Research Article

Mechanical Characteristics and Energy Dissipation Trends of Coal-Rock Combination System Samples with Different Inclination Angles under Uniaxial Compression

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Coal mines are composed of multiple complex rock strata with different mechanical characteristics and energy accumulation and release performances. This implies uneven energy distribution in the coal-rock combination system (CRCS). To explore the effect of the included angle between the loading direction and the coal-rock contact surface on the mechanical properties, crack propagation mode, and energy evolution characteristics of the CRCS, the uniaxial compression tests were carried out on the CRCS samples with zero and 30° inclination angles. The obtained mechanical properties and energy dissipation trends of the tested samples were similar to those of the pure (raw) coal and rock ones but strongly depended on the inclination angles. The impact energy index of the CRCS samples was smaller than those of the pure coal and pure rock samples, and its impact tendency was less pronounced. The deformation and failure of the CRCS samples occurred in the coal part, the rock part inhibiting the development and deformation of the coal. According to the deformation and failure characteristics of the CRCS, the coal support far away from the contact surface should be strengthened in engineering practice to avoid the rock mass failure caused by the expansion and evolution of cracks in the coal part. At a 30° inclination angle, the CRCS sample was tensioned at the coal-rock contact surface, and the original cracks and pores were gradually compacted under the stress component perpendicular to the contact surface. With an increase in the inclination angle, the difference between the total energy accumulated before the peak and the released energy after the peak was reduced, and the difference between the total energy accumulated before the peak and the dissipated energy increased gradually. CRCS samples with different inclinations exhibited three damage stages: initial damage, stable damage growth, and rapid damage growth. The results obtained are considered instrumental in rockburst preventing, monitoring, and early warning under different stress environments.

1. Introduction

As the depth and intensity of coal mining continue to increase, large deformation of the roadway and dynamic disasters become more and more topical [1, 2]. Isolated coal pillars turn into frequent zones of dynamic disasters. The coal-rock system structure composed of the coal seam and the surrounding rock is an important carrier of underground mining activities, which plays an important role in supporting the overlying strata and maintaining the roadway stability [3]. Therefore, it is of great significance to study the deformation, failure, and energy evolution mechanism of coal-rock combination systems (CRCS) for prevention, monitoring, and early warning of coal mine disasters.
The laboratory tests and numerical simulation of CRCS are common methods used to study the structure of the coal-rock system [4]. The mechanical characteristics, energy evolution, and impact tendency of the CRCS with different combination modes, coal-rock height ratios, strength ratios, and dip angles became topical for the global research community. Dou et al. [5, 6] experimentally studied the damage evolution in CRCS samples using AE signals and electromagnetic radiation signals. The correlation between the impact tendency of the CRCS and the AE signals was obtained. Zuo et al. [7, 8] carried out the strength and deformation failure tests on CRCS with different coal-rock combinations. They revealed the effect of different combinations on the impact tendency of the coal-rock system. Mou et al. [9] proposed the criteria of stable and unstable failures of the CRCS based on their instability and failure characteristics. Chen et al. [10] studied the variation trends of mechanical parameters of CRCS with different coal-rock height ratios. They analyzed the gradual instability process and failure mode of the coal-rock combination structure. Zhang et al. [11] carried out uniaxial and triaxial compression tests on samples of three different coal-rock combinations and analyzed the influence of combination modes on the CRCS mechanical properties and failure modes. Based on the energy evolution and failure mechanism of the CRCS, the energy driving mechanism of the crack initiation of the combination was determined by the energy storage characteristics, and the inclination angle effect of the whole instability failure of CRCS samples was revealed [12, 13]. Yang et al. [14] studied the energy evolution characteristics of the coal-rock system and proposed the system collaborative control technology. Chen et al. [8] carried out the uniaxial compression tests of CRCS samples and analyzed the evolution process of crack propagation in the CRCS under uniaxial loading based on CT scanning and the AE monitoring technology. Yang et al. [15] experimentally proved that shear fracture and axial splitting failure were the main failure modes of CRCS. The kinetic energy in the CRCS samples during a failure was related to the strength difference of the coal rock. In addition, the numerical simulation method was applied to study the effects of the strength ratio and height ratio of the CRCS samples on their impact tendency and failure mode [16]. The numerical simulation of different lithologic combinations performed in the study [17] revealed the phenomenon of local deformation and fracture migration of samples. The interface parameters of coal-rock combination have obvious influence on the mechanical and acoustic emission signal characteristics, which are mainly concentrated in prefabricated cracks, endogenous cracks, and mechanical and acoustic emission signals under different loading conditions [18, 19], especially the macro- and micromechanical characteristics and failure mechanism of the whole coal-rock combination [20]. There are few reports on the mechanical and energy evolution of different angles between the loading direction and the contact surface of the composite.

Previous studies were focused on the mechanical properties, deformation, and failure mechanism of CRCS. During the loading process, the damage evolution of CRCS was characterized by laboratory tests and numerical simulation, the AE technology, and the electromagnetic radiation method. However, studies on the energy partition evolution and the multistage damage of CRCS are quite scarce, to explore the mechanical characteristics and energy dissipation trend of CRCS with different inclinations under the uniaxial load. Given the above, this study performed uniaxial compression tests of CRCS samples via an RMT150 rock mechanics testing machine. The energy evolution and failure mechanism of different CRCS samples during loading were clarified. The relationship between the AE signal and the mechanical behavior was monitored in real time. The energy accumulation trends in the CRCS were analyzed to provide references for the prevention and monitoring of dynamic disasters in coal mines.

2. Test Design and Loading Scheme

2.1. Sample Preparation. The coal collected on-site is difficult to be processed into a combination with the inclined contact surface. The heterogeneity of the coal and rock mass causes its physical and mechanical properties to be quite discrete [21]. To unify the variables and highlight the main research object of the test, all the test samples were processed with similar materials, as shown in Figure 1(a). The test setup included the coal monomer, the rock monomer, and the CRCS samples with 50 mm × 100 mm standard samples. The CRCS samples were subdivided into two groups with inclination angles equal to zero and 30°, respectively.

The sample preparation materials included quartz sand, barite powder, iron powder, rosin, pulverized coal, sodium humate, and alcohol. The mass ratio of the standard rock sample was as follows: quartz sand : barite powder : iron powder = 1 : 2 : 1. The alcohol content was 5% of the aggregate mass, and the rosin binder concentration was 25%. The mass ratio of materials for the standard coal sample was as follows: 0–1 mm pulverized coal : 1–3 mm pulverized coal = 19 : 6, and the amount of water was 10% of the aggregate mass. The amount of a single standard rock sample from the trial test was as follows: 132 g of quartz sand, 264 g of barite powder, 132 g of iron concentrate powder, 26.4 g of alcohol, and 6.6 g of rosin. The material consumption of a single standard coal sample was as follows: 197.6 g of 0–1 mm pulverized coal, 62.4 g of 1–3 mm pulverized coal, 26 g of water, and 0.83 g of sodium humate. The material consumption of the standard coal-rock sample was half of the above one.

During the preparation, the material was weighed and stirred evenly according to the required proportion, put into the self-made steel mold, and formed with the testing machine. The forming pressures for the standard rock and standard coal samples were 4.9 and 29.4 kN, respectively, and their duration was 5 min, as shown in Figure 1(b). According to the China national standards and the International Society for Rock Mechanics standards, the nonparallelism of both ends of the formed samples was no more than 0.01 mm; the diameter deviation of both ends did not exceed 0.02 mm. Each formed sample was placed in a dry and well-ventilated place for seven days. Three standard rock samples, three standard coal samples, and six CRCS samples (three
with a 0° inclination and three with a 30° inclination) were prepared.

2.2. Testing System and Scheme. Laboratory tests were carried out in the State Key Laboratory of Anhui University of Science and Technology. The test system is shown in Figure 2. It mainly includes the loading device, the AE device, and the digital camera. During the test, the three devices were synchronized for later test data processing and analysis. The loading device was a Shenzhen SUNS UTM4000 electronic universal testing machine, servodriven by the AC motor, with good stability, high precision, and a maximum test load of 20 kN. The AE device was a DS2-8B acoustic emission signal analyzer, which was used to monitor the failure process of uniaxial compression in real time. To reduce the influence of external equipment on the AE signal acquisition, the threshold value of the AE system was set at 100 MV, and a Vaseline lubricator was placed between the AE probe and the sample to enhance the sensitivity of AE signal acquisition [22]. A Canon digital camera was used to capture the sample’s deformation and failure stage points under the uniaxial load. The load and AE signals were transmitted to the computer for real-time display and storage.

Twelve uniaxial compression tests were subdivided into four groups, with three standard samples in each group. Before the test, the prepared standard rock samples, the coal samples, and CRCS samples were numbered and weighed, and the test system was launched by connecting the line. Due to the small strength of samples, to prevent rapid failure, which would make it impossible to measure the continuous stress-strain curve, the displacement-controlled loading mode was adopted. The loading rate was 0.01 mm/s, and the loading was continuous until the sample’s final fracture.

3. Results and Analysis

3.1. Stress-Strain Characteristics of CRCS Samples with Different Inclinations. The stress-strain curves of typical CRCS samples under uniaxial compression are shown in Figure 3. According to the stress-strain curves, the sample deformation could be subdivided into four stages [23]. Due to the differences in material components and proportion of the samples, the stress-strain curves of the samples with different proportions under the uniaxial load varied greatly. The strength of the CRCS samples slightly exceeded that of pure coal monomers, indicating that the strength of the CRCS sample mainly depended on the coal. The decreasing order of the compressive strength of samples was as follows: pure rock sample > 0°-inclination CRCS sample > 30°-inclination CRCS sample > pure coal sample. The decreasing order of elastic moduli was pure rock sample > 0°-inclination CRCS sample > pure coal sample > 30°-inclination CRCS sample. The peak strains of the pure coal and pure rock samples were 0.878 and 1.026, respectively. The peak strain of the CRCS sample is less than that of the pure coal sample and pure rock sample, mainly because the rock mass part of the CRCS sample experienced no significant deformation under the uniaxial compression load [24, 25]. The brittle failure after the peak of the pure rock sample was strongly pronounced, and the stress dropped, while the CRCS and pure coal samples exhibited good continuity after the peak.

In the stress-strain curves constructed under the uniaxial compression load conditions, the ratio of the accumulated deformation energy before the peak to the loss of
deformation energy after the peak is referred to as the impact energy index [26]. The impact energy index of the CRCS samples was smaller than that of the pure coal and pure rock samples. That is, the CRCS impact tendency was weak. The deformation and failure of the CRCS samples mainly occurred in the coal part, while the rock part inhibited the development and deformation of the coal body. The coal part expanded and deformed for a long time before the peak stress was reached, so the deformation and failure mechanism of the CRCS sample changed.

The complete stress-strain curve of the rock reflected its damage evolution process. The rock experienced compaction stage (I), elastic stage (II), plastic stage (III), and residual deformation stage (IV). The rock’s mechanical properties in each stage were different. The stress state of rock can be revealed by analyzing the four stages of rock deformation. The boundary points of the four stages of the sample are shown in Figure 4. The results show that the strain in the 30° CRCS sample exceeded that of the 0° one, and the residual deformation was large in the four stages. It changed asynchronously with the other three stages, indicating that the sample was seriously damaged and prone to serious disasters.

3.2. AE Response of CRCS Samples with Different Inclinations.

The displacement controlled loading method was used in the test, and the loading rate was 0.01 mm/s until the specimen was destroyed. The sampling frequency of acoustic emission system is 1000 kHz, and the threshold is 40 dB. In order to enhance the coupling effect between the acoustic emission probe and the sample, Vaseline is smeared between the sensor and the sample to reduce the acoustic impedance difference and energy attenuation of the contact surface and improve the effectiveness of AE signal in the test process.

The failure characteristics and AE response of CRCS samples with different inclinations are shown in Figure 5. When the inclination of the coal-rock sample increased from 0° to 30°, the CRCS sample’s fracture mode evolved from splitting failure of the coal rock to the sliding failure at the interface of the CRCS. There was a close correlation between the AE and the stress drop of the rock sample. The stress curve fluctuated periodically.
greatly after the peak, and there existed an obvious stress drop, accompanied by large energy AE events. The AE signal of the coal sample under uniaxial loading was weak, and the correlation with stress drop was low. The AE events of large energy were mainly concentrated in the after-peak stage. The fluctuation of the stress-time curve of the CRCS sample occurred within a small range, and there was only one peak point. The correlation between the AE and the stress drop was not obvious, and numerous AE signals were mainly concentrated in the stable rising stage of stress before the peak.

The AE energy can better characterize the damage and fracture of the coal-rock sample and directly reflect the evolution process of crack initiation, propagation, and penetration in the sample [27, 28]. Therefore, the AE energy was used as a characteristic parameter to further analyze the damage process of the coal-rock samples with different inclinations.

Based on the statistical damage theory, the damage evolution equation of samples under uniaxial loading was established in the following form:

\[ \sigma = E(1-D)\varepsilon_1, \]  

where \( \sigma \) is the axial stress, in MPa; \( E \) is the elastic modulus, in MPa; and \( D \) is the damage factor, which is derived as the number of cracks in the microelement in the sample.

Assuming that the strength of the microelement in the sample followed the Weibull distribution law, the relationship between the damage factor and the AE energy parameters was obtained:

\[ D = \frac{N_t}{N_a}, \]  

where \( N_t \) and \( N_a \) are the AE cumulative energies at time \( t \) and sample’s fracture, respectively, in mV·mS units.

The samples had a certain residual strength after the peak under a uniaxial load. The damage factor and the AE energy parameter model based on the Weibull distribution disregarded the residual strength after the peak. It was assumed that the sample was destroyed when the maximum strain was reached, i.e., \( D = 1 \), which was inconsistent with reality. Therefore, the correction factor \( m \) was introduced, with the calculation equation of the damage factor reduced to the following form:

\[ D = m \frac{N_t}{N_a}. \]  

With an account of the residual strength, the correction factor \( m \) can be obtained as follows:

\[ m = \frac{\sigma_c - \sigma_p}{\sigma_c}, \]  

where \( \sigma_c \) is the compressive strength, in MPa and \( \sigma_p \) is the residual strength, in MPa.

By substituting Equations (3) and (4) into Equation (1), the damage evolution equation of the uniaxial compression of CRCS samples characterized by the AE energy was obtained:

\[ \sigma = E\left(1 - \frac{\sigma_c - \sigma_p}{\sigma_c} \frac{N_t}{N_a}\right)\varepsilon_1. \]  

The damage evolution process of a typical sample under uniaxial compression was obtained by transforming the damage variables of the CRCS sample based on the normalization method [29, 30]. As shown in Figure 5, the CRCS samples with different inclinations were characterized by the multistage damage mechanism, which included three stages,

Figure 4: Relationship between the 0° and 30° CRCS samples and the strain points.
Figure 5: Continued.
according to the damage factor-time curve. The first stage was the initial damage stage, with a damage factor of about zero and low damage. It mainly corresponded to the initial stage of the stress-strain compaction and the elastic stage. At this time, the original cracks closed, the internal structure was uniform, and there was no new crack initiation or propagation. The second stage was the stable growth stage of damage, in which the damage factor increased nonlinearly, and the damage degree was high, mainly in the middle and late portions of the elastic stress-strain stage and the early part of the plastic stage. At this time, the primary cracks reached their limit state, and new cracks initiated and propagated with increased loading pressure. The third stage was the rapid growth stage of damage, mainly located in the middle and late portions of the stress-strain plastic stage and the residual stage after the peak. At this time, the internal microcracks in the sample expanded rapidly, converged, formed a network of cracks, and merged, resulting in the macrofracture.

In comparison with Figure 5, acoustic emission signals and damage factors of different dip coal-rock assemblages show the characteristics of stage evolution. The stress-strain curve of rock sample is in drop type after the peak, and the stress-strain curve of the coal-bearing component decreases slowly, indicating that the rock sample has good brittleness [31]. The combined samples first appeared microcracks in the attachment of contact surface, and the microcracks developed gradually until the specimen was destroyed. The rock samples and coal samples first appeared cracks at the loading end and developed and expanded gradually.

### 3.3. Failure and Instability Characteristics of Coal-Rock Combination with Different Dip Angles

In the same stress state, coal is the first to be destroyed, and microcracks and weak planes appear. With the continuous loading, these microcracks gradually connect and develop with the weak surface, forming the macrofailure characteristics. In the combination, the coal component is mainly longitudinal failure, and the angle between the crack and the axial direction of the sample is in the range of 0° to 30° which belongs to shear failure. The failure process is that the local point begins to lose stability and then leads to the overall instability [32]. The failure mode of 30° composite specimen is “point type” incomplete failure.

To sum up, with the gradual increase of the dip angle of the coal-like rock combination, the combination failure mode gradually transits from shear failure and “point type” incomplete failure, and with the gradual increase of dip angle, the failure degree changes from complete failure to incomplete failure.

### 4. Energy Evolution in the CRCS Mass

#### 4.1. Energy Calculation Method

Energy evolution accompanies the whole process of damage and failure of the coal and rock mass, so it is more practical to reveal the coal and rock mass damage from the energy evolution standpoint [33, 34]. Based on this, the energy evolution of CRCS samples with different inclinations under uniaxial compression was performed to analyze the trend of total energy accumulated before the peak, total release energy after peak, elastic energy, dissipated energy, and surplus energy.

The uniaxial stress-strain curve of coal-like rock combination is obtained by the test, and the stress-strain curve is integrated according to the calculus method, as shown in Figure 6. During the cyclic loading experiment, it is found that the unloading curve is curved due to the viscous hysteresis. The elastic energy accumulated before the peak can be approximately calculated by means of elastic stage translation, and the formula is shown below:

$$U_e = \frac{1}{2} \sigma e,$$  \hspace{1cm} (6)
where $\sigma_i$ is compressive strength, in MPa and $\varepsilon^e$ is the elastic strain that can be recovered before the peak, in %.

According to the first law of thermodynamics, assuming that there is no heat exchange between the coal-rock combination and the outside world under uniaxial load, part of the work done by the testing machine is converted into elastic strain energy, which is stored in the sample, and part of it is consumed in the form of dissipative energy, i.e.,

$$ U = U^e + U^d, \tag{7} $$

$$ U = \int_0^{\varepsilon_1} \frac{\sigma_i + \sigma_{i+1}}{2} \, d\varepsilon, \tag{8} $$

where $U$ is the total energy before the peak, $U^d$ is the dissipated energy, $\varepsilon_1$ is the strain corresponding to the peak stress, and $\sigma_i$ and $\sigma_{i+1}$ are stresses in $i$th and $(i+1)$th microelements, respectively.

The postpeak energy $U^f$ of the sample is

$$ U^f = \int_{\varepsilon_1}^{\varepsilon_{\max}} \frac{\sigma_i + \sigma_{i+1}}{2} \, d\varepsilon, \tag{9} $$

where $\varepsilon_{\max}$ is the limit strain after the peak.

Part of the elastic energy stored before the peak is consumed by the sample rupture, and the remaining energy is converted into the initial kinetic energy of the sample ejection. Therefore, the surplus energy is the difference between the pre peak elastic energy and the postpeak released energy.

$$ U^r = U^e - U^f, \tag{10} $$

where $U^f$ is the total release energy after peak and $U^r$ is the surplus energy.

### 4.2. Energy Evolution of CRCS Samples with Different Inclinations

The evolution of rock damage is accompanied by energy transfer and conversion, presenting comprehensive information on stress and strain evolutions. It is of certain significance to evaluate the process of rock loading to catastrophe based on energy. Figure 7 shows the energy conversion law of CRCS samples with 0° and 30° inclination angles.

As shown in Figure 7, the stress-strain evolution can be subdivided into the following four stages, namely, compression stage (I), elastic stage (II), plastic stage (III), and after-peak stage (IV). The dissipated and elastic energies exist in the compression, elastic, and plastic stages; the released and surplus energies exist in the after-peak stage, while shares and forms of energy in each stage are adjusted. According to Equations (6) to (10), calculations were performed for the total energy accumulated before the peak, released energy after peak, elastic energy accumulated before the peak, dissipated energy, and surplus energy. The performed analysis revealed that the energy characteristics of 0° and 30° CRCS samples were similar, and the dissipated energy of the 30° CRCS sample was small.

Figure 8 shows the law of energy release after the peak in the rock. As expected, the variation trends of 0° and 30° CRCS samples were very similar. All samples with different inclinations satisfied the law of stable energy release in the initial, middle, and later stages exhibited a gradual slowdown in the later stage and maximum energy release. According to the curve’s slopes of samples with different inclinations, the energy release after the peak of 30° CRCS was intense.

Figure 9 shows the variation law of total energy, elastic energy, dissipated energy, released energy, and surplus energy accumulated before the peak of 0° and 30° coal-rock combination samples. From the horizon and trend relationship of the curve, it can be seen that the total energy accumulated before the peak is $> \text{elastic energy} > \text{released energy} > \text{dissipated energy} > \text{surplus energy}$, and there is no offside situation. It shows that the variation of samples of 0° and 30° coal-rock assemblages can meet the general law of energy evolution, and only fluctuates in numerical value. With the increase of the inclination angle, the positions of the total energy accumulated before the peak and the elastic deformation energy are closer and closer. The difference between the total energy accumulated before the peak and the released energy after the peak shows a decreasing trend, and the

![Figure 6: Energy conversion trend.](image)

**Figure 6: Energy conversion trend.**
difference between the total energy accumulated before the peak and the dissipated energy shows a gradually increasing trend. The results show that with the increase of dip angle, the energy storage characteristics of coal-like rock combination are gradually enhanced.

5. Analysis of Inclination Influence Mechanism in CRCS

The experimental results show that the AE signal is highly consistent with the loading failure process of the specimen, which is consistent with the previous research results. However, the mechanical and acoustic emission characteristics of coal-rock associations with different dip angles are significantly different. In order to explore the influence of contact angle on peak load and uniaxial compressive strength, a mechanical model as shown in Figure 10 is established. In the contact surface of the coal rock, \( \sigma \sin \alpha \) is the stress of the contact surface of the parallel coal rock, \( \sigma \cos \alpha \) is the stress of the contact surface of vertical coal rock, where \( \sigma \) is the axial stress applied and \( \alpha \) is the angle between the contact surface and the horizontal direction of the coal rock. With an increase in the inclination of the contact surface of the coal rock, \( \sigma \sin \alpha \) increased gradually and \( \sigma \cos \alpha \) decreased gradually, that is, the shear slip failure was enhanced during

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**Figure 7**: Energy conversion law of CRCS samples: (a) 0° CRCS samples and (b) 30° CRCS samples.

**Figure 8**: Law of energy release after the peak of the 0° and 30° CRCS samples.

**Figure 9**: Energy conversion law of the 0° and 30° CRCS samples.
loading, and the tensile splitting failure was weakened gradually. The crack morphology and mechanical properties of the CRCS samples with different inclinations exhibited different patterns under the external loads.

At $\alpha = 0^\circ$, the axial stress was normal to the contact surface of the coal rock of the combination, the original fractures and pores of the sample were compressed to a large extent, and numerous cracks perpendicular to the contact surface were produced, so the sliding instability failure did not occur easily. When the peak load was reached, the cracks perpendicular to the contact surface were not completely connected, showing good ductility failure. The small cracks perpendicular to the contact surface after the peak were rapidly connected, and the sample was damaged instantly. At $\alpha = 30^\circ$, there was a stress component parallel to the contact surface in the CRCS; the sample was tensioned at the contact surface; cracks were generated under the action of the stress component parallel to the contact surface, and the original cracks and pores of the sample were gradually compacted under the action of the stress component perpendicular to the contact surface. Therefore, the 30° CRCS samples were more prone to losing cohesion and experienced a sliding failure along the contact surface.

The CRCS samples with different inclinations can reflect the characteristics of the coal-rock contact surface. When the coal seam is the same, the angles between the principal stress and the contact surface are different, and the energy dynamic evolution and impact tendency differ as well. The larger strain energy is accumulated before the peak, the shorter the failure time after the peak, and the greater the impact tendency. The test results show that with an increase in the inclination angle $\alpha$ of the contact surface, the elastic energy accumulated before the peak increased, and the failure time decreased. Before the sample was loaded to the peak load, numerous AE signals appeared, and intensive AE signals were detected in the middle of the failure process.

6. Conclusions

The results obtained made it possible to draw the following conclusions:

(1) The coal and rock mass near the contact surface of the CRCS affected each other. The limiting effect of the rock mass in the failure stage before the peak was obvious, and the coal part effect in the failure stage after the peak was more pronounced. The sample failure mode was closely related to the inclination angle of the contact surface, i.e., the larger the inclination, the greater the shear slip failure.

(2) With an increase in the inclination angle of the contact surface, the positions of the total energy accumulated before the peak and the elastic energy of the CRCS shifted closer to each other. The difference between the total energy accumulated before the peak and the released energy after the peak decreased. The difference between the total energy accumulated before the peak and the dissipated energy tended to increase gradually.

(3) The rock art in the CRCS sample limited the strength of the coal part. Compared with the pure coal monomer, the pressure-bearing time of the sample in the expansion stage after the peak was longer, and the impact tendency of the CRCS sample was weaker. According to the deformation and failure characteristics of the combination, the support of the coal body far from the contact surface should be strengthened in engineering practice to avoid the rock damage caused by the expansion and evolution of cracks in the coal part.

Data Availability

The data used for conducting classifications are available from the corresponding author authors upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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