Research Article

Effect of Loading Rates on Mechanical Characteristics and Rock Burst Tendency of Coal-Rock Combined Samples

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According to the universal law of thermodynamics, the failure of any substance is closely related to its energy change. Understanding the strain energy and rock burst tendency of rock or coal under different loading rates is critical in many geological projects, such as mining, tunneling, and other underground engineering projects. The mechanical and energy evolution characteristics of the coal-rock combined sample under different loading rates of uniaxial compression were numerically investigated. And, the rock burst tendency was also calculated by the Rock Burst Energy Index \(K_E\). The results show that with the increase of the loading rate, the total input energy, elastic strain energy, and dissipation energy all show an increasing trend. But the growth trend is different. And, under the five loading rates, the Rock Burst Energy Index \(K_E\) of the coal-rock combined sample were all between \(1.5 \leq K_E < 5\). That is, they all have weak rock burst tendency. And the rock burst energy index increases first and then decreases with the increase of loading rates. This study provides references for propulsions speed of working face in the field mining practice.

1. Introduction

The coal-rock combined sample is often seen in the process of coal mining, such as the combined structure formed by coal pillars and roof and floor rocks [1–3]. Affected by the propulsion speed of working face, construction of adjacent working face, blasting, and other engineering disturbances, the coal-rock combined structure will be affected by different load rates [4–6]. Currently, the loading rate in rock mechanics is a variable parameter. Different loading rates should be considered for different engineering problems. Different loading rates have a great influence on the mechanical and energy characteristics of rock materials [7–10].

Scholars have done a lot of research on the strength and failure characteristics of coal-rock combined samples. The research focuses on theoretical research, numerical simulation tests, indoor rock mechanics tests and so on [11–13]. These studies have a good reference value for the strength and deformation characteristics of coal-rock combined samples. For a long time, the rock strength and failure criterion based on the classical elastic-plastic theory has been the basis for judging engineering failure. However, as a description of a specific mechanical state, stress-strain is only one aspect of the thermodynamic state of the rock. The mechanical parameters such as the stress-strain curve and rock strength obtained from laboratory tests are very discrete. Even the specimens from the same rock mass of the same rock will be quite different, and the engineering calculation will produce errors due to the inaccurate selection of parameters. Energy conversion is the essential feature of the material physical process, so it is necessary to study the energy characteristics of the coal-rock combined sample [14–17]. According to the structural characteristics of coal and rock, and the mechanical characteristics of the coal-rock combined sample, Chen et al. [18] gives the calculation formula of energy distribution before failure of equal diameter coal and rock combination and nonequal diameter coal and rock combination, and uses the energy distribution calculation formula to calculate the energy distribution before failure of the combination. Li et al. [19] used a split Hopkinson compression bar (SHPB) to carry out impact compression tests on coal and rock monomer and combined
samples, and analyzed the energy dissipation and fragmentation characteristics of the specimens. Yang et al. [20] analyzed the evolution laws of mechanical parameters such as input energy density, elastic energy density, dissipated energy density, elastic modulus, and uniaxial compressive strength of the coal-rock combined sample and obtained the energy storage characteristics of different samples. Zhao et al. [21] used the DYD-10 electronic universal testing machine and PCI-8 acoustic emission signal acquisition system to carry out the mechanical and energy characteristics experiments of the whole process of deformation and failure of coal-like rock materials with different coal thickness under a uniaxial load. Ma et al. [15, 17] studied the energy characteristics of the coal-rock combined sample with different coal-rock height ratios through numerical simulation. In conclusion, it can be seen that the research on the mechanical and energy characteristics of the coal-rock combined sample has made a wealth of research results. However, there is a lack of research on the energy characteristics and rock burst tendency of the coal-rock combined sample under uniaxial compression with different loading rates.

Therefore, taking the combined structure formed by roof rock, coal, and floor rock in mining engineering as the research background, according to the size standard recommended by the International Society of Rock Mechanics (ISRM), the energy evolution characteristics of the coal-rock combined sample under different loading rates are studied by numerical simulation, and the rock burst tendency of coal-rock combined samples under different loading rates is calculated by the Rock Burst Energy Index $K_E$.

2. Numerical Model and Energy Calculation Method for the Combined Sample

2.1. Numerical Model. The meso parameters of coal and rock in reference [2, 3, 22, 23] are selected for coal-rock combined sample simulation, as shown in Table 1. The ratio of normal stiffness to tangential stiffness of coal and rock particles, and the ratio of normal stiffness to tangential stiffness of parallel bond are set to 2.5. The multipliers of the parallel bond radius are all set to 1, and the particle contact modulus is equal to the parallel bond modulus. The normal strength of the parallel bond is equal to the tangential strength of the parallel bond (rock:coal = 3:1). The physical and numerical model is shown in Figure 1.

2.2. Energy Calculation Method for the Coal-Rock Combined Sample. The energy evolution characteristics in the uniaxial compression process of the coal-rock combined sample is complicated, accompanied by the transfer and transformation of energy between coal and rock. The dissipative energy ($U^d$) is used to form internal damage and plastic deformation of the coal-rock combined sample. $U^d$ is shown by the blue shadow area in Figure 2.

The releasable strain energy ($U^r$) is the elastic strain energy released after the coal-rock combined sample unit is unloaded. This part of energy is directly related to the unloading elastic modulus and the unloading Poisson’s ratio. The red shadow area ($U^r$) under the stress-strain curve shown in Figure 2 represents the releasable strain energy stored in the coal-rock combined sample. From a thermodynamic point of view, energy dissipation is unidirectional and irreversible, while energy release is bidirectional, as long as certain conditions are met [5, 24].

Considering the deformation of a rock under the action of external force, it is obtained from the first law of thermodynamics [5, 24].

$$U = U^d + U^m,$$

$$U = \int \sigma_j d\varepsilon_i = \sum_{i=1}^{n} \frac{1}{2} (\sigma_{ii} + \sigma_{ji+1}) (\varepsilon_{ii} + \varepsilon_{ii+1}),$$

$$U^c = \frac{1}{2E} \left[ \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2E (\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) \right],$$

where $\bar{E}$ and $\bar{\nu}$ are the average values of unloading elastic modulus and Poisson’s ratio, respectively.

Equation (3) is the calculation formula of elastic strain energy that can be released under triaxial compression. When the rock is under uniaxial compression ($\sigma_2 = \sigma_3 = 0$), equation (3) becomes

$$U^c = \frac{\sigma_1^2}{2\bar{E}}.$$

In this paper, the energy accumulation and dissipation characteristics of the coal-rock combined sample under different loading rates are calculated according to the aforementioned formulas.

3. Results and Analysis

3.1. Strength and Deformation Characteristics. The stress-strain curves of coal-rock combined samples under different loading rates are shown in Figure 3. It can be seen from Figure 3 that under different loading rates, the change trends of the stress-strain curves of the coal-rock combined samples are basically the same. Generally, they all experience three stages: initial compaction, linear elasticity, and macroscopic failure. At low loading rates, the postpeak stress-strain curve shows a “step-like” drop, while at high loading rates, the curve drops more smoothly with a smaller slope. As the loading rate increases, the opening of the stress-strain curve also increases.

The variation trends of elastic modulus, peak strength, and peak strain of coal-rock combined samples under different loading rates are shown in Figure 4. It can be seen from Figure 4(a) that with the increase of the loading rate, the elastic modulus of the coal-rock combined sample shows a nonlinear decreasing trend. Its change trend can be represented by $y = 9.503 + 0.988/(1 + (x + 0.055)^{1.535})$, $R^2=99.74\%$. The deceleration rate shows a trend of increasing first and then decreasing. It can be seen from Figures 4(b) and 4(c) that the peak strength and peak strain of the coal-rock combined sample increase nonlinearly with the loading rate. The increasing trend of peak strain can be
represented by \( y = 0.085 + 3.152/(1 + \exp((x + 0.996)/d)) \), \( R^2 = 92.74\% \), and the increasing trend of peak strength can be represented by \( y = 8.633 - 5.382/(1 + (x/18057.417)^{0.947}) \), \( R^2 = 96.53\% \).

### 3.2. AE Characteristics.

In the PFC2D parallel bonding model, each crack forms an AE signal [13]. When the loading rates are different, the AE characteristics and generation mechanism of coal-rock combined samples under loading are also different. By recording the number of cracks and data postprocessing during uniaxial compression of coal-rock combined samples under different loading rates, the AE counts during the failure process can be simulated. The AE characteristics of the coal-rock combined samples under different loading rates are shown in Figure 5.

The stress-strain, AE counts, and failure modes of coal-rock combined samples with different loading rates are shown in Figure 5.

| Mechanical parameters | \( \rho/\text{kg-m}^{-3} \) | \( R_{\min}/\text{mm} \) | \( R_{\max}/R_{\min} \) | \( E_c/\text{GPa} \) | \( K_a/K_s \) | \( E/\text{GPa} \) | \( K_a/K_s \) | \( \sigma_i/\text{MPa} \) | \( \tau_{ij}/\text{MPa} \) | \( \mu \) |
|----------------------|------------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Roof rock            | 2600             | 0.2             | 1.5            | 12             | 2.5            | 12             | 2.5            | 45             | 45             | 0.5            |
| Coal                 | 1800             | 0.2             | 1.5            | 4              | 2.5            | 4              | 2.5            | 15             | 15             | 0.5            |
| Floor rock           | 2600             | 0.2             | 1.5            | 12             | 2.5            | 12             | 2.5            | 45             | 45             | 0.5            |

Table 1: Micromechanical parameters of coal and rock [2, 3, 22, 23].

![Physical and numerical model of the coal-rock combined sample](image1.png)

Figure 1: Physical and numerical model of the coal-rock combined sample. (a) Physical model. (b) Numerical model.

![Relationship between dissipated energy and releasable strain energy in rock](image2.png)

Figure 2: Relationship between dissipated energy and releasable strain energy in rock [5, 24].

![Stress-strain curves of coal-rock combined samples under different loading rates](image3.png)

Figure 3: The stress-strain curves of coal-rock combined samples under different loading rates.
It can be seen from Figure 5 that under uniaxial compression conditions, the AE counts variation characteristics of coal-rock combined samples are basically the same. In the initial stage of uniaxial compression, when the stress of coal-rock combined samples is relatively small, AE counts are also small. With the increase of loading stress, internal cracks in the coal-rock combined samples propagate, secondary cracks form and propagate, and the number of AE counts increases gradually. Near the peak of the stress-strain curve, AE counts reach the maximum. Then, as the loading continued, AE counts gradually decreased. Until the loading was completed, internal cracks in the coal-rock combined samples penetrated, macro-cracks formed, and AE counts decreased significantly towards zero. When the loading rates are 0.05 mm/s and 0.10 mm/s, the maximum value of the AE counts is not synchronized with the peak strength, and the maximum value of AE counts coincides with the peak strength of other loading rates. In addition, the maximum AE count value increases with the increase of loading rates.

It can also be seen from Figure 5 that with the increase of loading rates, the failure of the coal-rock combined sample occurs not only in the coal part, but also in the rock part on both sides. And, with the increase of the loading rate, the failure of the rock parts on both sides of the coal-rock combined sample is becoming more and more serious.

3.3. Energy Evolution Characteristics. The stress-strain curves and the energy evolution of coal-rock combined samples at different loading rates are illustrated in Figure 6. It can be seen that the energy evolution curves at different loading rates exhibit similar trends: most of $U$, $U_{eb}$, and $U_e$ curves increase slowly first, fast afterwards, and changed very sharply at the peak stress points. Before failure, the total input energy, accumulated elastic properties, and dissipated...
energy increases with the increase of stress. The total input energy increases the fastest, followed by elastic energy, and the dissipated energy is the slowest. The elastic energy increases nonlinearly with the axial stress. The growth rate is small at the initial stage of loading, then increases slowly, and slows down near failure. The dissipative energy increases slowly at first and increases significantly in the stage of impending failure.

Figure 5: Stress-strain-AE count curves of the coal-rock combined sample under different loading rates. (a) 0.01 mm/s. (b) 0.02 mm/s. (c) 0.05 mm/s. (d) 0.10 mm/s. (e) 0.20 mm/s.
To compare the energy evolution of the coal-rock combined sample with different loading rates directly, the energy evolution curves are plotted in a single figure, as shown in Figure 7. As it can be seen, the accumulated input energy of the coal-rock combined sample increases approximately linearly with the strain and it also increases...
with loading rates (Figure 7(a)), reaching a maximum of 257.4 kJ/m$^3$ at 0.20 mm/s. Elastic energy reaches the maximum at the peak strength of stress-strain. In addition, the dissipated energy of the coal-rock combined sample increases more rapidly with loading rates (Figure 7(c)), and the peak value is also higher, reaching a maximum of 254.3 kJ/m$^3$ at 0.20 mm/s.

3.4. Energy Characteristics in the Peak Strength Point. Based on the variation of the coal-rock combined sample energy with the strain at different loading rates, the energy at the peak strength is further discussed. The total absorbed energy $U$, recoverable elastic strain energy $U_e$, and dissipated energy $U_d$ at the peak point of stress-strain curve are designated as $U_A$, $U_e^*_A$, and $U_d^*_A$ (Table 2), respectively. The relationships between $U_A$, $U_e^*_A$, $U_d^*_A$, $U_e^*/U_A$, and $U_d^*/U_A$ and the loading rates are illustrated in Figure 8 in an energy vs. loading rate plot.

It can be seen from Table 2 and Figure 8 that the accumulation and dissipation of energy at the peak strength are closely related to loading rates. $U_A$, $U_e^*_A$, and $U_d^*_A$ have the same variation trend with the loading rates of RCR and show an increasing trend with the increase of the loading rate. As the loading rate increases from 0.01 to 0.20 mm/s, $U_A$ increases from 51.93 to 183.93 kJ/m$^3$, $U_e^*_A$ increases from 6.20 to 57.30 kJ/m$^3$, and $U_d^*_A$ increases from 45.73 to 126.62 kJ/m$^3$, respectively.

With the increase of loading rates, $U_e^*/U_A$ decreases first and then increases. $U_e^*/U_A$ decreases from 88.1% to 64.0% first, then increases from 64.0% to 68.8%. The $U_d^*/U_A$ increases first and then decreases with the increase of loading.

![Figure 7](https://example.com/figure7.png)

**Figure 7**: Correlation between energy and strain of the coal-rock combined sample with different loading rates. (a) Cumulative input energy. (b) Releasable energy. (c) Dissipated energy.
3.5. Rock Burst Energy Index. According to China’s coal industry standard MT/T174-2000 classification and determination method of the Coal Seam Impact Tendency Index, the identification indexes of coal seam impact tendency include the Rock Burst Energy Index $KE$, Elastic Energy Index $WET$, and dynamic failure time $DT$ [25, 26]. The Rock Burst Energy Index $KE$ is an important classification index to judge whether coal seam has rock burst tendency. The calculation formula of the Rock Burst Energy Index $KE$ is as follows:

$$ KE = \frac{A_S}{A_X} $$

(5)

where $A_S$ is the deformation energy accumulated before the peak value and $A_X$ is the deformation energy lost after the peak value. When $KE < 1.5$, there is no rock burst tendency; when $1.5 \leq KE < 5$, there is a weak rock burst tendency; when $KE \geq 5$, there is a strong rock burst tendency. $KE$ actually refers to the ratio of the area of the rising section ($A_S$) to the area of the falling section ($A_X$) of the whole stress-strain curve (as shown in Figure 9). $\sigma_c$ is the peak stress.

The Rock Burst Energy Index of the coal-rock combined sample with different loading rates is shown in Figure 10(a). It can be seen from the figure that under the five loading rates, the Rock Burst Energy Index $KE$ of the coal-rock combined sample is between $1.5 \leq KE < 5$. That is, they all have weak rock burst tendency. With the increase of the loading rate, the Rock Burst Energy Index increases first and then decreases. That is, there is a critical loading rate, which is consistent with the study of Li et al. [27]. It is also consistent with the field observations of Dou et al. [28, 29]. Dou et al. [28, 29] pointed out that there is no nonlinear

| Coal-rock height ratio | $U_A$ (kJ/m³) | $U'_A$ (kJ/m³) | $U''_A$ (kJ/m³) | $U'_A/U_A$ | $U''_A/U_A$ |
|------------------------|--------------|----------------|----------------|------------|------------|
| 0.01                   | 51.93        | 45726.4212     | 6200.1228      | 0.881      | 0.119      |
| 0.02                   | 52.32        | 45526.7667     | 6753.621       | 0.871      | 0.129      |
| 0.05                   | 89.35        | 59110.9172     | 30229.7903     | 0.662      | 0.338      |
| 0.10                   | 110.26       | 70515.3816     | 39662.7844     | 0.640      | 0.360      |
| 0.20                   | 183.93       | 126620.68      | 57304.492      | 0.688      | 0.312      |
relationship between the propulsion speed and the times of rock burst after counting the data of several mines. When the propulsion speed of the working face is less than 1 m/d or the propulsion speed of the working face is about 3 m/d, the number of rock burst is the least. When the propulsion speed is 1.3–2.5 m/d, the rock burst times are the most frequent, which is the most unfavorable to safe mining, as is shown in Figure 10(b).

The Rock Burst Energy Index with different loading rates and rock burst proportion with propulsion speed by Dou et al. [28, 29].

4. Conclusions

(1) With the increase of loading rates, the elastic modulus of the coal-rock combined samples shows a nonlinear decreasing trend. And, the deceleration rate shows a trend of increasing first and then decreasing. The peak strength and peak strain of the coal-rock combined sample increase nonlinearly with the loading rates.

(2) The accumulated input energy of the coal-rock combined sample increases approximately linearly with the strain and it also increases with loading rates, reaching a maximum of 257.4 kJ/m³ at 0.20 mm/s. The elastic energy reaches the maximum at the peak strength of stress-strain. In addition, the dissipated energy of the coal-rock combined sample increases more rapidly with loading rates, and the peak value is also higher, reaching a maximum of 254.3 kJ/m³ at 0.20 mm/s.

(3) The accumulation and dissipation of energy at peak strength are closely related to the loading rates. \( U_A \), \( U'_A \), and \( U'_A \) have the same variation trend with the loading rates of the coal-rock combined sample and show an increasing trend with the increase of the loading rate. With the increase of loading rates, \( U'_A/U_A \) decreases first and then increases. The \( U'_A/U_A \) increases first and then decreases with the increase of loading rates.

(4) With the increase of loading rates, the Rock Burst Energy Index increases first and then decreases, which is consistent with the indoor study and field observations of the former study. Therefore, in the field mining practice, when the propulsion speed is too slow or too fast, it is beneficial to safe mining. At this time, the occurrence times of rock burst are relatively small.

Data Availability

The data presented in this study are available upon request from the first author or the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] J. Zuo, Z. Wang, H. Zhou, J. Pei, and J. Liu, "Failure behavior of a rock-coal-rock combined body with a weak coal interlayer," *International Journal of Mining Science and Technology*, vol. 23, no. 6, pp. 907–912, 2013.

[2] W. Y. Guo, Y. L. Tan, F. H. Yu et al., “Mechanical behavior of rock-coal-rock specimens with different coal thicknesses,” *Geomechanics and Engineering*, vol. 15, no. 4, pp. 1017–1027, 2018.

[3] S. J. Chen, D. W. Yin, N. Jiang, F. Wang, and W. J. Guo, “Simulation study on effects of loading rate on uniaxial compression failure of composite rock-coal layer,” *Geomechanics and Engineering*, vol. 14, no. 4, pp. 333–342, 2019.

[4] F. Gong, Y. E. Hao, and Y. Luo, "Rate effect on the burst tendency of coal-rock combined body under low loading rate range," *Journal of China Coal Society*, vol. 42, no. 11, pp. 2852–2560, 2017.
[5] B. X. Huang and J. W. Liu, “The effect of loading rate on the behavior of samples composed of coal and rock,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 61, pp. 23–30, 2013.

[6] D. W. Yin, S. Chen, W. Xing, D Huang, and X. Liu, “Experimental study on mechanical behavior of roof-coal pillar structure body under different loading rates,” *Journal of China Coal Society*, vol. 284, no. 05, pp. 67–75, 2018.

[7] Y. L. Chen, Y. Zhang, “Influence of loading rate on the Kaiser effect for different lithological rocks,” *Journal of China Coal Society*, vol. 43, no. 04, pp. 959–966, 2018.

[8] Z. L. Zhou, Y. Chang, and X. Cai, “Experimental study of infrared radiation effects of rock with different loading rates,” *Journal of Central South University*, vol. 50, no. 5, pp. 1127–1134, 2019.

[9] X. Wang, E. Wang, X. Liu, and X. Zhou, “Failure mechanism of fractured rock and associated acoustic behaviors under different loading rates,” *Engineering Fracture Mechanics*, vol. 247, no. 16, Article ID 107674, 2021.

[10] X. Wang, J. C. Li, X. B. Zhao, and Y. Liang, “Propagation characteristics and prediction of blast-induced vibration on closely spaced rock tunnels,” *Tunnelling and Underground Space Technology*, vol. 123, Article ID 104416, 2022.

[11] S. N. Dong, A. Li, Y. D. Ji, Y. X. Yang, and Q. Mu, “Mechanical and failure characteristics of rock-coal-rock combined body under different strain rates: a numerical study from micro perspective,” *Geotechnical and Geological Engineering*, vol. 39, pp. 1–7, 2020.

[12] J. Liu, E. Y. Wang, D. Z. Song, S Wang, and Y Niu, “Effect of rock strength on failure mode and mechanical behavior of composite samples,” *Arabian Journal of Geosciences*, vol. 8, no. 7, pp. 4527–4539, 2014.

[13] J. P. Zuo, Y. Chen, and F. Cui, “Investigation on mechanical properties and rockburst tendency of different coal-rock combined bodies,” *Journal of China University of Mining & Technology*, vol. 7, no. 1, pp. 81–87, 2018.

[14] L. Qiu, Y. Zhu, D. Song et al., “Study on the nonlinear characteristics of EMR and AE during coal splitting tests,” *Minerals*, vol. 12, no. 2, p. 108, 2022.

[15] Q. Ma, Y. L. Tan, X. S. Liu, Z. H. Zhao, and D. Y. Fan, “Mechanical and energy characteristics of coal-rock composite sample with different height ratios: a numerical study based on particle flow code,” *Environmental Earth Sciences*, vol. 80, no. 8, p. 309, 2021.

[16] H. P. Xie, R. D. Peng, Y. Ju, and H. W. Zhou, “On energy analysis of rock failure,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 15, pp. 5–10, 2005.

[17] Q. Ma, Y. L. Tan, X. S. Liu, Q. H. Gu, and X. B. Li, “Effect of coal thicknesses on energy evolution characteristics of roof rock-coal-floor rock sandwich composite structure and its damage constitutive model,” *Composites Part B: Engineering*, vol. 198, Article ID 108086, 2020.

[18] G. Chen, T. Li, G. Zhang, P. Teng, and B. Gong, “Energy distribution law of dynamic failure of coal-rock combined body,” *Geofluids*, vol. 2021, no. 7, Article ID 6695935, 14 pages, 2021.

[19] C. J. Li, Y. Xu, and Z. Y. Ye, “Energy dissipation and crushing characteristics of coal-rock-like combined body under impact loading,” *Chinese Journal of Geotechnical Engineering*, vol. 350, no. 05, pp. 190–197, 2020.

[20] L. Yang, F. Q. Gao, X. Q. Wang, and J. Z. Li, “Energy evolution law and failure mechanism of coal-rock combined specimen,” *Journal of China Coal Society*, vol. 44, no. 12, pp. 3894–3902, 2020.