...
Figure 3: Acoustic emission ringing count rates and cumulative ringing count rates in fractured sandstones with different dip angles. (a) A-intact. (b) A-0. (c) A-15. (d) A-30. (e) A-45. (f) A-60. (g) A-75. (h) A-90.

et al. [23] showed that when the fissure width was lower than 0.8 mm, the peak strength showed an obvious trend of first decreasing and then increasing, and a more obvious trend of increasing when the fissure width was greater than 0.8 mm.

In addition, there was a significant jump in peak strength when the fissure dip angle was 60°, which was related to the damage caused by the fissure. The cross-sectional area of the sandstone specimen consisted of the total pore area and the effective bearing area. The effective bearing area of the fissured sandstone specimens was reduced compared with that of the intact sandstone specimen, so the peak strength was smaller than that of the intact sandstone. The effective bearing area increased with the increase of the fissure angle. When the fissure dip angle was 45°~60°, the effective bearing area increased more.

The fitting equation and correlation coefficient between the fissure angle and compressive strength of the fissured sandstone are shown as

\[ UCS = 7.885 + 0.24281 \alpha, R^2 = 0.92084. \]  

Eq. 1

- **UCS**—peak fractured rock strength, MPa;
- **E** = 3.24799 + 0.05372α, \( R^2 = 0.96693 \)—fissured sandstone dip angle.
3.4. Elastic Modulus Analysis. Figure 5 reflected the relationship between the elastic modulus of the fissured sandstone and the fissure angle. As could be seen from the figure, the lowest specimen elastic modulus was 3.66 GPa when the dip angle was 0°. When the dip angle was 90°, the highest peak strength was 8.13 GPa, which was lower than the intact sandstone elastic modulus. This was because there were more pores and cavities in the fissured sandstone, and this expanded the surface area in contact with water, which enhanced the softening effect of water. The elastic modulus of the fissured sandstone increased with the increase of the fissure angle, indicating that the larger the dip angle was, the stronger the ability of the specimen to resist deformation was. In other words, the increased fissure angle had an optimization effect on the ability of the sandstone to resist deformation. It was worth noting that at the fissure dip angle of 60°, the elastic modulus had a jump increase, followed by a monotonic increasing trend, and the change form was similar to Figure 5.

The fitted equations and correlation coefficients for the relationship between the dip angle and the elastic modulus of the fissured sandstone are shown as follows:

\[ E = 3.24799 + 0.05372\alpha, \quad R^2 = 0.96693. \]  

Eq. 2— modulus of elasticity of the fissured sandstone, GPa.

3.5. Peak Strain Characteristics. Figure 6 reflected the relationship between the peak axial strain of the fissured sandstone and the fissure dip angle.

It could be seen from the figure that there was no obvious pattern between the peak strain and the fissure dip angle of the fissured sandstone. This was because the “stress drop” phenomenon occurred; the specimen axial, circumferential, and volumetric strains increased largely, and their values could not be compared. Therefore, there was no obvious pattern of peak strains in the fissured sandstone when the peak strength was reached.

3.6. Poisson’s Ratio Characteristics. Figure 7 reflected the relationship between Poisson’s ratio of the fissured sandstone and the fissure angle.
From the figure, there was no obvious pattern between Poisson’s ratio and the fissure angle of fissured sandstones. However, it could be found that the values of Poisson’s ratio of fissured sandstones were larger than those of intact sandstones, which was due to the fact that plastic deformation had been generated during the preparation of fissured specimens, and the ratio of transverse strain to longitudinal strain of fissured specimens became larger. It could be found that the peak strain value of the fissured sandstone was similar to that of the intact sandstone when the fissure angle was small, but Poisson’s ratio was relatively larger, which indicated that the rock was more prone to instability and swelling deformation under the external load. In addition, Poisson’s ratio was almost the same as that of the intact sandstone, and the peak strain value was the largest and significantly larger than that of the intact sandstone when the fissure dip angle was 90°, indicating that the lateral deformation of the fissured sandstone was larger at this time.

3.7. Analysis of Macroscopic Damage Patterns in Fractured Sandstones.

The macroscopic damage mode of intact sandstone specimens was splitting damage. Sandstone specimens with a fissure dip angle of 0° and 15° had wing cracks penetrating up and down to form the main rupture surface, which was typical of splitting failure. When the fissure dip angle increased from 30° to 45°, the development direction of wing cracks in sandstone specimens completely changed to the axial loading direction, and the failure mode changed from splitting failure to shear failure. Sandstone specimens with a fissure angle of 60° had the most abundant crack types, and wing cracks, secondary inclined cracks, secondary coplanar cracks, and far-field cracks all appeared. The development of wing cracks was incomplete, the secondary coplanar cracks and secondary inclined cracks penetrated up and down to form the main rupture surface, and the failure mode was shearing failure. Wing cracks were not obvious in the sandstone specimen with a fissure angle of 75°. The far-field cracks merge with the secondary cracks to form the secondary rupture surface, and the failure mode became splitting failure. Sandstone specimens with a fissure angle of 90° had obvious longitudinal penetration failure. The extension cracks were mainly far-field cracks, and the failure mode was splitting failure.

It could be found that the fissure angle gradually increased from 0°, the shear cracks were gradually more than tensile cracks in the failure mode, and the specimen failure mode changed from splitting failure to shear failure. The fissure angle increased to 60°; the peak strength had increased significantly. Therefore, there were more rock grains to reach weakening, resulting in more split surfaces. Moreover, tensile cracks gradually increased, and the failure mode gradually changed to splitting failure.

The number of wing cracks and their development gradually decreased, but the number of secondary cracks and their development gradually increased. From the energy point of view, each secondary crack could be regarded as a channel for strain energy consumption, and the greater number of them consumed more energy, thus requiring a greater load to destroy the rock sample [24], which also explained the phenomenon that the peak strength of the sandstone increased with the increase of the fissure dip angle.

4. Discussion

The fissures in the water-filled fissured sandstone under the freeze-thaw action deteriorate the mechanical properties of the sandstone, but the increase in the fracture angle has an optimized effect on the bearing capacity of the fractured sandstone. When the prefabricated fissure width is 2 mm, the peak strength increases with the increase of the fissure angle. Previous studies show that the peak strength decreases...
first and then increases with the increase of the fissure dip angle, which is different from our experimental results. This is not only related to the different width of the prefabricated fissure and the brittleness of sandstones but may also be influenced by the strength of the specimen, the friction angle, and the tension-compression ratio [25]. Moreover, the fissure sandstone in this study was in a water-filled state and experienced 20 freeze-thaw cycles, which is one of the factors that caused the different results. In addition, the relationship between the fissure angle and the peak strain of the fractured sandstone in the test was unclear. On the one hand, the effect of water made the axial strains, circumferential strains, and volumetric strains increase largely, and they cannot be compared.

On the other hand, the fractured sandstone is more porous and more easily damaged under the load used; at the same time the damage in the initial state has produced a certain plastic deformation, resulting in a reduction of the axial deformation during formal compression [26].

In actual engineering, there will be temperature damage during freeze-thaw cycles, and frost heave forces caused by temperature changes can damage the rock. In addition, the rock is often in a three-dimensional loading state for a long time, and future work should be combined with the surrounding pressure for creep to better restore the construction environment at the site and explore the effect of water content on the fractured sandstone in the freeze-thaw state.

5. Conclusion

(1) The stress-strain curve of water-filled fractured sandstones after freeze-thaw showed a “multi-peak type.” It was observed by acoustic emission that the greater the fissure angle, the longer the stable period of the cumulative ringing count rate curve of the fractured sandstone, and the stronger the resistance to deformation.

(2) The fissure played a deteriorating role in the mechanical properties of the sandstone. The peak strength and elastic modulus tended to increase with the increase of the fissure angle, and the peak strain and Poisson’s ratio have no obvious relationship with the change of the fissure angle.

(3) As the fissure angle increased, the dominant crack in the failure changed from tensile cracks to shear cracks and then to tensile cracks, and the failure mode changed from splitting failure to shearing failure and then to splitting failure.

Data Availability

All experimental data generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors’ Contributions

Yiquan Luan and Zihao Liu contributed equally to this work.

Figure 8: Destruction mode of fissured sandstones with different dip angles. (a) A-intact. (b) A-0. (c) A-15. (d) A-30. (e) A-45. (f) A-60. (g) A-75. (h) A-90.
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References


