Research Article

Experimental Study on the Crack Initiation and Propagation of Unequal Cracks in Rock-Like Materials

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The crack in the rock is a system that coexists with multiscale and interaction cracks, and it is necessary to evaluate the deformation, stability, and strength of rock mass in many engineering projects and the failure of rock are related to the distribution of cracks in the rock. Cracks of different lengths were set in rock-like materials, and uniaxial loading experiments were carried out under 30 test conditions by changing the length of the rock bridge and the short crack as well as the crack angle. During the experiment, a high-speed camera system was used to record the failure process of the specimens. The following conclusions were obtained: when the crack angle is in the range of 30° to 60° with the loading direction, the shorter cracks are more likely to propagate and coalesce. Most of the specimens initiate cracking from the outer tip of the longer crack and the key point of crack instability is the outer tip of the longer crack. The coalescence mode of the cracks is mainly related to the length of the rock bridge length and the crack angle.

1. Introduction

Rock mass fracture is a fracture system that combines determination and stochasticity. However, dominant fractures of a certain size and scale tend to dominate the stability of the rock mass. For example, in slope engineering, it is only the expansion of a certain fracture that causes slope instability. In coal mining, the formation of gas outflows or water inlet channels is only a major fissure in the surrounding rock mass. The main fractures in the rock mass and the secondary fractures around them constitute an interactive system. According to the system theory, all systems can be divided into finite subsystems. The final result of the system is not the simple accumulation of the subsystems that make up the system but the composition of each subsystem under the mutual influence of the system organization. While the major control fractures play a major role in the stability of the rock mass, what role do those relatively small fractures play in the process of rock mass failure? What are their modes of evolution and interactions? It is an important subject in the study of rock mass failure and instability. At the same time, a large number of engineering accident cases show that a large number of geotechnical engineering instabilities and failures are caused by the expansion of weak surfaces within them, such as joints or fissures. Therefore, it is of great theoretical and practical importance to deeply and carefully study crack systems in rock masses, to distinguish the dominant cracks that play a dominant role in rock mass stability, and to evaluate and analyze the interaction between primary and secondary cracks. However, at present, research on fractured rock mass mainly focuses on the propagation of cracks with equal length and equal spacing in form, but the crack systems encountered in practical projects are all crack combinations with multiple scales and tendencies, and the research on this unequal length crack model is relatively less.

Crack defects in brittle materials such as rocks, glass, and concrete are generally in a relatively stable state under normal stresses and crack initiation, propagation, and coalescence occur only when the stress reaches a critical value. A large number of researchers have conducted a lot of theoretical and experimental work on crack initiation, propagation, and coalescence from different aspects and research perspectives in order to clarify the nature of the phenomenon of fracture of brittle materials under the
influence of cracks [1–4]. Horii et al. [5–13] have conducted a lot of theoretical and experimental work on crack initiation, propagation, and coalescence, and Hoek and Bieniawski [14] and Brace and Byerlee [15] have studied the stress distribution at the crack tip of prefabricated cracked glass specimens under load. Ingraffea et al. [16] used CR39 material to make specimens and prefabricated two cracks in them and studied the crack expansion of the two pre-fabricated cracks under their own mutual influence. Chen and Wang [17, 18] have studied the theoretical aspects on one hand and have also conducted experimental studies using similar materials and using glass as the test material [11, 17]. Wong, Chau, Tang, and Lin of Northeastern University [19–26] conducted a series of experimental studies on crack expansion using sandstone-like materials and high-strength gypsum. Among the crack extension tests, the study of preplaced crack coalescence using real rock is relatively rare. Chen et al. [27] studied the coalescence mechanism of preplaced cracks in marble by performing crack defects in marble material. Haeri [28] studied the mechanism of crack propagation in concrete specimens containing cracks under shear loading conditions, and he found that the precracked concrete failure occurs in the mixed mode in the case of nonoverlapping cracks configuration and in the tensile mode for the overlapping cracks. Haeri [29–32] used a modified higher-order semi-infinite displacement discontinuity method (HSDDM) with third-order displacement discontinuity elements (cubic elements) to estimate the stress intensity factor in the fractured rocks underneath a single disc cutter. Yang et al. [33, 34] utilized DIC (digital image correlation) technology to monitor and analyze the failure process of specimens and investigated the relationship between the strength of the fractured rock and the crack propagation process. Lin et al. [35] established the corresponding stress field formulae under compression by comparing and analyzing the stress field at the flaw tip under tensile conditions. Based on the determined stress field formulae at the flaw tip, Lin et al. [35] derived the relationship between the crack initiation angle of the open flaw tip and the inclination angle of the prefabricated flaw.

Although a lot of theoretical and experimental studies on crack propagation and coalescence damage have been conducted by the abovementioned scholars, there are some shortcomings: the analysis of the crack stress state in the mechanical model is too simplistic in the theoretical studies, some studies [5–7] preset the crack extension direction, and some studies ignore the effect of the type II stress intensity factor. In terms of experimental studies [36], some scholars use relatively homogeneous materials (such as glass and gypsum) to simulate rocks, which may result in a significant difference between the experimental results and the crack expansion pattern in real rocks. In terms of crack settings, most studies set up double or multiple cracks of equal length, while the crack scales in real rocks are of different lengths. In terms of testing equipment, although there is a high-speed camera system for image acquisition, due to the performance limitations of early high-speed cameras, only a short time image can be recorded, and with the lack of a prerecording trigger function, it is difficult to grasp the timing of crack initiation and propagation, so that the process of crack initiation and propagation cannot be captured.

In this study, two cracks of different lengths were prefabricated from rock-like materials, and the spacing between the cracks, the angle with the loading direction, and the length of the shorter cracks were changed to analyze the expansion and damage patterns of shorter and longer cracks and the influence of the scale of small cracks on the expansion of large cracks. During the test, a high-speed camera system was used to capture the crack propagation process. The high-speed camera system has the key function of a pretrigger, which can capture the image information one second before the camera shutter is triggered, thus capturing the dynamic process of crack initiation and expansion in brittle rock-like materials.

2. Materials and Methods

2.1. FASTCAM SA1.1 High-Speed Camera System. One of the key points of this study is to capture a series of dynamic processes such as crack initiation, propagation, and lap bonding of brittle materials such as rocks under external loads with high-speed cameras, and observe the changes of crack initiation points and propagation lap bonding modes by changing different crack parameters. However, the crack growth rate in rock is very fast, and the crack growth rate of marble after loading to instability can reach $5 \times 10^3 - 1.2 \times 10^3$ m/s [37]. Therefore, the FASTCAM SA1.1 high-speed camera system produced by Photron Company was used to collect image information during the whole process of specimen loading, and the supporting software of the system was used for analysis and calculation. When the resolution of the camera is set to $1024 \times 1024$, the maximum shooting speed can reach up to $5400$ fps. When the resolution is reduced to $512 \times 512$, the shooting speed can reach up to $2000$ fps and the maximum shooting speed reaches $675000$ fps. We set the shooting frequency to $5400$ fps during the test. The crack initiation and propagation process can be captured by the high-speed camera. The basic device and supporting facilities of the high-speed camera system are shown in Figure 1.

2.2. Rock-Like Material Configuration. The key to the success of rock crack propagation tests simulated by rock-like materials is the direct similarity between rock-like materials and real rocks. However, rock is a complex nonhomogeneous, noncontinuous, and anisotropic brittle material, and there is a wide range of variation in the mechanical properties of rocks, both hard rocks with very high strength and elastic modulus (e.g., granite) and soft rocks with very low mechanical properties. In order to simulate such nonhomogeneous and brittle materials as rocks, most researchers use gypsum, cement mortar, etc., [19, 38, 39] with other mixed admixtures in a certain ratio to simulate the properties of rocks. For these materials to be able to simulate rock materials well, they should have some of the following properties [40]:
(a) The main mechanical properties of rock-like materials should be similar to the physical and mechanical properties of rocks and should have the brittleness characteristic of rocks and the dilatancy characteristic of rocks under uniaxial compression.

(b) Rock-like materials should have good workability and should be easy to mix and repair.

(c) The physical, mechanical, chemical, thermal, and other properties of the rock material should be relatively stable, and they should not be affected by the temperature, humidity, time, and other environmental conditions outside the test as far as possible.

(d) The mechanical properties of the material can be changed by changing the ratio of the rock-like material to cope with different test conditions.

(e) Rock-like materials are widely available, easy to make, and inexpensive.

(f) The material must not have toxic effects on the human body.

Gypsum and cement mortar basically possess these two characteristics of rock after certain configurations, so they have been widely used in previous experimental studies. Chen Congxin from Wuhan Institute of Geotechnics, Chinese Academy of Sciences, aimed at a similar model study of instability damage mechanism of rocky slope under reverse tilt conditions, used gypsum, cement, and quartz sand to simulate limestone, and investigated the ratio of cementing material and aggregate in rock-like material, the variation of the ratio of cementing material, and the influence law of changing the curing conditions on the strength of specimens. Gypsum was used as the cementing material for similar materials, but as a water-soluble material, the mechanical properties of gypsum change with the change of temperature and humidity, and it dries slowly [41]. The elastic modulus of gypsum is small and the adjustable range is limited, and the ratio of ultimate compressive strength to the tensile strength of gypsum is not large, which is different from the properties of rocks, thus its application effect is affected to some extent.

There were two main types of similar materials used in geomechanical models for the study of such problems in Italy and other European countries. The first category uses a mixture of gypsum and lead compounds (PbO or Pb₂O₃) as the cementing material, with sand or small stones as the aggregate. The other type of similar material mainly uses barite powder, glycerol, and epoxy resin as the main materials. The advantage of this type of similar material is that its breaking strength and elastic modulus are higher than that of the first type of model material, which is closer to the real rock. However, the production process of this type of similar material requires high-temperature firing to make it cured, and the material will emit harmful gases during the high-temperature firing process [42].

Guo of Shandong University [40] used transparent materials such as polyester resin and modified epoxy resin to develop similar materials that can simulate rocks, which are more transparent and can be prefabricated with three-dimensional cracks, and simulate crack initiation, propagation, twist, and lap joint under external loading can be well observed during the test. However, the brittleness of this class of materials is not high, and the tips of prefabricated cracks under loading will generate large plastic deformation under stress concentration, and the whole specimen will also generate plastic flow during subsequent loading, so it is not a good simulation of the damage characteristics of rocks under the influence of cracks. Li [37] used sintered ceramics as a similar material. The physical and mechanical properties of this material are closer to those of rocks through inspection, and three-dimensional coin-like cracks are prefabricated before firing the ceramics, which better simulates the expansion law of cracks in rocks and provides a new direction for studying the crack expansion test of rock-like materials. However, this material is more complicated to prepare, needs high-temperature firing, is not easy to make, and the cost is relatively high.

Figure 1: FASTCAM SA1.1 high-speed camera system: (a) FASTCAM SA1.1 high-speed camera and (b) information acquisition computer.
After several times of changing the ratio for testing, the mechanical properties of the similar material were basically close to those of sandstone, and the ratio of cement: river sand: water: early strength agent and water reducing agent were changed, and the crack damage morphology change was studied by changing the crack inclination angle and the distance of the inner tip of the crack as well as the length of the shorter crack, and the specimen containing the prefabricated crack is shown in Figure 2.

The length of the longer crack is \( L_{cd} \) and in this test, the length of the longer crack is 24 mm. The length of the shorter crack is \( L_{sb} \) and in this experiment, there are four lengths of 4 mm, 6 mm, 8 mm, and 12 mm, respectively. The spacing between the two crack tips is \( L_{bc} \), which is referred to as the rock bridge length. \( \alpha \) is the angle between the crack surface and the loading direction, and the five types of crack surface angles were set in the test. \( \beta \) is the angle between the crack surface and the horizontal plane. The test parameters were divided into two groups, and the test condition group A was mainly studied under the condition that the length of large and small cracks was fixed (the length of large cracks was 24 mm and the length of small cracks was 12 mm), and only the rock bridge length \( L_{bc} \) (the spacing between the tips inside the cracks) and the angle between the crack surface and the loading direction \( \alpha \) were changed, and the specific test conditions are shown in Table 2.

In order to study the influence of the change of the shorter crack length on the expansion law of the main crack under the action of load, the length of the fixed large crack in the condition group B was set at 24 mm, and the length of the rock bridge was 18 mm. Five kinds of crack surfaces with the angle of the loading direction and three kinds of shorter crack lengths were set for the test, plus five condition specimens with the rock bridge length of 18 mm in test condition A were compared and analyzed, totalling 20 specimens. The test specimens for the test conditions are shown in Table 3.

Photographs of the specimens in test condition A are shown in Figure 3.

The test condition B specimens are shown in Figure 4.

2.4. Test Procedure. The test was conducted at the State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), and the loading method was one-time uniaxial compression. The hydraulic servo experimental machine was loaded at a loading rate of 0.005 mm/s. While the loading started, the high-speed camera shutter was triggered manually to take the first set of high-speed camera pictures, and the high-speed camera was set to take 539 frames before the manual trigger, and the high-speed camera was taken for the specimen one second before the manual trigger. During the test, the high-speed camera was manually triggered once when the load reached 50 kN, 100 kN, and 125 kN to collect the picture information. When the stress-strain curve of the specimen on the main control computer flattens, the prefabricated crack slightly expands triggering the high-speed camera again to shoot. The load continues until the sound of the rupture of the specimen is heard, triggering the camera to take pictures to capture the crack expansion. The high-speed camera was triggered ten times in the entire process, shooting 5400 frames so as to complete the entire process of loading a single specimen. The condition of the damaged specimen is shown in Figure 5.

In order to show a series of processes from crack initiation to crack propagation, all the test photos were processed using a drawing software to mark the initial position of the crack and a series of dynamic processes such as crack initiation and crack propagation. The comparison of the test photos before and after processing is shown in Figures 6(a) and 6(b).

3. Results

3.1. Summary of Experimental Results. In order to facilitate the comparative analysis of the test results of specimens with different geometric parameters, the test results of all specimens are listed in Table 4, which shows whether the longer and shorter cracks propagate, the initial crack initiation point, whether the rock bridge is coalescence, and the ultimate strength of the specimen for each test condition, respectively.

From Tables 4 and 5, it can be seen that almost all the longer cracks \( (L_{cd}=24\,\text{mm}) \) expanded under external load, while the shorter cracks within the same specimen did not always expand during the test. From the variation of the rock bridge length, when the rock bridge length was 12 mm, the shorter cracks expanded in the specimens of test conditions 2 \( (\alpha=30^\circ) \) and 3 \( (\alpha=45^\circ) \). When the rock bridge length increased to 18 mm, the shorter cracks expanded in test conditions 8 \( (\alpha=45^\circ) \) and 9 \( (\alpha=60^\circ) \) during the test. When the length of the rock bridge increases to 24 mm, only the short cracks in test condition 14 \( (\alpha=60^\circ) \) propagated, which indicates that the interaction between cracks tends to weaken with the increase of rock bridge length, and the probability of short cracks growing gradually decreases.

From Table 4, it can be seen that the specimens with cracks arranged in parallel with the loading direction did not have prefabricated crack expansion. This result is not consistent with the existing theoretical analysis. It was found by studying the damaged specimen that the crack had actually propagated, but the torsional propagation of the crack developed inside the specimen but failed to appear on the surface of the specimen, making the crack propagation...
present a three-dimensional development trend. There are two main reasons for this phenomenon. First, the inhomogeneity of the specimen material makes the crack development have a certain randomness. Second, there is still a "hooping effect" in the loading process to limit the lateral expansion of the specimen. The friction between the specimen and the loading table made the specimen subject to certain constraints, which to some extent limited the development of cracks and increased the strength of the specimen. This phenomenon was found in test conditions 1, 6, and 11.

The change of crack angle has more influence on crack propagation. It can be seen from Tables 4 and 5 that cracks are more likely to propagate and coalesce in specimens with crack angles ranging from 30° to 60°. This is because the shear stress in the specimen is greater in this angle range. If the cracks are distributed at this angle, the section at this angle will be weakened, and the stress at the crack tip will be concentrated, thus causing crack propagation.

3.2. Location of Crack Initiation Point. By using a high-speed camera system, the moment of crack initiation was captured during the test, and the crack initiation point in each specimen was confirmed under different parameters, as shown in Figure 7(a) Among the 30 test conditions, 14 specimens had the initial crack initiation at the outer tip of the longer crack, 4 specimens had the crack initiation at both the inner and outer tips of the longer crack, and 2 specimens had the crack initiation at both the outer tip of the longer

| Table 1: Mechanical parameters of the rock-like material. |
|---------------------------------------------------------|
| Mechanical parameters of rock-like materials | $\sigma_c$ (MPa) | $\sigma_t$ (MPa) | $E$ (GPa) | $\mu$ | Apparent density (kg/m$^3$) |
|---------------------------------------------------------|
| Measured value | 50–55 | 2.3 | 15.2 | 0.15 | 2350 |

Table 2: Test condition A.

| Test conditions | $L_{bc}$ (mm) | $\alpha$ |
|-----------------|---------------|---------|
| Test condition 1 | 12            | $\alpha = 0°$ |
| Test condition 2 | 12            | $\alpha = 30°$ |
| Test condition 3 | 12            | $\alpha = 45°$ |
| Test condition 4 | 12            | $\alpha = 60°$ |
| Test condition 5 | 12            | $\alpha = 90°$ |
| Test condition 6 | 18            | $\alpha = 0°$ |
| Test condition 7 | 18            | $\alpha = 30°$ |
| Test condition 8 | 18            | $\alpha = 45°$ |
| Test condition 9 | 18            | $\alpha = 60°$ |
| Test condition 10 | 18           | $\alpha = 90°$ |
| Test condition 11 | 24            | $\alpha = 0°$ |
| Test condition 12 | 24            | $\alpha = 30°$ |
| Test condition 13 | 24            | $\alpha = 45°$ |
| Test condition 14 | 24            | $\alpha = 60°$ |
| Test condition 15 | 24            | $\alpha = 90°$ |

Figure 3: Test condition 1.
3.3. Crack Propagation Law. It can be seen from Tables 4 and 5 that there is a strong correlation between cracks propagated and the length of the rock bridge and shorter cracks. In test condition A, among the five cases with a rock bridge length of 12 mm, test condition 2 (α = 30°), test condition 3 (α = 45°) and test condition 5 (α = 90°) had rock bridge coalescence. When the rock bridge length increased to 18 mm, only two test conditions 8 (α = 45°) and test condition 9 (α = 45°) among the five cases had rock bridge coalescence. When the rock bridge length was further increased to 24 mm, only test condition 14 had rock bridge coalescence.

In test condition B, none of the five specimens with shorter crack lengths of 4 mm had crack initiation and coalescence during the test. Rock bridge coalescence occurred in the prefabricated cracks in test conditions 23 (α = 45°) and 24 (α = 60°) when the length of the shorter cracks was increased to 6 mm. When the shorter crack length was increased to 8 mm, the cracks in test conditions 27 (α = 30°), 28 (α = 45°), and 29 (α = 60°) coalesced.

Two trends are obvious from the test results of the specimens in these 30 test conditions. One trend is that when the crack length is constant, the interaction between the cracks tends to weaken with the increase of the rock bridge length, and the number of specimens with rock bridge coalescence also gradually decreases. When the rock bridge length reaches or exceeds the length of the longer crack, the interaction between the cracks is already relatively weak, and it is more difficult for the specimens to have rock bridge coalescence. Another obvious trend is that when the rock bridge length is constant, and as the length of shorter cracks gradually decreases, the interaction between the longer and shorter cracks also weakens. It is therefore difficult to have crack coalescence in the rock bridge area.

From the test results, it can be seen that when the rock bridge length is 3/4 times of the longer crack length, the shorter crack length is 1/6 times of the longer crack length, which makes the interaction between the two cracks negligible and thus no coalescence will occur in the bridge zone, and this was confirmed by the test results from test condition 16 to test condition 20. In terms of the coalescence mode, the shear mode occurs when the bridge length is shorter and the two crack tips are close to each other. As the length of the rock bridge increases, the interaction between cracks weakens, and the cracks’ propagation is interfered with by other factors (such as the lateral expansion of the specimen, microcrack defects, and anisotropic inhomogeneity of materials).

3.4. Effect of Cracks on Ultimate Strength. In the process of loading, the cracks of the specimen are in a mixed mode. According to the theory of linear elastic fracture mechanics, the stress field at the tip of I and II combined mode cracks can be calculated as follows:

\[
\sigma_r = \frac{1}{2\sqrt{2\pi r}} \cos \theta \frac{K_I}{\sqrt{\pi}} (3 - \cos \theta) + \frac{1}{2\sqrt{2\pi r}} \sin \theta \frac{K_{II}}{\sqrt{\pi}} (3\cos \theta - 1),
\]

\[
\sigma_\theta = \frac{1}{2\sqrt{2\pi r}} \cos \theta \frac{K_I}{\sqrt{\pi}} (1 + \cos \theta) - 3K_{II} \sin \theta,
\]

\[
\tau_{r\theta} = \frac{1}{2\sqrt{2\pi r}} \cos \theta \frac{K_I}{\sqrt{\pi}} \sin \theta - K_{II} (3\cos \theta - 1),
\]

(1)

\(r\) is the polar diameter, \(\theta\) is the polar angle, \(K_I\) and \(K_{II}\) are the type I and II stress intensity factors, and \(\sigma_r\), \(\sigma_\theta\) and \(\tau_{r\theta}\) are the stress components, respectively. By substituting the mode I and II stress intensity factors at each crack tip into the line area fracture criterion of mode I and II composite cracks, the
limit stress at each crack tip can be solved, and then the crack initiation strength of the specimen can be obtained.

From Figure 8, it can be seen that the ultimate strength of the specimen varies with the crack angle, rock bridge length, and shorter crack length. From the effect of crack angle on the ultimate strength, the specimen has the highest strength when the crack face is parallel to the loading direction (a crack angle of 0°). The ultimate strength of the specimen gradually decreases as the angle between the crack and the loading direction gradually increases. The ultimate strength decreases most significantly near about $\alpha = 45^\circ$ because this angle is closer to the maximum shear stress surface under uniaxial loading conditions. This results in a decrease in specimen strength.

It can be seen from Figure 8(a) that the change in the length of the bridge also causes a change in the ultimate strength of the specimen. When the length and angle of the long and short cracks are determined, the shorter the bridge length is, the lower the ultimate strength of the specimen will be. This is because the shorter the length of a rock bridge is, the closer the distance between the cracks is, and the cracks are easier to coalesce, resulting in a reduction in the specimen ultimate strength. The influence of short crack length on ultimate strength is the same. As shown in Figure 8(b), the greater the short crack length, the greater the initial defect of the specimen and the lower the ultimate strength of the specimen.

4. Discussion

A material’s fracture was previously thought to be the process of rapid expansion of cracks within the material due to an increase in external forces. The destruction process can be divided into three stages, from crack initiation to expansion [43]: (a) at the start of loading, the crack does not expand, but the edge of the crack grows due to stress concentration and damage, (b) as the load increases, the crack grows smoothly, and (c) when the load reaches the breaking strength of the material, the crack becomes unstable. It can be clearly seen from Figure 9 that the edge of the crack tip is divided into several different regions: the process region is directly facing the crack tip; the active region is adjacent to the active region; the plastic region is contained around the active region; and the elastic region is beyond the three regions around the crack. These regions are often used in theoretical analysis.

Some scholars [44, 45], assume the increase or decrease in crack propagation rate in the material depends on the degree of random deviation of the local conditions in which the crack is located from the overall macroscopic average conditions. This theory is more suitable for qualitative or quantitative analysis of the random expansion of cracks in materials, but the crack in the rock mass differs greatly from that assumed in the theoretical model. However, the cracking in the rock mass differs greatly from that assumed in the theoretical model, and it is also extremely difficult to count the crack expansion time during the actual stressing process of the rock mass. When sudden instability or damage occurs in the rock mass, leading to the unstable expansion of cracks in the rock mass for an extremely short period of time, it is difficult to count the exact time. Therefore, the research study in this article focuses on capturing the crack initiation point of prefabricated cracks and the interaction mechanism between the cracks when the prefabricated double-cracked rock-like material is unstable and damaged by a high-speed camera system.
In order to study the interaction and coalescence mechanism of two unequal cracks under load, 15 crack geometries were set up in test condition A by changing the length of the rock bridge and the angle of the crack face with the loading direction to study the change of the primary and secondary crack extensions when the bridge length and the angle of the crack face were changed. The dynamic picture of longer and shorter crack expansion and the sequence of crack expansion were captured through the application of a high-speed camera system. It was found that most of the specimens containing cracks produced many new cracks during uniaxial compression, and these cracks could be classified as tensile cracks (also known as wing cracks in some literature), shear cracks, mixed cracks (consisting of both tensile and shear crack), primary cracks, and secondary cracks, as shown in Figure 10. The reason for the various types of cracks is the existence of randomly distributed microcracks or small holes in the specimen of rock-like materials. When the specimen is compressed, the existence of microdefects makes the internal stress field of the specimen unevenly distributed, eventually leading to crack initiation in the

| Test condition | $L_{cb}$ = 24 mm and $L_{ab}$ = 12 mm |
|----------------|-------------------------------------|
|                | Longer crack propagation | Shorter crack propagation | Initial cracking location | Coalescence mode | Ultimate strength (MPa) |
| Test condition 1 | No | No | Specimen side | No coalescence | 47.07 |
| Test condition 2 | Yes | Yes | $c$ and $d$ | Mixed mode | 46.28 |
| Test condition 3 | Yes | Yes | $d$ | Shear mode | 36.55 |
| Test condition 4 | Yes | No | $c$ | No coalescence | 36.39 |
| Test condition 5 | Yes | No | $c$ | Shear mode | 36.67 |
| Test condition 6 | No | No | The lower end of the specimen | No coalescence | 48.82 |
| Test condition 7 | Yes | No | $d$ | No coalescence | 48.71 |
| Test condition 8 | Yes | Yes | $c$ and $a$ | Mixed mode | 45.74 |
| Test condition 9 | Yes | Yes | $d$ and $b$ | Mixed mode | 45.45 |
| Test condition 10 | Yes | No | $d$ | No coalescence | 41.54 |
| Test condition 11 | No | No | — | No coalescence | 51.64 |
| Test condition 12 | No | No | The lower right end of the specimen | No coalescence | 51.14 |
| Test condition 13 | Yes | No | $d$ | No coalescence | 42.19 |
| Test condition 14 | Yes | Yes | $d$ | Mixed mode | 43.75 |
| Test condition 15 | Yes | No | $d$ | No coalescence | 37.35 |

Table 4: The statistical table of the test condition A coalescence mode.
Table 5: The statistical table of the test condition B coalescence mode.

| Test condition | $L_{ad} = 24$ mm and $L_{bd} = 18$ mm | Ultimate strength (MPa) |
|----------------|-------------------------------------|-------------------------|
| Test condition 16 | $\alpha = 0^\circ$; $L_{ab} = 4$ | No No The lower end of the specimen No coalescence 58.64 |
| Test condition 17 | $\alpha = 30^\circ$; $L_{ab} = 4$ | Yes No $c$ and $d$ No coalescence 52.32 |
| Test condition 18 | $\alpha = 45^\circ$; $L_{ab} = 4$ | Yes No $d$ No coalescence 45.46 |
| Test condition 19 | $\alpha = 60^\circ$; $L_{ab} = 4$ | Yes No $c$ and $d$ No coalescence 43.24 |
| Test condition 20 | $\alpha = 90^\circ$; $L_{ab} = 4$ | Yes No $c$ No coalescence 42.42 |
| Test condition 21 | $\alpha = 0^\circ$; $L_{ab} = 6$ | Yes No $d$ No coalescence 51.52 |
| Test condition 22 | $\alpha = 30^\circ$; $L_{ab} = 6$ | Yes No $d$ No coalescence 38.48 |
| Test condition 23 | $\alpha = 45^\circ$; $L_{ab} = 6$ | Yes Yes $d$ Mixed mode 41.10 |
| Test condition 24 | $\alpha = 60^\circ$; $L_{ab} = 6$ | Yes Yes $d$ Shear mode 47.21 |
| Test condition 25 | $\alpha = 90^\circ$; $L_{ab} = 6$ | Yes No $c$ No coalescence 38.79 |
| Test condition 26 | $\alpha = 0^\circ$; $L_{ab} = 8$ | Yes No $c$ and $d$ No coalescence 55.81 |
| Test condition 27 | $\alpha = 30^\circ$; $L_{ab} = 8$ | Yes Yes $d$ Shear mode 44.54 |
| Test condition 28 | $\alpha = 45^\circ$; $L_{ab} = 8$ | Yes Yes $d$ Traction mode 51.98 |
| Test condition 29 | $\alpha = 60^\circ$; $L_{ab} = 8$ | Yes Yes $a$ Mixed mode 37.77 |
| Test condition 30 | $\alpha = 90^\circ$; $L_{ab} = 8$ | Yes No $d$ No coalescence 41.18 |

Figure 7: The moment of crack initiation and propagation: (a) the moment of crack initiation and (b) crack propagation.
weakest part of the specimen. Following crack initiation, various types of cracks are generated due to the influence of surrounding microcracks and other defects.

The cracks produced during the test are mainly tensile cracks (also called wing cracks), and the cracks generally turn in the direction of the maximum principal stress (loading direction) after the crack expansion. Figure 11 shows the stress distribution during crack expansion, from which it can be seen that the main reason for the generation of tensile cracks is that the cracks are subjected to radial tensile forces, leading to a reduction in closure pressure. Tensile cracks are generally generated at the tip of the preset crack, which is caused by the concentration and superposition of the stress field at the tip of the crack, causing the cracks to initiate, propagate, and coalesce, and this series of processes is the main cause of crack extension damage in brittle materials. Generally, the first initiation crack is called the primary crack, and the primary tensile crack generally arises from the two tips of the prefabricated crack and turns to the loading direction to develop cracks up and down, respectively. Sometimes, when the primary crack extends for a distance, a new crack called a secondary crack will initiate again at the original crack initiation point. Shear cracks are generated when the shear stress in the specimen exceeds a certain threshold. Shear cracks typically expand along the surface of the maximum absolute shear stress, which is generally coplanar or nearly coplanar with the preset crack’s 45° inclination. The shear crack stress state is shown in Figure 11. The sliding stress along the direction of the crack face causes relative slip of the preset or extended crack, and this shear effect causes large sliding friction between the crack faces. Compression cracks are cracks produced when the compressive stress in the specimen exceeds a certain threshold, and these cracks are characterized by the appearance of crushed fragments or

![Figure 8](image_url)
Figure 8: The experimental ultimate strength of specimens versus the rock bridge length: (a) relationship between rock bridge length, crack angle, and ultimate strength and (b) relationship between shorter crack length, crack angle, and ultimate strength.

![Figure 9](image_url)
Figure 9: The partition of the crack tip.

![Figure 10](image_url)
Figure 10: Schematic diagram of crack types and coalescence mode.
debris on the surface. Compression cracks usually appear in the propagation and coalescence tests of the preset cracks under the action of biaxial loading [46], and the loading method used in the tests in this article is uniaxial compression, so there are almost no compression cracks in this test.

When two precast cracks expand and approach a certain distance, there will be a strong interaction effect between the cracks that will cause the cracks to “attract” each other and expand together, eventually leading to crack lap coalescence to form a crack zone. Previous research studies [5, 10, 11, 21] divided the connection coalescence mode of two prefabricated cracks into three modes, which are shear mode caused by shear stress; tensile mode caused by tensile stress; and a mixed mode caused by the joint action of the two previous forces. Shear mode and mixed mode are shown in Figure 12. Lin [47] further classifies the coalescence mode of setting two cracked specimens into five kinds through physical and numerical tests and adds the traction mode and compression mode. The traction mode is formed by the joint action of the stress field at the tip of two prefabricated cracks and the stress field in the surrounding area. While compression mode is caused by the nucleation of many small tensile cracks caused by the concentration of compressive stress, as the shear mode, mixed mode, and traction mode were found in this experiment, hence, only these three coalescence modes were analyzed.

4.1. Shear Mode. Generally, the form of coalescence between cracks caused by the connection of two cracks caused by shear stress is called shear mode. During the test conditions of specimen 24 and specimen 27, the extended cracks developed along the angle of the original precast cracks and finally connected through, and these specimens were more typical of the shear mode. From the test results, the shear mode generally occurs when the precast cracks are at an angle of 30° to 60° with the loading direction, because the absolute shear stress value of the specimen is the highest in this angle range, and when the prefabricated cracks defects also exist in the specimen at this angle, it further aggravates the damage possibility in this angle range, and the ultimate strength of the specimen also decreases when shear coalescence damage occurs.

4.2. Mixed Mode. When the prefabricated cracks are formed by shear cracks and tensile cracks connected by coalescence, this mode produced by the joint action of shear and tensile stresses is generally referred to as the mixed mode, and some literature also refers to this mode as the tensile-shear coalescence mode.

4.3. Traction Mode. When more than two coalescence cracks are produced between two prefabricated cracks, the coalescence of the specimen in test condition 28 is called traction mode. This mode is a mixed mode caused by biaxial tensile or shear stress. Some scholars also classify this mode as the mixed coalescence mode of II shape [22].
5. Conclusions

The following conclusions were obtained through the analysis of the 30 specimens tested under these conditions:

1. When the specimen contains cracks of different lengths, the longer cracks play a dominant role in the failure of the specimen. Almost all the longer cracks propagated during the test. Whether the shorter cracks propagate or not is mainly related to the length of the rock bridge and the angle between the cracks and the loading direction. As the rock bridge length increases, the interaction between the cracks tends to weaken, and the chance of shorter crack propagation gradually decreases. When the crack angle is in the range of 30° to 60° with the loading direction, the shorter cracks are more likely to propagate and coalesce.

2. The moment of crack initiation in the brittle material specimens was captured by a high-speed camera system, and the location of the crack initiation point was determined. During the test, it was found that most of the specimens initiated cracking from the outer tip of the longer crack. The key point of crack instability is the outer tip of the longer crack.

3. Under uniaxial load, the crack coalescence is mainly related to the rock bridge, the shorter crack, and the crack angle. When the crack length remains constant, the interaction between the cracks weakens as the length of the rock bridge increases. When the rock bridge length is constant, as the length of shorter cracks gradually decreases, the interaction between the longer and shorter cracks will also weaken, making it difficult for crack coalescence. The coalescence mode of the cracks is mainly related to the length of the rock bridge and the crack angle.

Data Availability

The data that support the findings of this study are available from the corresponding author, Qingfeng Chen, upon reasonable request.
Consent

Not applicable.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Qingfeng Chen conceptualized the study, developed the methodology, developed software, validated the study, did formal analysis, investigated the study, provided resources, curated the data, wrote the original draft, reviewed and edited the manuscript, and visualized the study; Jingmin Duan supervised the study; Min Huang did project administration and acquired funding. All authors have read and agreed to the published version of the manuscript.

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