Investigations of the mechanical behavior and failure mechanism of fractured rock samples

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Abstract. As excavation is often very deep with large unloading forces in the construction of a high-level radioactive waste (HLW) disposal repository, microcracks in the surrounding rock are unavoidable. In this work, a series of uniaxial compression tests were conducted on intact samples and samples with fractures at different inclination angles (30°, 45°, and 60°), to investigate the mechanical behavior and failure mechanism of fractured rock samples. According to the experimental results, a more inclined angle of the fractures would dramatically reduce the compressive strength of the sample. After the compression tests, the granite samples with different fracture inclinations have different failure modes and distribution characteristics of cracks on sample outside surfaces and the premade fracture planes. Higher dip angles of the premade fractures have less surface density of cracks on the sample outside surface after compression. The instability failure of granite samples with 60° fracture inclination is entirely due to shear deformation between the premade fractures. Based on this single failure mode, the compressive strength of a granite sample with 60° fracture inclination has a positive correlation with the difference in fractal dimensions induced by compression. The greater the difference in fractal dimensions, the higher the compressive strength.

Keywords: fractured rock samples, uniaxial compression test, failure mode

1. Introduction

Deep geological disposal is considered a feasible and safe option to manage high-level radioactive waste (HLW) worldwide. In the development of HLW repositories, the underground research laboratory (URL) is one of the most important steps. During the excavation of these underground facilities, local damage of the surrounding rock may be induced by stress redistribution or loosening of surrounding rock mass. Moreover, as a complex and heterogeneous geologic body, the rock mass usually consists of various scales of fractures, the mechanical behavior of which may have a significant effect on the stability of the underground facilities. In view of this, numerous experimental and numerical studies have been carried out on the mechanical properties of fractured rock samples [11-6]. The influences of roughness, the inclination and numbers of asperities, stress level, and stress rate on the mechanical behavior of fractured rock samples have been analyzed[7-10].

In China, the Xinchang site in Beishan, located in Gansu Province, has been selected as the site of China’s first URL built in granite [11]. The rock types, faults, fracture distribution, and geological, hydrogeological, geochemistry and geomechanical conditions of the Xinchang site have been systematically characterized [12-14]. Extensive studies have been conducted on the mechanical
characteristics of Beishan granite \cite{15-17}. However, these investigations are mainly focused on intact rock and the mechanical behavior and failure mechanism of fractured rock samples have not been properly understood.

In this work, a series of uniaxial compression tests were conducted on intact granite and granite samples with fractures at different inclination angles (30°, 45°, and 60°), to investigate the mechanical behavior and failure mechanism of fractured rock samples. The strength and deformation characteristics, crack distribution and failure mode, and changes of the premade fracture surface induced by compression are analyzed. The roughness of the premade fracture surface has been characterized by fractal dimensions, with the help of three-dimensional (3D) point cloud data recorded by a 3D laser scanner.

2. Laboratory investigation

2.1. Sample preparation

The granite studied in this work is sourced from the Beishan area, which is considered as the potential host rock for HLW repositories in China. Standard granite samples were prepared from a massive intact granite block taken from a shallow depth at the Xinchang site in Beishan, the. The granite samples with fractures at different inclination angles were produced from the intact standard granite samples after separation by a special rock splitting device. As shown in Figure 1, three inclination angles were prefabricated in this study, i.e., 30°, 45°, and 60°.

![Figure 1. Granite samples with fractures at different inclination angles](image)

2.2. Experimental set-up and equipment

A series of uniaxial compression tests were carried out on intact and fractured rock samples. A rock triaxial rheological test system was used in this study, with a maximum axial loading capacity of 1500 kN, and a maximum confining pressure capacity and pore pressure capacity of 60 MPa. Information about the sample surface and the properties of the premade fracture planes in the fractured rock samples before and after the test were recorded by a 3D laser scanner.

3. Experimental results

3.1. Strength and deformation characteristics

In this work, the mechanical behavior of intact granite samples and granite samples with fractures at different inclination angles (30°, 45°, and 60°) were determined. Four specimens were selected for each of the angles. The uniaxial compressive strengths of intact samples and samples with fractures at different inclination angles are presented in Figure 2. It can be seen that the uniaxial compressive strengths of fractured granite samples are significantly lower than those of the intact samples. A more inclined angle of the fractures dramatically reduced the compressive strength of the sample. The average compressive strength of granite samples with 30° fracture inclination is 142.76 MPa, which is 7.97% lower than that of intact sample (155.12 MPa). However, for the granite samples with 60° fracture inclination, the average compressive strength is 43.93 MPa, which is only 28.32% of the
intact samples’ compressive strength. For granite samples with 45° fracture inclination, the average compressive strength is 109.86 MPa.

Figure 3 shows the axial strain at peak strength of different granite samples. The inset is the stress-strain curve of one of the granite samples with 60° fracture inclination. Experimental results show that there are no significant differences in the axial strains at peak strength between the intact samples and the granite samples with 30 or 45° fracture inclination. In spite of different uniaxial compressive strength, the average axial strain is about 0.38% for these samples. However, for the granite samples with 60° fracture inclination, the axial strain has a tendency of obvious dropping with the increase of compressive strength. The higher the uniaxial compressive strength, the smaller is the axial strain at peak failure. In addition, an obvious plastic deformation before peak strength can be observed for granite sample with 60° fracture inclination, as shown in the stress-strain curve in Figure 3. Consequently, their axial strain at peak strength may be higher.

For granite samples with 60° fracture inclination, the minimum and maximum compressive strengths are 27.19MPa and 58.41MPa respectively. There is large discreteness in compressive strength for different specimens, compared with intact samples and granite samples with 30 or 45° fracture inclination. The difference in the properties of fissure structure in a single fractured rock sample is thought to be one of reasons for discreteness. Therefore, we use the 3-d laser scanning technology to record the information of the sample surface and the properties of fracture plane before and after the test, in order to find the reasons behind the behavior.
3.2. Crack distribution and failure mode

In the laboratory test, the intact granite specimen generally exhibits typical brittle mechanical behavior. Under uniaxial compression, the failure mode of the intact granite sample usually dominates by axial splitting or spalling failure. The crack distribution characteristics and the influence of a single fracture on the failure mode will be discussed in this section.

The crack distribution characteristics of the intact and the fractured rock samples are presented in Figure 4 and Figure 5, respectively. As shown in Figure 4(a), the sample’s surface is covered in numerous tensile cracks after the uniaxial compression test, which results in breaking off of stone particles and volume expansion of the sample. To evaluate the crack distribution characteristics and the degrees of particle peeling and volume expansion, the geometric shape of cracks on the sample surface (Figure 4(b)) and point cloud features of the expanded drawing of the sample outside surface (Figure 4(c)) are analyzed.

For the intact samples and samples with 30° fracture inclination, the sample surface was found to be dominated by two large-size vertical symmetrical tensile cracks and some small secondary cracks around the main cracks. The difference is the secondary cracks on the intact sample’s surface are relatively abundant. For a fractured rock sample with 30° fracture inclination, the microcracks are also formed firstly in the weak points of the sample, and then extend to the two end surfaces of the sample. When the microcracks extend to the premade fracture of the fractured sample, some energy is released by the premade fracture, which results in a decrease in compressive strength. Moreover, the shear stress on the premade fracture surface is far below the shear strength of the sample, which is not sufficient to cause shear deformation between the fissures. Then the microcracks will cut through the premade fracture and extend to the end surface of the sample; consequently, two main cracks similar to that in the intact sample will be formed. In addition, the energy release induced by the premade fracture will significantly reduce the number of secondary cracks.

Compared with the fractured rock samples with 30° fracture inclinations (Figure 5(a)), the shear stress on the premade fracture surface of the fractured sample with 45° fracture inclination is higher, maybe even close to the shear strength, but cannot cause complete slippage in the premade fracture surface. The asperities on the premade fracture surface keep the fracture surface from sliding, and cause local stress concentration. Then a Z-shaped shear–tensile failure mode along the premade fracture surface usually can be observed (Figure 5(b)). For a granite sample with 60° fracture inclination (Figure 5(c)), the shear deformation between the premade fractures is immediately obvious. Some rock debris on both ends of the long axis of the premade fracture may drop down during sliding. Figure 6 shows the surface density of cracks on the sample outside surface at different dip angles of premade fractures. It can be seen that higher dip angles of premade fractures have lower surface density of cracks on the sample outside surface.

**Figure 3.** Axial strain at peak strength of different granite samples (The inset is the stress-strain curve of one of the granite samples with 60° fracture inclination.)
Figure 4. Crack distribution characteristics of an intact sample.
Figure 5. Crack distribution characteristics of fractured rock samples

(b) Granite sample with 45° fracture inclination

(c) Granite sample with 60° fracture inclination

Figure 6. Surface density of cracks at different dip angles
3.3. Changes to the premade fracture surface

For fractured rock samples, considerable variation in the premade fracture will occur under uniaxial compression. Figure 7 shows the premade fracture surfaces of fractured samples with different dip angles after the uniaxial compression test.

It can be seen that the state of the premade fracture surface is always in accordance with the distribution characteristics of the cracks on the sample outside surface. For the granite sample with 30° fracture inclination, the main microcracks are found to cut across the premade fracture (Figure 5(a)). Accordingly, on the premade fracture surface of the sample with 30° fracture inclination (Figure 7(a)), some evident indentations or even connected cracks can be observed. For the granite sample with 45° fracture inclination, the fracture surface tends to slip but some asperities present an obstacle to the sliding, because the shear stress on the premade fracture surface is close to the shear strength. Therefore, the friction-sliding zone and tensile cracks near the asperities exist on the premade fracture surface after uniaxial compression (Figure 7(b)). When the angle of inclination is increased to 60°, the shear stress on the premade fracture surface is much higher than the shear strength and, consequently, the failure and sliding of the grains on the premade fracture surface can be significant. A large number of rock grains and powder can be observed on the premade fracture surface (Figure 7(c)).

The failure characteristics of the premade fracture are also verified by 3D point cloud data of the premade fracture surface before and after axial compression, as presented in Figure 8(a–f). On this basis, the fractal dimensions of the premade fracture surface are calculated to measure the changes before and after axial compression. The uniaxial compressive strength of the fractured rock sample is related to the difference in fractal dimensions before and after compression. Let the fractal dimensions before and after the test be \( d_1 \) and \( d_2 \), respectively. The horizontal axis in Figure 9 shows the difference in fractal dimensions induced by compression \((d_2 - d_1)\). That means the fractal dimensions after the test are higher than those before test, and the premade fracture surface becomes rougher after compression. This is attributed to the indentations or cracks on the premade fracture surface, which result in high surface roughness and increased fractal dimensions. Due to the friction-sliding zone on the premade fracture surface after compression, the difference in fractal dimensions of fractured rock samples with 45° fracture inclination is relatively low, compared with fractured rock samples with 30° fracture inclination. For fractured rock samples with 60° fracture inclination, due to the failure and sliding of the grains on the premade fracture surface, the fractal dimensions are decreased and the difference in fractal dimensions induced by compression \((d_2 - d_1)\) is negative. Overall, for the fractured rock samples with the same fracture inclinations, the greater the difference in fractal dimensions induced by compression, the higher the compressive strength.

![Images showing changes to the premade fracture surface](image-url)
Figure 7. The premade fracture surfaces after tests.

(a) Angle of 30° (before test)  
(b) Angle of 30° (after test)  
(c) Angle of 45° (before test)  
(d) Angle of 45° (after test)  
(e) Angle of 60° (before test)  
(f) Angle of 60° (after test)

Figure 8. Three-dimensional (3D) point cloud images of the premade fracture surfaces.
4. Discussion

As mentioned in this work, there is a large amount of discreteness in compressive strength for granite samples with 60° fracture inclinations, compared with intact samples and granite samples with 30° or 45° fracture inclinations. The maximum compressive strength (58.41 MPa) is more than double the minimum compressive strength (27.19 MPa). For granite samples with 30° or 45° fracture inclination, the difference between the maximum and minimum compressive strength is not significant. We consider that the failure mode may be an important factor in affecting the compressive strength.

According to the experimental results, the instability failure of granite samples with 60° fracture inclination is entirely due to shear deformation between the premade fractures. Then, the main factor affecting compressive strength is the roughness of the premade fracture surface. Meanwhile, the fractal dimensions are a means to measure the surface roughness. For granite samples with 60° fracture inclination, good agreement can be observed between the compressive strength and the difference in fractal dimensions induced by compression. The greater the difference in fractal dimensions, the higher the compressive strength.

The failure mode of granite samples with 30° fracture inclination is similar to that of intact samples. Microcracks formed first in the weak points of the sample, then cut through the premade fracture and extended to the two end surfaces of the sample. The premade fracture plays a part in reducing the compressive strength of the sample, but not in changing the main failure mode. For granite samples with 45° fracture inclination, although there is a friction-sliding zone on the premade fracture surface, many tensile cracks can be clearly observed and tensile failure is the main failure mode of the granite. Therefore, although the failure modes of granite samples with 30° or 45° fracture inclinations are complex, their compressive strengths have low discreteness.

5. Conclusions

In this study, the mechanical behavior and failure mechanism of fractured rock samples are investigated with the help of a rock triaxial rheological test system. Essential conclusions are drawn as follows:

(1) The uniaxial compressive strengths of fractured granite samples are significantly lower than those of intact samples. A more inclined angle of the cracks dramatically reduced the compressive strength of the sample. Moreover, there are no significant differences in the axial strains at peak strength between intact samples and granite samples with 30° or 45° fracture inclinations. However,
for granite samples with 60° fracture inclination, the axial strain obviously decreases with the increase of compressive strength.

(2) Higher dip angles of premade fractures have fewer cracks on the sample outside surfaces after compression. For samples with 30° fracture inclination, the sample surface was dominated by two large-size vertical symmetrical tensile cracks and some small secondary cracks around the main cracks. For the samples with 45° fracture inclination, a Z-shaped shear–tensile failure mode along the premade fracture surface usually can be observed. When the angle of inclination is increased to 60°, only some rock debris on both ends of the long axis of the premade fracture may fall out during sliding of the premade fracture surface.

(3) After uniaxial compression, the failure modes of premade fracture surfaces at different dip angles are different. For granite samples with 30° fracture inclination, the main microcracks are found to cut across the premade fracture and some evident indentations or even connected cracks can be observed on the premade fracture surface. For granite samples with 45° fracture inclination, the friction-sliding zone and tensile cracks existed on the premade fracture surface. When the angle of inclination is increased to 60°, the failure and slide of the grains on the premade fracture surface dominate the failure mode. Accordingly, good agreement between the compressive strength and the difference in fractal dimensions induced by compression can be observed.

6. References
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