

Article

An Energy Preservation Index for Evaluating the Rockburst Potential Based on Energy Evolution

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Abstract: The estimation of rockburst potential has attracted great attention in the field of rock mechanics and engineering. In this study, an original energy preservation index is proposed to evaluate the rockburst potential in view of the energy evolution characteristics of rock materials. To investigate the energy evolution during rock deformation and failure, a number of cyclic uniaxial compression experiments on five kinds of rocks were carried out. The results showed that the curves of energy evolution exhibited obvious stages and there were significantly different weakening degrees for different rock materials embodied by the decreasing degrees of the ratios of elastic strain energy to dissipated strain energy at the weakening stage. Then, the energy preservation index was further formulated based on the decreasing ratio. Furthermore, by analyzing the acoustic emission activities at the failure stage and failure modes of the five rock materials, the rockburst potential was analyzed according to the energy preservation index.

Keywords: rockburst potential; energy evolution; energy preservation index; cyclic loading–unloading test

1. Introduction

Rockburst poses severe risks to the safety of underground excavations. During the exploitation of mineral resources, rockbursts may lead to secondary hazards such as gas outbursts and dust explosions [1]. With the growing intensity and mining depth in resource exploitation, cases of rockburst hazards have been increasing in recent years [2,3]. Rockburst mechanisms have been explicated from the viewpoints of rock strength, stress–strain curves, and mineral compositions [4–7]. However, there are still no widely accepted rockburst potential indices in rock mechanics. The entire process of rock deformation is always accompanied by the energy conversion. Rock failure is an outcome of instantaneous elastic energy release accumulated in rocks [8–11]. Hence, from the perspective of strain energy, studies on the rock deformation and failure can more accurately reveal the nature of the rock failure.

In terms of strain energy, there have been plenty of studies on the energy release and energy accumulation to evaluate rockburst potential. Conventional rockburst indices based on energy theory include the strain energy storage index, energy release rate, and the bursting efficiency ratio. The strain energy storage index is the simplest rock-burst liability indicator and is defined as the ratio of elastic energy to dissipation energy (U_e/U_d) in the stress level of 80–90% of the peak strength [12]. For the convenience of calculation, Gong et al. [13] proposed the peak-strength strain energy storage index for rockburst potential. Cook [14] proposed the energy release rate for the first time when studying the rock stability problem in a gold mine. The energy release rate represents the energy releases per unit volume from the rock failure [15]. Additionally, the bursting efficiency ratio was also proposed as

the ratio of the throw energy of fragments to maximum elastic strain energy [12]. The idea of throw energy evaluation was originally suggested by Drzewiecki, and it was based on the experimental determination of the mass and throw radius (flight length) of each detectable coal fragment after the brittle failure of a sample under uniaxial compression [12]. Pan [16] proposed a burst energy index to analyze the rockburst potential of coal. The index refers to the ratio of the accumulated strain energy before peak point to the dissipated energy after peak point, and it is based on stress–strain curves under uniaxial compression. Furthermore, the effective burst energy index was put forward, and it combines the strain energy storage index and the burst energy index [17]. The index can be expressed as the ratio of U_e/U_d , where the elastic strain energy is represented at the peak point and the dissipated energy is after the peak point. Additionally, the surplus energy index was also applied to analyze rockburst potential and expressed with the ratio of surplus energy to the dissipated energy after the peak point [18]. Surplus energy refers to the difference between the elastic energy at the peak point and the dissipated energy after the peak point. Additionally, the energy emission speed was also considered for the evaluation of rockburst potential [19,20]. The energy emission speed comprehensively considers strain energy and dynamic failure time. As a result of various studies, in recent years, it has been widely accepted that the strain energy stored in a rock's mass plays an important role in inducing rockburst. Beck and Brady [21] pointed out that the potential for rock failure and the strain energy density distribution in the rock are the most relevant parameters that affect the occurrence of induced seismicity. By tracking the energy density evolution, the local energy release rate was proposed to predict the intensity of the rockburst [22]. The property and quantity of energy accumulation in rocks were examined by U_d/U_e [23]. Mansurov [24] pointed out that induced seismicity (rockburst) and its temporal and space changes can be considered as temporal flows with a magnitude of energy that is added to each seismic event. A triaxial compression system was conducted to simulate the failure process of released stress by confining pressure reduction methods. The results showed that the strain energy was absorbed and stored during the loading stage in the rock. The energy was sufficiently large to cause failure when it was released [25]. Su et al. [26] investigated the rockburst in a circular tunnel under high in-situ stress conditions with a numerical method coupled with the rock failure process theory and discontinuous deformation theory. They indicated that much of the strain energy may be released through rockbursts if the elastic module of rock blocks has not fundamentally changed, there are some long cracks, and there are a small quantity of dispersed failure points. Many strategies to evaluate rockburst potential from energy balance in rock engineering have focused on the energy state at failure points and residual points. The energy evolution characteristics during rock deformation are lacking. Different evolution paths may lead to the same energy states at failure and residual points. However, few studies have investigated the rockburst potential from the view of energy evolution, which maybe become an effective way to evaluate rockburst potential.

In present study, we introduce the energy preservation index, which was determined with the decreasing ratio of U_e/U_d at the weakening stage. A number of cyclic uniaxial compression tests were carried out for five kinds of rocks. Based on the experimental data, the energy evolution characteristics of five rock materials were analyzed. On the basis of the energy evolution, the energy preservation index could be obtained. Furthermore, in view of acoustic emission features at the failure stage and the failure modes of five rock materials, the rockburst potential was analyzed according to the energy preservation index.

2. Strain Energy Calculation of One Cycle

The loading process of a specimen can be considered a thermodynamic process [27]. It is assumed that the deformation of a specimen is a closed system without heat dissipation. Therefore, based on the first and second law of thermodynamics, external work is transformed into elastic strain energy and dissipated energy [28], that is:

$$U = U_e + U_d, \quad (1)$$

where U is the total input strain energy, U_e is the reversible elastic strain energy, and U_d is the irreversible dissipated energy.

Figure 1 is a typical stress–strain curve under loading–unloading conditions. It also shows the relationship between U_e and U_d in the axial direction. The area under the unloading curve represents U_e , as embodied by the shadow area by the points. The area between the loading and unloading curves represents U_d and is marked by the shadow area by lines. U_e can be stored as internal energy in the material during the loading process and is released as recoverable strain during the unloading process. U_d is induced by elastic–plastic damage originating from plastic strain and elastic damage in the material, and it is unrecoverable during both the loading and unloading processes.

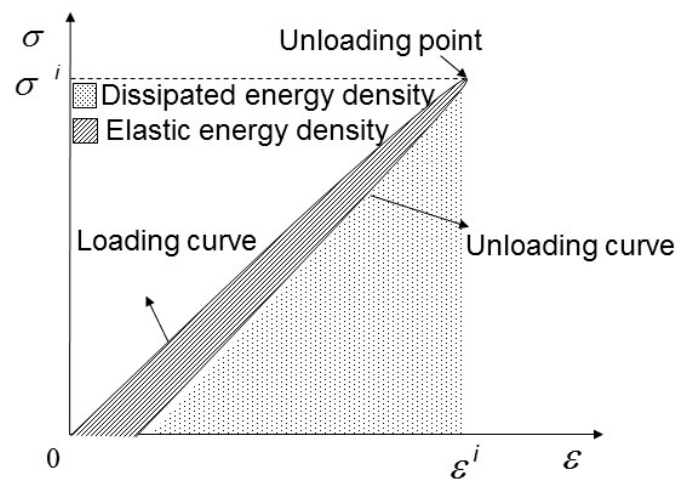


Figure 1. Calculation of dissipative energy and elastic energy in a cycle.

For uniaxial compression, input strain energy occurs only in axial direction. Therefore, the strain energy can be obtained by the following form [29]:

$$U = \int_0^{\varepsilon_i} \sigma d\varepsilon, \quad (2)$$

$$U_e = \frac{1}{2} \sigma \varepsilon_i^e, \quad (3)$$

$$U_d = \int_0^{\varepsilon_i^p} \sigma d\varepsilon^p = U - U_e, \quad (4)$$

3. Test Materials and Methods

3.1. Specimen Preparation

According to the strength and stiffness characteristics of rocks, five materials—including granite, red sandstone, coal, gypsum, and a high-water material—were chosen to perform the uniaxial cyclic loading–unloading tests. The specimens for granite, red sandstone, coal, and gypsum were taken from Jier Mine at Yanzhou area, a quarry in Xuzhou, Pingdingshan Mine, and Pizhou Gypsum Mine, respectively. The high-water material was mixed with lime powder and cement in definite proportions. The five materials were processed into standard cylinder specimens with diameter 50 mm and height 100 mm (Figure 2). Table 1 lists the basic physical properties of the five materials.



Figure 2. Prepared rock samples for uniaxial cyclic compression tests.

Table 1. Physical properties of rock specimens.

Lithology	Specimen Number	Diameter/mm	Height/mm	Weight/g	Longitudinal Wave Speed/Km·s ⁻¹
Red sandstone	S1	49.49	100.33	474.56	2.358
	S2	49.35	100.38	481.47	2.632
	S3	49.70	100.22	475.53	2.315
Gypsum	G1	49.32	100.20	439.99	4.808
	G2	49.30	100.30	434.33	4.032
	G3	49.33	100.10	438.22	4.630
Granite	g1	50.00	100.30	510.31	3.676
	g2	49.70	100.16	506.56	3.731
	g3	49.90	100.23	508.49	3.676
Coal	C1	49.30	100.00	231.52	1.852
	C2	49.16	99.60	232.64	1.838
	C3	49.19	99.74	235.55	1.880
High-water material	H1	49.42	98.64	238.55	1.724
	H2	47.90	96.72	236.55	1.724
	H3	48.30	98.22	237.64	1.761

3.2. Experimental Instrument and Method

The uniaxial cyclic loading–unloading experiments were performed on an MTS816 electro-hydraulic servo-controlled rock testing system. The machine has a compression load capacity of 1459 KN and a maximum stroke of ± 100 mm. The system consists of the loading system, a controller, and a computer system, as shown in Figure 3a. It can record real-time load and displacement. A PCI-2 acoustic emission system with dynamic range larger than 85 dB and signal amplitude of 100 dB was employed to collect the acoustic emission signal, as shown in Figure 3c.

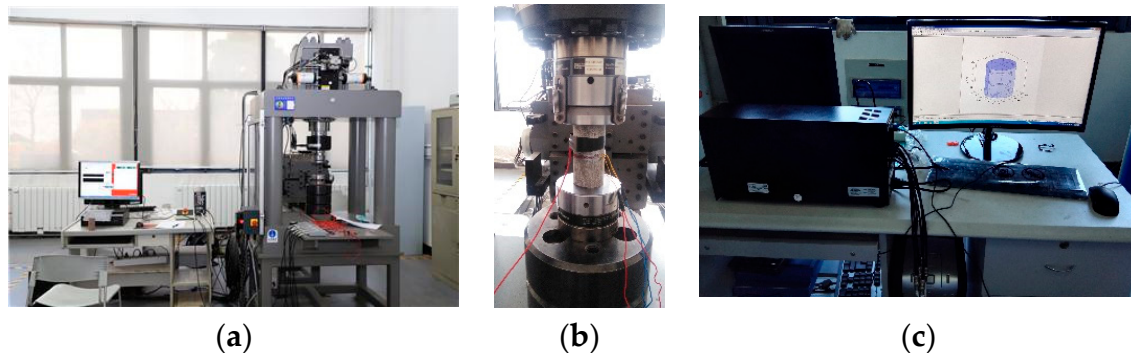


Figure 3. Photos of experimental system. (a) Loading system, (b) specimen pedestal, and (c) specimen pedestal.

Firstly, uniaxial compression tests of the 5 kinds of rocks were carried out to obtain the uniaxial compressive strength (UCS). According to the obtained UCS, 30 loading–unloading cycles were designed for each specimen in the uniaxial cyclic tests. The specimen was loaded and unloaded until failure at a constant force loading rate. The loading process within the n th load–unload cycle is shown in Figure 4. The amplitudes of load for each cycle were increased by the loading step (d). The strength and loading schemes of different rocks are listed in Table 2. At the same time, both the acoustic emission and stress–strain relationships were recorded synchronously.

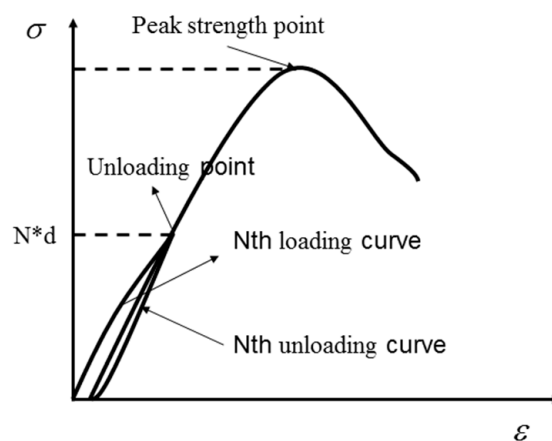


Figure 4. Typical stress–strain curve with the n th load–unload cycle.

Table 2. Strength and loading parameters for different rocks. UCS: uniaxial compressive strength.

Lithology	Red Sandstone	Gypsum	Granite	Coal	High-Water Material
UCS/M Pa	60	25	120	15	6
Loading step/KN	4.00	1.5	8	1	0.5
Loading rate/(KN/s)	1	1	1	1	1

4. Experimental Results and Analysis

4.1. Stress–Strain Curves Characteristics

The Figure 5 shows the stress–strain relationships for various lithologies under uniaxial cyclic experiments. Significant differences were noticed for the rocks. The UCS of granite, red sandstone, gypsum, coal, and the high-water material were 134.14, 84.37, 25.52, 14.10, and 5.97 MPa, respectively. The peak strains of granite, red sandstone, gypsum, coal, and the high-water material were 0.0104, 0.0150, 0.00569, 0.00602, and 0.0113, respectively. At the post-peak failure stage, the slope of the stress drop of red sandstone and granite was dramatic (see Figure 5a,b). On the contrary, a relatively slow stress drop was observed in the other three rock materials.

As displayed in Figure 5, the hysteresis phenomena of the five rocks were similar but diverse. At the initial stage of loading, the hysteresis loops under cyclic stressing were oval in shape. The hysteresis loops gradually showed pointed leaf shapes as the loading increased. The hysteresis loop reflects the non-elastic mechanism of the rocks affected by the process of crack formation and development [30]. The inelastic mechanism controls the rate and the mode of energy dissipation [31]. The hysteresis phenomena of gypsum (Figure 5e) and the high-water material (Figure 5d) were more obvious than that of red-sandstone, coal, and granite (Figure 5a–c). This indicated that the plastic deformations of gypsum and the high-water material were more than those of the other three rocks during compression. It is noteworthy that the existence of the mutation stage in the red sandstone and granite was caused by the inhomogeneity of the samples.

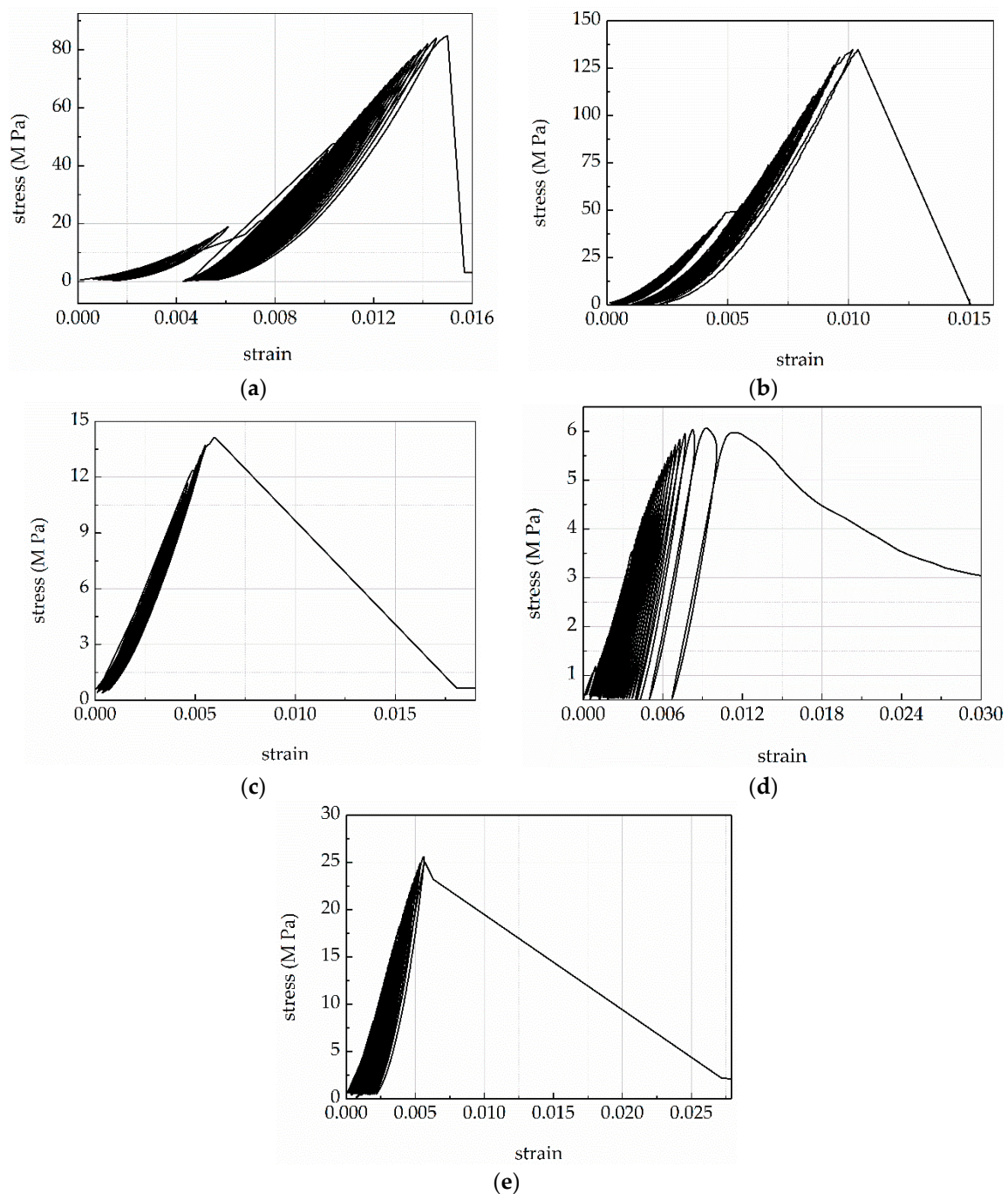


Figure 5. Stress–strain curves of uniaxial cyclic experiments for different rocks. (a) Red sandstone, (b) granite, (c) coal, (d) high-water material, and (e) gypsum.

4.2. Energy Evolution Characteristics

Using Equations (2) and (4), the energy evolution for the rocks was obtained, as presented in Figure 6. The energy evolution patterns of the five rocks were similar. The curves of energy evolution had no obvious crack closure stage. During the elastic deformation process, most of the input strain energy accumulated in the rock units in form of elastic energy, and a small proportion dissipated as inside elastic damage and elastic–plastic damage. There was almost no change for dissipated energy in the elastic stage. When entering the crack initiation stage, the elastic energy still kept increasing, just as before. However, the dissipated energy obviously increased due to the crack initiation. Once the crack damage stage was reached, the dissipated energy displayed a more dramatic rise resulting

from the crack initiation and coalescence. The elastic energy remained almost constant, as in the crack initiation stage except for the high-water material. The elastic energy of the high-water material suffered drops before failure due to its strengthening plasticity. In conclusion, rock lithology is a control factor of energy evolution. The elastic energy density kept increasing during the whole loading process except for the strong plastic material. The dissipated energy density started to increase slowly when entering the crack initiation stage while distinctly increasing at the crack damage stage. The increase rate of the dissipated energy was closely related to the rock brittleness. The differences in energy evolution are expanded on below. Figure 6 shows the evolution of the total input energy, elastic energy, and dissipated energy of every rock.

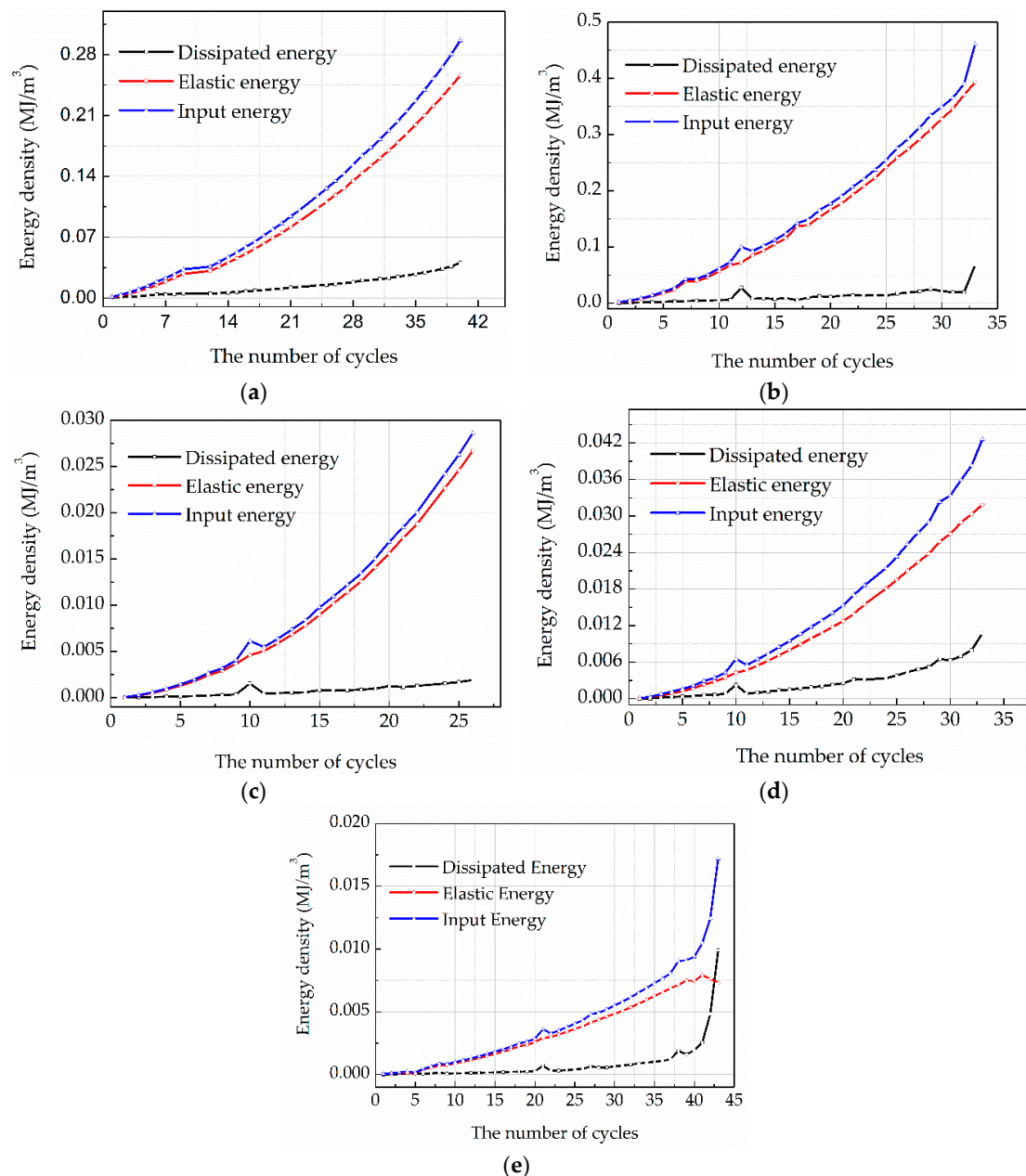


Figure 6. Energy evolution processes for different rocks. (a) Red sandstone, (b) granite, (c) coal, (d) gypsum, and (e) high-water material.

As shown in Table 3, every rock showed different energy evolution characteristics. Firstly, the total input energy represented the capacity of accumulating strain energy. The results showed that rocks with

greater strength possessed a greater capacity of accumulating strain energy. Secondly, the larger elastic energy density indicated a greater occurrence of elastic deformation, and the larger dissipated energy implied more occurrences of damage. However, the separate elastic energy density and dissipated energy density for different kinds of rock materials showed no comparability. The generation of unit elastic deformation or damage required different energy absorption and dissipation for different rock materials.

Table 3. Strain energy density at peak point for the five rock materials.

Rock Type	Granite	Red Sandstone	Coal	Gypsum	High-Water Material
Total input energy (MJ/mm ³)	0.461	0.297	0.0286	0.0426	0.0172
Elastic energy (MJ/mm ³)	0.393	0.256	0.0267	0.0319	0.0073
Accumulative dissipated energy (MJ/mm ³)	0.409	0.659	0.0242	0.0969	0.0369

Previous studies have shown that brittle rocks fail with a small amount of strain that mainly occurs in the elastic region, while ductile rocks undergo a large plastic strain without losing their bearing capacity before failure [32]. Therefore, the elastic energy ratio and the dissipated energy ratio can reflect deformation characteristics at failure. Because the thermal dissipation was neglected in our energy calculations, the dissipation energy ratio was essentially complementary to the elastic energy ratio. Hence, only the dissipation energy ratio was calculated, as follows:

$$K_d = \frac{U_d}{U}, \quad (5)$$

The results of K_d are shown in Figure 7. The evolution of K_d exhibited three obvious stage characters. In the crack closure stage, K_d is at a higher level due to compression of fissures. As the load increased, K_d decreased in the elastic stage. In this stage, the dissipated energy ratio for gypsum and red sandstone were around 18%, and it was 10% for coal, gypsum, and the high-water material. While entering the crack initiation stage, K_d experienced a sharp increase for the high-water material and gypsum. There was also a small increase for red sandstone. However, there was no significant change for coal and granite. At the peak point, K_d was 0.57 for the high-water material, 0.25 for gypsum, 0.14 for red sandstone, 0.067 for coal, and 0.049 for granite; the results are summarized in Figure 8. In general, the elastic energy was always in a dominant position during the deformation process. It seemed that the more brittle rocks had a lower dissipation energy ratio but a higher elastic energy ratio at failure.

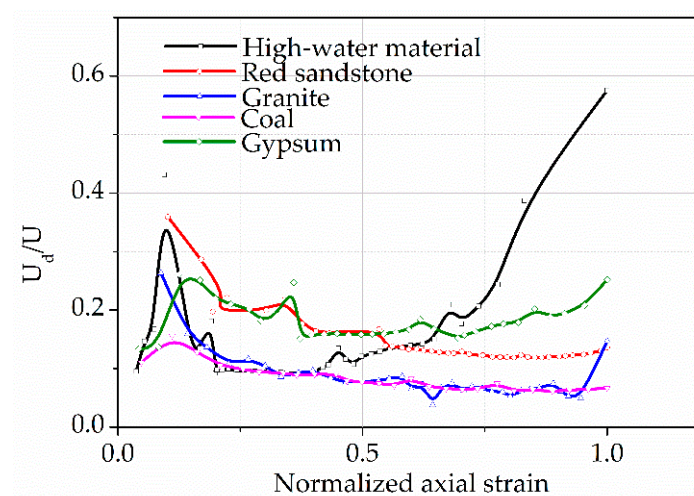


Figure 7. Evolution of the ratio of dissipated energy to total input energy for the rocks.

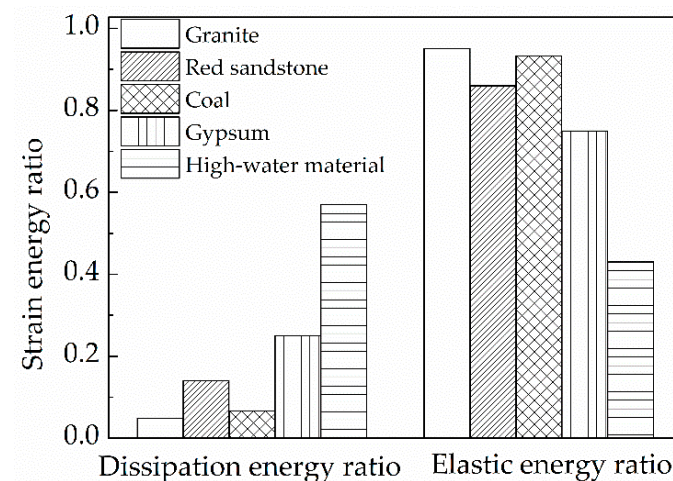


Figure 8. The dissipation energy ratios and elastic energy ratios for the five rock materials.

4.3. The Energy Preservation Index

As mentioned above, the rate of dissipation energy during the crack initiation and crack damage stages showed obvious differences between the five rock materials, as is clearly shown in Figure 9. The rate of dissipation energy represented the speed of damage. It was found that the damage degree of the five rock materials had great differences. It was unreasonable to study the rockburst potential from just one aspect of elastic energy or dissipated energy. Therefore, to further understand the differences in energy balance for the rocks, the ratio of elastic strain energy to dissipated energy (K_{ED}) was analyzed. It is defined as Equation (6):

$$K_{ED} = \frac{U_e}{U_d}, \quad (6)$$

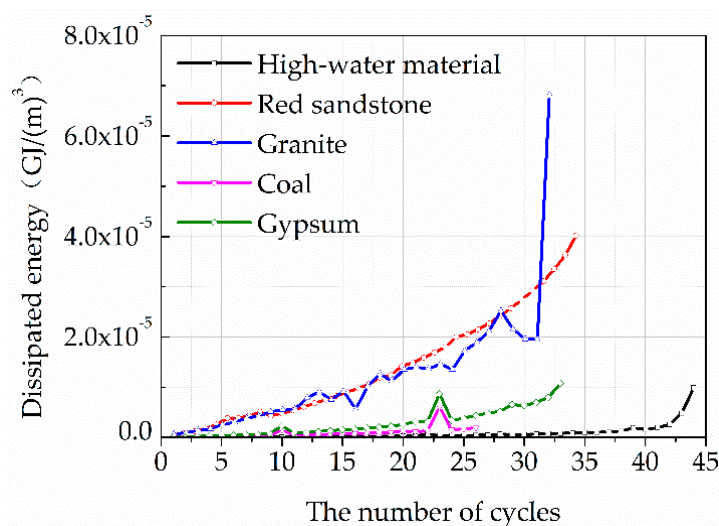


Figure 9. Variation of dissipated energy for different rocks.

The evolutions of K_{ED} for different rocks during the entire deformation process are shown in Figure 10. The K_{ED} of the five rocks all increased at first and then decreased with the increase of deformation. At the initial stage, K_{ED} showed a slight drop due to the compression of fissure. When the elastic deformation stage came, K_{ED} increased to accumulate elastic energy at a descending rate. As damage increased, K_{ED} began to decrease due to the initiation and joint of cracks inside the rocks. The extent of crack development depended on the extent of dissipated and accumulated energy.

Damage weakened the ability of the energy preservation of the rock. Lithology was found to be a major factor affecting the damage evolution and energy evolution modes. When more energy was dissipated, less elastic energy was accumulated, which meant less energy could be released at failure, as with the high-water material and gypsum. Inversely, when less energy was dissipated, more elastic energy was accumulated, which implied more energy was released at failure, as with granite. Another two modes of energy evolution were personified by the coal and red sandstone. For the mode of red sandstone, there was more absorbed elastic energy and more dissipated energy. As for the mode of coal, there was relatively less elastic absorption and less energy dissipation. As discussed above, the energy accumulated for rock rupture was depended on the interaction between the absorbed elastic energy and the dissipated energy. We defined the interaction as the energy preservation ability of rocks. Therefore, the ability of energy preservation can affect the storage energy used for release at failure and, thus, further affect rockburst potential.

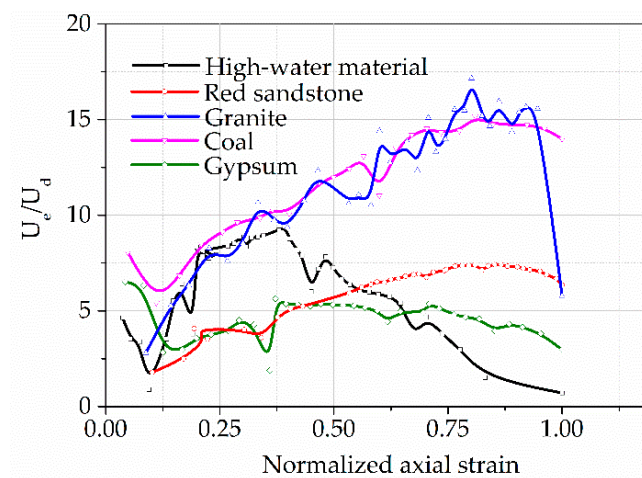


Figure 10. Evolution of the ratio of elastic strain energy to dissipated energy (K_{ED}) for the rocks.

As mentioned above, the decreasing ratio of K_{ED} can effectively characterize the energy preservation ability of rocks during the weakening stage. In fact, the energy preservation ability of rocks determines their rockburst potential. A stronger ability of energy preservation means a higher rockburst potential. Therefore, the decreasing ratio of K_{ED} is proposed as the strain energy preservation index (W_p). Figure 11 shows the calculation method for W_p . W_p is obtained by:

$$W_p = 1 - \frac{K_{ED}^p - K_{ED}^f}{K_{ED}^p} = \frac{K_{ED}^f}{K_{ED}^p}, \quad (7)$$

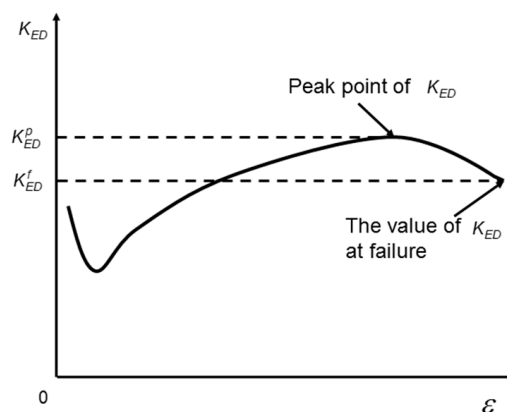


Figure 11. Calculation of the energy preservation index.

Based on K_{ED} , W_p of each rock specimen are given according to Equation (7) (see Table 4). In the weakening stage, the K_{ED} of the high-water material decreased from 9.39 to 0.703 and reduced by 92.5%. The K_{ED} of gypsum dropped by 44.61% from 5.36 to 2.96. For red sandstone, K_{ED} fell by 14.56% from 7.42 to 6.33. There was also a 7.81% decrease of K_{ED} for coal. Additionally, it should be noticed that the fall of the last cycle for granite was not considered in the weakening stage because the granite was destroyed at this cycle. From the stress–strain curve of granite, it can be seen that the peak stress was equal to the stress of the last cycle. The reason why it is not unstable at this circle is the hysteretic behaviors in rocks and the sudden unloading process. Therefore, the drop ratio of K_{ED} for granite was 2.2%. In summary, W_p of the five rocks were ranked as granite, coal, red sandstone, gypsum and the high-water material. Accordingly, the rockburst potential of the five rocks was also in this order, as presented in the previous section.

Table 4. The strain energy preservation indices of five rock materials.

Rock Type	Granite	Red Sandstone	Coal	Gypsum	High-Water Material
K_{ED}^p	15.94	7.42	15.17	5.36	9.393
K_{ED}^f	15.58	6.33	13.99	2.96	0.703
$W_p(\%)$	97.8	85.4	92.2	55.4	7.6

Gong et al. developed an energy storage index (W_{et}^p) to assess rockburst potential [13]. The W_{et}^p index was defined as U_e/U_d , corresponding to the peak compressive strength of the rock specimen. Based on the experimental data, the W_{et}^p index was calculated for the five rock materials, as shown in Figure 12.

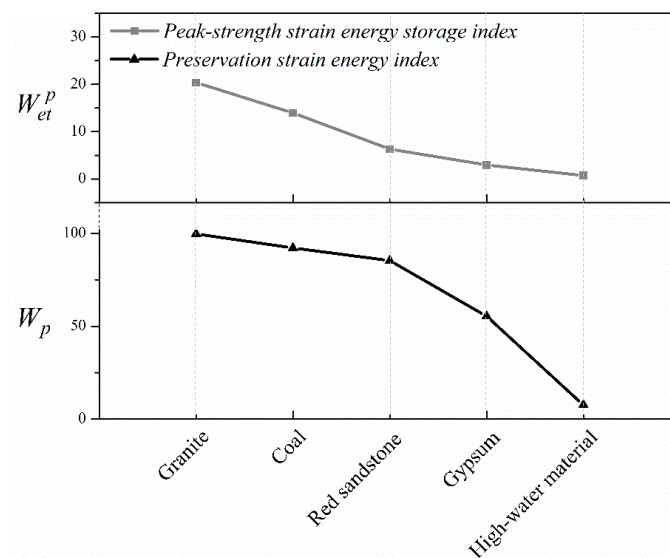


Figure 12. The indexes for rockburst tendency of five rock materials.

From Figure 12, it can be seen that the W_p index corresponded well to the W_{et}^p index for all rock materials. The W_{et}^p index represents the strain energy storage ability. Additionally, the bigger W_{et}^p index implies a stronger energy storage ability and a greater rockburst potential. At the meantime, the bigger W_p index implied the stronger strain energy preservation ability and the greater rockburst potential. The results showed that the W_p index was a good index for evaluating the rockburst potential. The W_p index will be instrumental in forecasting rockbursts, and forecasting is an important component in safety management.

5. Analysis of Rockburst Based on W_p

Rockburst is a dynamic instability process resulting from instantaneous elastic energy release accumulated in rocks [8–11]. Acoustic emission (AE) can capture and record the energy dissipation process during the entire loading process [33,34]. Thus, the AE characteristics of rock samples in the failure process were studied for the evaluation of the rockburst potential. AE parameters include AE count, amplitude, rise time, duration time, and AE energy rate. Those parameters have been widely applied to analyze the AE characteristics and evaluate the damage of materials [35–37]. The AE energy rate can be proportional to the true energy [38]. The AE energy is preferred for analyzing the AE characteristics over the AE count. Therefore, The AE energy and cumulative AE energy were chosen to analyze the AE test results, as shown in Figure 13.

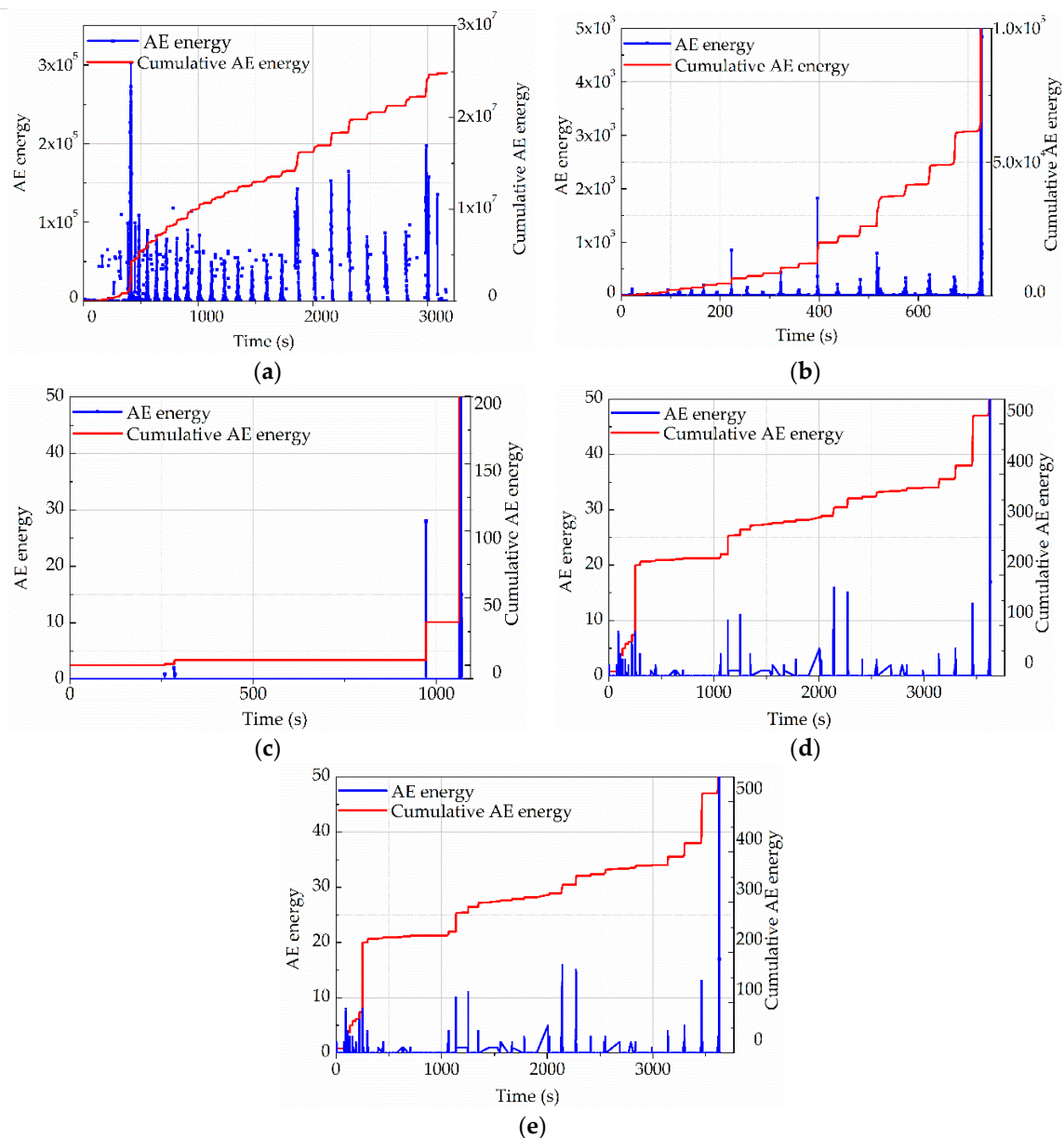


Figure 13. Cumulative acoustic emission (AE) energy and AE energy rate with respect to time. (a) Granite, (b) coal, (c) high-water material, (d) red sandstone, and (e) gypsum.

As shown in Figure 13, at the fracture failure stage, AE energy increased rapidly on account of the original cracks' growth, the initiation of numerous cracks, and crack convergence. Compared to the other

four rocks, the energy–time curve of the high-water material was less hopping. Owing to the bonding properties between particles, the high-water material was difficult to destroy. The failure duration of the high-water material was obviously longer than that of the other four rocks. The energy–time curves for granite, coal, red sandstone, and gypsum all show small step changes, especially when entering the yield stage. At the fracture failure stage, the step amplitudes of the cumulative AE energy were 1.57×10^5 for granite, 1.94×10^4 for red sandstone, 8.34×10^4 for coal, 1.15×10^3 for gypsum, and 4.93×10^3 for the high-water material.

The more released energy per unit time at the failure stage implies the severer failure. The step amplitude at the failure stage, and the failure durations of the rocks are listed in Table 5. As shown, the granite had the maximum step amplitude at the failure stage, followed by coal, red sandstone, the high-water material, and gypsum. From the stress–strain curves, the failure duration can be obtained. The failure durations were 0.5 s for granite, 0.8 s for red sandstone, 1 s for coal, 1.5 s for gypsum, and 8 s for the high-water material. The released strain energy per unit time was ranked as granite, coal, red sandstone, gypsum, and the high-water material in decreasing order. This implies that the failure intensity was also ranked as granite, coal, red sandstone, gypsum, and the high-water material.

Table 5. The failure duration and the step amplitude at the failure stage for five rock materials.

Rock Type	Granite	Coal	Red Sandstone	Gypsum	High-Water Material
Step amplitude at failure	1.57×10^5	8.34×10^4	1.94×10^4	1.15×10^3	4.93×10^3
Failure duration (s)	0.5	1	0.8	1.5	8
Released energy per unit time	3.14×10^5	8.34×10^4	2.43×10^4	7.67×10^2	6.16×10^2

In addition to the AE characteristics, the failure mode is also an important feature that reflects rockburst potential [13]. Figure 14 presents the failure modes of the five rock materials. The high-water material was almost integrated with small-scale cracks across the sample after failure, which demonstrated that the high-water material has no burst potential. For gypsum, only a macroscopic crack and a small amount of rock fragments were formed at failure. These phenomena indicated that gypsum has a weak rockburst potential. However, a large quantity of rock fragments were produced at failure for coal, red sandstone, and granite. The failure of granite showed more obvious ejection phenomenon, as shown in Figure 14a. Therefore, the rockburst potential of coal, red sandstone, and granite was high, and the rockburst potential of granite was higher than that of coal and red sandstone.

After the analysis of the AE characteristics and the failure modes, the rockburst potential was able to be graded into four levels: no, weak, relatively strong, and strong. The statistical results are listed in Table 6. A W_p index greater than 0.978 indicates a strong rockburst potential with high-level release energy and more fragments at failure, such as with granite. A W_p index between 0.85 and 0.92, such as that for coal and red sandstone, represents a relatively strong rockburst potential. The W_p index of gypsum was 0.55, corresponding to a weak rockburst potential. There was no rockburst potential for a W_p index below 0.076, as exhibited by the high-water material.

As shown in Table 6, the W_p index was a good index for describing the rockburst potential. Compared to the criterion with the W_{et}^p index, the evaluation of rockburst potential for relatively brittle rocks by the W_p index was more sensitive. However, the weaknesses of the method proposed in this paper are the lack of energy analyses in the post-peak stage due to the uncontrollability of post-peak deformation under uniaxial compression. The influence of the stiffness of the loading system was also neglected in the analysis of rock failure. Additionally, due to the kind of the laboratory experiments performed, a field rockburst case analysis was missing. In view of those weaknesses, future experiments and analyses will be improved. The proposed method should be verified by a case study, including a rockburst in an underground space before it can be used to evaluate the rockburst potential for a large-scale project.



Figure 14. Failure mode of five rock materials. (a) Granite, (b) gypsum, (c) red sandstone, (d) coal, and (e) high-water material.

Table 6. The failure characteristics of five rock materials.

Rock Type	AE Energy	Failure Mode	W^p	Rockburst Proneness
Granite	Great	Numerous fragments	0.978	High
Coal	Relatively great	Numerous fragments	0.922	Relatively high
Red sandstone	Relatively great	Numerous fragments	0.854	Relatively high
Gypsum	Minor	A macroscopic	0.554	Low
High-water material	Minimum	Small cracks	0.076	No

6. Conclusions

Based on the uniaxial compression and cyclic loading–unloading uniaxial compression tests of five rock materials, the stress–strain curves and energy evolution processes of five rock materials were analyzed. The energy preservation index was defined with a decreasing ratio of U_e/U_d . In addition, the AE characteristics and failure mode were discussed. The main conclusions are shown as follows:

(1) The energy evolution characteristics were analyzed based on the stress–strain relationship. The results showed that the more brittle rocks had the higher elastic energy proportion and the lower dissipated energy proportion. Additionally, the ductile rocks showed a faster energy dissipation before failure.

(2) Based on the energy evolution characteristics, an energy preservation index (W_p) was proposed. This index revealed the weakening degree each rock material at the weakening stage. In addition, according to the AE characteristics and failure modes, the actual rockburst potentials of five kinds of rocks were analyzed. It was revealed that the W_p index is a good index that can contribute to the assessment of rockburst potential.

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