Experimental Study on Briquette Coal Sample Mechanics and Acoustic Emission Characteristics under Different Binder Ratios

Han Meng, Liyun Wu,* Yuzhong Yang, Fei Wang, Lei Peng, and Lei Li

ABSTRACT: In order to find briquette coal with mechanical characteristics close to those of raw coal samples, we conducted triaxial compression experiments on raw coal and briquette coal samples with different proportions of cement contents. The mechanical characteristics and acoustic emission (AE) characteristics of the coal samples in the triaxial compression process were analyzed in detail. The test results show that the evolution of deformation and strength characteristics of the briquette coal and raw coal samples follow certain common laws. The confining pressure can improve the mechanical properties of both types of coal samples: as the confining pressure continues to increase according to the set values, the elastic modulus, peak strain, and peak strength of both samples show an increasing linear trend. When the value of the confining pressure setting was the same, the compressive strength of the raw coal samples exceeded that of briquette ones, but the deformation and shape variations of the latter exceeded those of the former. When performing triaxial compression experiments on both kinds of coal samples, the AE amplitude and counts showed a close correlation with the stress evolution curves. When the confining pressure was set to 5 MPa, 20% cement content briquette coal was seen to be the closest to raw coal samples regarding mechanical and AE characteristics.

1. INTRODUCTION

Coal is a complex solid combustible organic rock with high heterogeneity. Many natural pores, cracks, and bedding are unevenly distributed in the coal body. The heterogeneity of the coal has a relatively large impact on the coal’s mechanical properties; even if the coal samples come from the same coal seam, they have different mechanical properties. Most scholars report that coal is a material with dual pore structure characteristics. The dual-porosity-media model can well describe the gas storage and migration in coal seams. In the process of underground coal road excavation and working face mining, the coal seam is always subject to the loading and unloading of the moving supporting pressure in front of the coal mining face. Since the original coal body is in a state of three-way stress underground, only carrying out triaxial compression experiments can truly reveal the original coal body’s mechanical properties underground. The whole stress–strain curves of the triaxial compression provide abundant information on the coal sample’s failure stages, which is the mechanical basis for studying the destruction of coal samples and determining their structural relationships.

The triaxial compression of coal and rock mass has been extensively researched. In the 1960s, Hobbs analyzed the influence of confining pressure on the stress–strain curve trend characteristics of coal samples. Medhurst and Brown used large-sized specimens to identify the most appropriate strength criteria for coal and the failure mechanism of the transition from axial splitting to shear. Hua et al. conducted extensive studies on marble, siltstone, and coal rock masses’ failure characteristics during unloading of confining pressure. Su et al. systematically carried out conventional triaxial loading and unloading experiments on coal samples.
et al.34 carried out experiments on the AE characteristics of stress path loading conditions using triaxial compression. Zhou samples. Wang et al.21 conducted mechanical and permeability properties test of coal rock mass under triaxial conditions. The results showed that coal and sandstone’s strength was the highest, followed by coal and mudstone. Zhu et al.25 conducted true triaxial experiments on coal samples under two loaded stress paths. It was concluded that coal samples were more prone to damage under the condition of triaxial unloading. Zhang et al.23 explored the mechanical and AE characteristics of the two kinds of cement under the triaxial loading test. However, there are relatively few reports on a comparative study of the AE signals of raw coal and briquette coal samples with different rations of cement under the triaxial loading test.

In the experimental research on briquette coal and raw coal samples, many meaningful research conclusions have emerged. Yao et al.37 measured the triaxial compressive strength and deformation characteristics of more than 200 gas-containing coal samples. A regression equation expressing the relationship between coal body strength, pore gas pressure, and water pressure was obtained. Yin et al.38 compared raw coal and briquette coal and found that the two kinds of coal samples have different regulations of deformation characteristics in gas-containing triaxial experiments. Cao et al.39 performed a triaxial seepage experiments on briquette coal and raw coal samples. The results showed that the whole stress–strain curves of both types of coal samples could be subdivided into five stages.

The above research results show that laws binding the AE signals with different stress path loading conditions using triaxial compression. The above findings gave insight into the AE signals feature of coal and rock masses during the condition of uniaxial and triaxial loading. However, there are relatively few reports on a comparative study of the AE signals of raw coal and briquette coal samples with different rations of cement under the triaxial loading test.

The results showed that the whole stress–strain curves of both types of coal samples could be subdivided into five stages.

Figure 1. Geographical location of No. 13 coal mine.

Figure 2. Prepared coal samples used for the test: (a) raw coal samples; (b) part of the briquette coal samples.

experiments on raw coal samples. Tang et al.20 used a three-dimensional digital image and a transparent pressure sensor to perform uniaxial and triaxial compression experiments on coal samples. Wang et al.21 conducted mechanical and permeability properties test of coal rock mass under triaxial conditions. The results showed that coal and sandstone’s strength was the highest, followed by coal and mudstone. Zhu et al.25 conducted true triaxial experiments on coal samples under two loaded stress paths. It was concluded that coal samples were more prone to damage under the condition of triaxial unloading. Zhang et al.23 explored the mechanical and AE characteristics of the two kinds of cement under the triaxial loading test. However, there are relatively few reports on a comparative study of the AE signals of raw coal and briquette coal samples with different rations of cement under the triaxial loading test.

In the experimental research on briquette coal and raw coal samples, many meaningful research conclusions have emerged. Yao et al.37 measured the triaxial compressive strength and deformation characteristics of more than 200 gas-containing coal samples. A regression equation expressing the relationship between coal body strength, pore gas pressure, and water pressure was obtained. Yin et al.38 compared raw coal and briquette coal and found that the two kinds of coal samples have different regulations of deformation characteristics in gas-containing triaxial experiments. Cao et al.39 performed a triaxial seepage experiments on briquette coal and raw coal samples. The results showed that the whole stress–strain curves of both types of coal samples could be subdivided into five stages.

The above research results show that laws binding the AE signals with different stress path loading conditions using triaxial compression. The above findings gave insight into the AE signals feature of coal and rock masses during the condition of uniaxial and triaxial loading. However, there are relatively few reports on a comparative study of the AE signals of raw coal and briquette coal samples with different rations of cement under the triaxial loading test.

The results showed that the whole stress–strain curves of both types of coal samples could be subdivided into five stages.

Figure 1. Geographical location of No. 13 coal mine.

Figure 2. Prepared coal samples used for the test: (a) raw coal samples; (b) part of the briquette coal samples.
2. COAL SAMPLE PREPARATION AND EXPERIMENTAL METHODS

2.1. Raw Coal Samples for the Experiment. The raw coal blocks were obtained from the Ji 15-17-11110 fully mechanized mining face of No. 13 Coal Mine of the Pingdingshan Tian’an Coal Industry Co., Ltd., located in Xiangcheng County, Xuchang, Henan Province of China. Figure 1 shows the geographic location map of No. 13 coal mine. The size of the coal blocks was 300 mm × 300 mm × 300 mm; they were retrieved from the above-mentioned fully mechanized mining face and placed in a wooden box and transported back to the laboratory. Because the coal was relatively soft, we used a coring drill to core the coal blocks by vertical bedding, and then cut and ground the coal to obtain raw coal samples with the standard size of coal samples (ϕ50 mm × h100 mm). The accuracy of the processed samples met the ISRM suggested method.40

Table 1. Basic Parameters of the Raw Coal Samples

| number | diameter (mm) | height (mm) | mass (g) | density (t/m³) | wave speed (m/s) |
|--------|---------------|-------------|----------|----------------|-----------------|
| MJ2    | 49.50         | 99.75       | 266.26   | 1.39           | 1529.91         |
| MJ3    | 50.09         | 100.18      | 263.68   | 1.34           | 1447.69         |
| MJ4    | 49.44         | 100.49      | 266.81   | 1.38           | 1484.34         |
| MJ5    | 49.49         | 99.42       | 265.96   | 1.39           | 1784.92         |
| MJ6    | 50.17         | 99.82       | 285.66   | 1.45           | 1363.66         |
| MJ7    | 50.18         | 100.01      | 271.73   | 1.37           | 1477.25         |
| average| 1.39          |             | 1514.63  |                |                 |

2.2. Preparation Technology of the Briquette Coal Samples. The coal samples used to made the briquette coal samples were also from the 11 110 mining face. After the raw coal was cored, the remaining raw coal blocks was crushed on a hammer stone crusher. The granular coal was sieved with a standard sieve and the coal particles were pulverized to a diameter between 0.18 and 0.25 mm. The particles in the above-mentioned size range were used to make the briquette coal samples.

Because cement has excellent hydration, hardening, and impermeability properties, it can be used as a good binder for making briquette coal samples.41,42 In this experiment, we chose 42.5 grade silicate cement as an additive for the production of briquette coal samples. Water and cement were mixed with coal particles of diameter 0.18–0.25 mm according to the ratio specified by the experimental design to make briquette coal samples. The mixture was stirred well and put into a forming mold, maintained at a pressure of 100 MPa for 30 min, and then retreated into the mold. The size of the prepared standard briquette coal sample was ϕ50 mm × h100 mm. Table 2 shows the proportions of the briquette coal samples.

Table 2. Proportioning Scheme of the Briquette Coal Samples

| number | coal | cement | water |
|--------|------|--------|-------|
| group I| 1.00 | 0.00   | 0.05  |
| group II| 0.95 | 0.05   | 0.069 |
| group III| 0.90 | 0.10   | 0.072 |
| group IV| 0.80 | 0.20   | 0.083 |

The prepared briquette coal samples were cured for 28 days in a thermostat at a temperature of 20 °C and humidity of 95%. Part of the briquette coal samples were made according to the above steps as shown in Figure 2b.

2.3. Experimental Method. The samples were subjected to conventional triaxial compression tests on an RMT-150B electro-hydraulic servo rock test system. The test methods for the two kinds of coal samples were as follows.

(1). Confining pressures of the raw coal samples were set to 2, 5, 10, 15, 20, and 25 MPa. A displacement sensor with a range of 5 mm was used to monitor the axial deformation of the coal samples, and 1000 kN force sensors were applied to monitor the axial load of the coal samples. First, the predetermined confining pressure value was gradually applied according to the hydrostatic pressure condition σ₁ = σ₃, with a loading rate of 0.5 MPa/s. Then, keeping the confining pressure constant, the control mode was changed to displacement control. At this point, the loading rate of stress was set to 0.01 mm/s, and the axial pressure was continuously applied until the raw coal samples were completely fractured.

(2). Confining pressures of the briquette coal samples were set to 1, 2, 3, 4, and 5 MPa. The further measuring and testing...
procedures were similar to those described above for the raw coal sample. The loading rate of the confining pressure was also 0.5 MPa/s. Similarly, the pressure was kept constant until it reached the set value. The axial

Figure 4. Triaxial test stress–strain curves of raw coal samples (a) and briquette coal samples (b–e) with different cement contents: (b) I, 0% cement; (c) II, 5% cement; (d) III, 10% cement; and (e) IV, 20% cement.
pressure was continuously applied at a uniform loading speed of 0.005 mm/s until the briquette coal samples were fractured.

During the triaxial compression test of the two types of coal samples, the DS-5 type 8-channel AE system was used to monitor the AE information synchronously. The AE sensor was located on the cushion block under the three-axis pressure chamber. The acquisition frequency of the instrument was set to 3 MHz. The threshold of the external environmental noise was calculated as 50 dB, while the sensor frequency of the RS-2A AE was set to 150 kHz. The AE control system connects the computer to record simultaneously the energy, amplitude, and count. The layout of the triaxial compression and AE test system is shown in Figure 3.

3. TEST RESULTS AND ANALYSIS
3.1. Deformation Characteristics of the Coal Samples.

The full-process stress−strain curve of the triaxial compression of the two kinds of coal samples in this experiment is shown in Figure 4.

It can be concluded from Figure 4 that the two kinds of coal samples have undergone the four stages of compaction, elasticity, yield, and failure. The overall destruction stage of the coal body can show the stress−strain and the changing characteristics of the internal pore fissures. The failure characteristics of the briquette samples under uniaxial compression are more obvious than those under triaxial compression, because of the strong plastic characteristics of the briquette coal sample.43

Analysis of Figure 4a shows that the compaction stage of raw coal samples MJ2 and MJ5 is more obvious, with the corresponding \( \sigma_3 = 2 \) and 5 MPa, respectively. It shows that...
when the confining pressure is at a low value, the vertical pressure loading process is not sufficient to compact the coal body’s primary fractures. When the confining pressure gradually increases according to the predetermined value, the compaction stage gradually becomes shorter and the yield stage becomes more obvious before the coal sample reaches its peak strength. There is an obvious peak deformation before reaching the peak, and the peak strength shows an overall increasing trend. This indicates that the confining pressure closes the original fissures in the coal body and prevents slippage of fissures. The higher the confining pressure, the less obvious the high pressure and dense stage performance. When the raw coal enters the elastic deformation stage, the effect of the surrounding pressure is relatively small, and the raw coal sample shows good linear characteristics in the elastic stage, although at different confining pressures. The deformation stage of the raw coal samples during the triaxial loading process is mainly elastic or plastic. The raw coal sample exhibits obvious plastic characteristics after the peak strength under high confining pressure, and the deformation characteristics of the raw coal sample also have certain

| Table 3. Results on Coal Specimens under Triaxial Compression |
|---------------------------------------------------------------|
| coal sample type | number | σ$_3$/MPa | R$_c$/MPa | $E_T$/Gpa | $E_c$/Gpa | $e$/$10^{-3}$ | c/MPa | ϕ/deg |
| briquette coal samples with 0% cement content | MS-2  | 1  | 10.30 | 0.41 | 0.30 | 31.56 | 1.48 | 38.03 |
| | MS-3  | 2  | 14.15 | 0.39 | 0.34 | 45.11 |
| | MS-4  | 3  | 19.21 | 0.59 | 0.40 | 49.13 |
| | MS-6  | 4  | 22.78 | 0.67 | 0.46 | 55.89 |
| | MS-11 | 5  | 27.03 | 0.72 | 0.64 | 61.15 |
| briquette coal samples with 5% cement content | M2−8  | 1  | 9.29 | 0.41 | 0.32 | 26.76 | 1.02 | 40.18 |
| | M2−9  | 2  | 12.75 | 0.37 | 0.38 | 44.95 |
| | M2−10 | 3  | 19.21 | 0.60 | 0.56 | 41.51 |
| | M2−11 | 4  | 22.92 | 0.70 | 0.52 | 51.79 |
| | M2−6  | 5  | 27.39 | 0.94 | 0.65 | 45.54 |
| briquette coal samples with 10% cement content | M3−5  | 1  | 9.35 | 0.34 | 0.26 | 34.68 | 0.67 | 39.90 |
| | M3−6  | 2  | 10.04 | 0.45 | 0.37 | 29.42 |
| | M3−7  | 3  | 16.04 | 0.54 | 0.44 | 41.28 |
| | M3−9  | 4  | 20.69 | 0.71 | 0.72 | 36.01 |
| | M3−4  | 5  | 26.92 | 0.87 | 0.62 | 51.48 |
| briquette coal samples with 20% cement content | M4−11 | 1  | 9.78 | 0.53 | 0.44 | 23.97 | 1.38 | 41.08 |
| | M4−10 | 2  | 16.08 | 0.69 | 0.48 | 32.68 |
| | M4−9  | 3  | 21.56 | 0.82 | 0.67 | 33.43 |
| | M4−8  | 4  | 26.72 | 0.93 | 0.7 | 38.67 |
| | M4−6  | 5  | 28.62 | 0.99 | 0.81 | 45.73 |
| raw coal samples | MJ2  | 2  | 26.38 | 3.66 | 3.52 | 9.99 | 7.19 | 25.44 |
| | MJ3  | 5  | 35.82 | 3.65 | 2.72 | 14.39 |
| | MJ4  | 10 | 44.64 | 4.33 | 4.23 | 12.22 |
| | MJ5  | 15 | 66.84 | 4.72 | 5.32 | 16.53 |
| | MJ6  | 20 | 73.61 | 4.76 | 4.66 | 17.54 |
| | MJ7  | 25 | 82.19 | 5.98 | 5.94 | 27.01 |

Figure 7. Relationship between the confining pressure and peak strength: (a) raw coal; (b) briquette coal.
directions in the raw coal sample, and there are also various fully closed. The slippage of
When the pressure continues to increases, the fracture slip, and gradual closure of the pores. The existence of compression process mainly includes elastic deformation, reduction in the coal sample. From the raw coal sample type number of groups I–IV, corresponding to Figure 4b–e, group IV of briquette coal samples is closer in deformation characteristics to those of raw coal samples under the corresponding confining pressure value.

It can be found from Figure 5 that, under the same confining pressure ($\sigma_3 = 5$ MPa), the elastic modulus of the raw coal samples is 3.4 to 4.3 times that of briquette ones. The elastic moduli of briquette and raw coal samples increase with confining pressure. The relationship curve between the confining pressure and elastic modulus exhibits a linear law. Therefore, it can be considered that the confining pressure controls the rigidity of the raw and briquette coal samples.

It can be seen in Figure 6 featuring the peak strain results of coal samples that the deformation of briquette coal samples is much larger than that of raw coal samples. This indicates that briquette coal samples have better plastic flow characteristics than raw coal samples, a trend similar to that of the deformation characteristics of ideal plastic materials. Figure 6a shows that the peak strain of the raw coal sample increases with confining pressure. Figure 6b indicates that at higher confining pressures,
the peak deformation of the briquette coal sample shows an overall increasing trend.

3.2. Strength Characteristics of the Coal Samples. Table 3 shows the results of the two kinds of coal samples under conventional triaxial loading. $\sigma_3$ is the confining pressure value, MPa; $R_c$ is the peak strength, MPa; $E_T$ is the elastic modulus, GPa; $E_c$ is the deformation modulus, GPa; $\varepsilon$ is the axial peak strain, $10^{-3}$; $c$ is the cohesion, MPa; and $\varphi$ is the internal friction angle, $^\circ$.

Based on the Mohr–Coulomb strength criterion

$$\sigma_1 = Q + K\sigma_3$$

(1)

where $\sigma_1$ is the peak strength; $Q$ and $K$ are material strength parameters, and their relationship with the internal friction angle $\varphi$ and cohesion $C$ is as follows

$$\varphi = \arcsin\left(\frac{K - 1}{K + 1}\right)$$

(2)

$$C = \frac{Q(1 - \sin \varphi)}{2 \cos \varphi}$$

(3)

The relationship between the peak intensity and confining pressure is obtained using formula (1) and is shown in Table 3. As can be found in Table 3 and Figure 7, the peak strength of the raw and briquette coal samples showed a gradual increase with $\sigma_3$. In line with the Mohr–Coulomb strength criterion, the peak strength and the confining pressure are roughly proportional to the relationship. This is because as the confining pressure continues to increases, the sliding resistance of the coal sample increases, increasing the material’s bearing capacity. Therefore, the compressive strength of the coal samples is improved. The cohesion and internal friction angle values of the two kinds of coal samples under triaxial compression were calculated using formulas (2) and (3) (Table 3). The raw coal sample’s cohesion force under triaxial compression is 7.19 MPa and the internal friction angle is 25.44°. The briquette coal sample’s cohesion force is about 1.0 MPa, while the internal friction angle is about 40°. From the data analysis of the triaxial compression, it is
concluded that the cohesive force of raw coal is greater than that of the briquette coal samples, and the internal friction angle of briquette coal is greater than that of the raw coal samples. This shows that briquette coal samples are more likely to be fractured, and the strength difference between the two coal bodies had an important relationship with the coal body fracture. Figure 8 shows the relationship between the cohesion, internal friction, and the cement content in briquette coal samples. The cohesive force of briquette coal samples first decreases and then increases with cement content. Only when the cement content reaches 20% does their cohesive force change significantly. With the increasing content of cement, the cement hydration reaction occurs, which changes the structure of the briquette coal samples. The internal friction angles of the cement content briquette coal samples show a positive relationship. Still, the absolute value of the internal friction angle variation is small, which shows that the internal friction angle reflects the material’s mechanical properties. The cohesion is related to the weakest surface in the coal sample, and there is a large difference before and after the coal sample fracture. According to the data listed in Table 3, under the same confining pressure (σ₃ = 2.5 MPa), the raw coal sample’s compressive strength is 1.6 to 2.6 times that of the briquette coal sample. The raw coal sample’s cohesion is 4.86 to 10.73 times that of the briquette coal sample, and the internal friction angle of the raw coal sample is 0.62 to 0.67 times that of briquette coal samples.

3.3. Characteristics of the AE Parameters of the Coal Samples. The coal sample generates a variety of AE signal parameters in the process of being destroyed by load deformation. In this article, we choose AE amplitude ($A$, $\sum A$), ring count ($N$, $\sum N$), and energy ($E$, $\sum E$) to analyze the destructive characteristics of the triaxial compression of the coal samples. Table 4 shows the triaxial and AE signal test results of the coal samples at $\sigma₃ = 5$ MPa. $\sigma₃$: confining pressure, MPa; $\sum A$: AE cumulative amplitude, mV; $\sum N$: AE cumulative ring count, times/s; and $\sum E$: AE cumulative energy, mV·ms.
Figures 9–13 show the AE monitoring results of the raw coal sample MJ3 and briquette coal samples MS11, M2−6, M3−5, and M4−6 under a confining pressure of 5 MPa.

Figure 9 shows the AE characteristics of the raw coal sample MJ3 during the conventional triaxial test process; the stress−time curve appears slightly concave in the initial compaction stage. The stress rate gradually increases, and signals at this stage feature different-intensity and lower-energy AE events. The reason for the above characteristics is that the original fissures in the coal sample are closed under the action of 5 MPa confining pressure. In the process of increasing the axial pressure, some rough surfaces that have been closed will undergo occlusal failure and generate AE events with relatively low energy. When the axial stress continues to increase, the raw coal sample’s triaxial compression enters the elastic stage. Under the action of the external confining pressure, the axial stress causes the coal sample to produce new microcracks. The coal sample is in an elastic state, the time−stress curve shows a linear relationship, and the stress rate remains stable. However, there will be slippage between the closed cracks in the internal structure of the coal sample, and at the same time, AE events with relatively low energy will be generated. But overall, the AE signals in the elastic stage are relatively small.

When the axial stress continues to increase, the raw coal sample’s deformation enters the yield stage, the stress−time relationship curve deviates from the straight line, and the stress rate gradually decreases. At this time, the coal sample shows the development process of preliminary damage. The microcracks in the internal structure of coal sample start to form, the internal expansion of the coal sample appears, and the number of AE events begins to show activity. The amplitude, count, and energy of AE increase significantly, which can be used as an obvious feature to judge the damage of the coal sample.

When the axial stress reaches the raw coal sample’s ultimate bearing capacity, the raw coal sample enters the stage of failure. The new microcracks aggregate and penetrate, leading to the formation of macroscopic fracture surfaces, and the interaction between the cracks is continuously enhanced. The AE signals are
obviously more active and the characteristic value of AE increases rapidly. When the coal sample is fractured, the characteristic values of AE reach the peak stage. Then the coal sample slips along a certain fracture surface as a whole. The axial stress drops rapidly, the number of AE events gradually decreases, and the AE signal intensity also drops.

It can be seen from Figures 10 to 13 that under a confining pressure of 5 MPa, the AE signals of the briquette coal samples are relatively active during the compaction and elastic stages of loading. The numerical intensities of the amplitude, count, and energy are relatively high. The occurrence of this phenomenon is related to the coal body structure of the briquette coal sample. It can be understood that the briquette coal does not develop fractures compared to the raw coal sample. Under the action of the confining pressure, the arrangement of particles becomes denser. After being subjected to axial load, the internal microcracks are closed and slippage occurs between closed cracks. Simultaneously, the sliding failure between the coal particles and the occlusal failure between the rough surfaces will also produce a certain number of AE events. In this stage, the characteristics of the AE signals are roughly linear. At the same time, the slope of the time–stress curve is relatively flat.

When the axial load continues to increase, the briquette coal sample starts developing into the yield stage. The AE events in the M3–5 and M4–6 briquette coal samples are relatively active, showing the development process of the internal coal sample damage. Microcracks nucleate and grow in the coal sample, the stress–time curve begins to deviate from a straight line, and the coal sample’s initial damage begins to develop. The coal sample’s internal microcracks start to expand, which is an early signal that the coal sample is damaged.

The AE signals of the M2–6 briquette coal sample in the yield stage is not obvious because its strength is relatively low. When the value of the confining pressure is relatively high, the deformation of the coal body itself is relatively large, so the
number of AE events caused by the destruction of the briquette coal body after the axial load is relatively small. When the briquette coal samples enter the destruction stage, the microcracks in the briquette coal samples will aggregate and penetrate to form a macroscopic fracture surface. Moreover, four groups of briquette coal samples’ AE signals are relatively active, and the deformation value of the briquette coal sample is also very large. It causes the briquette coal sample’s bearing area to grow during triaxial compression, and the load continues to be applied after the peak stress is reached. Therefore, there are still many AE events after the peak intensity of the briquette coal sample under triaxial compression.

4. DISCUSSION

Because the raw coal samples have a relatively high heterogeneity, the results often show a relatively large dispersion when carrying out conventional mechanical property experiments. Even the mechanical properties of coal samples prepared from the same raw coal are often quite different. Different from the raw coal samples, the briquette coal samples have a relatively...
high homogeneity, so they will show better regularity when testing the conventional mechanical parameters.

4.1. Coal Sample Failure Characteristics. The raw coal samples showed obvious brittle failure characteristics when the value of the confining pressure was relatively low and plastic deformation characteristics under high confining pressure in this triaxial experiment. With an increase in confining pressure, the coal samples’ brittleness characteristics decrease, while plastic failure characteristics increase. Overall, the elastic modulus and peak strength of the raw coal samples show a linear increase with confining pressure.

The destruction characteristics of the raw coal samples are closely related to the confining pressure. When the set confining pressure value range is below 10 MPa, the coal sample shows a dilatancy failure. The coal sample’s fracture surface is relatively complex and swelling cracks occur during the shear-slip failure process. The characteristics of tensile failure also appear locally (Figure 14a). When the sample MJ5 is subjected to a confining pressure of 15 MPa, the coal sample shows a single failure form, usually in the form of shear surface failure (Figure 14b). It presents diagonal failure, and the failure characteristics of the raw coal samples are closely related to the original joints and confining pressure.

The peak strain, peak strength, and elastic modulus of the same type of briquette coal samples increase with confining pressure. This directly indicates that the confining pressure can strengthen the stiffness of the briquette coal samples. The triaxial failure patterns of the briquette samples are more complicated than those of raw coal samples under the same conditions. The reason is that the briquette coal samples have the characteristics of low strength and high plasticity. After being subjected to confining pressure, the briquette coal samples are more severely broken. The fracture of briquette coal samples is dominated by dilatancy failure and their axial deformation is relatively large. Therefore, the damage to briquette coal samples when performing the triaxial test mostly shows the form of dilatancy failure. Due to the relatively large amount of deformation of the briquette coal sample, when we collected the sample from the triaxial cylinder, it was found to be severely broken. Therefore, the three-axial failure model of the briquette coal samples in this experiment was not proved by the corresponding photographs.

4.2. AE Features of the Coal Samples. The AE signals can well characterize the failure characteristics of coal samples under triaxial test. The AE characteristics of the coal samples in this experiment are compared and analyzed. When $\sigma_3 = 5$ MPa, the triaxial compression AE characteristic parameters of the fourth group (M4–6) has a cumulative energy of $3.131 \times 10^6$ mV·ms ($\text{Table 4}$). The cumulative count is $4.86 \times 10^5$ times/s, which is the closest to the cumulative energy of the MJ3 raw coal sample ($3.847 \times 10^6$ mV·ms), and the cumulative count is $1.049 \times 10^6$ times/s. Furthermore, comparison of the AE signals of the fourth group of briquette coal samples with the time–stress curve shows that the characteristics of the AE signals of M4–6 are similar to those of the raw coal sample. Therefore, among the briquette coal samples in the triaxial test, the fourth group of briquette coal sample (M4–6) has the closest AE signal characteristics to the raw coal sample MJ3.

5. CONCLUSIONS

By carrying out conventional triaxial compression experiments of raw and briquette coal samples, the mechanical and AE parameter characteristics of the two kinds of coal samples were analyzed. The main conclusions are as follows:

1. The conventional triaxial compression process of raw and briquette coal samples can be roughly divided into four stages: compaction, elastic, yield, and failure stages. The raw coal sample’s damage in the range of the experimental confining pressure is mainly a brittle failure; plastic failure will only occur under higher confining pressure. The raw coal sample continues to bear the load with the existing friction after reaching the peak strength. The damage to the briquette coal samples with cement content below 10% is dominated by plastic failure, and the 20% cement content sample first undergoes brittle failure and then plastic failure.

2. Under conventional triaxial compression, the two types of coal samples exhibit a linear relationship between the peak strength, elastic modulus, and confining pressure. Under triaxial compression, the deformation, strength, and AE characteristics of the briquette coal samples with 20% cement are most similar to those of the raw coal samples.

AUTHOR INFORMATION

Corresponding Author

Liyun Wu — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China; orcid.org/0000-0003-3655-0437; Email: jitwly@hpu.edu.cn

Authors

Han Meng — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China; orcid.org/0000-0003-1650-6287

Yuzhong Yang — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China

Fei Wang — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China

Lei Peng — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China

Lei Li — School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c06178

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research is financially supported by the National Natural Science Foundation of China (51674102 and 51874121), the key Scientific and Technology Research Plan of Henan Province, China (182102310002), the NSFC-Key projects supported by the Henan Province United Fund, China (U1904210), and the funding for Special Research Funds for Colleges and University in Henan Province, China (NSFRF180104). The authors thank the editor and anonymous reviewers for their careful work and thoughtful suggestions that have helped improve this paper substantially.

REFERENCES

1. Tang, Z. Q.; Zhai, C.; Zou, Q. L.; Qin, L. Changes to coal pores and fracture development by ultrasonic wave excitation using nuclear magnetic resonance. Fuel 2016, 186, 571–578.

2. Liu, S. M.; Li, X. L.; Wang, D. K.; Zhang, D. M. Experimental study on temperature response of different ranks of coal to liquid nitrogen soaking. Nat. Resour. Res. 2020, 30, 1467–1480.
(3) Yang, S. Q.; Gao, F.; Xu, T. Nonlinear visco-elastic and accelerating creep model for coal under conventional triaxial compression. Geomech. Geophys. Geo. 2015, 1, 109–120.
(4) Du, F.; Wang, K. Unstable failure of gas-bearing coal-rock combination bodies Insights from physical experiments and numerical simulations. Process Saf. Environ. Prot. 2019, 129, 264–279.
(5) Zhang, L.; Aziz, N.; Ren, T.; Nemick, J.; Tu, S. H. Influence of coal particle size on coal adsorption and desorption characteristics. Arch. Min. Sci. 2014, 59, 807–820.
(6) Shaw, D.; Mostaghimi, P.; Armstrong, R. T. The dynamic behavior of coal relative permeability curves. Fuel 2019, 253, 293–304.
(7) Xin, C. P.; Du, F.; Wang, K.; Xu, C.; Huang, S. G.; Shen, J. T. Damage evolution analysis and gas-solid coupling model for coal containing gas. Geomech. Geophys. Geo. 2021, 7, No. 7.
(8) Wang, K.; Du, F. Coal-gas compound dynamic in China: A review. Process Saf. Environ. Prot. 2020, 133, 1–17.
(9) Kang, H. P.; Fan, M. J.; Gao, F. Q.; Zhang, H. Deformation and support of rock roadway at depth more than 1000 meters. Chin. J. Rock Mech. Eng. 2015, 34, 2227–2241. Chinese Journal.
(10) Xie, H. P.; Zhang, Z. T.; Gao, F.; Zhang, R.; Gao, M. Z.; Liu, J. F. Stress-fracture-seepage field behavior of coal under different mining layers. J. Chin. Sustain. Soc. 2016, 41, 2405–2417. Chinese Journal.
(11) Li, X. L.; Cao, Z. Y.; Xu, Y. L. Characteristics and trends of coal mine safety developments. Energy Sources, Part A 2020, 1–19.
(12) Huang, J. J.; Qin, Y. G.; Zhao, S.; Wang, W.; Lei, W. Stress response characteristics and coupling support of deep roadway in soft rock masses. Cogent Eng. 2017, 4, 1–15.
(13) Hobbs, D. W. The strength and stress-strain characteristics of Oakdale coal under triaxial compression. Geol. Mag. 1960, 97, 422–435.
(14) Hobbs, D. W. The strength and the stress-strain characteristics of coal in triaxial compression. J Geol. 1964, 72, 214–231.
(15) Medhurst, T. P.; Brown, E. T. A study of the mechanical behavior of coal for pillar design. Int. J. Rock Mech. Min. Sci. 1998, 35, 1087–1104.
(16) Hua, A. Z.; You, M. Q. Rock failure due to energy release during unloading and application to underground rock burst control. Tunnelling Underground Space Technol. 2001, 16, 241–246.
(17) Su, C. D.; Zhai, X. X.; Li, Y. M.; Liu, Z. Y. Study on deformation and strength of coal samples in triaxial compression. Chin. J. Rock Mech. 2006, 23, 3055–3058. Chinese Journal.
(18) Su, C. D.; Gao, B. B.; Nan, H.; Li, X. J. Experimental study on Acoustic emission characteristics during deformation and failure processes of coal samples under different stress paths. Chin. J. Rock Mech. 2009, 28, 757–766. Chinese Journal.
(19) Su, C. D.; Xiong, Z. Q.; Zhai, X. X.; Gu, M. Analysis of deformation and strength characteristics of coal samples under the triaxial cyclic loading and unloading stress path. J. Min. Saf. Environ. 2014, 21, 456–461. Chinese Journal.
(20) Tang, Y.; Okubo, S.; Xu, J.; Peng, S. J. Study on the progressive failure characteristics of coal in uniaxial and triaxial compression conditions using 3D- Digital image correlation. Energies 2018, 11, No. 1215.
(21) Wang, K.; Du, F.; Zhang, X.; Wang, L.; Xin, C. P. Mechanical properties and permeability evolution in gas-bearing coal-rock combination body under triaxial conditions. Environ. Earth Sci. 2017, 76, No. 815.
(22) Zhu, G. A.; Dou, L. M.; Wang, C. B.; Ding, Z. W.; Feng, J. Z.; Xue, F. Experimental study of rock burst in coal samples under overstress and true-triaxial unloading through passive velocity tomography. Saf. Sci. 2019, 117, 388–403.
(23) Zhu, L. Z.; Sun, X.; Xie, H. P.; Zhang, R.; Zhang, Z. T.; Gao, M. Z.; Jia, Z. Q.; Xie, J. Deformation damage and energy evolution characteristics of coal at different depths. Rock Mech. Rock Eng. 2019, 52, 1491–1503.
(24) Bruning, T.; Karakus, M.; Nguyen, G. D.; Goodchild, D. Experimental study on the damage evolution of brittle rock under triaxial confinement with full circumferential strain control. Rock Mech. Rock Eng. 2018, 51, 3321–3341.