Research Article

Bedding Effect on the Deformation: Damage Differentiation of Coal Mass

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Abstract

In order to reveal the mechanical properties and damage mechanism of coal with parallel multibedding under stress disturbance, the raw coal samples with parallel multibedding were selected. The uniaxial compression and acoustic emission damage measurement were carried out using the coal-rock mechanics damage coupling test system, revealing the bedding effect of coal deformation-damage failure differentiation under different loading methods; based on the test results, a coupling characterization model of mechanical damage of coal and rock with parallel multibedding is established. The results show that (a) the acoustic emission of raw coal samples under different loading modes has obvious differentiation characteristics of bedding effect. When the vertical bedding is loaded, the peak stress of raw coal samples is relatively high and the acoustic emission activity period is relatively long; when the parallel bedding is loaded, the active degree of acoustic emission is relatively strong, and there is an obvious mutation period after the acoustic emission enters the acute period. (b) Under different loading modes, the difference in the influence of bedding on the fracture evolution of raw coal specimens is mainly concentrated before the stress turning point. In stage I, the acoustic emission $b$ value of raw coal specimens decreases first, then becomes stable under vertical bedding loading, and decreases under parallel bedding loading; in stages II and III, the acoustic emission $b$ value of raw coal samples showed the same change trend under different loading modes. (c) Combined with the basic principle of continuous damage mechanics and based on the difference of bedding effect, the relationship between cumulative acoustic emission ringing count and stress and damage variable of the raw coal samples was established. The rationality and effectiveness of the model are verified by experiments.

1. Introduction

Compared with rock matrix, bedding is mostly a weak structure or weak plane. The bedding has an obvious effect on the physical and mechanical properties of rock [1], and the bedding effect has a significant impact on the construction and follow-up maintenance of geotechnical engineering, such as slope, tunnel, and traffic engineering [2]. Moreover, when rock is under external loads, the evolution and development of new and old fissures inside the rock are often accompanied by sound waves with different frequencies and energy [3]. Based on this, experts and scholars at home and abroad carried out different tests on different types of rock using acoustic emission systems and explored the acoustic emission characteristics and failure characteristics of the rock mass with bedding.

Zhang et al. studied the failure characteristics and acoustic emission characteristics of roof sedimentary rock with bedding using an uniaxial compression test and proposed a calculation method of in situ stress based on the Kaiser effect of acoustic emission [4]. Zhang et al. investigated the deformation and failure characteristics and
acoustic emission characteristics of coal-rock mass in different bedding directions [5]. Hou et al., using a high-speed camera system and an acoustic emission system, carried out the Brazilian test on shale with different bedding angles and studied the bedding effect of the acoustic emission characteristics of shale [6]. Song et al. studied the acoustic emission characteristics during the evolution of red sandstone deformation field using a digital speckle and acoustic emission test system [7]. Liu et al. researched the relationship between load size and acoustic emission cumulative count under uniaxial compression using particle flow code numerical simulation software [8]. Zhao et al. studied the acoustic emission characteristics of Chongqing Huangnibao rock-soil in the process of uniaxial compression and splitting by combining tests and numerical simulation and conducted geotechnical stability assessment [9]. Liang et al., using RFPA2D software, simulated acoustic emission time series and spatial distribution rules of three rock specimens with different homogeneity in the process of uniaxial compression loading [10]. Wu and Zhang researched the damage failure model of rock under uniaxial compression from the perspective of phenomenology based on the Weibull distribution theory and determined the damage measurement method [11]. Zhang investigated acoustic emission characteristics of different types of coal samples in the process of deformation and failure [12]. Tan et al., from the perspective of energy transfer, established a physical cellular automata PCA theory to simulate acoustic emission and chaos characteristics of heterogeneous rock specimens in the failure process [13]. Based on the view that acoustic emission cumulative count is consistent with the damage variable, Zhang et al. established an acoustic emission damage model for quasibrittle materials and deduced the expression of acoustic emission rate and Kaiser effect [14].

The above studies were on the deformation and failure characteristics and acoustic emission characteristics of coal-rock mass with bedding through laboratory tests, numerical simulation, and theoretical analysis and produced many valuable results. However, there are few reports on the bedding effect on the deformation-damage differentiation of coal-rock mass under different loading modes. Therefore, this article selects raw coal samples with parallel multibedding by ultrasonic, uniaxial compression tests and acoustic emission tests for damage detection were performed on raw coal specimens with parallel multibedding to study the bedding effect on the deformation-damage differentiation of coal-rock mass under different loading modes. The difference in the internal fissure evolution of coal-rock mass under different loading modes was revealed. In addition, combined with the basic principle of continuous damage mechanics, the constitutive relation between acoustic emission cumulative ringing count and mechanical parameters of coal-rock mass with bedding was established based on the differentiation of the bedding effect. The research results provide an effective basis for selecting key space-time areas for stress failure monitoring of coal-rock mass with parallel multibedding and can predict the damage evolution process of coal-rock mass with parallel multibedding under external load.

2. Test Procedures and Scheme

2.1. Test Equipment and System. The equipment used in the damage and failure and acoustic emission study of coal-rock with parallel bedding is mainly comprised of two systems, namely, a loading system and an acoustic emission monitoring system. The main equipment of the loading system is a microcomputer-controlled servo testing machine, of which the loading device adopts electronic oil pump pressurizing equipment, with the maximum loading pressure value of 300 kN, the minimum loading speed of 0.02 mm/min, and the maximum loading speed of 100 mm/min. The main equipment of the acoustic emission monitoring system is a digital PCI-II acoustic emission monitoring system, with a maximum signal amplitude of 100 dB. With a built-in 18-bit A/D converter and processor, the monitoring system is suitable for the acquisition of acoustic emission signals at low-amplitude and low-value threshold (17 dB) and real-time analysis of sampling. It also has a high signal processing accuracy. The test system is shown in Figure 1.

2.2. Test Sample Selection and Scheme. The test adopted square raw coal samples with a side length of 70 mm, which were made by cutting and grinding a whole block of raw coal, and there are a lot of parallel beddings in the samples. As there were internal defects such as pores and fissures in the raw coal samples, ultrasonic wave velocity detection was first carried out on the selected samples before the test. The average wave velocity was 1500 m/s as the reference wave velocity, and the defective samples with wave velocity error of ±100 m/s were removed to ensure the accuracy of the test. After the wave velocity detection, eight raw coal samples were selected and numbered, as shown in Table 1.

In the test, loading was at a constant speed of 0.2 mm/min. According to different loading directions relative to the bedding of the raw coal samples, the test samples were divided into two groups: (1) the loading direction was perpendicular to the bedding plane; (2) the loading direction is parallel to the bedding plane, and the loading diagram is shown in Figure 2. In order to accurately capture the damage position of the raw coal samples under load, eight acoustic emission sensors were arranged for each raw coal sample, namely, with 2 on each side, and all of them were located on the central line of the side, 15 mm away from the top and bottom edges of the raw coal Figure 3 is a photograph of the test process.

3. Analysis of Test Results

Acoustic emission of rock materials is an elastic wave accompanying internal damage of rock materials [15], and there must be a correlation between acoustic emission and internal damage and failure of rock materials [16]. Therefore, the degree of damage and failure of rock materials can be indirectly determined by monitoring the acoustic emission during the test of rock materials. (Limited by the length of this article, only the test results of raw coal samples V1-1, V1-2, P2-1, and P2-2 were analyzed.)
3.1. Analysis of the Damage Evolution Characteristics of Coal Mass under Different Loading Modes.

Figure 4 shows the stress-acoustic emission parameter-time relationship curve of the raw coal sample with parallel multibedding obtained in the test.

According to the stress-acoustic emission parameter-time curve in Figure 4, the bearing capacity of the raw coal samples under different loading modes is different: the peak stress of the raw coal samples under load axially vertical to bedding plane is higher than that under load axially parallel to the bedding plane. After the samples under load entered the plastic stage, there are obviously many fluctuation points in the stress curve of samples under load axially parallel to the bedding plane; in terms of acoustic emission activity, the activity degree of samples under load parallel to the bedding plane is obviously higher than that under load axially vertical to the bedding plane.

Under different loading modes, the acoustic emission activity degree of raw coal samples presents obvious stages and differences:

(a) At the beginning of the sample being loaded, the original pores and fissures inside the sample were gradually closed under the action of axial stress, and the sample was then compressed. At this time, the sample was in the microelastic stage, there were almost no new pores and fissures produced inside it, the acoustic emission ringing count was relatively small, and the activity level was low. Therefore, this stage is called the acoustic emission quiet period OA [17]. As can be seen from Figure 4, low-frequency acoustic emission signals are found in the raw coal samples under load axially vertical to bedding, while there are almost no acoustic emission signals in samples under load axially parallel to bedding in the early quiet period, and low-frequency acoustic emission signals are released only in the middle and late period. The analysis suggested that under the action of low axial stress, the internal pores and fissures of raw coal samples are in a close state, and almost no new fissures are generated. Due to the different loading modes, the internal pores and fissures of raw coal samples are closed differently, thus releasing acoustic emission signals with different activity degrees.

(b) As the axial stress increases, the raw coal samples enter the early elastic stage, the acoustic emission activity degree of the samples enhances, and the acoustic emission ringing count changes in a concave curve. This stage is the transitional period AB [17]. As can be seen from Figure 4, at this AB period, the acoustic emission activity degree of the raw coal samples under load axially parallel to bedding is higher than that under load axially vertical to bedding, and the concave degree of the stress curve is higher. Analysis showed that as the axial stress on the sample increases, the closure of original pores and fissures inside the sample gradually approaches the limit. Under the action of low axial stress, new microfissures begin to appear in the bedding area inside the raw coal sample, releasing low-amplitude and high-density acoustic emission signals. However, the low axial stress is not enough to cause new microfissures in the matrix area of the raw coal. Under different loading modes, due to the difference of load on bedding, the initiation rate of new fissures in the samples under load axially parallel to bedding is relatively faster, so the release of acoustic emission signals is more active.

(c) As the axial stress continues to increase, the samples enter the end of the elastic stage and then gradually to the plastic stage. The acoustic emission activity degree of the raw coal samples under different loading modes increases significantly, and the acoustic emission ringing count grows compared with that in the quiet period and transitional period, so this stage is called the active acoustic emission period BC [16]. As can be seen from Figure 4, in the BC period, different loading modes show differentiation. The acoustic emission ringing counts of raw coal samples under load axially parallel to bedding loading are roughly the same in the period, while those of raw coal samples under load axially vertical to bedding loading are roughly the same at the initial stage of this period, but multiple peaks are present at the end of this period. Analysis suggested that the raw coal samples under load axially vertical to loading enter the end of the elastic stage, and the fissures inside the samples enter a stable development stage. Under the action of axial stress, the shear fissures inside the samples are in a close state. As the

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Table 1: Ultrasonic velocity measurement of raw coal sample.

| Number | Load type             | Ultrasonic wave velocity (m/s) |
|--------|-----------------------|-------------------------------|
| V1-1   | Vertical bedding loading | 1502                          |
| V1-2   | Vertical bedding loading | 1530                          |
| V1-3   | Vertical bedding loading | 1476                          |
| V1-4   | Vertical bedding loading | 1486                          |
| P2-1   | Parallel bedding loading | 1554                          |
| P2-2   | Parallel bedding loading | 1538                          |
| P2-3   | Parallel bedding loading | 1567                          |
| P2-4   | Parallel bedding loading | 1522                          |
axial stress continues to increase, the raw coal samples enter the plastic stage, and the tangential stress on the fissures inside the samples increases, and when the tangential stress is greater than the cohesive force of bedding, the friction causes the release of relatively active acoustic emission signals, thus showing multiple peaks; the internal fissures of the raw coal samples under load axially parallel to bedding are basically in the elastic stage in the acoustic emission active period and are in a stable development state, so the acoustic emission activity degrees are relatively uniform.

(d) The samples are completely in the plastic deformation stage, and the stress-time curve deviates from the straight line development stage. In this stage, the acoustic emission ringing count is the highest, and the multipeak phenomenon is frequent, showing a stepped growth. Under the action of axial stress, the internal fissures of the raw coal samples surge rapidly, and macroscopic failure is found in the samples. Therefore, this stage is called the acoustic emission acute period CD [16]. It can be seen from Figure 4 that in the CD period, the raw coal samples are in the plastic stage, and their acoustic emission under different loading modes shows a significant difference. There is an obvious abrupt change period CE for the raw coal samples under load axially parallel to bedding, where their maximum ringing counts for the entire period are generated, and their ringing counts decrease after the period CE; in the acute period, the raw coal samples under load axially vertical to bedding present an obvious multipeak phenomenon and the highest acoustic emission ringing count for the whole period. Analysis showed that fissures in the raw coal samples continue to develop under the continuous action of axial stress. When the load is axially vertical to bedding, the raw coal samples fracture along the bedding plane under stress at point C, causing macrofractures, intense release of acoustic emission signals, and thus a sharp increase of ringing counts; when the load is axially parallel to bedding, the raw coal samples fracture along the bedding plane under stress at point C, causing an intense release of acoustic emission signals, and as the axial stress continues to increase, some macrofractures in the raw coal matrix area continue to develop and connect to each other to form macrocracks, weakening the release of acoustic emission signals. However, the acoustic emission activity degree is still higher than that of samples under load axially vertical to bedding.

To sum up, under the influence of bedding structure, the acoustic emission of raw coal samples under different loading modes are different, which are mainly concentrated in the acoustic emission acute period. As raw coal samples accumulate a large amount of energy successively in the quiet period, transitional period, and active period of acoustic emission; when they enter the acute period of acoustic emission, fissures along the bedding plane develop rapidly in a short time, forming bedding fissures. Due to the different loading angles relative to bedding, the differences in acoustic emission of raw coal samples under different loading modes are reflected in the early stage of the acute period; with the continuous increase of axial stress, the raw coal matrix area began to fail and connect with bedding fissures, resulting in instability failure. Hence, the focus of loading direction

Bedding plane Acoustic emission sensorRaw coal matrix
Z
X
Y

Figure 2: Loading diagram of sample and arrangement of acoustic emission sensor. (a) Axial parallel bedding loading. (b) Axial vertical bedding loading.

Figure 3: Loading of raw coal sample.

Figure 4 Shock and Vibration
monitoring the failure of coal-rock samples with parallel bedding should be on the end of the active period and the beginning of acute period of acoustic emission.

3.2. Analysis of Spatial-Temporal Evolution of Coal Fissures under Different Loading Modes. To reveal the failure characteristics of raw coal samples with parallel bedding under different loading modes, the G-R relation was used to calculate the $b$ value of acoustic emission. The method of calculating the $b$ value has been introduced in the literature and will not be described here [18].

The relationship between acoustic emission amplitude and stress was established using the intermediate variable, time. The cumulative number of events when the stress was $0\sim10\%$, $0\sim20\%$, $0\sim30\%$, $0\sim40\%$, $0\sim50\%$, $0\sim60\%$, $0\sim70\%$, $0\sim80\%$, $0\sim90\%$, and $0\sim100\%$.
0~80%, 0~90%, and 0~100% and the amplitude was greater than or equal to 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, and 95, respectively. Data fitting was carried out using the least square method, and acoustic emission $b$ values of raw coal samples with parallel bedding under different loading modes were obtained, as shown in Figures 5 and 6.

The acoustic emission $b$ value can reflect the evolution law of fissures inside samples. The larger the $b$ value, the slower the new fissure initiation and crack propagation inside the samples within the statistical intervals, whereas the smaller the $b$ value, the faster and more unstable the crack propagation inside the samples. According to the variation curve of $b$ value given in Figure 6 above, the raw coal samples with parallel bedding under different loading modes have the same stress turning point (70% peak stress) and there is a $b$ value intersection point (about 45% peak stress). The differences in the $b$ value of the samples are mainly concentrated before the intersection point:

(a) Stage I: through analysis according to Figure 4, the samples are in the elastic stage, and the acoustic emission $b$ value intersection point is located at the late stage of the transition period, approaching the acoustic emission active stage. As can be seen from Figure 6, at this stage, the $b$ value of the raw coal samples under load axially vertical to bedding shows a downward trend at the initial stage and then tends to be stable. This shows that at the initial stage of axial low-stress action, the original pores and fissures in the raw coal samples under load axially vertical to bedding close quickly, and then the fissure evolution enters a relatively stable stage. The $b$ value of raw coal samples under load axially parallel to bedding has been declining in this stage, indicating that the fissure evolution in these samples keeps being active in this stage.

(b) Stage II: according to Figure 4, it can be judged that this stage is in the acoustic emission active period, where the samples are at the end of the elastic stage and near the plastic stage, and the fissures inside them enter a stage of rapid and stable development. Hence, at this stage, the acoustic emission $b$ value of raw coal samples under different loading modes is small and its variation trend is relatively stable. Based on Figure 4, the analysis suggested that the variation of acoustic emission activity degree at this stage is mainly caused by the evolution of microfissures in the bedding part, but no macroscopic damage is formed. At this time, the axial stress is not enough to cause new fissures in the raw coal matrix part.

(c) Stage III: in this stage, the raw coal samples completely enter the plastic stage, and the acoustic emission also enters the intense stage. Therefore, the acoustic emission $b$ value presents a downward trend on the whole. As the raw coal samples under load axially parallel to bedding has a period of abrupt change at the early stage of the acute period, the acoustic emission $b$ value of such samples is slightly smaller at the beginning of this stage. Through analysis according to Figures 4 and 6, it can be seen that the $b$ value changes significantly in this stage, and the acoustic emission is also the most active for the whole period. At this time, the axial stress is enough to induce new fissures in the raw coal matrix area, thus causing great changes in the $b$ value and activity degree of raw coal.

Based on the above analysis, the acoustic emission $b$ value of raw coal samples under different loading modes has an obvious turning point under 70% peak stress. The existence of this turning point indicates that the acoustic emission is approaching the acute period. In addition, the existence of the turning point can also provide a basis for the partial failure of bedding and matrix of coal-rock mass with parallel bedding; and the existence of stress intersection point also provides a preliminary judgment for the angle of bedding in coal-rock mass.

4. Construction and Verification of Coal Damage Model Based on Bedding Effect Differentiation

4.1. Construction of Coal Damage Model Based on Bedding Effect Differentiation. As the physical and mechanical properties of the bedding plane are relatively weak, the bearing capacity of the bedding plane is also different under different loading modes, and the acoustic emission of the raw coal samples with bedding also shows different stage characteristics. According to the acoustic emission parameters of the raw coal samples analyzed above, there are obvious differences in acoustic emission ringing counts of the raw coal samples under different loading modes, which are closely related to the evolution of the internal structure of such samples and change with axial stress [19]. Figure 7 shows the relationship between cumulative ringing count and time of the raw coal samples under different loading modes.

According to the curve given in Figure 7, the cumulative acoustic emission ringing count and time of the raw coal samples under different loading modes approximately follow an exponential distribution, and the fitting degree is favorable. Therefore, the relationship between them can be defined as follows:

$$N = ae^{bt}, \quad (1)$$

where $N$ is the acoustic emission cumulative ringing count of a raw coal sample and $a$ and $b$ are the fitting coefficients.

In this test, it can be seen from the monitoring data that there is an obvious linear relationship between strain $\varepsilon$ and time $t$ of the raw coal samples under different loading modes:

$$\varepsilon = kt + \varepsilon_0, \quad (2)$$

where $k$ is the strain rate of the raw coal sample and $\varepsilon_0$ is the initial strain of the sample, which can be obtained by data fitting.
Figure 5: Cumulative frequency amplitude distribution of acoustic emission of raw coal sample with parallel bedding. (a) V1-1, (b) V1-2, (c) P2-1, and (d) P2-2.
where $\sigma$ is the effective stress, $E$ stands for the deformation modulus of the material, $\varepsilon$ represents the strain, and $D$ is the damage variable. Based on this, the relationship between the effective stress, the damage variable and the acoustic emission cumulative ringing count of the sample can be established as follows:

$$\sigma = E(1 - D)(\frac{k}{b}\ln\frac{N}{a} + \varepsilon_0).$$

(5)

Assuming that microunit strength distribution of rock follows Weibull distribution, Tang Chunan deduced the relation between rock constitutive relation and acoustic emission [20]; namely,

$$\sigma = E\varepsilon_0\left(1 - \frac{\Omega}{\Omega_m}\right),$$

(6)

where $\Omega_m$ and $\Omega$ are the acoustic emission cumulative count in the case of total failure and in the case of strain $\varepsilon$, respectively. When $(\Omega/\Omega_m)$ is equal to the following formula,

$$\frac{\Omega}{\Omega_m} = 1 - \exp\left[-\frac{\varepsilon}{\varepsilon_m}\right] = D.$$

(7)

Equation (6) can be transformed into

$$\sigma = E\varepsilon_0\exp\left(-\frac{\varepsilon}{\varepsilon_m}\right).$$

(8)

where $\alpha$ is the dimension parameter related to the microunit strength and $m$ represents the constant related to material uniformity. In order to further determine the parameters $\alpha$ and $m$, Yang Minghui proposed the relationship between $\alpha$ and $m$ under uniaxial compression [21]; namely,

$$m = \frac{1}{\ln(E\varepsilon_0/\sigma_t)},$$

(9)

$$\alpha = m\varepsilon_t^m,$$

where $\varepsilon_t$ and $\sigma_t$ are the peak strain and stress, respectively.

By combining equations (3), (7), and (8), the coupling relationship $D$ between acoustic emission cumulative ringing count $N$ and effective stress $\sigma$ and damage variable of coal-rock with parallel bedding under uniaxial compression can be obtained as follows:

$$\sigma = E\left(\varepsilon_0 + \frac{k}{b}\ln\frac{N}{a}\right)\exp\left[\frac{1}{\alpha}\left(\varepsilon_0 + \frac{k}{b}\ln\frac{N}{a}\right)^m\right],$$

(10)

$$D = 1 - \exp\left[\frac{1}{\alpha}\left(\varepsilon_0 + \frac{k}{b}\ln\frac{N}{a}\right)^m\right].$$

(11)

4.2. Validation and Discussion of the Model. To verify the validity and rationality of the model, based on the test data obtained from the raw coal samples under different loading modes, the acoustic emission accumulative ringing count and time, as well as strain and time, are fitted, and the values after fitting were obtained. According to the peak stress and peak strain obtained, the Weibull distributed constant was
calculated, and the parameter list obtained is as shown in Table 2.

To further verify the accuracy of the proposed model, relevant data obtained by fitting in Table 1 were substituted into equations (10) and (11), and the relationship curve between the cumulative acoustic emission ringing count and stress and damage variable of the raw coal samples under different loading modes under uniaxial compression was determined, as shown in Figures 8 and 9.

According to the test curve of acoustic emission ringing count and stress of raw coal as shown in Figure 8 and the model result curve, the test results of acoustic emission cumulative ringing count and stress of the raw coal samples under different loading modes under uniaxial compression was determined, as shown in Figures 8 and 9.

According to the test curve of acoustic emission ringing count and stress of raw coal as shown in Figure 8 and the model result curve, the test results of acoustic emission cumulative ringing count and stress of the raw coal samples under different loading modes under uniaxial compression was determined, as shown in Figures 8 and 9.

According to the test curve of acoustic emission ringing count and stress of the raw coal samples under different loading modes under uniaxial compression was determined, as shown in Figures 8 and 9.

Table 2: Fitting parameters of raw coal samples under different loading modes.

| Load type                  | Number | Number | m     | a     | b     | k     | $\epsilon_0$ |
|----------------------------|--------|--------|-------|-------|-------|-------|--------------|
| Vertical bedding loading   | V1-1   | 3.204  | 9.846E-06 | 0.663 | 0.0056 | 2.371E-05 | -9.617E-04  |
|                            | V1-2   | 3.605  | 1.995E-06 | 0.634 | 0.0047 | 2.287E-05 | -9.496E-04  |
| Parallel bedding loading   | P2-1   | 2.586  | 5.586E-05 | 0.44  | 0.0062 | 2.372E-05 | -1.448E-05  |
|                            | P2-2   | 3.011  | 1.786E-05 | 0.426 | 0.0059 | 2.211E-05 | -1.403E-05  |

Figure 8: Comparison of test results and model results of cumulative ringing count $N$ and stress $\sigma$. (a) V1-1 and (b) P2-1.
5. Conclusion

According to the study on the differentiated bedding effect on the deformation and damage of raw coal samples under different loading modes, the following conclusions were drawn:

(a) Under the action of axial stress, the peak stress and acoustic emission activity degree of the raw coal samples under different loading modes show obvious differences. For the raw coal samples under load vertical to bedding, the peak stress is greater, and the acoustic emission duration is also longer; for the raw coal samples under load parallel to bedding, the acoustic emission activity degree is higher.

(b) Affected by the internal bedding plane of the raw coal samples, the acoustic emission activities of such samples under different loading modes show certain differences. Under different loading modes, the acoustic emission of the raw coal samples presents obvious stages. The failure of the raw coal samples mainly occurs in the acoustic emission acute period; there is an obvious abrupt change stage in the acoustic emission acute period for the samples under load axially parallel to bedding.

(c) As the axial stress increases, the evolution of pores and fissures in the raw coal samples shows differences. Under different loading modes, the fissure evolution of the raw coal samples has the same stress turning point and shows certain differences.

(d) Based on the difference of bedding effect and the basic theory of continuous damage mechanics, the relationship between cumulative acoustic emission ringing count and mechanical parameters of raw coal samples was established, and the rationality and validity of the model were verified based on the test data.

Data Availability

All relevant data have been presented in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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