

Article

Study on the Loading Rate Effect of Mechanical-Energy Properties and Acoustic Emission Characteristics of Rock-like Materials

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Abstract

In goafs formed by underground mineral resource extraction, the remaining pillars are often subjected to uniaxial loading at different loading rates, and their mechanical responses and failure mechanisms directly affect the long-term stability of the goafs. This study uses rock-like materials to conduct uniaxial compression tests at loading rates ranging from 0.001 mm/min to 0.05 mm/min, combined with acoustic emission (AE) monitoring, to systematically investigate the effects of loading rate on the mechanical properties, energy distribution, constitutive model, and AE characteristics of the material. The results show that an increase in loading rate significantly enhances the stiffness and strength of the material, promotes a transition in failure mode from a shear–tension composite to tension-dominated, intensifies brittle characteristics, and simultaneously inhibits full crack development and fragments generation. In terms of energy evolution, an increased loading rate enhances the pre-peak total strain energy and elastic strain energy storage but reduces the efficiency of energy dissipation, leading to an intensified mismatch between energy storage and dissipation capacities at peak stress. A damage variable induced by loading rate was proposed, and a damage constitutive model considering the loading rate was established, with the theoretical curves showing good agreement with the experimental data. AE characteristic analysis further reveals that an increase in loading rate causes the crack type to transition from shear-dominated to tension-dominated, and the fluctuating increase in the *b*-value reflects a reduction in pre-peak fracture scale and a decrease in the degree of material fragmentation. The research findings are expected to deepen the understanding of the damage and failure mechanisms of rock materials under different loading rates, thereby laying a research foundation for the stability assessment of goaf pillars and disaster warning.



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1. Introduction

With the continuous growth in the global economy and the acceleration of industrialization, mineral resources, as the fundamental support for national economic development,

are experiencing a significant trend towards large-scale, intensive, and deep mining operations [1–4]. To meet the growing demand for resources, mining enterprises are continuously expanding their mining scales, with stope structures becoming increasingly complex and mining intensity continuing to rise. Against this backdrop, the open-stope mining method has been widely adopted due to its technical and economic advantages in accommodating large-scale mining, resulting in the formation of large-volume goafs underground [5]. To control stope ground pressure and maintain the stability of overlying strata, a large number of pillars are typically left in place during mining design [6,7]. These pillars, serving as the core structural elements that bear the load of the overlying strata, have their stability and failure characteristics directly related to the safety of the entire mining area [8].

During the mining production process, the mechanical environment in which the pillars are situated is not constant [9]. As the scale of the goaf continues to expand, the process of ground pressure redistribution occurs continuously [10]. In particular, the extraction of adjacent stopes, the caving of ore, and the adjustment of stope structural parameters all lead to the gradual transfer and concentration of stress acting on the pillars [11–14]. Variations in the stress rate adjustment process determine the significant differences in the actual loading rates experienced by the pillars [15]. Specifically, during periods of relatively stable mining activity, the rate of stress change is low, and the pillars are in a state of slow loading; whereas during phases of high mining intensity, stress transfer is more rapid, resulting in the pillars being subjected to relatively fast loading.

Extensive mining rock mechanics tests and engineering practices have shown that loading rate is one of the key factors affecting the mechanical response characteristics of rock materials. Gao et al. [16] investigated the mechanical behavior and deformation characteristics of coal samples under different mining rates using uniaxial compression tests and digital image correlation methods. They identified a threshold range of loading rate for coal samples and revealed the differences in failure mechanisms under different loading rates. Wang et al. [17] conducted uniaxial compression tests on coal–rock composite specimens under different loading rates, and combined with AE monitoring and SEM meso-analysis, systematically revealed the influence of loading rate on the mechanical behavior, energy evolution, and macro–meso-damage characteristics of the composite. They found that an increase in loading rate significantly shortened the failure response time, increased the number of cracks and AE energy, and enhanced the brittle failure characteristics. Zhang et al. [18] conducted uniaxial compression tests on deep sandstone under five loading rates, systematically revealing the influence of loading rate on the mechanical properties, failure mode, energy evolution, and damage variables of deep sandstone. They found that the peak strength, elastic modulus, and various types of strain energy all increased with increasing loading rate, and the rock mass transitioned from plastic–elastic–plastic to plastic–elastic behavior with intensified damage. Shen et al. [19] conducted cyclic loading–unloading tests under different loading rates and freeze–thaw cycles, systematically revealing the fatigue mechanical behavior and damage evolution mechanism of sandstone under the coupled effect of freeze–thaw damage and loading rate. They found that although a high loading rate could increase cyclic strength, it could not alter the dominant role of strength deterioration after more than 30 freeze–thaw cycles, and a high loading rate promoted the development of shear cracks and induced sudden instability. Wen et al. [20] conducted uniaxial loading tests on coal–rock composites under three strain rates, simultaneously monitoring AE ring count, energy, surface strain, and temperature changes. Combined with PFC3D numerical simulation and the Weibull micro-damage model, they systematically revealed the influence of strain rate on the strength, elastic modulus, failure mode, and energy evolution of the composite. They found that under low strain rates, progressive failure and strain localization characteristics were observed, while under high strain rates,

brittle sudden failure occurred with rapid overall temperature rise. In summary, the loading rate is a significant factor leading to the differentiation of rock failure characteristics [21].

In existing research, many scholars have studied the loading rate effect on real rock materials, confirming the general trends of strength and stiffness enhancement with increasing rate. However, systematic investigations into the coupled effects of loading rate on energy evolution mechanisms, rate-dependent damage constitutive modeling, and multi-parametric acoustic emission characteristics remain relatively limited, particularly for homogeneous rock-like materials. Rock-like materials offer advantages such as high homogeneity and low cost, which can isolate the intrinsic rate effect from material variability and highlight the fundamental regularity of rate dependency. Therefore, taking rock-like materials as the research object, this study systematically conducts uniaxial compression tests under different loading rates to address several specific gaps in the current understanding: quantifying the rate-dependent mismatch between energy storage and dissipation, establishing a damage constitutive model that explicitly incorporates loading rate effects, and elucidating the transition in crack types and fragmentation scale through AE multi-parameter analysis. The findings have important reference value for scientifically evaluating the failure mechanism of goaf pillars and guiding safe production in underground mines.

2. Materials and Methods

2.1. Sample Preparation

Due to the disadvantages of poor homogeneity and high cost associated with real rock materials extracted from engineering sites [22], rock-like materials were adopted as the research object. The raw materials for the rock-like material and their mass ratio were P.O 52.5 Portland cement, silica fume, quartz sand, potassium feldspar, sodium feldspar, water, nano-clay, water reducer, and defoamer in a ratio of 600:180:780:390:390:265:62.4:11.7:1, where the quartz sand was composed of a mixture of 10–20 mesh, 20–40 mesh, 40–80 mesh, and 80–120 mesh quartz sand in a mass ratio of 1:1:1:1. In addition, the slurry of the rock-like material was mixed using the slurry wrapping method: First, cement, micro-silica fume, potassium feldspar, sodium feldspar, halloysite nano-clay, water reducer, defoamer, and water were mixed and stirred using a JJ-5 planetary cement mortar mixer (Shaoxing Shangyu Yueda Instrument Manufacturing Co., Ltd., Shaoxing, Zhejiang Province, China). After the slurry was uniformly mixed, the quartz sand was added, and mixing continued until the cementitious slurry with a suitable consistency evenly coated the surface of the quartz sand. The mixed slurry was poured into 150 mm × 150 mm × 150 mm cubic all-steel molds, which were then placed on a vibration table and vibrated until no obvious bubbles appeared on the slurry surface and slight bleeding occurred. The samples were then left indoors for 1 day, and after demolding, the cubic samples were placed in an SHBY-90B standard constant temperature and humidity curing box (Xianxian Leixing Luye Instrument Sales Department, Cangzhou, Hebei Province, China) at 22 °C and 95% humidity for 28 days of curing. The cured cubic samples were then drilled, cut, and ground to produce standard cylindrical samples with a diameter of 50 mm and a height of 100 mm. The specific preparation process of the rock-like material is shown in Figure 1.



Figure 1. Sample preparation process.

Samples with numerous defects and abnormal data were sequentially eliminated using direct observation, density measurement, and ultrasonic testing methods. The average density of the rock-like material finally used for the experiments was 2.2636 g/cm^3 with a range of 2.2052 to 2.3229 g/cm^3 , and the average ultrasonic wave velocity was 4.8030 km/s with a range of 4.6348 to 4.9603 km/s . In total, 12 qualified cylindrical specimens were selected for the uniaxial compression tests. These were divided into four loading rate groups, namely 0.001 , 0.005 , 0.01 , and 0.05 mm/min , with three specimens in each group. For brevity, only a representative curve from each group is shown in the subsequent figures, for which the specimen whose peak stress and elastic modulus values were closest to the group mean was selected.

2.2. Test Equipment and Test Plan

Figure 2a shows the GCTS RTR-1000L high-pressure rock testing equipment of Sichuan University, which has a maximum axial load capacity of 1000 kN , a maximum confining pressure of 70 MPa , and a maximum axial displacement rate of 700 mm/min . Axial deformation and radial deformation were measured using an axial extensometer and a radial extensometer, respectively, with a measurement range of -2.5 to 2.5 mm and a measurement accuracy of $\pm 0.25\%$. Uniaxial compression tests were conducted using this equipment, with loading rates set to 0.001 mm/min , 0.005 mm/min , 0.01 mm/min , and 0.05 mm/min , respectively. The Micro-II AE system was used to monitor in real time the AE signals generated during sample fracturing throughout the loading process, capturing real-time AE information such as amplitude, ring count, and energy. A total of six AE sensors (No. 1–No. 6) were mounted on the outer curved surface of the specimen, with their specific positions indicated in Figure 2b. Six sensors were employed to ensure that all the AE events generated during the loading process could be comprehensively captured without omission, and to satisfy the requirement that a minimum of four sensors is necessary for reliable AE event acquisition and subsequent parameter calculations (such as RA-AF and b -value analyses). The AE sensors have a resonant frequency of 150 kHz , a preamplifier gain of 40 dB , and a sampling rate set to 5 MSPS , with a threshold set at 45 dB . The AE timing parameters PDT, HDT, HLT, and maximum duration were set to $300 \mu\text{s}$, $800 \mu\text{s}$, $1000 \mu\text{s}$, and 1000 ms , respectively. It should be noted that the loading rates employed in this study fall within the static or quasi-static loading range defined in the literature [23–25]. Since in situ mine pillars are generally subjected to static loading conditions [15,23], the laboratory loading rates correspond well to the stress state experienced by actual pillars.

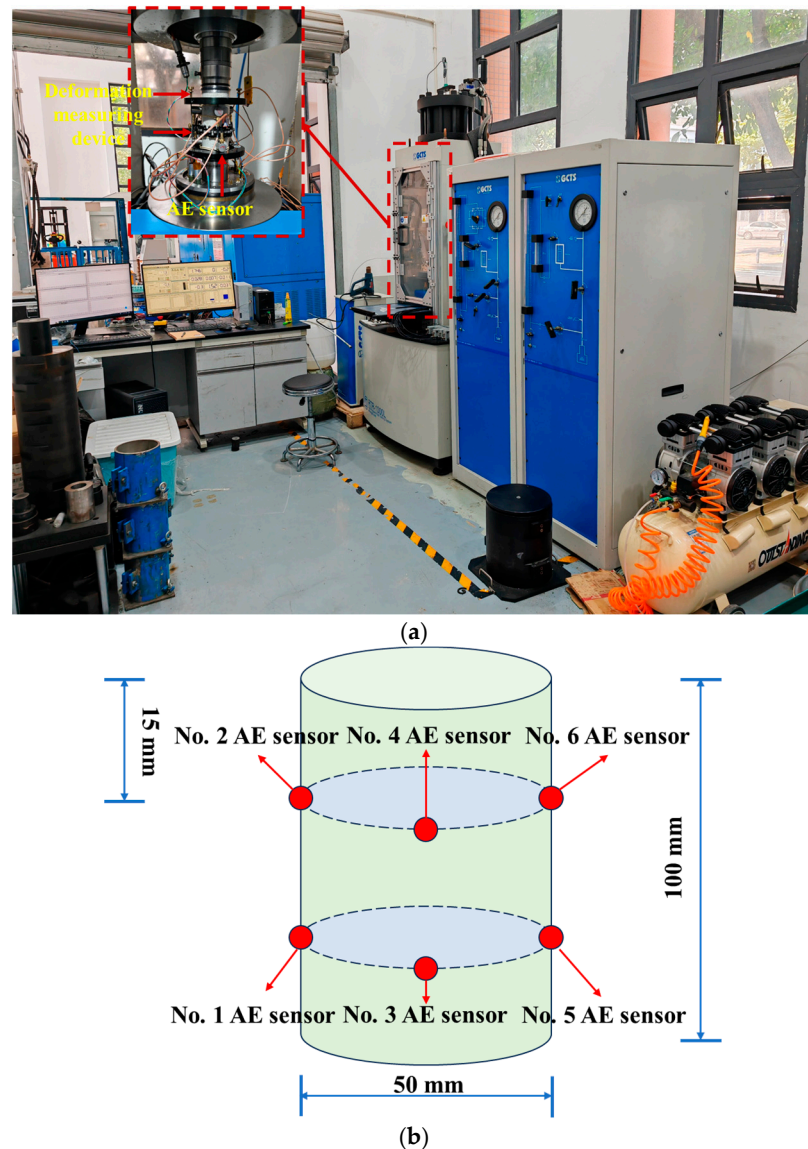


Figure 2. GCTS RTR-1000L high-pressure rock testing equipment and AE system: (a) overall and local setup diagrams of mechanical testing equipment; (b) schematic diagram of AE sensor layout.

Before the uniaxial compression test, each specimen was encased in a heat-shrinkable polyethylene tube with an initial diameter of 60 mm and a wall thickness of 0.38 mm. The tubing was heated using a heat gun until it shrank completely and achieved tight contact with the specimen surface. It should be noted that the shrinkage of the tubing may exert a minor lateral confining pressure on the specimen. However, based on the material properties and shrinkage ratio, this lateral pressure is estimated to be less than 1 MPa, which is negligible compared to the peak stress measured in this study. Moreover, the use of heat-shrinkable tubing is a common practice in uniaxial compression testing of brittle materials to prevent post-failure fragmentation and protect strain gauges, and its influence on the uniaxial test results is generally considered insignificant [26,27]. To ensure consistency, all the specimens were prepared using the identical wrapping procedure.

3. Mechanical Characteristics and Constitutive Relationship

3.1. Macroscopic Mechanical Behavior and Fracture Characteristics

The mechanical behavior of rock-like materials under different loading rates is shown in Figure 3. As shown in Figure 3a, under uniaxial compression, the rock-like material

exhibits a linear elastic stage, a plastic stage, and a post-peak stage, but no compaction stage, which is similar to the mechanical properties of real deep rocks [28]. In addition, the rock-like material exhibits typical brittle failure characteristics [29]. As shown in Figure 3b, with the loading rate increasing from 0.001 mm/min to 0.05 mm/min, both the peak stress and elastic modulus increase nonlinearly. Compared to the baseline rate of 0.001 mm/min (peak stress 82.54 MPa, elastic modulus 23.95 GPa), the peak stress increases by 13.75%, 25.16%, and 59.83% at loading rates of 0.005, 0.01, and 0.05 mm/min, respectively. Correspondingly, the elastic modulus increases by 11.36%, 13.41%, and 45.58% at the same loading rates. This is because a faster increase rate of axial stress prevents microcracks in the rock-like material from fully developing, resulting in increased material stiffness and correspondingly higher strength. It should be noted that in conventional stress–strain curves, the initial non-linear segment observed corresponds to the closure of pre-existing microcracks and pores within rock-like materials [30]. Although this stage is not pronounced in the present study, the elastic modulus for each specimen was determined from the linear portion of the stress–strain curve, which consistently fell within the range of 40% to 50% of the peak stress, in accordance with standard rock mechanics-testing procedures.

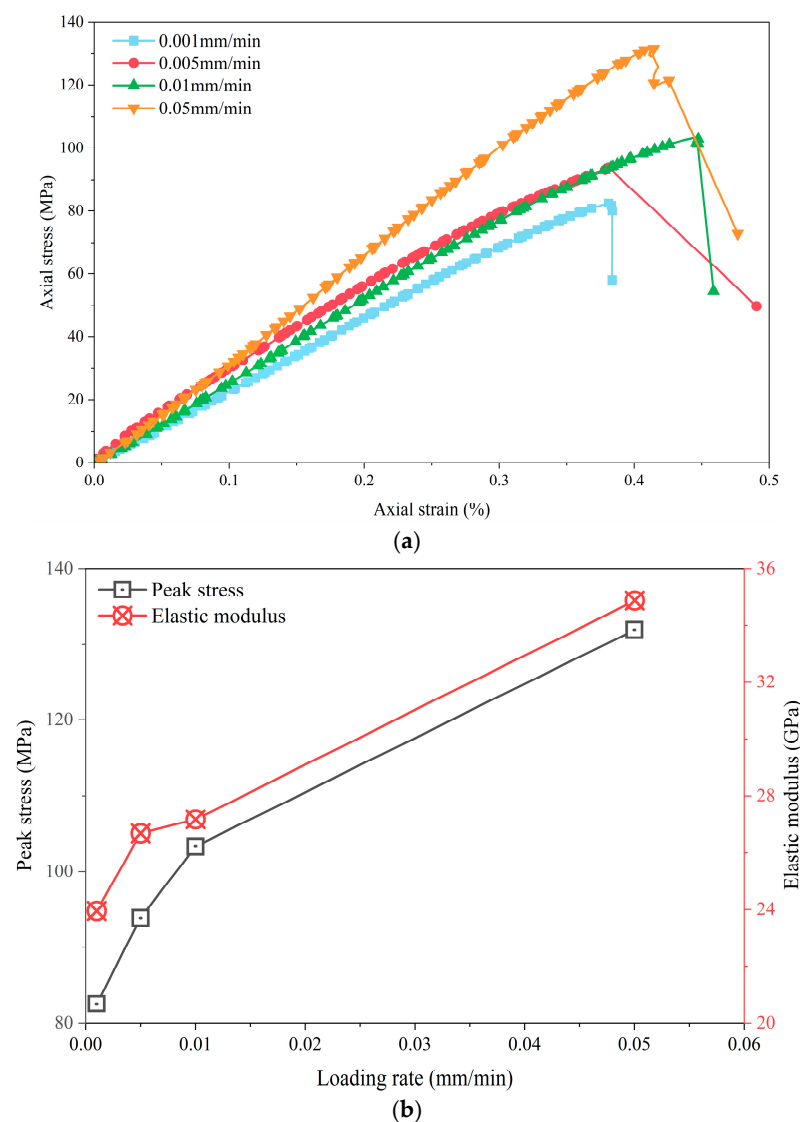


Figure 3. Mechanical behavior of rock-like materials under different loading rates: (a) stress–strain curve; (b) strength parameter.

Close-up photographs of the samples after loading were taken to record the fracture distribution on the sample surfaces, as shown in Figure 4. It can be seen from the figure that the heat-shrinkable tubing tightly wrapped around the specimens effectively preserved the original morphology of the fractures. As the loading rate increases, the fracture features on the specimen surface become progressively clearer, while the angle between the main fracture propagation direction and the axial stress loading direction, as well as the amount of fragments near the fractures, gradually decrease. At the lowest loading rate of 0.001 mm/min (Figure 4a), the specimen exhibits a shear–tension composite failure mode with relatively dispersed cracking and a noticeable amount of fragments. At 0.005 mm/min (Figure 4b), the main fracture becomes more distinct, and the failure mode begins to shift toward tension-dominated behavior. At 0.01 mm/min (Figure 4c), the fracture propagation direction further aligns with the axial loading direction, and fragment generation is reduced. At the highest loading rate of 0.05 mm/min (Figure 4d), the failure is clearly tension-dominated, characterized by a well-defined axial tensile crack with minimal fragments, indicating pronounced brittle behavior. A lower loading rate implies that the material is subjected to the adverse effects of loading for a longer duration before peak failure, allowing microcracks to fully develop during the pre-peak stage, thereby resulting in the absence of prominent large-scale cracks. From the perspective of the main fracture propagation direction, an increase in the axial loading rate causes the crack development direction to approach the direction of stress application, with the failure mode transitioning from a shear–tension composite failure to tension-dominated failure, and the brittle failure characteristics become increasingly pronounced. In addition, the amount of fragments generated shows a clear decreasing trend with increasing loading rate. This also demonstrates that a high loading rate subjects the material to a shorter duration of loading, and the macroscopic manifestation of insufficient crack interconnection is that the material remains relatively intact, resulting in a smaller amount of fragments.

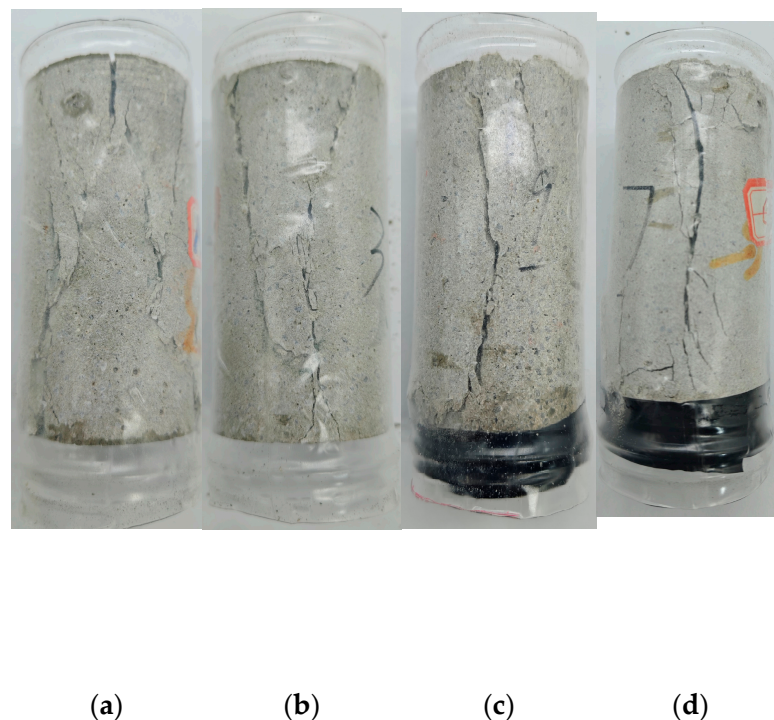


Figure 4. Fracture characteristics of rock-like materials under different loading rates: (a) 0.001 mm/min; (b) 0.005 mm/min; (c) 0.01 mm/min; (d) 0.05 mm/min.

3.2. Energy Evolution Mechanism

The stress–strain curve is commonly used to describe the complex mechanical behaviors of materials such as rock and concrete under external loading, including compression, fracturing, and dilatancy. However, this is merely an external description of the mechanical state of the material, which essentially originates from energy distribution [31]. Therefore, analyzing deformation and failure from the perspective of energy conversion is an effective approach to understanding the characteristics of mechanical responses. The total strain energy (U_t) of the rock-like material is transformed into elastic strain energy (U_e) and dissipated strain energy (U_d). The calculation equations for each energy index are as follows [32]:

$$\begin{cases} U_t = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 \\ U_e = \frac{\sigma_1^2}{2E} \\ U_d = U_t - U_e \end{cases} \quad (1)$$

where σ_1 is the axial stress, MPa; ε_1 is the axial strain, %; and E is the elastic modulus, GPa.

A schematic representation of these energy indexes is provided in Figure 5, where the area under the loading curve represents U_t , the triangular area represents U_e , and the enclosed area between the loading curve and triangular area represents U_d .

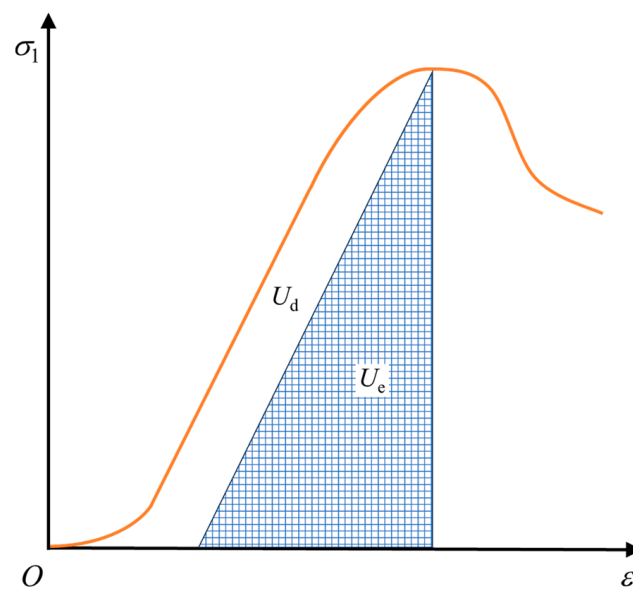


Figure 5. Schematic diagram of the relationship between elastic strain energy and dissipated strain energy under uniaxial loading conditions.

Using Equation (1), U_t , U_e , and U_d during the deformation and failure process of rock-like materials under uniaxial compression were calculated respectively. The evolution patterns of each energy index of rock-like materials with the axial stress–axial strain curve under different loading rates are shown in Figure 6. Overall, during the pre-peak stage, U_t , U_e , and U_d all exhibit a nonlinear increasing trend, reflecting that the material remains in a state of energy conversion under loading, with only the proportions of energy distribution within the material varying. Specifically, in the initial loading stage, U_t and U_e are relatively close, with the majority of U_t being converted into U_e , while U_d remains close to zero. When the axial load gradually approaches the peak stress, its growth rate decreases, and a relatively larger proportion of U_t is converted into U_d . This is because the material enters the plastic stage, where microcracks gradually develop and interconnect, leading to a significant increase in U_d . In the post-peak stage, as the axial stress decreases, U_e exhibits a

variation similar to that of the axial stress, while U_d shows a sharp increasing trend overall. This is because the strain energy is primarily consumed in forming large-scale fractures during peak failure, resulting in a significant increase in U_d .

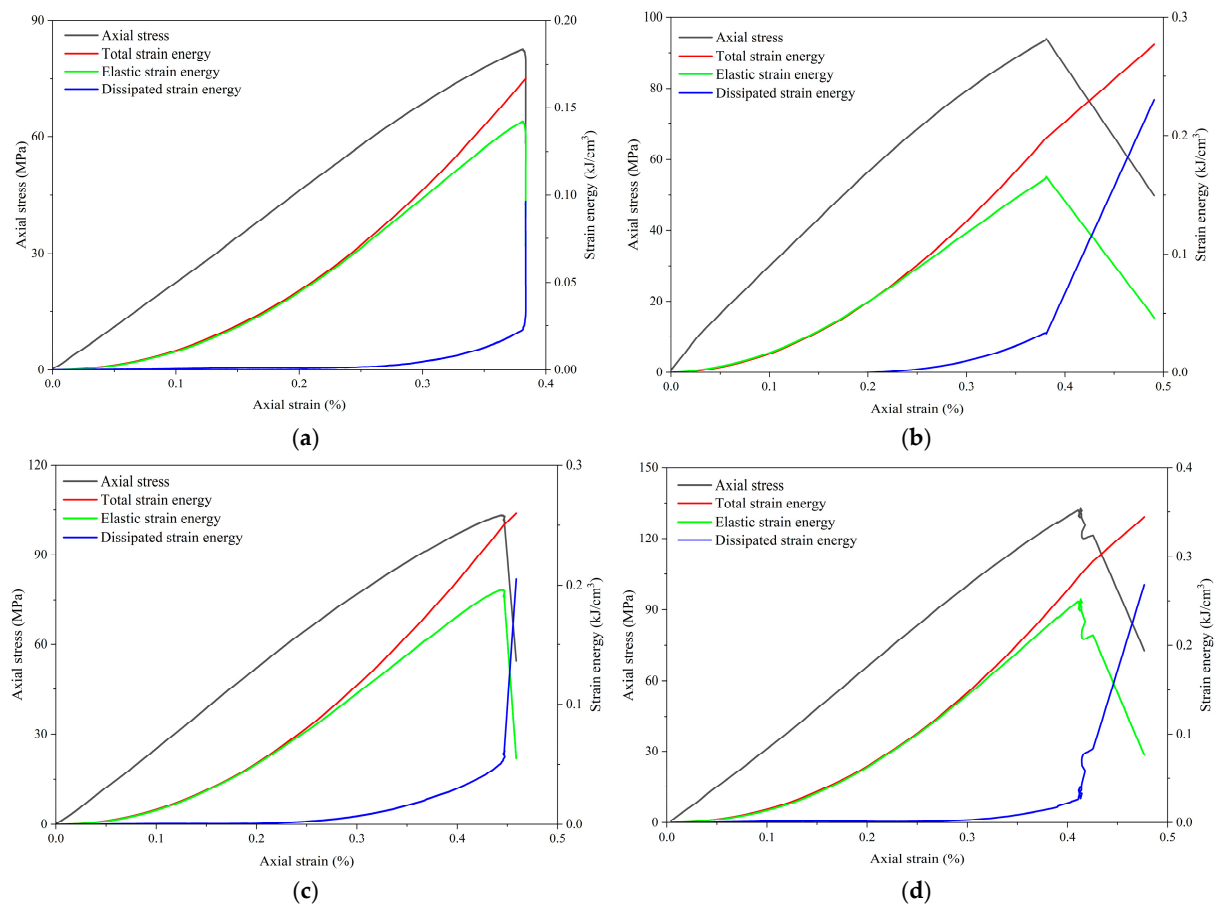


Figure 6. Axial stress–axial strain–energy curves of rock-like materials under different loading rates: (a) 0.001 mm/min; (b) 0.005 mm/min; (c) 0.01 mm/min; (d) 0.05 mm/min.

To better compare the influence of loading rate on energy indices, a graph showing the variation in energy indices at peak stress under different loading rates is presented in Figure 7. An increase in loading rate significantly increases U_t and U_e , whereas its effect on U_d is not evident. This implies that an increase in loading rate leads to insufficient crack development, enhancing the material's resistance to elastic deformation and its load-bearing capacity, and consequently, the energy input and stored in the material also increase correspondingly. Further calculation of the difference between U_e and U_d at peak stress reveals that it increases from 0.1194 kJ/cm³ to 0.2229 kJ/cm³ as the loading rate increases. This essentially reflects that a faster increase rate of axial load leads to an increasing mismatch between the material's energy storage and dissipation capacities. Under high loading rates, the material stores a large amount of energy at peak stress while dissipating relatively little, indicating that the material tends more toward storing energy rather than dissipating it. This indicates that the brittle characteristics of the material become more pronounced.

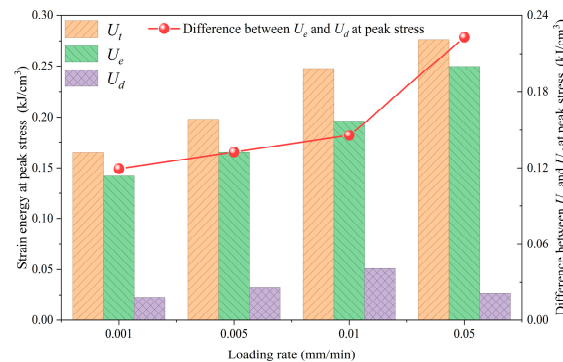


Figure 7. Energy index at peak stress under different loading rates.

3.3. Damage Constitutive Model Considering the Influence of Loading Rate

Previous studies have shown that the material damage constitutive model and damage variable considering only uniaxial compression conditions are as follows [33,34]:

$$\begin{cases} \sigma_1 = E_0 \varepsilon_1 (1 - D_M) \\ D_M = 1 - \exp \left[- \left(\frac{\varepsilon_1}{F_0} \right)^m \right] \end{cases} \quad (2)$$

where E_0 is the initial elastic modulus, GPa; D_M is the damage variable induced by axial load; and F_0 and m are the Weibull parameters, respectively. It should be noted that in this study, the elastic modulus of the rock-like material under a loading rate of 0.001 mm/min is taken as the initial elastic modulus.

Material damage is influenced by multiple factors, with load being only one of them. According to the previous study, the loading rate also induces changes in the damage state of the material. Therefore, it is necessary to establish a material damage constitutive model that considers the dual influencing factors of load and loading rate. Drawing on the principles for defining non-load-related damage variables such as high-temperature damage and freeze-thaw damage, the damage variable D_v induced by loading rate is defined as follows [35,36]:

$$D_v = 1 - \frac{E_v}{E_0} \quad (3)$$

where E_v is the elastic modulus at a given loading rate, GPa.

Because the total damage (D_T) of the material cannot be obtained by simply superimposing the damage induced by load and the damage induced by loading rate, the total damage of the material can be expressed according to the strain equivalence principle as follows:

$$D_T = D_M + D_v - D_M D_v \quad (4)$$

Then, by substituting Equations (3) and (4) into Equation (2), a damage constitutive model and damage variable considering the influence of loading rate can be established as follows:

$$\begin{cases} \sigma_1 = E_0 \varepsilon_1 (1 - D_T) \\ D_T = 1 - \frac{E_v}{E_0} \exp \left[- \left(\frac{\varepsilon_1}{F_0} \right)^m \right] \end{cases} \quad (5)$$

The expressions for the Weibull parameters are obtained based on the geometric characteristics of the stress–strain curve as follows:

$$\begin{cases} F_0 = \varepsilon_p m^{\frac{1}{m}} \\ m = \frac{1}{\ln \frac{E_{ep}}{\sigma_p}} \end{cases} \quad (6)$$

where σ_p is the peak stress, MPa, and ε_p is the axial strain corresponding to the peak stress, %.

By substituting the model parameters F_0 , m , and E of the rock-like material under different loading rates, the theoretical curves of the constitutive relationship are compared with the experimental values, as shown in Figure 8. It can be seen that the two are in good agreement. The predictive accuracy of the model was evaluated using both the Root Mean Square Error (RMSE) and the coefficient of determination (R^2). The RMSE values were calculated as 1.32 MPa, 2.62 MPa, 2.63 MPa, and 4.19 MPa for loading rates of 0.001, 0.005, 0.01, and 0.05 mm/min, respectively. In addition, the R^2 values were determined to be 0.9972, 0.9906, 0.9930, and 0.9889, respectively. All R^2 values exceed 0.98, demonstrating that the developed damage constitutive model provides an excellent fit to the experimental data and reliably captures the rate-dependent mechanical response of the rock-like material.

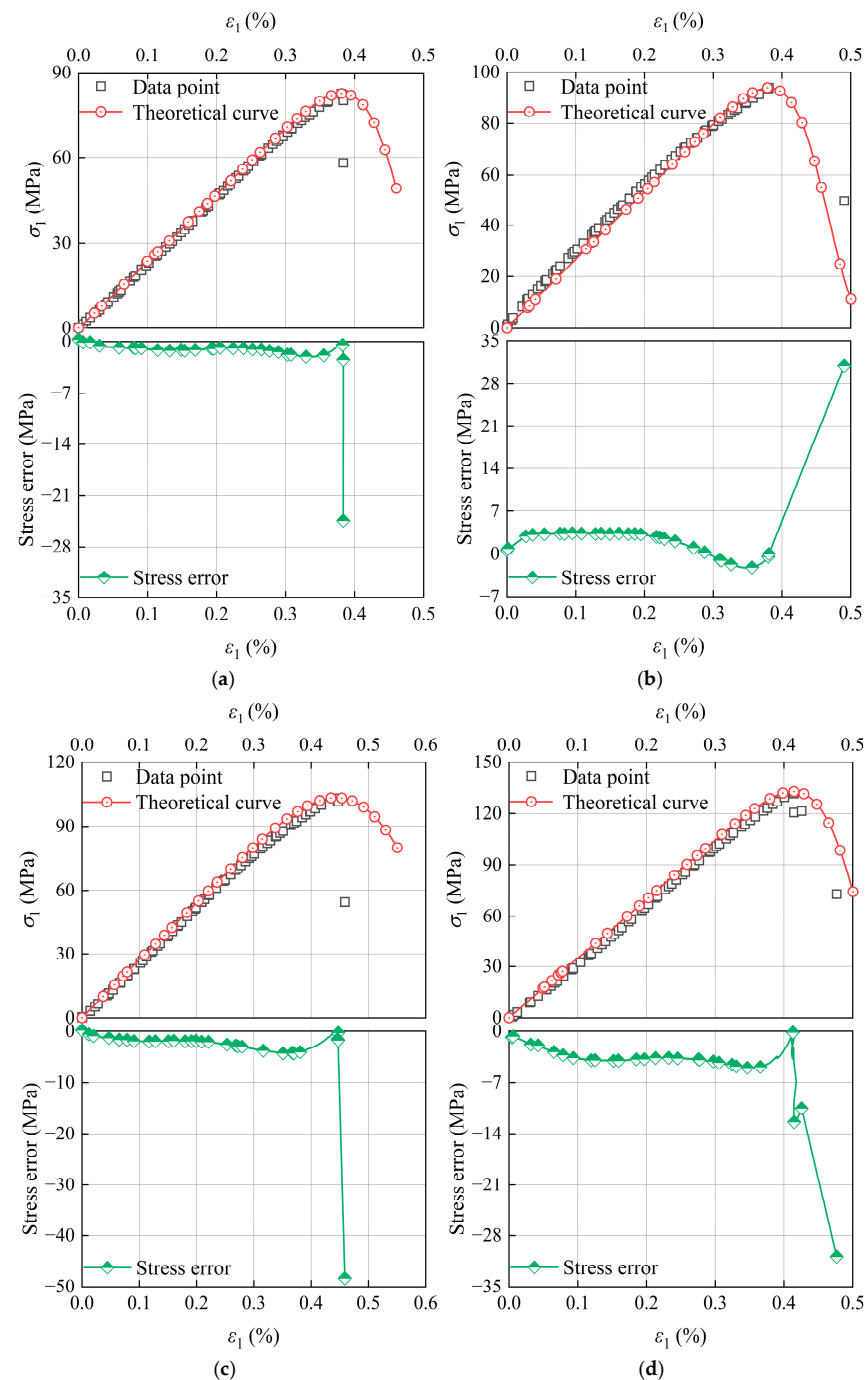


Figure 8. Comparison of experimental and theoretical curves of rock-like materials under different loading rates: (a) 0.001 mm/min; (b) 0.005 mm/min; (c) 0.01 mm/min; (d) 0.05 mm/min.

4. AE Characteristics

4.1. RA-AF Relationship

AE technology can non-destructively obtain fracture information from within the material. Since the crack evolution type is closely related to the failure mechanism of the material, accurately identifying the crack type has become a key aspect of AE signal analysis. Among these methods, the approach based on the ratio between the RA value (rise time/amplitude) and the AF value (average frequency) is currently a commonly used and effective method for distinguishing crack types [37,38]. The ratio of the maximum AF value ($AF_{\max}$) to the maximum RA value ($RA_{\max}$) was adopted as the threshold for distinguishing tensile cracks from shear cracks; specifically, when the ratio exceeds this threshold, the crack is classified as a tensile crack, otherwise it is classified as a shear crack. Based on this method, scatter plots of RA values and AF values over time for rock-like materials under different loading rates were processed and plotted, as shown in Figure 9. It can be observed that the correlation between AF values and RA values for rock-like materials under different loading rates exhibits similar trends with increasing time. At the initial stage of axial stress loading, the ratio of AF value to RA value is relatively low, fluctuating below or around the threshold, indicating that the cracks at this stage are mostly shear cracks or mixed tension-shear cracks. As the axial stress increases, the ratio begins to deviate from the threshold, with data points appearing significantly above or below the threshold, indicating that the mechanism of crack formation in the rock-like material becomes more pronounced and distinct under higher stress. Towards the end of the loading process, the number of data points increases and their distribution becomes more dispersed, indicating that more cracks are generated and the fracturing characteristics become more evident. In addition, the high frequency of data points near the threshold also suggests that the cracks are most likely generated under the combined influence of tensile and shear actions, rather than being caused by a single factor. Moreover, the maximum AF value decreases with increasing loading rate, and the scale of cracks formed in the rock-like material gradually increases [39], which is consistent with the macroscopic fracture characteristics observed.

To investigate the effect of loading rate on the cumulative crack types and their proportions at peak stress, the cumulative shear crack proportion r_s was calculated using the following formula:

$$r_s = \frac{N_s}{N_a} \quad (7)$$

where N_s is the cumulative number of shear cracks and N_a is the cumulative total number of cracks. It should be noted that here, the cracks represented by data points near the threshold, which may be generated by combined shear-tension action, are disregarded, and the crack types are strictly distinguished based on the magnitude relationship between the data points and the threshold.

Figure 10 shows the evolution characteristics of the cumulative shear crack proportion of rock-like materials at peak stress under different loading rates. As the loading rate increases from 0.001 mm/min to 0.05 mm/min, the r_s value exhibits a fluctuating decrease from 0.9655 to 0.1778. This indicates that an increase in loading rate leads to a decrease in the proportion of shear cracks and an increase in the proportion of tensile cracks at peak failure, resulting in gradually more pronounced brittle failure characteristics of the material.

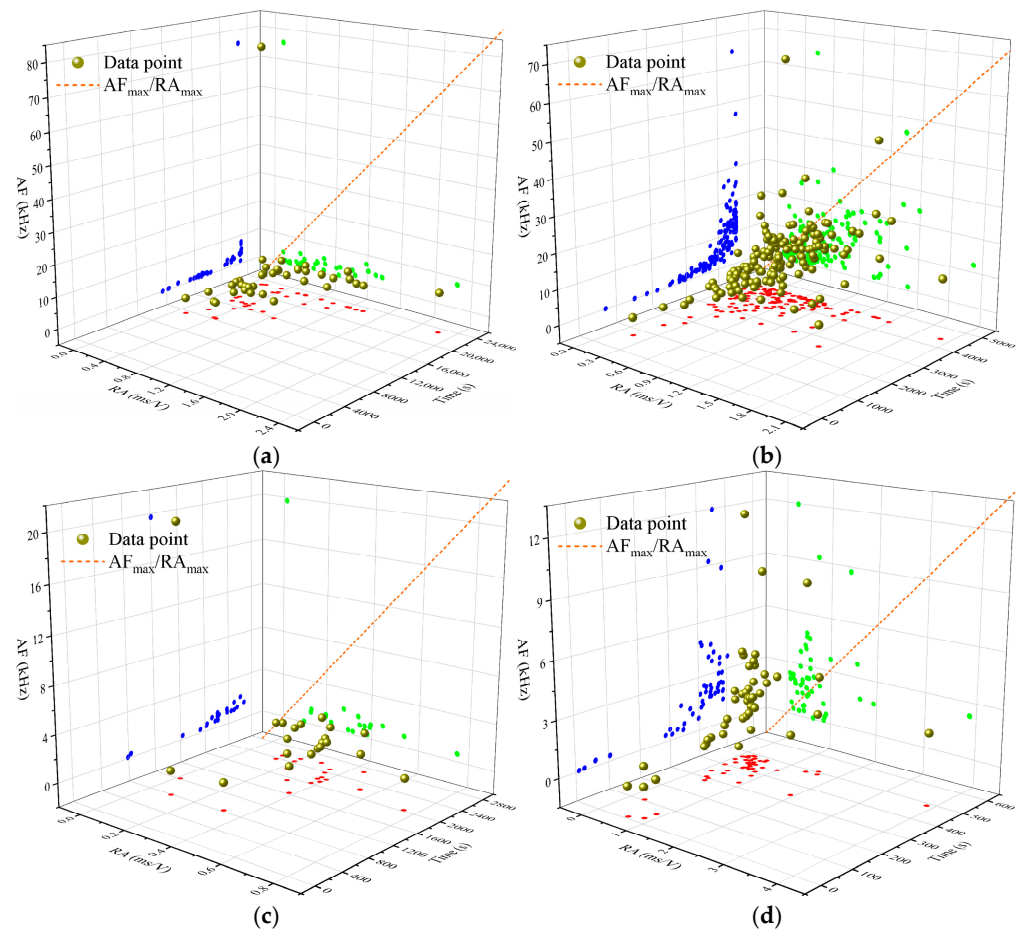


Figure 9. Scatter plots of RA-AF temporal distribution of rock-like materials under different loading rates: (a) 0.001 mm/min; (b) 0.005 mm/min; (c) 0.01 mm/min; (d) 0.05 mm/min.

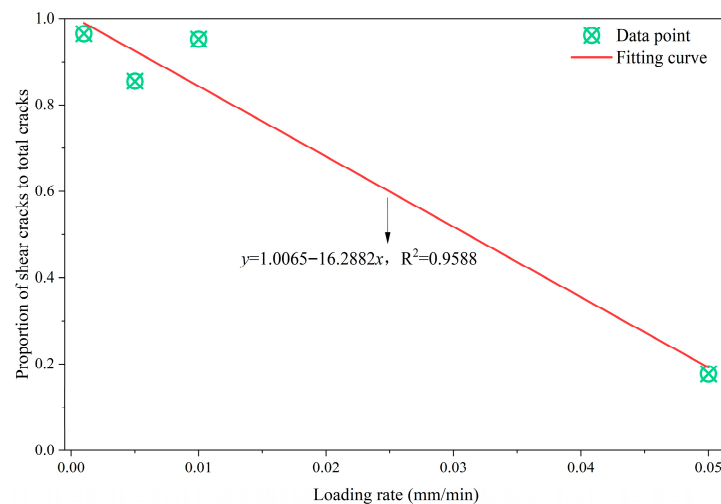


Figure 10. Characteristics of shear crack proportion in rock-like materials at peak stress under different loading rates.

4.2. *b*-Value

The *b*-value in AE, originating from seismology, is a statistical indicator based on amplitude, and its variations often signal the failure of materials such as rock and concrete.

The mathematical relationship between cumulative frequency and magnitude can be quantitatively described by an empirical formula as follows [40]:

$$\lg N = a - bM \quad (8)$$

where M is the magnitude; N is the number of magnitude events with an amplitude greater than a predetermined threshold; and a and b are constants.

Since the fracturing of materials such as rock and concrete are analogous to seismic phenomena, when calculating the b -value, the magnitude is equivalently represented by the ratio between the amplitude A_{AE} and 20. Therefore, when analyzing AE parameters, Equation (8) can be modified as follows [41]:

$$\lg N = a - b \frac{A_{AE}}{20} \quad (9)$$

The b -value is related to the proportion of AE events with different amplitudes. When the b -value is large, it reflects that most of the fractures formed in the rock-like material are of small scale; conversely, a small b -value indicates that large-scale fractures predominantly occur.

Figure 11a shows the correlation between the number of AE events and the seismic magnitude during the pre-peak stage of rock-like materials under different loading rates. The larger the amplitude, the smaller the number of AE events exceeding that amplitude, indicating that the fracture characteristics of the rock-like material are predominantly small-scale fractures. In addition, the effect of loading rate on the correlation between the number of AE events and the magnitude is not significant. Linear fitting was performed on the linear segments of the curves in Figure 11a to obtain b -values in the pre-peak stage of rock-like materials under different loading rates, as shown in Figure 11b. It can be observed that as the loading rate increases, the b -value in the pre-peak stage exhibits an overall increasing trend, fluctuating from 1.2041 to 2.5575. This reflects that the scale of fracture characteristics in the pre-peak stage under low loading rates is relatively larger than that under high loading rates, resulting in a relatively more fragmented structure of the rock-like material during the pre-peak stage at low loading rates. Previous studies have shown that structural integrity affects the energy conversion characteristics of materials, thereby controlling their failure characteristics. Therefore, when the structure of the rock-like material is relatively fragmented during the pre-peak stage, the macroscopic failure characteristics formed after peak failure become increasingly less pronounced. This is consistent with the previous research findings.

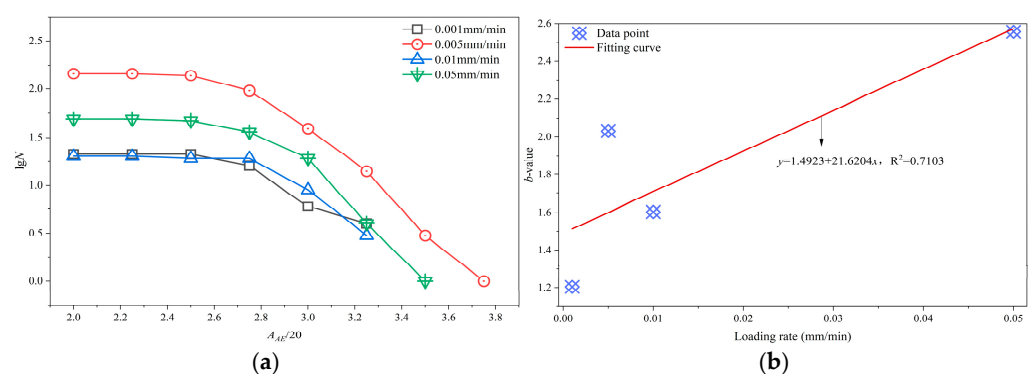


Figure 11. Number of AE events, magnitude, and b -value of rock-like materials under different loading rates: (a) the relationship between the number of AE events and the magnitude; (b) distribution characteristics of the b -value.

5. Conclusions

- (1) This study reveals the influence of loading rate on the mechanical behavior and failure characteristics of rock-like materials. When the loading rate increases from 0.001 mm/min to 0.05 mm/min, the peak stress exhibits a nonlinear increase from 82.54 MPa to 131.93 MPa (an increase of approximately 59.8%), and the elastic modulus correspondingly increases from 23.95 GPa to 34.87 GPa (an increase of approximately 45.6%). This enhancement is attributed to the fact that a higher rate of axial stress increase inhibits the full development of microcracks. As the loading rate increases, the propagation direction of the main fracture gradually approaches the axial loading direction, the failure mode transitions from shear–tension composite failure to tension-dominated failure, brittle characteristics become more pronounced, and the amount of fragments generated decreases, confirming the insufficient crack coalescence under high loading rates.
- (2) The loading rate exerts a significant regulatory effect on the energy evolution of rock-like materials. Beyond confirming the known rate-dependence of strength and stiffness, this study provides a quantitative characterization of the energy storage–dissipation mismatch induced by loading rate. During the pre-peak stage, the total strain energy, elastic strain energy, and dissipated strain energy all exhibit nonlinear growth. In the initial loading stage, the energy is mainly converted into elastic strain energy, while the proportion of dissipated energy increases significantly as the peak stress is approached. In the post-peak stage, the elastic strain energy decreases with the axial stress, while the dissipated strain energy increases sharply. Increasing the loading rate significantly increases the total strain energy and elastic strain energy, but has a limited effect on the dissipated strain energy. The difference between the elastic strain energy and dissipated strain energy at peak stress increases from 0.1194 kJ/cm³ to 0.2229 kJ/cm³ with increasing loading rate, quantitatively demonstrating an intensified mismatch between energy storage and dissipation capacities at higher rates. This energy imbalance provides a mechanistic basis for the observed transition from shear–tension composite failure to tension-dominated brittle failure.
- (3) Based on the traditional statistical damage constitutive model, the influence of loading rate on the elastic modulus of the material was introduced, a damage variable induced by loading rate was proposed, and a damage constitutive model considering the loading rate was subsequently established. Model validation shows that the theoretical curves are in good agreement with the experimental data under different loading rates, with RMSE values ranging from 1.32 MPa to 4.19 MPa, confirming the predictive capability of the model for the constitutive relationship of rock-like materials under varying loading rates. It should be noted that this study focused exclusively on the influence of loading rate under uniaxial compression conditions, without considering other critical factors such as temperature and humidity encountered in actual mining environments. Furthermore, the rock-like material employed in this study is relatively hard and brittle; therefore, the findings and the developed constitutive model may not be directly applicable to soft rocks such as mudstone or coal, which exhibit distinct deformation and failure characteristics. Future research will extend the experimental scope to uniaxial compression tests incorporating temperature and humidity, and will also investigate a wider range of rock types to further refine the model's applicability to pillar stability assessment.
- (4) The loading rate has a significant regulatory effect on the AE characteristics of rock-like materials, as revealed by a multi-parametric analysis combining RA-AF crack classification and *b*-value evolution. The crack identification method based on the RA-AF ratio indicates that in the initial loading stage, cracks are predominantly

shear-type or mixed tension-shear type; as the peak stress is approached, the crack formation mechanism becomes more distinct; and at the later loading stage, the fracturing behavior is significantly intensified. Increasing the loading rate reduces the cumulative shear crack proportion from 0.9655 to 0.1778, while the proportion of tensile cracks increases correspondingly, making the brittle failure characteristics more pronounced. The b -value in the pre-peak stage exhibits an overall increasing trend from 1.2041 to 2.5575 with increasing loading rate, punctuated by a pronounced peak at 0.05 mm/min associated with high-energy brittle rupture. This indicates that the material undergoes a higher degree of fragmentation at lower loading rates, whereas at higher rates, failure is dominated by fewer but more energetic tensile cracks. The integration of AE multi-parameter analysis with mechanical and energy data provides a comprehensive framework for understanding the rate-dependent damage evolution in rock-like materials.

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References

1. Li, P.; Cai, M.F. Challenges and new insights for exploitation of deep underground metal mineral resources. *Trans. Nonferrous Met. Soc. China* **2021**, *31*, 3478–3505. [\[CrossRef\]](#)
2. Ghorbani, Y.; Nwaila, G.T.; Zhang, S.E.; Bourdeau, J.E.; Cánovas, M.; Arzua, J.; Nikadat, N. Moving towards deep underground mineral resources: Drivers, challenges and potential solutions. *Resour. Policy* **2023**, *80*, 103222. [\[CrossRef\]](#)
3. Bian, Z.F.; Zhang, Q.Z.; Tong, R.F.; Zheng, N.S.; Preusse, A. Mine surveying science and technology for contemporary and future mining industries. *Int. J. Min. Sci. Technol.* **2026**, *36*, 251–275. [\[CrossRef\]](#)
4. Li, F.; Wang, X.; Zhou, L.; Yang, Z.D. Study on mechanical behavior and microscopic failure characteristics of deep rocks considering the influence of internal stress. *Therm. Sci.* **2025**, *29*, 1295–1300. [\[CrossRef\]](#)
5. Wu, A.X.; Huang, M.Q.; Han, B.; Wang, Y.M.; Yu, S.F.; Miao, X.X. Orthogonal design and numerical simulation of room and pillar configurations in fractured stopes. *J. Cent. South Univ.* **2014**, *21*, 3338–3344. [\[CrossRef\]](#)

6. Zhou, Z.L.; Zang, H.Z.; Cao, W.Z.; Du, X.M.; Chen, L.; Ke, C.T. Risk assessment for the cascading failure of underground pillar sections considering interaction between pillars. *Int. J. Rock Mech. Min. Sci.* **2019**, *124*, 104142. [\[CrossRef\]](#)
7. Zhu, W.C.; Dong, H.Y.; Liu, X.G.; Niu, L.L.; Dai, F.; Guan, K. Review of bearing and instability failure of multi-pillar in metal mines. *J. Min. Strat. Control Eng.* **2022**, *4*, 5–31. [\[CrossRef\]](#)
8. Wu, Y.F.; Wang, Y.; Li, C.H.; Zhou, B.K.; Li, P.; Cai, M.F.; Sun, C.K.; Tian, Z.C. Effect of loading rate on the mechanical response and energy evolution of skarn rock subjected to constant-amplitude cyclic loading. *J. Cent. South Univ.* **2025**, *32*, 1117–1140. [\[CrossRef\]](#)
9. Hamediazad, F.; Bahrani, N. Simulation of hard rock pillar failure using 2D continuum-based Voronoi tessellated models: The case of Quirke Mine, Canada. *Comput. Geotech.* **2022**, *148*, 104808. [\[CrossRef\]](#)
10. Bu, Q.W.; Tu, M.; Fu, B.J. Research on the Redistribution Law of Lateral Mining Stress and the Bearing Characteristics of Section Coal Pillar in Extra-Thick Fully Mechanized Top-Coal Caving Mining. *Shock Vib.* **2021**, *2021*, 4355977. [\[CrossRef\]](#)
11. Li, C.Q.; Zhou, J.; Du, K.; Dias, D. Stability prediction of hard rock pillar using support vector machine optimized by three metaheuristic algorithms. *Int. J. Min. Sci. Technol.* **2023**, *33*, 1019–1036. [\[CrossRef\]](#)
12. Mitelman, A.; Elmo, D.; Stead, D. Development of a spring analogue approach for the study of pillars and shafts. *Int. J. Min. Sci. Technol.* **2018**, *28*, 267–274. [\[CrossRef\]](#)
13. Tan, X.Y.; Chen, W.Z.; Wang, L.Y.; Qin, C.K. Spatial deduction of mining-induced stress redistribution using an optimized non-negative matrix factorization model. *J. Rock Mech. Geotech. Eng.* **2023**, *15*, 2868–2876. [\[CrossRef\]](#)
14. Li, Z.; Fan, J.Y.; Feng, G.R.; Qi, C.E.; Zhang, J.Y. A New Method for Identifying Coal Pillar Instability Based on Energy and Stress Correlation Characteristics and Its Engineering Application. *Minerals* **2023**, *13*, 1507. [\[CrossRef\]](#)
15. Li, G.W.; Lu, S.F.; Liu, S.F.; Liu, J.; Shi, P.; Fan, B.W. Application and Effect of Loading Rates on Coal Sample Failure. *Shock Vib.* **2021**, *2021*, 6681082. [\[CrossRef\]](#)
16. Gao, M.Z.; Xie, J.; Gao, Y.A.; Wang, W.Y.; Li, C.; Yang, B.G.; Liu, J.J.; Xie, H.P. Mechanical behavior of coal under different mining rates: A case study from laboratory experiments to field testing. *Int. J. Min. Sci. Technol.* **2021**, *31*, 825–841. [\[CrossRef\]](#)
17. Wang, K.; Zuo, X.H.; Du, F.; Sun, J.Z.; Ju, Y.; Shu, L.Y.; Cai, Y.B. Damage evolution and failure behavior of coal-rock combination subjected to different cyclic loading paths and loading rates: Insights from energy-driven effects. *J. Cent. South Univ.* **2025**, *32*, 3447–3469. [\[CrossRef\]](#)
18. Zhang, J.W.; Ding, L.J.; Song, Z.X.; Fan, W.B.; Wang, S.Y. Mechanical properties of deep sandstones under loading rate effect. *J. Cent. South Univ.* **2022**, *29*, 1933–1944. [\[CrossRef\]](#)
19. Shen, D.K.; Wang, X.; Yang, D.X. Fatigue damage evolution mechanism of sandstone under Freeze-Thaw and loading rate coupling based on NMR and AE techniques. *Front. Earth Sci.* **2026**, *14*, 1758932. [\[CrossRef\]](#)
20. Wen, G.; Gong, P.L.; Zhao, T.; Yi, K.; Ma, J.M.; Zhang, W.; Zhu, Y.H.; Li, P.; Bai, L.B. Study on the Mechanical Properties and Microscopic Damage Constitutive Equation of Coal-Rock Composites Under Different Strain Rates. *Appl. Sci.* **2026**, *16*, 579. [\[CrossRef\]](#)
21. Liu, B.; Sun, X.; Ling, C.W.; Huang, Z.J.; Zhang, H.W. Mechanical Behaviors and Acoustic Emission Fractal Characteristics of Bump-Prone Coal under Different Loading Rates. *Fractal Fract.* **2023**, *7*, 45. [\[CrossRef\]](#)
22. Cui, G.J.; Zhou, C.Y.; Liu, Z.; Xia, C.; Zhang, L.H. The synthesis of soft rocks based on physical and mechanical properties of red mudstone. *Int. J. Rock Mech. Min. Sci.* **2022**, *151*, 105037. [\[CrossRef\]](#)
23. Yin, D.W.; Chen, S.J.; Xing, W.B.; Huang, D.M.; Liu, X.Q. Experimental study on mechanical behavior of roof-coal pillar structure body under different loading rates. *J. China Coal Soc.* **2018**, *43*, 1249–1257. [\[CrossRef\]](#)
24. Liang, C.Y.; Li, X.; Li, S.D.; He, J.M.; Ma, C.F. Study of strain rates threshold value between static loading and quasi-dynamic loading of rock. *Chin. J. Rock Mech. Eng.* **2012**, *31*, 1156–1161.
25. Cai, M.; Kaiser, P.K.; Suorineni, F.; Su, K. A study on the dynamic behavior of the Meuse/Haute-Marne argillite. *Phys. Chem. Earth* **2007**, *32*, 907–916. [\[CrossRef\]](#)
26. Chu, C.Q.; Wu, S.C.; Cao, Z.S.; Zhang, C.J.; Zhang, Y.L. Experimental research on fracture characteristics of granite with acoustic emission technology. *J. Cent. South Univ. (Sci. Technol.)* **2021**, *52*, 2919–2932.
27. Zhao, K.; Qiao, C.S.; Luo, F.R.; Hao, Z.H. Experimental study of fatigue characteristics of limestone samples subjected to uniaxial cyclic loading with different frequencies. *Chin. J. Rock Mech. Eng.* **2014**, *33*, 3466–3475. [\[CrossRef\]](#)
28. You, S.; Li, F.; Sun, J.C.; Ji, H.G.; Wang, H.T. Experimental study on hydraulic failure mechanism and energy storage characteristics of deep granite. *J. Cent. South Univ. (Sci. Technol.)* **2021**, *52*, 2839–2848.
29. Liu, M.X.; Xie, J.; Du, Y.Z.; Zhu, Z.Y.; Ren, L.; Yang, B.A.; Feng, G.; Gao, Y.N.; Gao, M.Z. Experimental investigation and numerical simulation on Multiphysics coupling of shale under laser irradiation. *Int. J. Rock Mech. Min. Sci.* **2025**, *195*, 106299. [\[CrossRef\]](#)
30. Zhu, Z.Y.; Xie, J.; Du, Y.Z.; Ren, L.; Yang, B.G.; Feng, G.; Liu, M.X.; Ai, T.; Tang, R.F.; Wang, Y.L.; et al. Fracturing behavior of tight sandstone containing hollow double-wing crack (HDWC) under microwave irradiation. *J. Rock Mech. Geotech. Eng.* **2026**, *18*, 2215–2237. [\[CrossRef\]](#)

31. Li, F.; Gao, M.Z.; Ye, S.Q.; Xie, J.; Deng, H.C.; Yang, B.G.; Liu, J.J.; Yang, Z.D.; Tang, R.F. Formation mechanism of core discing during drilling under deep in-situ stress environment: Numerical simulation and laboratory testing. *J. Cent. South Univ.* **2023**, *30*, 3303–3321. [[CrossRef](#)]
32. Li, F.; Li, C.X.; He, H.L.; Yang, B.G.; Lu, J.L. Research on physical-mechanical properties and energy evolution characteristics of granite after high temperature treatment. *Therm. Sci.* **2023**, *27*, 497–504. [[CrossRef](#)]
33. Zhao, L.L.; Cui, Z.D.; Peng, R.D.; Si, K. Numerical Simulation and Evaluation on Continuum Damage Models of Rocks. *Energies* **2022**, *15*, 6806. [[CrossRef](#)]
34. Feng, T.; Yu, X.; Cheng, G. Damage constitutive model of rock and application based on strength theory. *J. Mech.* **2024**, *40*, 336–353. [[CrossRef](#)]
35. Meng, G.; Liu, Z.Z.; Cao, P.; Zhang, Z.Y.; Fan, Z.; Lin, H.; Deng, H.J. An Initial Damage Model of Rock Materials under Uniaxial Compression Considering Loading Rates. *Materials* **2022**, *15*, 5589. [[CrossRef](#)]
36. Xu, X.L.; Karakus, M. A coupled thermo-mechanical damage model for granite. *Int. J. Rock Mech. Min. Sci.* **2018**, *103*, 195–204. [[CrossRef](#)]
37. Miao, S.S.; Su, L.J.; Zhang, C.L.; Pan, Y.L.; Tian, H.Y. Creep properties and acoustic emission characteristics of soft-hard interbedded rock masses with different initial damage. *J. Cent. South Univ.* **2026**, *33*, 276–298. [[CrossRef](#)]
38. Gao, M.Z.; Liu, J.J.; Li, C.X.; Yang, B.G.; Li, F.; Zhou, X.M.; Yang, L.; Yang, Z.D.; Xie, J. Damage and fracture behavior and spatio-temporal evolution of acoustic emission of sandstone before and after laser radiation. *J. Cent. South Univ.* **2024**, *31*, 3264–3280. [[CrossRef](#)]
39. Wang, L.C.; Wang, L.; Xu, M.; Long, W. Damage evolution and destabilization precursors in granite under splitting load at different temperatures. *Trans. Nonferrous Met. Soc. China* **2024**, *34*, 977–994. [[CrossRef](#)]
40. Zhao, Y.E.; Li, X.B.; Huang, L.Q.; Zhang, Z.C.; Xu, Z.H. Characteristic stress variation and microcrack evolution of granite subjected to uniaxial compression using acoustic emission methods. *J. Rock Mech. Geotech. Eng.* **2024**, *16*, 3511–3523. [[CrossRef](#)]
41. Zeng, H.; Hartell, J.A.; Soliman, M. Damage evaluation of prestressed beams under cyclic loading based on acoustic emission monitoring. *Constr. Build. Mater.* **2020**, *255*, 119235. [[CrossRef](#)]

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