Research Article

Loading Rate and Bedding Plane Coupled Effect Study on Coal Failure under Uniaxial Compression: Acoustic Emissions and Energy Dissipation Analysis

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The mechanical behavior of coal is significantly influenced by the loading rate and bedding plane. In this paper, the uniaxial compression tests at different loading rates were conducted on coal specimens with vertical bedding (CSVB) and coal specimens with parallel bedding (CSPB), which were prepared by the coal with bursting liability from the Ordos deep mining areas, China. The results show that the uniaxial compressive strengths of CSVB and CSPB are positively correlated with the loading rate. The peak values of acoustic emission (AE) counts and accumulated absolute AE energy of CSVB and CSPB increase with the loading rate, and the AE parameters of CSVB are larger than those of CSPB. The variation rules of input energy density and elastic energy density are similar for CSVB and CSPB, but the variation rules of dissipated energy density in stage IV are different. As the axial load increases, the energy storage rate and energy dissipation rate of both coal specimen types increase and decrease, respectively. The bedding planes of coal and the loading conditions in the field should be fully considered when identifying the bursting liability of coal and forecasting coal burst. This study can provide a reference for coal burst warning and prevention under similar geological conditions in Ordos deep mining areas.

1. Introduction

In the last decades, coal plays an important role as China’s main energy source [1–3], and according to the 2020 Annual report on the development of the coal industry in China, 59.7% of raw coal is produced in Western China [4]. However, some mining hazards, such as severe roof fall, instability of coal pillars, and coal burst, occur frequently in Ordos deep mining areas in Western China [5, 6], which severely restricts safe and sustainable coal production. Moreover, the coal burst is greatly influenced by the mining speed and the weak structural planes in coal mass [7–9], as different mining speeds result in different loading rates [10]. Therefore, to better predict and control the coal burst, and consequently, rock mass instabilities, it is necessary to study the effects of loading rate and bedding plane on the mechanical behavior of coal.

The effect of loading rate on rock mechanical behavior has taken some attention from the scientific community [11–15]. Zhao et al. [16] studied the effect of loading rate on coal strength by three-dimensional reconstruction modelling technology and proposed an empirical relationship between coal strength and loading rate. Li et al. [17] found out that coal’s uniaxial compressive strength (UCS)
increases with the loading rate increasing, but from a certain critical loading rate value, the opposite behavior is observed, and given these results, a coal bursting liability method is proposed. Mahanta et al. [18] conducted a series of UCS tests on shales with different loading rates and found that the elastic modulus, UCS, and tensile strength increase with the loading rate increasing, and an empirical formula was obtained to evaluate the shales mechanical properties. It is accepted that the phenomenon of acoustic emissions (AE) accompanies rock progressive cracking and failure [19–24]. Using AE technique, Li et al. [25] found that with the loading rate increasing, the peak value of AE hits of coal specimens increases, while the cumulative AE counts decreases. Under marble specimens, Li et al. [26] tested nine different loading rates and found that the absorbed energy increases as the loading rate increases.

Knowing that coal is a rock type with bedding planes, previous researches have proved that the bedding angle plays an important role in rock strength, AE, and energy characteristics [27–32]. Moreover, Kossovich et al. [33] found that the UCS and elastic modulus of coal specimens have significant anisotropy, which is related to the bedding angle. Song et al. [34] found that a U-shaped distribution of UCS with anisotropy angle, the maximum intensity was observed on coal specimens with vertical bedding (CSVB), and the second-largest value was observed on coal specimens with parallel bedding (CSPB). Under UCS tests, Liu et al. [35] found that the bedding angle significantly can affect AE spatial distribution. Wang et al. [36] analyzed the effect of shale bedding angle on AE parameters, and the cracking modes were classified based on AE characteristics. Hou et al. [37] studied the bedding angle effect on shale energy characteristics and showed that the parallel bedding specimens have higher energy release compared with the vertical bedding specimens.

The above studies have achieved fruitful results about loading rate and bedding angle influence on coal and rock strength, AE, and energy characteristics. However, considering the coupled effects of loading rate and bedding plane on mechanical properties, AE and energy dissipation characteristics of coal with bursting liability were barely mentioned. In the current research, uniaxial compression tests with different loading rates were conducted on both CSVB and CSPB, collected from Hongqinghe coal mine in Ordos deep mining areas. The loading rate effect on UCS and elastic modulus of both coal specimen types were analyzed, and the AE and energy dissipation characteristics during the failure process at different loading rates were studied. The results can provide a reference for coal burst hazard monitoring and prevention under the similar geological conditions in this mining area.

2. Materials and Methods

2.1. Specimen Preparation. The coal specimens for the test were collected from the working face of the Hongqinghe coal mine in the Xinjie mining area, Ordos, China. The location of the Hongqinghe coal mine is shown in Figure 1. According to identifying the bursting liability of coal, and coal burst in the roadway of the Hongqinghe coal mine, the coal seam has been identified as having a strong bursting liability [5, 38].

According to the ISRM suggested methods [39], the collected coal blocks (Figure 1) were prepared into standard cylinders with a 50 mm diameter and 100 mm height along the vertical and parallel bedding planes, as shown in Figures 2(a) and 2(b), respectively.

2.2. Experimental Method. The testing apparatus and monitoring system are shown in Figure 3. In order to analyze the mechanical response characteristics of coal specimens at different magnitude strain rates (10^{-5}, 10^{-4}, 10^{-3} s^{-1}). CSVB and CSPB were tested under uniaxial compression at loading rates of 0.2, 0.6, 3.0, and 6.0 mm/min, by using the MTS e45.305 electronic universal loading system, with a maximum working load of 300 kN (±0.3%) and a pace range of 0.001–254 mm/min. The loading methods are presented in Figure 4(a). It is worth mentioning that 3 CSVB and CSPB were tested for each loading rate, and the different loading rates were controlled by the movement speed of the load frame.

Simultaneously, a PCI-Express 8 multichannel AE system was used to synchronously monitor and analyze the AE waveform and related parameters during the loading
of coal specimens in real-time. In addition, 6 nano 30 miniature contact sensors with a size of $\Phi \times 8 \times 8 \text{mm}$ and central frequency of 140 kHz and 6 signal preamplifiers were used. In the AE monitoring system, the threshold and acquisition frequency were set to 40 dB and 1 MHz, respectively. It is worth mentioning that the 6 AE sensors were placed on the top and bottom with a distance of 20 mm to the end of the coal specimens, as shown in Figure 4(b), and vaseline was used as a coupling agent to improve AE event detection.

Through this experiment, the effects of loading rate and bedding plane on UCS, elastic modulus, AE counts, cumulative absolute AE energy, and energy characteristics of the tested coal specimens were analyzed.

3. Results and Discussion

3.1. Effect of Loading Rate on Mechanical Properties of CSVB and CSPB. The uniaxial compression experiments were conducted at loading rates of 0.2, 0.6, 3.0, and 6.0 mm/min on
CSVB and CSPB. The relevant physical and mechanical parameters are listed in Tables 1 and 2.

As shown in Tables 1 and 2, the UCS values of CSVP are higher than those of CSBP at any loading rate. However, for each specimen type, higher average UCS values were obtained with the loading rate increasing. No substantial changes were observed concerning the elastic modulus.

3.1.1. Variations of UCS. The UCS variation of CSVB is presented in Figure 5(a). Table 1 and Figure 5(a) show that the CSVB average UCS values at 0.2 and 6.0 mm/min loading rates are 24.65 and 39.26 MPa, respectively, and a growth rate of 59.27% is observed. The average UCS of the coal increases linearly as the loading rate increases. The reason is that the high loading rate does not allow enough time for the expansion and development of internal joint fractures in coal specimens [40, 41], and the weakening effect of joint fractures on the coal specimens is reduced. The UCS of coal increases with the loading rate increasing. At the same time, the UCS of coal shows dispersibility due to the complexity of coal and significant anisotropy.

The typical stress-strain curves of CSVB are shown in Figure 5(b). The variations of stress-strain curves at different loading rates are consistent and can be divided into four stages [42–44]: compaction, linear elastic, plastic yield, and postpeak failure. In the initial loading stage, the nonlinear behavior is characterized by the closure of pores and cracks. As the loading continues, the elastic stage is initiated, and the stress-strain curve approaches a linear relationship between stress and strain, with the development of some internal microcracks. After further loading, the curve deviates from its linear behavior, in a convex manner, which is the yield stage. Due to the large brittleness of the coal specimens, this stage is not apparent. When the applied load reaches the limit of coal specimens, the microcracks quickly pass through and form large cracks, the coal specimens fail, and the stress suddenly decreases. The peak stress significantly increases with the loading rate increasing.

Table 1: Physical and mechanical parameters of CSVB at different loading rates.

<table>
<thead>
<tr>
<th>Loading rates (mm/min)</th>
<th>Coal specimen no.</th>
<th>Height (mm)</th>
<th>Diameter (mm)</th>
<th>Density (g/cm³)</th>
<th>UCS (MPa)</th>
<th>Average UCS (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Average elastic modulus (GPa)</th>
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<td>0.2</td>
<td>V1-1</td>
<td>100.40</td>
<td>49.50</td>
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<td>24.65</td>
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<td>1.78</td>
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<tr>
<td></td>
<td>V1-2</td>
<td>100.30</td>
<td>49.65</td>
<td>1.26</td>
<td>21.07</td>
<td>24.65</td>
<td>1.81</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>V1-3</td>
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<td>49.60</td>
<td>1.23</td>
<td>28.69</td>
<td>1.81</td>
<td>1.78</td>
<td></td>
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<tr>
<td>0.6</td>
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<td>26.21</td>
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<tr>
<td></td>
<td>V2-2</td>
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<td>1.76</td>
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<td>6.0</td>
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<td></td>
<td>V4-2</td>
<td>100.29</td>
<td>49.24</td>
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<td>37.53</td>
<td>1.63</td>
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Table 2: Physical and mechanical parameters of CSPB at different loading rates.

<table>
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<tr>
<th>Loading rates (mm/min)</th>
<th>Coal specimen no.</th>
<th>Height (mm)</th>
<th>Diameter (mm)</th>
<th>Density (g/cm³)</th>
<th>UCS (MPa)</th>
<th>Average UCS (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Average elastic modulus (GPa)</th>
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<td></td>
<td>P1-2</td>
<td>99.60</td>
<td>49.35</td>
<td>1.23</td>
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<td>9.92</td>
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<td>13.14</td>
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<td>P2-2</td>
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<td>12.94</td>
<td>1.75</td>
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<td></td>
<td>P2-3</td>
<td>99.37</td>
<td>49.83</td>
<td>1.25</td>
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<td>3.0</td>
<td>P3-1</td>
<td>99.66</td>
<td>48.57</td>
<td>1.18</td>
<td>12.19</td>
<td>12.19</td>
<td>1.57</td>
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<td></td>
<td>P3-2</td>
<td>99.26</td>
<td>49.63</td>
<td>1.23</td>
<td>12.78</td>
<td>12.23</td>
<td>1.53</td>
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<tr>
<td></td>
<td>P3-3</td>
<td>99.46</td>
<td>49.94</td>
<td>1.19</td>
<td>11.73</td>
<td>11.73</td>
<td>1.64</td>
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<tr>
<td>6.0</td>
<td>P4-1</td>
<td>90.05</td>
<td>50.02</td>
<td>1.33</td>
<td>17.57</td>
<td>17.57</td>
<td>1.89</td>
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<td></td>
<td>P4-2</td>
<td>99.12</td>
<td>47.86</td>
<td>1.21</td>
<td>16.86</td>
<td>16.76</td>
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<td>99.56</td>
<td>48.21</td>
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<td>15.86</td>
<td>15.86</td>
<td>1.74</td>
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The UCS variation of CSPB is presented in Figure 6(a). Table 2 and Figure 6(a) show that the average UCS values of CSPB increase with the loading rate increasing. The UCS values of CSPB are 25.27% ~ 67.99% of UCS values of CSVB. At the loading rates of 0.2 and 6.0 mm/min, the average UCS values of CSVB are 9.92 and 16.76 MPa, respectively, and the growth rate is 68.95%, which is higher than that of CSVB (the growth rate is 59.27%), demonstrating that the loading rate has a more remarkable influence on UCS of CSPB compared with its influence on UCS of CSVB. The reason is that the loading direction of CSPB is the same as the direction of bedding planes, and the coal specimens are more likely to crack along the direction of the bedding planes. The parallel bedding has a critical impact on UCS of coal. At the low loading rate, the weak bedding planes are fully expanded, and UCS of coal is low. In contrast, the weak bedding planes are not fully expanded at the high loading rate, and UCS of coal is high. Compared with CSVB, the loading rate has a more pronounced effect on UCS of CSPB.

The typical stress-strain curves of CSPB are shown in Figure 6(b). Compared with CSVB, the main difference in the stress-strain curve is that the local failure in coal specimens occurs when the peak strength is reached, with a rapid decrease in stress. However, due to the small failure load, the residual strength of locally failed coal specimens could still bear the small load, the stress-strain curve shows a “stepped” stress drop, and the coal specimens eventually fail as the loading continues. As the loading rate increases, the phenomenon that the coal specimen can continue to bear the load even after local failure gradually disappears, and the peak stress significantly increases.

3.1.2. Variations of the Elastic Modulus. The elastic modulus measures the elastic deformation ability of the material. It shows the elastic deformation characteristics of coal after the primary cracks are closed under external force. The variations of elastic modulus of CSVB and CSPB are shown in Figure 7.

As shown in Table 1 and Figure 7(a), when the loading rates are 0.2, 0.6, and 6.0 mm/min, the average elastic modulus of CSVB is 1.78, 1.87, and 1.69 GPa, respectively. The growth rate and reduction rate are 5.06% and 9.63%, respectively. The average elastic modulus increases and then decreases as the loading rate increases. At the loading rate of 0.6 mm/min, the variation trend turns, showing obvious nonlinear variation characteristics, which is consistent with the rule described in the literature [25]. It should also be noted that the complexity and anisotropy of coal cause the dispersion of the elastic modulus.

As shown in Table 2 and Figure 7(b), when the loading rates are 0.2 and 0.6 mm/min, the average elastic modulus of CSPB is 1.32 and 1.85 GPa, respectively, and the growth rate is 40.15%. Compared with CSVB, the elastic modulus of CSPB is smaller, but the difference is not significant. The deviation is within 21.90%, indicating that the influence of the bedding planes on the elastic modulus is small. When the loading rate increases, the average elastic modulus of CSPB increases, which is different from that of CSVB. Due to parallel bedding, the strain changes more slowly than the stress as the loading rate increases; so, the elastic modulus increases with the increase of loading rate.

3.2. Effect of Loading Rate on AE Characteristics of CSVB and CSPB

3.2.1. Variations of Stress, AE Counts, and Cumulative Absolute AE Energy. The variations of typical stress and AE characteristic parameters of CSVB are shown in Figure 8. During the loading progress, the AE activity of coal specimens is related to the generation, propagation, and fracture of internal cracks and structural planes [45–47]. The test loading rate affects the AE activity of coal specimens.
by influencing the coalescence and propagation of cracks. In Figure 8, the variations of AE counts and cumulative absolute AE energy of CSVB with time are similar. Based on previous studies [48, 49], the whole failure process can be divided into four stages according to the AE characteristics:

Stage I is as follows: the original open structural planes, cracks, pores, and other original defects in the coal specimens are gradually closed under the external load. The surface of coal specimens deforms and forms microcracks, generating a small amount of AE, resulting in a slow increase in cumulative absolute AE energy. As the loading rate increases, the strength of the external load on cracks and pores in coal specimens increases, and more AEs are generated at a high loading rate than at a low loading rate.

Stage II is as follows: as the load increases, the new cracks form in the coal specimens, while the primary cracks are activated. The rapid rate of crack generation produces a large number of AE, resulting in a slow increase in AE counts and a steady and continuous increase in the cumulative absolute AE energy.

Stage III is as follows: the cracks and fracture structural planes in the coal specimens expand rapidly with continuous loading. With the rapid generation of cracks, macroscopic failure finally occurs. The AE counts rapidly reach the maximum, and the cumulative absolute AE energy increases sharply.

Stage IV is as follows: some coal specimens do not undergo this stage. When the applied load exceeds the peak
strength of coal specimens, the energy stored in the coal specimens is fully released, resulting in a decrease in AE activity. At the same time, due to the large brittleness of the coal specimen, it collapses instantly, and some AE sensors fall off so that only a small amount of AE is monitored. The decrease in AE counts leads to a slow rise in the cumulative absolute AE energy.

The variations of typical stress and AE characteristic parameters of CSPB are shown in Figure 9. Although the variations of AE counts and cumulative absolute AE energy of CSPB with time are different, the overall loading process can also be divided into four stages based on AE characteristics.

Compared with the test results of CSVB, the variations of AE counts and cumulative absolute AE energy of CSPB are the same as those in CSVB in stages I and II. In stages III and IV, the variation rules in CSPB are different from those in CSVB. In Figure 9(d), the AE counts of CSPB reach the maximum before stage III, which may be related to the parallel bedding. Compared with CSVB, CSPB is more likely to cause microcracking or macroscopic failure during loading, and the effect of loading rate is more obvious. At the high loading rate, the internal cracks and pores of coal specimens are subjected to high loading intensities, and the crack initiation and propagation are earlier than those at the low loading rate. Many macroscopic failures occur in coal specimens in stage II, generating a large number of AE, and AE counts reach the maximum. At the same time, the variations of AE counts and cumulative absolute AE energy of CSPB are more likely to appear stage IV compared with CSVB. Due to the macroscopic failure in the postpeak failure stage, the accumulated energy in the coal specimens is fully released, the AE activity decreases, the AE counts decrease, and the cumulative absolute AE energy slowly increases.

3.2.2. Variations of Peak Values of AE Counts and Cumulative Absolute AE Energy. The variations of peak values of AE counts and cumulative absolute AE energy for CSVB and CSPB are shown in Figure 10.
Figure 9: Continued.
Figure 10(a) shows that the loading rate significantly affects the peak values of AE counts and cumulative absolute AE energy of CSVB. A higher loading rate results in a stronger effect of external load on the internal cracks and pores in coal specimens, producing more AE activities. The peak values of AE counts are 1267 and 8226 when the loading rates of 0.2 and 6.0 mm/min, respectively, and the growth rate is 549.25%. The peak values of AE counts enhance with the increase of the loading rate, but the growth rate decreases as the loading rate increases. When the loading rates are 0.2 and 3.0 mm/min, the peak values of cumulative absolute AE energy are $2.73 \times 10^9$ and $11.40 \times 10^9 \text{aJ}$, respectively, and the growth rate is 317.58%. When the loading rate is 6.0 mm/min, the peak value of cumulative absolute AE energy decreases. Higher loading rate might reduce the time to accumulate AE energy or cause the coal specimens to fracture instantaneously as they reach the peak strength, resulting in the dislodgement of some AE sensors and only a small amount of AE is monitored. However, the peak value of cumulative absolute AE energy and the loading rate are positively correlated.

Figure 10(b) shows that the loading rate remarkably influences the peak values of AE counts and cumulative absolute AE energy of CSPB. As the loading rate increases, the effect of external load on the internal cracks and pores in coal specimens becomes more significant, producing more AE activities. When the loading rates are 0.2 and 6.0 mm/min, the peak values of AE counts are 4528 and 6670, respectively, and the growth rate is 47.31%. Both the peak values of AE counts and the growth rate increase with the increase of the loading rate. In addition, the peak values of cumulative absolute AE energy are $1.37 \times 10^9$ and $4.53 \times 10^9 \text{aJ}$ at loading rates of 0.2 and 6.0 mm/min, respectively, and the growth rate is 230.66%. The peak value of cumulative absolute AE energy increases with the loading rate increasing, but the growth rate decreases. Compared with CSVB, the peak values of AE counts and cumulative absolute AE energy of CSPB are smaller, and the results are consistent with the literature [35]. The overall deformation of CSVB is the main cause. Once the failure occurs, the accumulated energy is released instantly, and the failure scale and scope are large, showing strong AE characteristics. However, CSPB is mainly associated with local deformation and local progressive failure, which makes it difficult to develop a high energy accumulation and leads to small AE parameters.

The loading rate and bedding plane have a significant influence on AE characteristics of coal specimens. Therefore, when using AE data to analyze and predict coal burst, the bedding planes of coal and the loading conditions in the field should also be carefully considered.

3.3. Effect of Loading Rate on Energy Dissipation and Release of CSVB and CSPB

Failure and damage of coal specimens are caused by the generation, expansion, connection, penetration, and slip page of the internal microcracks [50]. Sliding friction between the fracture planes dissipates energy, and the generation of new fracture planes requires energy absorption, which means that the failure and damage of coal specimens is a process of energy accumulation, dissipation, and release [51–53]. The changes in stress and energy of coal specimens are shown in Figure 11 [54–57].

During coal failure, there are energy input, accumulation, dissipation, and release [45, 58]. When heat radiation and heat exchange during the test are excluded, the input energy density (IED) is the sum of the dissipated energy density (DED) and the elastic energy density (EED) as follows [37, 53, 59]:

$$U = U^d + U^e,$$  

(1)
where \( U, U^d, \) and \( U^e \) are IED, DED, and EED of coal specimen, respectively.

As shown in Figure 11, the blue area represents DED \( U^d \), the green triangle area represents EED \( U^e \), and the area enclosed by the horizontal axis and stress-strain curve represents IED \( U \). The energy density incremental \( dU \) between any two consecutive points \( i \) and \( i + 1 \) can be approximated by the trapezoidal cell area in Figure 11. IED can be obtained by summing all cell areas \( dU \):

\[
U = \int_0^\epsilon \sigma \, d\epsilon = \sum \left( \frac{1}{2} (\sigma^i + \sigma^{i+1}) (\epsilon^{i+1} - \epsilon^i) \right),
\]

where \( \sigma \) is stress, \( \epsilon \) represents strain, \( i \) and \( n \) are the number of incremental segments and the total number of incremental trapezoids, respectively, \( \sigma^i \) and \( \sigma^{i+1} \) represent the axial stress at any continuous point \( i \) and \( i + 1 \), respectively, and \( \epsilon^i \) and \( \epsilon^{i+1} \) represent the axial strain at any continuous point \( i \) and \( i + 1 \), respectively.

According to Figure 11, \( U^e \) can be calculated by the green triangle acreage \([52]\):

\[
U^e = \frac{1}{2} \sigma^e \epsilon^e = \frac{\sigma^2}{2E_u} \approx \frac{\sigma^2}{2E},
\]

where \( \epsilon^e \) is the elastic strain, \( E_u \) is the unloading elastic
modulus, and $E$ is the elastic modulus. $E_u$ is approximately equal to $E$ in the initial loading stage [26, 59, 60].

According to Eqs. (1)-(3), $U^d$ can be determined as follows:

$$U^d = U - U^e. \quad (4)$$

### 3.3.1. Variations of IED, EED, and DED

Based on Eqs. (2)-(4), the variations of typical stress, IED, EED, and DED of CSVB at loading rates of 0.2, 0.6, 3.0, and 6.0 mm/min are shown in Figure 12. The variations are similar, and the variation rules of three energy densities can be divided into four stages:

**Stage I** is as follows: IED, EED, and DED increase slowly as the loading time increases, indicating that a large amount of energy is consumed by the closure of microcracks, original defects, and friction slip in the coal specimens. Moreover, most of the input energy is transformed into dissipated energy, only a small part of the energy is stored as elastic energy, and DED is larger than EED.

**Stage II** is as follows: IED and EED increase rapidly, while DED remains stable, indicating that a small part of the energy absorbed by coal specimens is converted into dissipated energy, and most of the energy is stored as elastic energy.

**Stage III** is as follows: due to the large brittleness of coal specimens, IED and EED continue to increase at a high rate, while DED slightly decreases. This result indicates that the coal specimens accumulate elastic energy before reaching the peak stress, and the input energy is still mainly stored as elastic energy.

**Stage IV** is as follows: some coal specimens do not undergo this stage. The microcracks in the coal specimens extend, connect, and penetrate, forming a macroscopic fracture plane. When the load reaches its peak strength, the coal specimens are instantly destroyed, accompanied by an immediate release of the elastic energy stored in the coal specimens. EED decreases rapidly, and DED increases instantly to reach the maximum value.

According to Eqs. (2)-(4), the variations of typical stress, IED, EED, and DED of CSPB at loading rates of 0.2, 0.6, 3.0, and 6.0 mm/min are shown in Figure 13. Although the variations of IED, EED, and DED of CSVB are different, the variation rules of the three energy densities can also be divided into four stages.

Compared with the test results of CSVB, the variation of IED of CSPB at different loading rates is consistent with that of CSVB. In stages I and II, the variations of EED and DED of CSPB are the same as those of CSVB, but in stages III and IV, the variation rules are different from that of CSVB. In Figure 13, DED generally increases as loading time increases in stage III. The reason is that the internal cracks of CSPB in the yield stage are more prone to unstable propagation, connectivity, and friction slip than those of CSVB. A large amount of energy is consumed in this stage, and DED increases rapidly as the loading time gradually increases in stage IV. Stage IV is more likely to appear compared with CSVB. In stage IV, and EED decreases sharply while DED rapidly increases.

The loading rate affects IED by influencing the loading characteristics of coal specimens. The variations of peak values of IED and EED for CSVB and CSPB are shown in Figure 14.

Figure 14(a) shows that when the loading rates are 0.2 and 6.0 mm/min, the peak values of IED of CSVB are 173.34 and 475.07 kJ/m$^3$, respectively, and the growth rate is 174.07%. The peak value of IED increases with the loading rate increasing, but the growth rate decreases.

According to Eq. (3), the value of accumulated EED of coal specimens during loading is not directly related to the loading rate, but the loading rate affects EED by influencing the stress and elastic modulus of coal. Based on the analysis in Section 3.1, the peak strength of the coal increases as the loading rate increases, while the elastic modulus decreases. Therefore, the maximum cumulative elastic energy of coal specimens before failure increases as the loading rate increases. Figure 14(a) shows that when the loading rates are 0.2 and 6.0 mm/min, the peak values of EED are 166.134 and 456.65 kJ/m$^3$, respectively, and the growth rate is 174.87%. The peak value of EED enhances with the loading rate increasing, but the growth rate decreases.

Figure 14(b) shows that when the loading rate is 0.2 mm/min, the peak values of IED and EED of CSPB are 63.96 and 38.52 kJ/m$^3$, respectively. When the loading rate is 6.0 mm/min, the peak values of IED and EED are 119.31 and 79.51 kJ/m$^3$, respectively, and the growth rates are 86.54% and 106.41%, respectively. Overall, the peak values of IED and EED of CSPB increase with the loading rate increasing. However, at the loading rate of 3.0 mm/min, the peak values of IED and EED are lower than those at 0.6 mm/min. The reason may be that the coal specimens used for a test at the loading rate of 3.0 mm/min have more original cracks or defects, the strength of coal specimens increases less than at the loading rate of 0.6 mm/min, and the loading time is significantly shortened. Finally, IED and EED reduce, fully indicating that the internal structure of coal specimens is complex, and there is dispersion in the test data. The smaller peak values of IED and EED of CSPB compared with CSVB are mainly related to the decrease of UCS and loading time of CSPB.
3.3.2. Variations of ESR and EDR. In this study, the ratio of EED to IED was defined as energy storage rate (ESR) $\eta^e$. The ratio of DED to IED was defined as energy dissipation rate (EDR) $\eta^d$. $\eta^e$ and $\eta^d$ can be calculated as follows [61, 62]

$$\eta^e = \frac{U^e}{U}, \quad (5)$$

$$\eta^d = \frac{U^d}{U}. \quad (6)$$

According to Eqs. (5) and (6), the variations of ESR and EDR of CSVB with axial load before the failure of the coal specimen are shown in Figure 15.

It can be noted that the variations of ESR of CSVB are nonlinear from Figure 15(a). ESR continuously increases before the failure of the coal specimen, but the growth rate gradually decreases. The trend of ESR variation of coal specimens is consistent at different loading rates. The loading rate has little effect on the growth rate of ESR but has a consequential impact on the axial load that reaches the peak value of ESR, which increases with the loading rate. ESR increases sharply when the axial load goes from 0 to 7.5 ~ 12 kN. Compared with Figure 15(b), EDR is larger than ESR in this stage. When the axial load is greater than 7.5 ~ 12 kN, it enters the elastic stage, and the increase of ESR begins to slow down and gradually stabilizes. EDR of coal specimens also changes nonlinearly with the axial load, as shown in Figure 15(b), where EDR decreases continuously before the failure of the coal specimens at a progressively slower rate.

According to the variation rules of ESR and EDR, the peak value of EDR appears in the initial compaction stage, demonstrating that the energy dissipation effect of coal specimens is vigorous and the energy storage effect is weakened. As the axial load increases, the cracks and pores in coal specimens gradually close, EDR gradually decreases, and ESR gradually increases. Then, the elastic stage starts with a strong energy storage effect and a weak energy dissipation effect.
Figure 13: Curves of stress and energy density of CSPB with time at different loading rates. (a) 0.2 mm/min. (b) 0.6 mm/min. (c) 3.0 mm/min. (d) 6.0 mm/min.

Figure 14: Variations of peak values of IED and EED for coal specimens at different loading rates. (a) CSVB. (b) CSPB.
According to Eqs. (5) and (6), the variations of ESR and EDR of CSPB with axial load before the failure of the coal specimen are shown in Figure 16.

In Figure 16(a), the variations of ESR of CSPB with axial load are nonlinear at different loading rates. When the coal specimen is close to failure, ESR increases continually, but the growth rate gradually decreases. The axial load that reaches the peak value of ESR increases with the increase of the loading rate. The trend of ESR of coal specimens at different loading rates is different. Compared with CSVB, the loading rate has a more obvious influence on the growth rate of ESR for CSPB. The reason is that the loading direction is consistent with bedding planes, which significantly influences the mechanical behavior of the coal. ESR increases sharply when the axial load goes from 0 to 3.8 – 7 kN. Compared with Figure 16(b), EDR is larger than ESR in this stage. When the axial load is greater than 3.8 – 7 kN, it enters the elastic stage, and the increase of ESR begins to slow down and gradually stabilizes. As shown in Figure 16(b), EDR of coal specimens also varies nonlinearly with the axial load and continues to decrease before the failure of the coal specimen, and the reduction rate gradually decreases.

The UCS and energy characteristics of coal are important indexes to access the bursting liability of coal [9, 17]. This study showed that the loading rates (0.2, 0.6, 3.0, and 6.0 mm/min) and bedding angles (90° and 0°) significantly affected UCS and energy characteristics of coal. Therefore, the bedding planes of coal and the loading conditions in the field should be considered when identifying the bursting liability of coal.
4. Conclusions

In this study, the uniaxial compression tests at loading rates of 0.2, 0.6, 3.0, and 6.0 mm/min were carried out for CSVB and CSPB. The effects of loading rate and bedding plane on mechanical properties, AE, and energy dissipation characteristics of coal were analyzed. The main conclusions are as follows:

(1) The UCS of coal has a significant anisotropy, and UCS of CSVB is significantly larger than that of CSPB. The UCS of CSVB and CSPB is positively correlated with the loading rate. The loading rate and bedding plane also have significant effects on the elastic modulus of coal.

(2) The AE evolution process of CSVB and CSPB at different loading rates can be divided into four stages. The peak values of AE counts and cumulative absolute AE energy of CSVB and CSPB generally increase with the loading rate, and the AE parameters of CSVB are generally larger than those of CSPB. The loading rate and bedding plane have significant effects on AE parameters.

(3) The variation rules of IED and EED of CSVB and CSPB are similar, but the variation rules of DED in stage IV are different. CSVB shows a slightly decreasing trend, while CSPB shows an increasing trend. The primary reason is that the internal cracks in CSPB are more prone to propagation and friction slip, which leads to an increase in DED. When the axial load increases, ESR and EDR of both coal specimen types increase and decrease, respectively, and EDR is larger than ESR in the initial loading stage.

(4) The loading rate and bedding plane have remarkable influences on the mechanical properties, AE characteristic parameters, and energy characteristics of coal. The bedding planes of coal and the loading conditions in the field should be carefully considered when identifying the bursting liability of coal and using AE data to analyze and predict the coal burst.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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