Evolution of Mechanical Properties and Acoustic Emission Characteristics in Uniaxial Compression: Raw Coal Simulation Using Briquette Coal Samples with Different Binders

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

ABSTRACT: Simulation of raw coal using briquette coal samples with similar mechanical properties and acoustic emission (AE) characteristics is quite instrumental in various analog models. Uniaxial compression with AE monitoring of raw coal and briquette coal samples with a 7% content of different types of binders was conducted using an RMT-150B electrohydraulic test bench. The compression process could be split into compaction, elastic, plastic (yield), and failure stages, with intrinsic AE features. Except for the MA group briquette coal samples, the AE signal average values of briquette coal samples always exceeded those of the raw ones. The maximal and minimal cumulative values of uniaxial compressive strength, peak strain, and AE signal were observed in briquette coal groups, containing 7% of coal tar or water, respectively. Measurements via the similarity method based on the Euclidean distance were used to construct space vectors, with the peak strength, peak strain, and elastic and deformation moduli of briquette and raw coal samples as characteristic values. The mechanical characteristics and deformation patterns of the briquette coal group with 7% rosin as a binder had the best compliance compared to those of raw coal samples, which makes them lucrative for further analog modeling of the raw coal behavior.

1. INTRODUCTION

Coal is a solid combustible organic rock produced by complex chemical reactions and phase transformations of petrified peat made from decaying plants that left their imprints in mud and clay as they hardened into shale stone.1 Since a coal body is a porous medium with a very developed pore structure, most scholars adopt the dual-pore medium model of the coal body. The pore structure characteristics of coal become more and more topical with the depletion of shallow coal mines and more intensive deep mining efforts, due to higher risks of rockburst, water inrush, roof area pressure, and goaf instability under deep mining conditions.2,3 A joint action of ground stresses, gas pressure, high karst water, and mining disturbance factors is a very complex dynamic phenomenon, involving coal and gas interaction. After the first recorded coal and gas outburst (CGO) accident in the Issac Colliery, Loire coalfield, France, in 1843, research efforts for identifying this process mechanism have started worldwide, yielding the gas effect, ground stress effect, and comprehensive effect hypotheses.4,5 Based on the comprehensive effect hypothesis, numerous scholars have carried out a series of CGO simulation experiments in the laboratory.6−11 Scholars have also carried out a series of studies on similar simulation materials for CGO. Shiping12 used carbon dioxide crystal ice, rosin, cement, and coal particles to make briquette coal samples. The adsorption performance of this similar material was quite different from the natural coal. Shi et al.13 used cement and gypsum as cementing materials and quartz sand and barite powder as aggregate similar materials and used regression analysis to determine the ratio of similar materials. Lin et al.14 found that coal:cement:gypsum = 1.5:1:1 through a similar ratio and the triaxial hydraulic fracturing effect was the best. Wang et al.15 found that the briquette coal samples with 5% sodium humate aqueous solution have good adsorption properties, which were close to those of raw coal samples. Zhang et al.16 used cement, gypsum, and activated carbon, sand, and water as the auxiliary materials and obtained a mixture of materials that had similar mechanical properties and adsorption and desorption characteristics to the outburst coal. Zhu et al.17 used cement, gypsum, and sodium humate to make briquette coal samples, and the strength and gas desorption performance of briquette coal sample were studied.

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We can know from the above research that different binders were added to the pulverized coal to enhance the strength of briquette coal samples and obtain their physical and mechanical characteristics closer to the raw coal. However, the evaluation of deformation, strength, and AE characteristics of briquette coal samples under uniaxial compression also needs further research efforts.

As a nondestructive evaluation method, the AE technology can monitor the process of instability, fracture, and evolution of rock materials. AE can directly reflect the morphological changes inside the rock and detect crack nucleation and propagation during the rock loading process. The energy of the deformed rock will generate AE signals in the form of stress waves, which reflect the microscopic failure characteristics of the rock. Therefore, by studying the rock’s AE signal, it is possible to infer the internal changes in the rock and specify the failure mechanism and fracture degree of the rock.

Some research results have also been made in the study of coal sample mechanics and AE. Su et al. carried out a systematic study on the deformation and AE characteristics of coal samples under uniaxial compression, conventional triaxial compression, and triaxial unloading confining pressure. Liu et al. established a uniaxial compression and rock damage model based on the AE characteristics, yielding the coal and rock damage evolution curves and equations. Cao et al. found that the number of AE count events could more accurately reflect the AE pattern during coal fracture than the signal energy parameter. Huang et al. studied the AE parameters of composite coal samples during rapid loading and unloading, using them to predict dynamic disasters under composite coal mining conditions. Backers and Prikryl et al. used AE to measure rock damage and predict the type of rock failure. Ranjith used the AE technology to record Australian black coal samples’ strain energy release rate under uniaxial compression after carbon dioxide saturation. Perera et al. carried out comprehensive unconfined compressive strength tests on Australian black coal and lignite coal samples and identified the crack propagation behavior using AE devices. Zhang et al. performed uniaxial compression tests with AE monitoring of granite and reported that the AE events closely correlated with the rock mass cracking process. Ai et al. and others conducted triaxial compression tests on coal samples and studied their AE spatial characteristics during the deformation and failure processes. Zuo et al. carried out AE tests on rock samples, coal samples, and coal-rock combination under uniaxial compression and reported essential differences in their failure patterns: with an increase in the load, the AE signals grew in rock samples, dropped in coal samples, and initially grew with a further drop in coal-rock samples. Shu et al. conducted AE tests on raw coal, briquette coal, and raw coal-briquette coal combination specimens under uniaxial compression. It was concluded that the failure of raw coal was mainly a weak-face shear failure, while briquette coal samples were mainly damaged by shear and pulverization. Liu et al. found that as the temperature increased, the strength, elastic modulus, Poisson’s ratio, and AE parameters of the coal body dropped. Meng et al. found that the AE signal and mechanical characteristics of briquette coal samples with a 20% cement content are closest to those of raw coal samples.

In the comparative study of mechanical characteristics of raw coal and briquette coal samples, many research results have also been obtained. Jasinge et al. found that the briquette coal samples with a 4% cement content and a 50% water content had the closest mechanical properties to the those of natural coal samples under uniaxial compression test conditions. Xu et al. carried out a three-axial servo seepage test on raw coal and cement-containing briquette coal samples. They reported that with an increase in the cement content, the peak principal stress of briquette coal samples grew, while their elastic modulus exhibited an increasing trend of the positive exponential function. Yin et al. carried out triaxial compression tests with two types of coal samples, and the results showed that the elastic moduli and Poisson’s ratios of raw coal samples significantly exceeded those of briquette ones. However, the latter samples showed larger deformations than the former ones. Zhao et al. carried out a triaxial experiment on briquette coal samples, and the AE characteristics and damage equation were derived. Pang et al. carried out uniaxial and triaxial compression tests on briquette coal samples with different particle sizes and found that their mechanical parameters improved with decreasing particle size.

The above survey implies that the strength and deformation characteristics of raw coal and briquette coal samples under uniaxial and triaxial loading conditions as well as their AE characteristics can be obtained using the available test methods and models. However, most of CGO simulation tests carried out in the laboratory used briquette coal samples with cement and other binders added to improve their strength. To the best of the authors’ knowledge, there are few studies on the deformation, strength, and AE characteristics of briquette coal samples containing different types of binders.

Therefore, carrying out uniaxial compression AE experiments on raw coal and briquette coal samples with different binders has an important practical application value, further revealing the role of CGO under laboratory conditions.

2. COAL SAMPLE PREPARATION AND TEST METHODS

2.1. Preparation of Raw Coal Samples. Coal samples were collected from the 11,110 fully mechanized mining face of the No. 13 Coal Mine (owned by the Pingdingshan Tian’an Coal Industry Co., Ltd.) located in the Xiangcheng County, Xuchang, Henan Province of China. The collected coal samples were wrapped in a plastic film and transported to the laboratory. The coal core was drilled by parallel bedding, cut, and smoothed into standard coal samples with a height of 100 mm and a diameter of 50 mm. Their edges were ground and polished to allow for consistent contact with the test platens. The accuracy of the processed samples met the ISRM suggested method (ISRM 2007). A total of 14 standard coal samples was processed. Their apparent natural density ranged from 1305 and 1448 kg/m³. Figure 1 shows the raw coal samples obtained from the lump coal core.

Figure 1. A view of raw coal samples under study.
samples. Briquette coal samples of about 2000 g were obtained from crushed raw coal particles. After drying for 6 h, several coal sample sieves with different specifications were used for sieving. Then, their weights were adjusted to obtain the required ratios of sieved raw coal particle sizes, as shown in Table 1.

### Table 1. Groups of Briquette Coal Samples and Ratios of Various Particle Sizes and Binders

| group title | coal powder(%) | binder additives(%) |
|-------------|----------------|---------------------|
|             | 0~0.3 mm | 0.3~1 mm | 1~3 mm | water | cement | rosin | coal tar |
| MA          | 32.5     | 41.7     | 25.8   | 7      | 0      | 0      | 0        |
| MD          | 32.5     | 41.7     | 25.8   | 0      | 0      | 7      | 0        |
| ME          | 32.5     | 41.7     | 25.8   | 8.7    | 7      | 0      | 0        |
| MJ          | 32.5     | 41.7     | 25.8   | 0      | 0      | 0      | 7        |

This table shows the particle size distribution of the raw coal after screening, which was used to determine the respective ratios in briquette coal samples. The MA group represents briquette coal samples containing 7% water; MD group represents briquette coal samples containing 7% rosin; ME group represents briquette coal samples containing 7% cement and 8.7% water; and MJ group represents briquette coal samples containing 7% coal tar.

According to the ratios and particle sizes of ingredients of briquette coal samples listed in Table 1, the corresponding groups of briquette coal samples were prepared separately. The ingredients were mixed and placed into a forming mold. Using a test machine with a 200 t axial load capacity, the molding pressure was stabilized at 30 MPa for 30 min and then demolding was applied to produce a standard coal sample with a height of 100 mm and a diameter of 50 mm. The additives (water, cement, rosin, and coal tar) used as binders for briquette coal samples are shown in Figure 2. The devices and semi-products used for the preparation of briquette coal samples are shown in Figure 3.

#### 2.3. Experimental Method.

The uniaxial compression tests were carried out using an RMT-150B electrohydraulic servo rock test system, as shown in Figure 4.

The axial load was measured using a 100 kN force sensor, with a load accuracy of $1.0 \times 10^{-3}$ kN. The axial deformation was measured using a 5.0 mm displacement sensor, with an accuracy of $1.0 \times 10^{-3}$ mm. The displacement-controlled lading mode was adopted, with a loading rate of 0.005 mm/s. During the coal sample’s mechanical loading, a DS-5 type 8-channel AE system was used for online AE monitoring. The AE sensor was installed in the middle of the coal base, and the sensor was attached to the base using adhesive tape. The sampling frequency was set to 3 MHz, the RS-2A AE sensor frequency was 150 kHz, and the threshold value for mechanical and ambient noise was set at 45 dB. The data acquisition system recorded a series of parameters, such as AE amplitude, count, and energy, on a real-time scale.

#### 3. RESULTS AND ANALYSIS

##### 3.1. Deformation Characteristics of Coal Samples.

Table 2 lists the uniaxial compression test results of raw coal and briquette coal samples with different binders. In Table 2, $R_c$ is the uniaxial compressive strength, MPa; $E_T$ is the elastic modulus, GPa; $E_C$ is the deformation modulus, GPa; $\varepsilon$ is the peak strain of the sample; $\sum A$ is the AE cumulative amplitude, $\sum N$ is the cumulative count, times/s; and $\sum E$ is the cumulative energy, mv-ms.

Figure 5 shows the stress–strain curves of the coal samples recorded during the uniaxial compression test. They can be subdivided into the following four stages: compaction, elastic, plastic (yield), and failure. At the first compaction stage, the coal sample’s elastic modulus increases with the axial stress. The pores and microcracks in the coal sample are closed, and its volume is gradually reduced. At the second elastic stage, the stress–strain relationship is linear and obeys the conventional Hook’s law. At the third plastic (or yield) stage, the coal sample reaches its yield strength limit, the coal sample ingredients with lower internal strength are damaged, and the stress–strain curve deviates from a straight line. This marks the initial damage development process of the coal sample. At the final failure stage,
the axial stresses in the coal sample reached its limiting load-bearing capacity, and macroscopic slippage occurs in the coal sample along a certain fracture surface. The tensile stresses in the longitudinal direction are produced by the internal friction, and the coal sample rapidly loses its overall bearing capacity.

The characteristics of the stress—strain curves of raw coal and briquette coal samples during uniaxial compression are different. The latter and former ones remain linear before the peak strength is reached or during the total loading process, respectively. However, there was also secondary damage in some raw coal samples, which correlated with their heterogeneity. As shown in Figure 5a, the raw coal’s performance at the plastic (yield) was not obvious. After reaching the peak stress, most raw coal samples, for example, MB6 and MB7, exhibited a stress drop, while MB3 maintained its integrity and brittleness until final fracture. The analysis of the raw coal sample’s stress—strain curves, strength, elastic modulus, and deformation modulus revealed that their mechanical characteristics were relatively discrete. This can be related to the nature of the raw coal samples, whose mechanical properties are strongly affected by pores, cracks, and the development of coal seam joints.

It can be seen from Figure 5b that the MA group of briquette coal samples (with 7% of water) exhibited good linear characteristics. Their compaction and yield stages were not strongly manifested, there was a short stress yield plateau near the peak stress, and the stress drop level and duration after the peak were lower than those of raw coal samples. This can be attributed to the low strength and plastic characteristics of the MA group briquette coal samples.

It can be observed from Figure 5c that the step-dropping phenomenon of the MD group of briquette coal samples shows high similarity with the deformation characteristics of raw coal samples. The MD group’s plastic (yield) stage of the uniaxial compression deformation process is not pronounced. After the vertical stress reaches its peak stress, a stepped stress drop appears. The MD-1, MD-2, and MD-3 briquette coal samples also exhibit this stress-dropping pattern, which is repeatedly observed after the peak stress. The MD group briquette coal samples show a larger peak deformation than the raw coal samples, and their elastic modulus and deformation are smaller than those of the raw coal. Still, the MD group samples have larger peak strength and elastic modulus values than the MA group ones. Due to the addition of rosin with relatively high cohesiveness in the MD group of briquette coal samples, their stresses and strains under uniaxial compression are not very discrete, which is in line with the homogeneity characteristics of briquette coal samples.

From Figure 5d, it can be concluded that the uniaxial compression deformation characteristics of the ME group are roughly the same, showing linear characteristics as a whole. The compaction stage of this group’s briquette coal samples is not obvious. Their plastic (yield) and failure stages have larger durations, and there is an obvious peak stress plateau during the uniaxial compression. For example, the briquette coal sample ME-3 had an obvious peak stress plateau near the peak stress. After the latter is reached, the stress gradually drops as the compression deformation increases. After the peak stress, the ME group briquette coal samples did not show a stepped drop. The average peak strain of the briquette coal samples of the ME group was 8.24, exceeding by 1.47 and 1.68 times the average values of MA and MD groups, respectively. This indicates that the deformation of ME briquette coal samples is relatively large, and their plastic characteristics are high.

From Figure 5e, it can be concluded that the compaction and yield stages of the MJ group briquette coal samples during uniaxial compression were not obvious, and they contained an obvious peak stress plateau. Taking the MJ-4 briquette coal sample as an example, an obvious peak stress plateau appeared at the peak stress, and then a stress drop was observed. After the peak stress, the stress drop rate was reduced, indicating the coal sample’s brittleness reduction and plasticity increase. The peak strain of briquette coal samples of the MJ group was 11.65, exceeding by 2.08, 2.37, and 1.41 times the peak strains of MA, MD, and ME groups, respectively. The deformation of the briquette coal samples in the MJ group was relatively large due to the coal tar binder in this group of briquette coal samples.

Judging from the deformation characteristics of the above groups of briquette coal samples, it is concluded that they underwent plastic failure. Among them, the MD group damage characteristics were similar to those of the raw coal samples. During the failure process, a stepped drop of stress appeared, showing a brittle failure pattern.

3.2. Strength Characteristics of Coal Samples. The average uniaxial compressive strength of raw coal samples was 4.34 MPa, while those of MA, MD, ME, and MJ groups of briquette coal samples were 0.24, 2.99, 1.18, and 3.50 MPa, respectively. It can be seen that the uniaxial compressive strength of briquette coal samples containing coal tar in the MJ group was closest to that of raw coal samples. The uniaxial compression strength of other briquette coal samples showed relatively good homogeneity, and their degree of dispersion was relatively small. The uniaxial compressive strength distribution of raw coal and briquette coal samples is shown in Figure 6.

3.3. AE Characteristics of Coal Samples. The coal sample’s damage by external loading during deformation and failure manifests itself by a series of AE signals characterized by
several AE parameters. In this work, the AE amplitude (A, \( \sum A \)), ring count (N, \( \sum N \)), and energy (E, \( \sum E \)) are used to analyze the AE signals of raw coal and briquette coal samples under uniaxial compression during deformation and failure. The amplitude of AE (A, \( \sum A \)) is the maximum amplitude of the voltage signal released by the coal sample during the load damage event. The AE ring count (N, \( \sum N \)) reflects the frequency of the AE event. The AE energy (E, \( \sum E \)) is the relative energy released by the AE event. Thus, the AE amplitude, count, and energy reflect the AE events’ intensity and fluency during the coal sample’s deformation and fracture.

Figures 7–11 show the monitoring results of AE characteristics (amplitude, ring count, and energy) of raw coal and briquette coal samples during uniaxial compression and failure. For brevity sake, the AE monitoring results of a single typical coal sample are given per each group.

It can be seen from Figure 7 that the AE event’s energy values of the raw coal sample MB1 at the compaction and plastic phases are relatively low and the amplitude, count, and energy of the AE signal are relatively small. This is because the raw coal sample body has a certain degree of hardness and cannot form new microcracks under lower stress levels. Still, the initially open structural surface or original microcracks inside the rock are closed. A relative slippage occurs during the closure process and between closed cracks, and the occlusal failure between the structural surface will also cause relatively low-energy AE events.

When the stress continues to increase and enters the plastic (yield) stage, the coal sample undergoes internal structural damage. The internal microcracks begin to appear. At this stage, the AE events begin to manifest themselves more actively. The AE count and energy started to increase significantly, reaching \( 6.35 \times 10^3 \) times/s and \( 2.38 \times 10^4 \) mv-ms, respectively, which can be used as a precursor to determine the failure of coal samples. When stress was continuously applied to the coal sample until the peak strength was reached, the coal sample entered the failure stage. New microcracks were generated inside the coal sample that then aggregated and propagated, forming a macroscopic fracture surface. The fracture stage’s AE activity was relatively active, and the instantaneous amplitude, count, and energy of the AE during the destruction reached the peak value of the failure stage. Subsequently, the coal sample bulk experienced overall slippage along the macroscopic fracture surface. During the slippage process, the friction force produced hoop tensile stress, which resulted in a tensile fracture. As the deformation increased, a stepped stress drop was observed. A relatively intensive AE event occurred before each stress drop, but the amplitude, count, and absolute value of the AE energy decreased with the stress drop.

The uniaxial compression AE characteristics of the MA-2 briquette coal sample are shown in Figure 8: its compaction and plastic (yield) stage are not obvious. During the compaction and elastic phases of the briquette coal sample, smaller AE signals were observed due to the closure of microcracks inside the sample, as well as a certain number of AE events caused by the sliding friction between particles. At this stage, the amplitude of the AE signal, the cumulative value of counts and energy, and

### Table 2. Uniaxial Compression Test Results for Various Coal Samples

| number | \( R_c \)/MPa | \( E_c \)/Gpa | \( E_c \)/Gpa | \( \epsilon \) | \( \sum A/10^6 \) | \( \sum N/10^5 \) | \( \sum E/10^5 \) |
|--------|--------------|---------------|---------------|------------|----------------|----------------|----------------|
| MB1    | 4.82         | 1.46          | 1.08          | 4.48       | 2.01           | 7.69           | 9.07           |
| MB3    | 6.23         | 1.70          | 1.43          | 4.36       | 1.52           | 4.88           | 6.16           |
| MB4    | 2.36         | 0.87          | 0.64          | 3.68       | 1.53           | 4.11           | 4.73           |
| MB6    | 3.93         | 1.75          | 1.32          | 2.96       | 0.97           | 1.54           | 1.97           |
| MB7    | 3.94         | 1.31          | 1.13          | 3.49       | 2.72           | 6.82           | 11.86          |
| MH3    | 4.76         | 0.96          | 0.97          | 4.93       | 0.47           | 3.38           | 3.53           |
| average| 4.34         | 1.34          | 1.10          | 3.98       | 1.54           | 4.74           | 6.22           |
| MA-1   | 0.19         | 0.04          | 0.06          | 4.65       | 0.004          | 0.045          | 0.016          |
| MA-2   | 0.27         | 0.05          | 0.05          | 6.34       | 0.049          | 0.054          | 0.026          |
| MA-3   | 0.23         | 0.05          | 0.05          | 5.78       | 0.041          | 0.050          | 0.024          |
| MA-4   | 0.23         | 0.05          | 0.06          | 5.22       | 0.047          | 0.051          | 0.030          |
| MA-5   | 0.27         | 0.05          | 0.05          | 5.98       | 0.11           | 0.075          | 0.039          |
| average| 0.24         | 0.048         | 0.05          | 5.59       | 0.25           | 0.06           | 0.03           |
| MD-1   | 2.79         | 0.79          | 0.53          | 4.35       | 5.81           | 16.9           | 67.58          |
| MD-2   | 2.87         | 0.84          | 0.61          | 4.44       | 0.80           | 3.77           | 2.89           |
| MD-3   | 3.28         | 0.88          | 0.61          | 4.46       | 5.19           | 8.41           | 14.32          |
| MD-4   | 3.09         | 0.76          | 0.62          | 4.59       | 5.55           | 10.36          | 42.88          |
| MD-5   | 2.94         | 0.72          | 0.44          | 6.73       | 8.85           | 13.08          | 90.04          |
| average| 2.99         | 0.80          | 0.56          | 4.91       | 5.24           | 10.50          | 43.54          |
| ME-1   | 1.17         | 0.20          | 0.23          | 7.63       | 7.58           | 4.50           | 60.63          |
| ME-2   | 1.26         | 0.20          | 0.22          | 7.86       | 7.11           | 4.52           | 61.20          |
| ME-3   | 1.12         | 0.17          | 0.15          | 9.34       | 10.47          | 5.61           | 105.44         |
| ME-4   | 1.21         | 0.18          | 0.19          | 9.13       | 9.22           | 4.52           | 80.83          |
| ME-5   | 1.12         | 0.2           | 0.22          | 7.25       | 8.39           | 5.55           | 84.37          |
| average| 1.18         | 0.19          | 0.20          | 8.24       | 8.55           | 4.94           | 78.49          |
| MJ-2   | 4.24         | 0.61          | 0.58          | 8.51       | 14.16          | 12.10          | 75.76          |
| MJ-3   | 3.86         | 0.60          | 0.53          | 9.40       | 15.61          | 8.07           | 71.01          |
| MJ-4   | 2.87         | 0.40          | 0.42          | 12.03      | 20.13          | 13.62          | 171.51         |
| MJ-6   | 2.91         | 0.28          | 0.31          | 15.19      | 17.85          | 10.50          | 110.74         |
| MJ-13  | 3.63         | 0.36          | 0.33          | 13.10      | 19.60          | 13.00          | 104.20         |
| average| 3.50         | 0.45          | 0.43          | 11.65      | 17.29          | 10.62          | 101.45         |
time showed roughly a linear relationship, and the slope of the curve was relatively shallow. When the stress continued to increase and entered the yield stage, the internal damage of the briquette coal sample began to occur. The AE emission events at this stage became active, the amplitude, counts, and energy of the AE increased significantly, and AE events became active. This stage can be used as a precursor for judging the coal sample damage. When the stress approached the peak strength and
entered the failure stage of the coal sample, new microcracks started to nucleate and propagate, resulting in a macroscopic fracture and gradual damage of the load-bearing structure. After reaching the peak strength, the yield stress plateau appeared and then the briquette coal sample bulk slippage occurred along a certain macroscopic fracture surface. In the process of slippage/sliding, hoop tensile stresses were generated due to friction, which led to tensile rupture. The deformation of the briquette coal sample in this process was also relatively large and was mainly plastic deformation. As the stress dropped, the AE signal continued to be generated until the stress dropped completely and the AE signal disappeared.

As shown in Figure 9, which shows the AE characteristics of the MD-1 briquette coal sample during the uniaxial compression process, there was a smaller number of AE events at the compaction stage of the initial coal sample loading. At this time, the energy of the AE signal is lower. When the stress continues to increase and enters the elastic phase, the amplitude and count of the AE signal increase. The AE energy value is still not high, and

![Figure 6](image)

Figure 6. Test result of uniaxial compression strength of coal samples.

![Figure 7](image)

Figure 7. Monitoring results of AE characteristics of raw coal sample MB1 under uniaxial compression: (a) stress and amplitude; (b) stress and counts; and (c) stress and energy.
the yield stage of the MD-1 briquette coal sample is not obvious. Before the briquette coal sample reaches the peak stress, the AE count and energy events become active and the values of the AE count and energy increase significantly. This can be considered as a precursor to the failure of the MD-1 briquette coal sample. The latter entered the stage of failure, and macroscopic slippage occurred along a certain fracture surface. During the slippage, a hoop tensile stress would be generated due to friction, which caused a tensile fracture. After reaching the peak stress, the briquette coal sample will show multiple stress drops. When the briquette coal sample undergoes a stress drop, it also generates a relatively large energy. The count and energy values of the AE signal at the drop point are lower than the value corresponding to the peak intensity.

The uniaxial compression AE characteristics of ME-3 and MJ-3 briquette coal samples have certain similarities. It can be seen from Figure 10 that the compaction stage of the ME-3 briquette coal sample is not obvious. At its compaction and elastic stages, the AE amplitude, count, and energy begin to become active. The reason why the AE signal is active is that the microcracks inside the briquette coal sample are closed, the coal particles will slip between the closing process and the closed cracks, and the slip failure will cause a certain degree of AE events. When the stress continues to increase and enters the yield stage of the coal sample, the AE energy begins to concentrate, and the precursor to the failure stage of the coal sample is not obvious. A certain yield stress platform will appear near the peak stress of the coal sample. Then, as the stress gradually increases, the stress−time relationship curve shows a drop. During the stress drop, the briquette coal sample will be damaged along a certain macroscopic fracture surface. Therefore, a certain amount of energy with a relatively high degree of concentration would be observed, and energy peaks would appear. As the stress gradually drops, the energy value gradually decreases.

**Figure 8.** Monitoring results of AE characteristics of the MA-2 briquette coal sample under uniaxial compression: (a) stress and amplitude; (b) stress and counts; and (c) stress and energy.
4. DISCUSSION

4.1. Discussion of Deformation and Failure Characteristics of Coal Samples. It can be seen from the uniaxial compression fracture morphology of raw coal and briquette coal samples shown in Figure 12 that shapes of all samples after uniaxial compression failure can be approximately regarded as a split failure parallel to the coal sample axis. One or several main cracks are observed first, and before other cracks are fully propagated, the entire coal sample breaks into multiple flake-like fragments. At the same time, there is a shear failure surface inside the coal sample. It can be concluded that the uniaxial compression failure of all coal samples simultaneously has a double fracture surface of tension and shear.

The peak strains of MA, MD, ME, and MJ group samples were 1.40, 1.23, 2.07, and 2.93 times those of the raw coal samples, and their elastic moduli were 0.04, 0.60, 0.14, and 0.34 times those of the raw coal samples. Their deformation moduli were 0.05, 0.51, 0.18, and 0.39 times those of the raw coal samples. The result shows that the elastic and deformation moduli of raw coal samples under uniaxial compression significantly exceeded those of briquette coal samples, while their peak strain values exhibited a reverse trend.

Judging from the failure mode of the coal samples’ uniaxial compression, the deformation of the briquette coal samples of the MJ group is more severe and the axial deformation is also relatively large. This is related to the nature of coal tar added to the MJ group’s coal samples, which provides better cohesion between coal particles, thereby increasing the sample strength. The uniaxial compressive strength of the MJ group is greater than those of MA, MD, and ME groups. The uniaxial compressive strength of the MA group’s briquette coal samples is relatively small, which is related to the absence of any binder. The elastic and deformation moduli are 0.04 and 0.05 times of the raw coal samples, respectively.

In terms of the stress–strain curves of the raw coal and briquette coal samples, the evolution trend of MD group briquette coal samples is most similar to that of raw coal samples: both exhibit the stepped stress drop phenomenon. Figure 12c shows several large cracks in the MD group briquette coal samples. They also feature a shear fracture surface, which is also similar to the damage pattern of raw coal samples.

Figure 9. Monitoring results of AE characteristics of the MD-1 briquette coal sample under uniaxial compression: (a) stress and amplitude; (b) stress and counts; and (c) stress and energy.
4.2. AE Characteristics of Coal Samples. In the process of uniaxial compression of raw coal and briquette coal samples, the compaction, elastic, plastic (yield), and failure stages are always accompanied by intrinsic AE signals. The AE emission signals have a close correlation with the final (failure) stage behavior. The AE amplitude, count, and energy values of the briquette coal samples of MD, ME, and MJ groups are higher than those of raw coal samples. The reason is that these groups of briquette coal samples show relatively high plastic deformation characteristics during the uniaxial compression failure process and their strength is improved by the addition of different types of binders. Taking the MD group briquette coal samples as an example, their AE amplitude, count, and energy are strongly manifested at the compaction and elastic phases. When the stress reaches the yield strength, the amplitude, count, and energy of the AE signal are all close to their peak values, which can be used as a precursor to the failure of briquette coal samples. At each stress drop in the MD group of briquette coal samples, a certain peak AE signal will be generated but its value will drop, compared to the previous stress drop case. At the failure stage of briquette coal samples, a certain number of AE events will also occur and the AE signal will decrease as the stress gradually drops.

The AE energy value of the briquette coal samples of ME and MJ groups will increase during the stress drop process. This shows that both groups of briquette coal samples produce a relatively concentrated energy at the failure stage. Then, as the stress gradually drops, their AE energy values start to drop. It can be seen from Table 2 that the AE signal’s cumulative amplitude and energy values of the MJ group briquette coal samples are larger than those of the other briquette coal samples. Simultaneously, the peak intensities of the MJ group are also relatively large. This shows that among the briquette coal samples with 7% rosin, water, cement, and coal tar as binders, the uniaxial compressive strength and AE signal values of the MJ group briquette coal samples containing 7% coal tar are the largest.

The deformation and failure characteristics of coal samples can be judged from the AE signals, but the AE signals can only represent the damage characteristics of coal to a certain extent.
The similarity between several groups of briquette coal samples and raw coal samples needs to be judged and explained using the similarity criteria.

4.3. Quantitative Evaluation of Mechanical Characteristics of Coal Samples. To further evaluate the mechanical properties of raw coal samples and briquette coal samples with the same content of different types of binders, the four parameters of peak strength, peak strain, elastic modulus, and deformation modulus of raw coal and briquette coal samples under uniaxial compression were selected for a comparative study. By comparing the data listed in Table 2, it can be found intuitively that the peak strength of the briquette coal samples of the MJ group is closest to that of raw coal samples, while the peak strain of the MD group is closest to the raw coal samples. Therefore, it is hard to determine which type of briquette coal samples is closest to the raw coal samples, unless a strength- or strain-based criterion is specified. Therefore, this study adopted the similarity measurement method based on the Euclidean distance, which is evaluated via multiple indices of uniaxial compression to identify the briquette coal sample type that has the mechanical properties closest to those of raw coal.

The principle of the similarity measurement method based on the Euclidean distance is based on two space vectors $x$ and $y$

$$x = (x_1, x_2, x_3, \ldots, x_k)$$

$$y = (y_1, y_2, y_3, \ldots, y_k)$$

(1)

The Euclidean geometric distance is calculated using the $d(x, y)$ space vector as follows

$$d(x, y) = \left[ \sum_{n=1}^{m} (x_k - y_k)^2 \right]^{1/2}$$

(2)

Formula 2 determines the similarity of the two space vectors given in formula 1. The smaller the value, the greater the similarity between the two space vectors and vice versa. In this work, the peak strength, peak strain, elastic modulus, and
corresponding to the peak strength (10 Gpa); and samples with 7% water is of briquette coal samples can be obtained.

The eigenvalue space vector of the raw coal samples is

Let \( A \) denote the space vector of raw coal samples; then, the eigenvalue space vector of the raw coal samples is

\[
A = \{ \sigma_{\text{max}}, \varepsilon_{\text{max}}, E_T, E_C, \}
\]

where \( \sigma_{\text{max}} \) is the peak strength (MPa), \( \varepsilon_{\text{max}} \) is the axial strain corresponding to the peak strength \((10^{-3})\); \( E_T \) is the elastic modulus (Gpa); and \( E_C \) is the deformation modulus (Gpa). To simplify expression 3, we will introduce coefficients \( a_i \) to \( a_4 \)

\[
\begin{align*}
    a_1 &= \sigma_{\text{max}} \\
    a_2 &= \varepsilon_{\text{max}} \\
    a_3 &= E_T \\
    a_4 &= E_C
\end{align*}
\]

Let \( A \) denote the space vector of raw coal samples; then, the eigenvalue space vector of the raw coal samples is

\[
A = \{ a_1, a_2, a_3, a_4 \}
\]  

At the same time, similar considerations are made for briquette coal samples with the same content of different types of binders, and the space vector of the characteristic values of briquette coal samples can be obtained.

The eigenvalue space vector of the MA group briquette coal samples with 7% water is

\[
B = \{ b_1, b_2, b_3, b_4 \}
\]  

The eigenvalue space vector of the MD group briquette coal samples with 7% rosin is

\[
C = \{ c_1, c_2, c_3, c_4 \}
\]  

The eigenvalue space vector of the ME group briquette coal samples with 7% cement is

\[
D = \{ d_1, d_2, d_3, d_4 \}
\]  

The eigenvalue space vector of the MJ group briquette coal samples with 7% coal tar is

\[
E = \{ e_1, e_2, e_3, e_4 \}
\]

To get dimensionless parameters, the normalization method is applied to the processed experimental data, taking the characteristic value of the raw coal sample as the base. The corresponding characteristic values of the other briquette coal samples containing different types of binders are divided by the characteristic values of the raw coal samples. Combining data in Table 2, we can reduce formulas 5–9 to the following system

\[
A = (1.00, 1.00, 1.00, 1.00)
\]

\[
B = (0.05, 1.40, 0.04, 0.05)
\]

\[
C = (0.69, 1.23, 0.60, 0.51)
\]

\[
D = (0.28, 2.08, 0.14, 0.19)
\]

\[
E = (0.81, 2.93, 0.34, 0.39)
\]

Using formula 3, the Euclidean distances of the eigenvalue space vectors for the raw coal and briquette coal samples of MD, ME, and MJ groups are calculated as

\[
d(A, B) = 1.70
\]

\[
d(A, C) = 0.74
\]

\[
d(A, D) = 1.75
\]

\[
d(A, E) = 2.14
\]

Comparing the calculation results of formulas 11–14, we get

\[
d(A, C) < d(A, B) < d(A, D) < d(A, E)
\]

The smaller the value of \( d(x, y) \), the greater the similarity between the two space vectors. The value of \( d(A, C) \) is the smallest, that is, the MD group of briquette coal samples with 7% rosin content have the closest mechanical properties to the raw coal.

5. CONCLUSIONS

This study carried out uniaxial compression tests and AE monitoring of raw coal and briquette coal samples with different types of binders. Their deformation, strength, and AE characteristics were analyzed and studied. The following conclusions were drawn.

(1) The uniaxial compression of raw coal and briquette coal samples can be subdivided into compaction, elastic, plastic (yield), and failure stages, but the compaction and elastic stages of briquette coal samples are not obvious. Except for the MD group briquette coal samples, the stress–strain curves of other briquette coal samples contain a yield stress plateau, which is related to their strong plasticity.

(2) Under uniaxial compression, the AE signal of briquette coal samples is more obvious than that of raw coal samples, except for the MA group briquette coal sample. For briquette coal samples with 7% content of different binders, the mechanical properties and AE signal characteristics during uniaxial compression are also quite different. Among the briquette coal samples tested in this work, the MJ group briquette coal samples containing 7% coal tar have the largest uniaxial compressive strength and the axial strain at the peak strength is also the largest; their AE cumulative amplitude, count, and energy values were also the largest. The MA group briquette coal samples with 7% of water had the worst strength and strain values. It can be seen that the type of binder has a greater impact on the mechanical and AE characteristics of briquette coal samples.
The similarity measurement method based on the Euclidean distance was used to quantitatively analyze and compare briquette coal and raw coal samples’ mechanical parameters under uniaxial compression. The physical and mechanical properties of the MD group briquette coal samples containing 7% rosin are closest to those of the raw coal samples. At the same time, the MD group briquette coal samples have a certain similarity with the failure characteristics of the raw coal samples due to the stepped stress drop phenomenon during uniaxial compression. Therefore, the MD group briquette coal samples can be used as analog materials to simulate raw coal.

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