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Examination on Brittleness Evaluation Index Based on Energy Evolution of Rock Failure Process

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Abstract: With the economic development and technological advancement around the world, many people are now considering the development of underground space engineering such as underground buildings, underground parking lots, river crossing tunnels, subways, and deep mine mining. Underground rock masses belong to a class of discontinuous and heterogeneous anisotropic brittle materials. The crustal movement of millions of years makes the internal structure extremely complex. Brittleness is a key mechanical feature of rock and is critical to a variety of engineering practices. Based on the energy evolution of rock failure process, the evolution law of strain energy such as pre-peak dissipation energy and post-peak fracture energy during the transformation from plastic deformation to brittle fracture under compression is analyzed. Combining these two energies, the brittleness evaluation index which can comprehensively reflect the mechanical characteristics before and after rock failure is established. The brittleness characteristics of different rock materials under different confining pressures are evaluated. The fracture morphology of shale under different bedding angles is analyzed. The results show that the brittleness evaluation index established in this paper can simultaneously reflect the difficulty of brittle fracture and the strength of brittleness. It can not only describe the brittleness of different rock materials with confining pressure, but also describe the law of change for shale brittleness index based on bedding dip.

1. Introduction

With the economic development and scientific and technological progress all over the world, whether it is infrastructure construction such as surface construction, transportation, or exploitation of resources such as open-pit minerals, it has entered a period of decline after the peak. They are now facing underground buildings, underground parking lots, and river crossings. The development of underground space engineering such as tunnels, subways and deep mine mining. Underground rock masses belong to a class of discontinuous and heterogeneous anisotropic brittle materials. The crustal movements of millions of years have made their internal structures extremely complex and derived from various natural defects such as cracks, cavities and joints. Due to the existence of these different kinds of natural defects, the large differences in engineering performance of various rock masses are caused. The deeper the development level of underground space, the more various types of surface and deep rock mass engineering involved are more and more complex. The problem that people will inevitably face is deep rock explosion, especially brittleness and impact tendency. The rock burst problem is most prominent. The occurrence of these rock burst phenomena is often caused by various high-pressure environments, such as various underground space buildings and deep-hole mining, which may cause damage to the entire engineering rock mass, and the rock mass instability will give underground Engineering projects and production bring huge security risks, which will cause significant losses in public property and personal safety. Brittleness is a key mechanical feature of rock and is critical to a variety of engineering practices, particularly the design of effective fracturing stimulation of unconventional shale gas reservoirs [1]. It plays an important role in assessing the risk of rock outbursts and analyzing well bore stability during shale gas development. Brittleness is also a key parameter in hydraulic fracturing design [2]. Various brittleness definitions and evaluation criteria have been proposed to describe rock failure behavior, but their applicability and reliability have not been verified. The concept of brittleness in rock mechanics is still not widely accepted.

When the rock is destroyed by force, rock brittleness is an inherent property of rock. The brittleness index characterizes the degree of transient change before rock rupture, reflecting the complexity of crack formation after reservoir fracturing. In general, formations with high brittleness indices are hard and brittle, sensitive to fracturing operations, and can quickly form complex network cracks; conversely, formations with low brittleness indices tend to form simple biplane cracks. Therefore, the rock brittleness index is an indispensable parameter for characterizing reservoir fracture. At present, the evaluation of shale brittleness mainly considers the mechanical properties before and after the peak, and does not reflect the brittle characteristics of the whole process of rock failure. The pre-peak peak dissipated energy and the post-peak fracturing energy level are the key factors determining whether brittle fracture occurs [3]. Brittle minerals reflect the brittleness of rock matrix. The stress sensitivity of wave velocity reflects the development degree of natural fracture system. They are the key factors controlling the shape of propagation fractures, which is of great significance for evaluating the hydraulic fracturing effect of unconventional reservoirs in the future [4].

As an important basic feature of rock, brittleness evaluation is of great significance to rock engineering. At the end of the eighteenth century, petrology evolved from mineralogy and developed into an independent discipline. In the early days of petrology development, igneous rocks were mainly studied. At present, petrology is developing along three major branches: magmatic petrology, sedimentary petrology and metamorphic petrology. Lizcano has studied the brittleness of rock by many scholars. The shale brittleness index is calculated by exploiting the effective mechanical properties obtained from micromechanical self-consistent modeling to help identify more brittle regions in shale gas reservoirs [5]. Taking into account the limitations of the existing brittleness indicators, Chen established a new brittleness index based on the overall stress-strain process of the rock mass. The stress growth rate between the peak stress and the pre-peak crack initiation stress is also considered, as well as the stress reduction rate after the peak. Uniaxial and triaxial compression tests were performed to evaluate the new index. The test results show that the new index can accurately determine the brittleness of the rock according to the prestressed strain curve under the condition of uniaxial loading system, and make up for the inaccuracy of the post-peak curve of the brittle rock. Under triaxial compression conditions, the new index more clearly shows the effect of confining pressure on the brittleness of marble. The reliability and comprehensiveness of the new indicators are verified, and these research results can improve the existing rock brittleness evaluation [6]. Tan studied the brittle plastic transition based on the stress-strain relationship. The results show that the brittleness index calculated by static elastic parameters is negatively correlated with the stress reduction coefficient, and the brittleness index is closely related to the stress drop. Brittleness index B2, Young's modulus and Poisson's ratio are related to brittle mineral content; based on index B2, the correlation between pore fluid and porosity and dynamic brittleness characteristics is also studied. Pore fluid increases the plasticity of the rock and reduces the brittleness; in addition, as the porosity increases, the brittleness of the rock decreases. The brittleness index of gas-saturated siltstone is higher than that of oil-saturated siltstone; the brittleness index of oil-water saturated siltstone is very small [7]. Qamar believes that understanding brittle and ductile behavior in low-permeability shale formations is critical to optimizing completion and stimulation of shale formations. In order to quantify the brittleness of shale, he proposed several methods for estimating the fracture index. The modified fracture index (FI) model by Yuan etc. was used to clarify the interpretation of plasticity to determine where the perforation clusters and compressible indices are placed and how best to determine brittleness. The improved FI accurately predicts brittle and ductile regions compared to the use of Frac, and provides a relatively better idea of favorable fracturing in the TOC enrichment region, with estimated effective crack initiation and expansion and Additional advantages of proppant embedded resistance. In this study, mechanical rock properties were derived from sonic log data to develop a mechanical earth model and design a brittle template to distinguish the brittle and ductile regions of the Longmaxi shale gas reservoir. The effectiveness of the design's brittle template was verified by a modified FI evaluation model and pre-existing cracks [8]. Li numerically studied the effects of rock brittleness on failure modes and stress-strain characteristics of shale specimens. It has been found that brittle shale samples are more likely to rupture in multiple cross-destructive surfaces, while ductile specimens are more susceptible to fracture at the fracture surface, from which we conclude that brittle shale is more likely to form more natural fractures than toughness. Through numerical simulation, the influence of natural cracks on complex hydraulic fracturing networks is further studied, and the positive effect of rock brittleness is indirectly verified. It has been found that hydraulic fracturing preferably propagates in brittle minerals, i.e. hydraulic fracturing always selects brittle minerals as the preferred path for spreading or selecting thin or weak portions of ductile minerals to penetrate and be blocked by ductile minerals. In addition, the hydraulic fractures generated in the brittle shale are tortuous and multi-branched, which is more conducive to the formation of hydraulic fracturing networks than the smooth hydraulic fracturing produced in ductile shale. This may be one of the reasons why the treatment pressure required for the ductile shale layer is higher than that of the brittle shale layer [9]. Zhou believes that the fracture behavior of ductile multi-fractured rock mass is very different from that of brittle multi-defect rock mass. With the increase of brittleness index, the crack initiation mode changes from shear crack to tensile crack; the coalescence mode changes from shear crack coalescence to tensile crack and shear crack coalescence; with the increase of brittleness index, pull the crack is coalesced. Observations on the final failure mode show that as the brittleness index increases, the failure mode changes from shear failure to mixed tensile shear failure and then to split failure [10]. Jadoon calculates the brittleness and plasticity index in reservoirs to understand rock performance under stress, as well as assessing the fracture performance of clay-rich shale reservoirs and assessing wellbore stability. Murteree shale has more than Roseneath shale. Favorable brittleness and considered to be more suitable for hydraulic fracturing in natural gas production [11]. Hernandez proposed a systematic method for quantifying mudstone brittleness based on micromechanical measurements of scratch tests. Brittleness is expressed as the ratio of the energy associated with brittle failure to the total energy required to perform the scratch. Soda-lime glass and polycarbonate were used for comparison to identify failures in the brittle and ductile modes and to verify the developed method. The microscratch test method can be used to study mudstone brittleness. This method is particularly suitable for reservoir characterization methods using large quantities of drill cuttings or large samples that cannot be recovered by triaxial tests or fracture mechanics tests [12].

Based on the stress-strain curves of the whole process of rock failure, the evolution of the strain energy of the pre-peak energy and the post-peak energy of the rock from plastic deformation to brittle fracture are analyzed. It is believed that the pre-peak dissipated energy and the post-peak fracture energy respectively reflect the ability of the rock to resist inelastic deformation and maintain crack propagation. It is an important factor in determining whether a rock has a brittle fracture. Combining these two energies, a brittleness evaluation index that can fully reflect the mechanical properties before and after rock failure is established, and the brittleness characteristics and shale brittleness anisotropy under different surrounding rock pressures are evaluated. The results show that the brittleness evaluation index established in this paper can reflect the difficulty and brittleness of brittle fracture. It can not only describe the brittleness of different rock materials with confining pressure, but also describe the anisotropy of layered shale brittleness.

2. Proposed Method

2.1. Destructive Form of Rock

Rock is a natural mineral aggregate with a certain structural structure, which is the material basis of the crust and upper mantle. According to the genesis, it is divided into magmatic rocks, sedimentary rocks and metamorphic rocks. Magmatic rocks are rocks formed by condensation of surface or underground high-temperature molten magma, also known as igneous rocks; sedimentary rocks are formed by migration, sedimentation and diagenesis of external forces such as water, air and glaciers under weathering, biological and volcanic activity conditions. Rocks; metamorphic rocks are rocks formed by pre-formed magmatic rocks, sedimentary rocks or metamorphic rocks that have undergone metamorphism due to changes in their geological environment.

The forms of failure are: brittle failure, plastic failure, and weak surface shear failure. Brittle failure, most hard rock exhibits brittle failure under certain conditions. That is to say, the deformation of these rocks without sudden changes under load is suddenly destroyed, which may be the result of the occurrence and development of rock cracks. Plastic failure, in the case of two-way or three-way force, the rock is damaged before deformation, without obvious damage load, it shows obvious plastic deformation, flow or extrusion, which is plastic damage. Plastic deformation is the result of lattice misalignment within the rock and is more pronounced in some weak rocks. The integrity of the formation is destroyed by the weak surface shear failure of weak structural surfaces such as joints, cracks, bedding and weak interlayers in the formation. Under load, when the shear stress on the weak structural surface is greater than the surface strength, the rock mass will produce shear failure along the weak surface, causing the entire rock mass to slide.

2.2. Type of Energy Destroyed by Rock

During the entire deformation and failure process of the rock, the energy conversion in the loaded rock system obeys the law of conservation of energy, the total amount is certain, and the form of energy is varied, and the change of rock from one state to another is exactly The results of the mutual transformation of these various energies mainly include the following forms:

(1) Elastic energy

The molecular bonds between the particles in the rock, the attraction or repulsion of the ionic bonds and the covalent bonds exhibit the characteristics of elastic energy. External energy input (mechanical and thermal) makes the interaction between the particles more pronounced and the energy is stored in the form of elastic energy. The ideal elastic energy storage is reversible. Rock structures do not undergo irreversible changes during this energy conversion process. In fact, due to the influence of various defects inside the rock, the energy input always causes the valence bond between some particles to break, resulting in irreversible structural damage. When the elasticity stored in the rock reaches a certain level, it will cause overall damage and instability, and convert it into other forms of energy. From the perspective of force and deformation, elastic energy can be expressed as:

$$E_e = \int_v^{v'} \sigma_{ij} d\varepsilon_{ij}^e \tag{1}$$

Where Ee is the elastic energy stored in the rock with a volume of V; σ_ij is the stress tensor of the unit body within the rock; ε_ij^e is the elastic strain tensor of the unit body within the rock.

Decompose both the stress tensor and the strain tensor into two parts: the ball and the offset:

$$\begin{cases} \sigma_{ij} = s_{ij} + \sigma_m \delta_{ij} \\ \varepsilon_{ij}^e = e_{ij}^e + \varepsilon_m^e \delta_{ij} \end{cases} \tag{2}$$

Where s_{ij} is the deviatoric stress tensor; σ_m is the hydrostatic stress; e_{ij}^e is the partial elastic strain tensor; ε_m^e is the average positive strain; δ_{ij} is the Kronecher symbol.

(2) Plastic properties

When the unit body stress in the rock exceeds its elastic limit, the rock particles will be plastically deformed and consumed in the cumulative amount of plastic deformation. Except for a small amount of thermal energy, most of them are in the form of irreversible plastic properties.

(3) Damage energy

The rock itself has initial micro-cracks and micro-pores, and the energy input causes the valence bond between the particles in the rock to break. On the one hand, these initial micro-damages are further developed, and on the other hand, new micro-cracks and micro-holes are generated. hole. As the energy input increases step by step, the amount of damage energy is becoming larger and larger, and the degree of rock damage is also increasing.

(4) Radiation energy

During the deformation and destruction of rocks, especially in the critical rupture stage, some radiation phenomena, such as acoustic emission, electromagnetic radiation, infrared radiation, etc., are generated. Acoustic emission refers to the phenomenon of stress concentration in the local area of the material, the rapid release of energy and the generation of transient elastic waves. It can be produced simultaneously by dislocation motion, plastic deformation and crack formation and expansion. Most other transformations are the surface energy, lattice strain energy and thermal energy of the new interface. If the elastic wave energy emitted by the source event can be measured and the energy distribution function determined, the energy of the source event can be calculated, which will provide a means to understand the microcrack process of the material.

(5) Kinetic energy

When the rock reaches its energy storage limit, an overall instability rupture occurs during which the internally stored elastic energy is converted to the surface energy of the new ruptured surface. It causes the rock fragments to overflow and become the kinetic energy of the rock.

(6) Thermal energy

The thermal energy in the deformation and failure of rock mainly includes the dislocation diffusion and heat dissipation generated by the crack tip when the rock microcrack expands. Internal microcracks, frictional heat generation between particles, and thermal energy released by friction between fragments during local failure. When these heat energy is exchanged with the surrounding environment when it is conducted inside the rock, this heat energy causes changes in the internal temperature and surface temperature of the rock.

(7) Gas expansion energy

The rock mass can contain a large amount of gas and exists in a free state and an adsorbed state. The gas in the rock mass can expand and release a lot of energy.

2.3. Energy Conversion in Rock Deformation and Failure

The energy conversion is driven by a strain hardening mechanism and a strain softening mechanism. The strain softening mechanism converts the strain energy in the rock into other forms of energy, such as damage energy and heat energy, and converts higher mass energy into lower mass energy

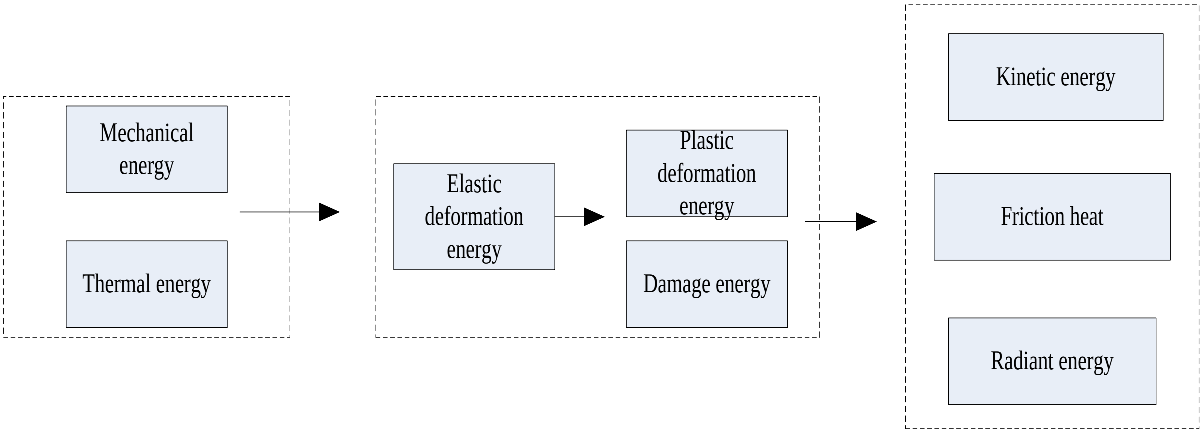

Figure 1. Four energy processes of a loaded rock system

As shown in Figure 1, for a loaded rock system, its energy conversion is roughly divided into four processes: energy input, energy accumulation, energy dissipation, and energy release. The energy input from the outside mainly includes mechanical energy (external force action) and thermal energy brought by ambient temperature, generally mechanical energy; part of the input energy accumulates in the form of elastic deformation energy, which is reversible and can be released during unloading. The other part is dissipated in the form of plastic deformation energy, damage energy (mainly surface energy), and is irreversible. At the same time, a small amount is released to the outside in the form of frictional heat; when the elastic deformation can be stored to a certain limit and exceeds the extreme value of the rock system, the rock will be broken and unstable. And released to the outside world, the released energy includes rock kinetic energy, frictional heat energy, and various radiant energy. The energy conversion of rock during deformation until failure and instability is a dynamic process, which is manifested by the conversion and balance of mechanical energy, rock strain energy and damage energy. For a particular deformation state, there is a specific energy state corresponding to it.

From an energy point of view, each stress-strain state of the rock corresponds to a corresponding energy state, and the same stress-strain state may correspond to a completely different energy state. Similarly, different stress-strain states may also correspond to the same energy state. In essence, the evolution of energy states in rocks leads to different lithological rocks exhibiting different stress-strain characteristics and also leading to different deformation and failure modes of rocks.

3. Experiments

3.1. Energy Evolution Index of Rock Failure Process

From the energy point of view, the rock full stress-strain curve is an external manifestation of its internal energy state transition, from elastic deformation and microcrack evolution. Before the entire destruction process, the rock material is always accompanied by the exchange of energy with the outside world, on the one hand, the energy transmitted from the outside, on the other hand, it releases energy to the outside in various forms to maintain the energy balance. Rock failure is the process of continuously absorbing external energy before the stress reaches the peak intensity, and the energy is continuously released after reaching the peak, that is, the deformation and destruction of the rock is basically the result of energy dissipation and release. The energy evolution of the whole process of rock failure can be divided into three stages: energy accumulation, energy dissipation, energy conversion and release.

The energy value before and after rock rupture is closely related to its rupture mode. Describe the energy evolution characteristics of rocks and illustrate the scale and severity of rock rupture. The stronger the impact trend, the greater the elasticity of rock accumulation, the less energy is dissipated, and the greater the energy release rate at the time of rupture; the weaker the impact tendency, the opposite.

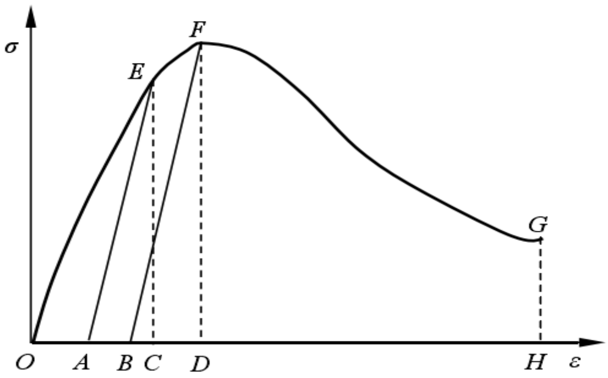

Figure 2. Rock energy characteristic index

As shown in Figure 2(The picture comes from the network, *www.baidu.com*), the elastic energy index WET is also called an elastic strain energy index or an elastic deformation energy index. It is defined as the ratio of elastic energy to dissipated energy between 80% and 90% of the intensity before the peak. The area SEA between the line EA and the strain axis is unloaded. The ratio of the area SEO between the loading and unloading lines is the elastic energy index.

3.2. Brittleness Index Based an Energy Evolution

The less energy dissipated in the pre-peak phase of the rock and the crack energy used to maintain crack propagation in the post-peak phase, the stronger the brittleness of the rock. Although there is a certain conversion relationship between the energy before and after the peak, there is no unified understanding of the correlation between the mechanical properties and energy evolution before and after the peak. To this end, we first establish a pre-peak index that measures pre-peak brittleness and a post-peak index that reflects post-peak brittleness. Then use the appropriate method to synthesize the two indicators into the brittleness evaluation index of the whole process. The brittleness index constructed in this way has a certain relationship with the energy evolution before and after the peak, but it does not reflect the specific influence of the energy dissipation level on the post-peak fracture characteristics. It can be seen that this index is suitable for evaluating the brittleness of the whole process of rock failure and cannot analyze the correlation between pre-peak brittleness and peak brittleness.

When the load reaches the yield stress, the elastic energy accumulated in the rock increases dW_e; after the load reaches the peak intensity, the total elastic energy accumulated in the pre-peak stage increases dW_a and the total energy dW_c accumulated in the plastic yielding stage. This can be obtained:

$$dW_c = dW_d + dW_a - dW_e \tag{3}$$

For an ideal brittle rock, the energy absorbed by the crack propagation is all used to overcome the intrinsic cohesion of the rock, the energy dissipation process before the rock reaches its peak strength. Therefore, when dWe_c and dWe_A are constant, the sizes of $dW*_d$ and dW_d can reflect the brittle characteristics of the rock in the pre-peak stage. That is to say, in the plastic yielding stage, which is less noticeable before the peak, the smaller the proportion of energy dissipated before the peak, the stronger the brittleness of the rock. Thus, two pre-peak indices B1, B2, which characterize the brittleness of the rock, can be obtained:

$$\begin{cases} B_1 = \dfrac{dW*_d}{dWe_c - dWe_A} \\ B_2 = \dfrac{dW_d}{dWe_c - dWe_A} \end{cases} \tag{4}$$

These two indices are used to characterize the degree of brittleness exhibited by the pre-peak stage of the rock, and dW^*_d represents the energy increase throughout the plastic yield stage. Therefore, B1 is used to measure the degree of plastic yield in the pre-peak stage, and includes the pre-peak dissipated energy dW_d, and the index of B2 is the level of energy dissipation in the pre-peak stage.

4. Discussion

4.1. Evaluation and Analysis of Brittleness Index

As shown in Table 1, it is the triaxial compression brittleness index of red sandstone and granite. It can be seen from Table 1 that the peak energy of red sandstone and granite is 0.202 and 0.338 J mm-3 when the confining pressure is 0 MPa. The results show that the elastic energy accumulated inside the granite is released faster than the red sandstone, and the additional energy required to maintain the fracture is smaller. It has stronger self-sustainability and is more brittle.

Table 1. Triaxial compression index of red sandstone and granite

Rock Type	Confining Pressure /Mpa	Pre-Peak Energy Consumption dW_e (J mm^{-3})	Post-Peak Energy dW_f (J mm^{-3})	B_1	B_2
Red Sandstone	0	0.051	0.202	3.08	0.68
	10	0.180	0.672	3.96	1.06
	20	0.438	0.775	8.16	3.94
Granite	0	0.038	0.338	1.35	0.07
	10	0.085	0.678	1.93	0.13
	20	0.297	1.471	2.11	0.22

As shown in Figures 3 and 4, as the confining pressure increases, the B1 and B2 of the two rock materials gradually increase. This indicates that the energy ratio of the pre-peak dissipated energy and the post-peak fracture energy is positively correlated with the confining pressure level. However, the B1 and B2 of the red sandstone increase more than the granite, indicating that the confining pressure has a greater influence on the pre-peak energy dissipation and post-peak fracture energy of the red sandstone. The brittleness of red sandstone is more sensitive to confining pressure. When the confining pressure is increased from 20 MPa to 30 MPa, B1 and B2 show a steady increase trend. This indicates that there is some difference between the peak pre-dissipated energy and the post-peak fracture energy as the confining pressure increases. If only the energy evolution characteristics before or after the peak are considered, contradictory results may occur.

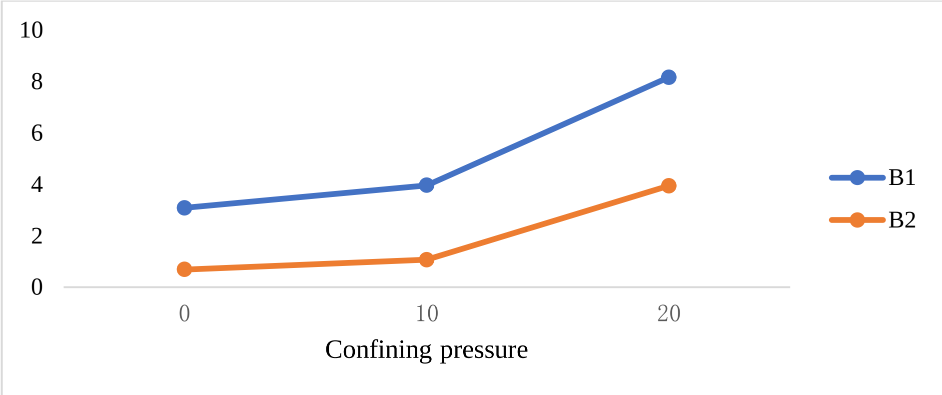

Figure 3. The variation of B1 and B2 indexes of red sandstone with confining pressure

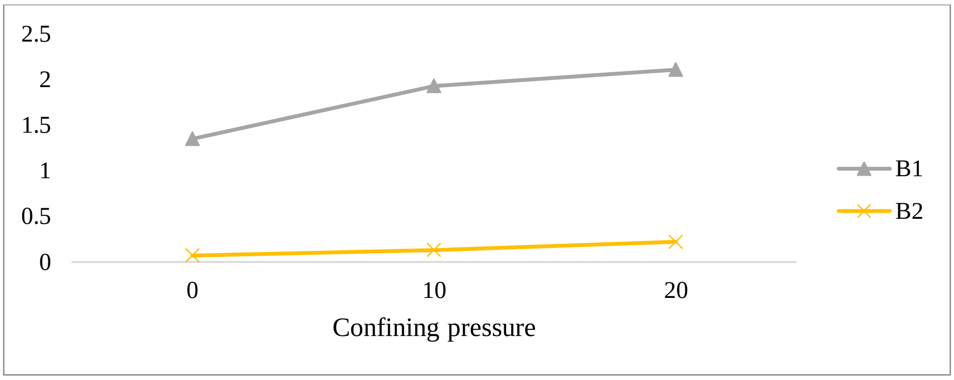

Figure 4. The variation of B1 and B2 indexes of granite with confining pressure

Under the external load, the internal microscopic defects of the rock material evolved from disordered to orderly development, forming macroscopic cracks and making the rock unstable. The deformation and destruction process of rock is basically the whole process of energy dissipation and energy release. The degree of energy dissipation before the peak determines the level of energy after the peak.

4.2. Brittleness Analysis

As shown in Figure 5, it is the variation law of B1 and B2 of shale with the bedding angle. As the bedding angle increases, B2 shows a trend of increasing and decreasing. It can be seen that the shale brittleness changes with the increase of the bedding angle: (1) When the bedding angle is 0 degrees to -30 degrees, the brittleness index hardly changes, indicating the change of shale brittleness within the angle range. It is not obvious; (2) When the bedding angle is 300 to 60, Bl and B2 start to increase greatly, indicating that the shale brittleness is greatly reduced within the angle range. When the bedding angle reaches 60 degrees, the brittleness index reaches a maximum. (3) When the bedding angle exceeds 60 degrees, the brittleness index begins to decrease, and the brittleness index when the bedding angle is 90 degrees is higher than the brittleness index when the bedding angle is 0 degrees, indicating that the bedding is perpendicular to the loading direction. The brittleness of the shale is higher than when the bedding is parallel to the loading direction.

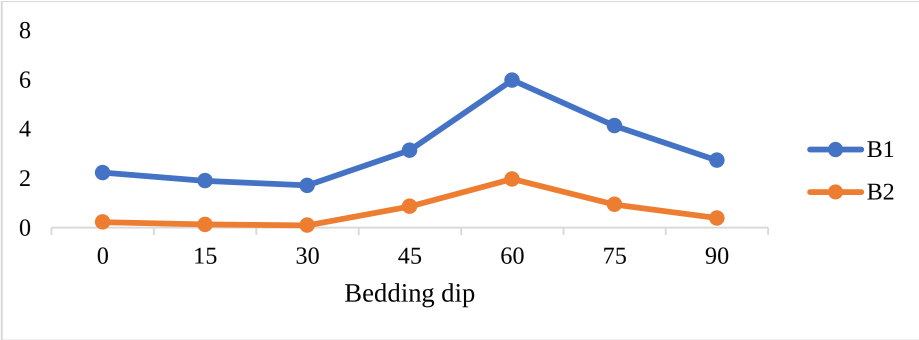

Figure 5. The variation of B1 and B2 indicators of shale with the bedding angle

As shown in Figure 6(The picture comes from the network,*www.baidu.com*), the fracture morphology of the shale under different lamination angles. At the low confining pressure level, the shale sample is dominated by the tensile splitting-shear composite fracture mode, and the transverse crack formed by the bedding expansion around the main fracture surface. As the confining pressure increases, the shale test the sample gradually transforms into a failure mode dominated by shear failure. When the bedding angle is between 0 ° and 30 °, a variety of macroscopic cracks appear in the post-press shale samples, including major fracture cracks, secondary splitting cracks, and cracks along the bedding, combined with stress-strain It can be seen from the curve that in this angle range, due to the large angle between the bedding and the loading direction, the shale bedding is not easy to open or shear slip in the pre-peak stage as the load is gradually increased. Only a small amount of dissipated energy is needed to satisfy the opening of microcracks inside the sample. As the load continues to increase, the elastic energy accumulated inside the sample increases continuously. When the stress exceeds the peak intensity, the energy accumulation reaches the limit and is rapidly released. The instantaneous release of the elastic energy requires more fracture cracks to provide a release path, thus producing a greater number of macroscopic cracks. Moreover, in the energy release process, since the cementation strength of the bedding surface is low, it is easier to form an open crack and provide a release path for energy, so a composite fracture mode including a plurality of fracture faces occurs. When the bedding angle is 60 °, the shale samples are mainly sheared along the bedding shear, and the number of cracks is small.

This is because at this angle, as the axial load increases, the bedding surface inside the shale is more likely to lose the cohesive force and shear slip occurs, resulting in more microcrack-derived expansion, so the pre-peak stage needs to be consumed. A large amount of energy is scattered. Before the stress reaches the peak intensity, some of the bedding planes inside the sample may already be in a critical expansion state. Therefore, when the load exceeds the peak intensity, the elastic energy inside the sample can be more easily extended along these. The layered surface or microcracks are released, which induces the generation of macroscopic cracks. Due to the large amount of energy dissipated in the pre-peak stage, the additional energy dWa required in the post-peak stage is also large, and the characteristics are shown on the stress-strain curve. There is a relatively small yield modulus D and a weakened modulus M. When the bedding angle is 75 °~90 °, the microcracks in the laminar direction of the sample are opened or slipped in the pre-peak stage with the increase of the load. It is necessary to dissipate a certain amount of energy. After reaching the peak intensity, the elastic energy is obtained. The rapid release of the micro-cracks in the pre-peak period continues to expand, eventually leading to overlapping and connecting adjacent cracks to form longer cracks, and continuously expanding toward the direction of the maximum principal stress, forming a longitudinal multiple splitting failure mode.

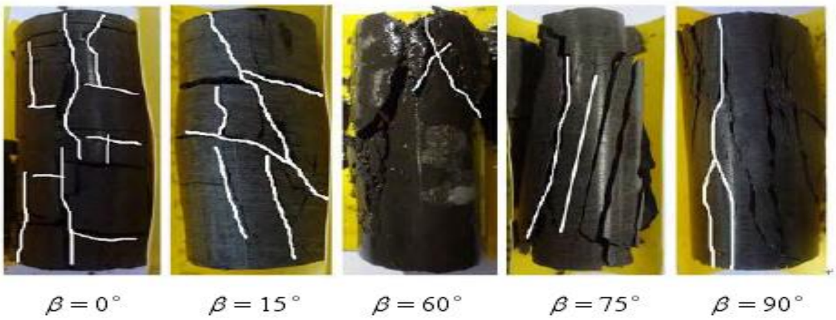

Figure 6. Shale fracture morphology under different bedding angles

5. Conclusion

(1) The essence of brittle fracture of rock is the dynamic instability caused by high energy accumulation in the pre-peak stage and rapid release of energy in the post-peak stage. The pre-peak dissipation energy and post-peak fracture energy are the essential factors determining whether the rock is brittle fracture. When the elastic energy accumulated inside the rock is constant, the smaller the ratio of the pre-peak dissipation energy and the post-peak fracture energy, the stronger the brittleness of the rock.

(2) The brittleness index established in this paper considers the evolution law of various energies in the whole process of rock failure. It can not only evaluate the brittleness characteristics of rocks under different mechanical conditions, but also describe the whole scale of rock from ideal plasticity to ideal brittleness. The calculation results are monotonous and continuous. The brittleness of different rocks under different confining pressures was evaluated. The results show that the brittleness of rock has different decreasing trend with the increase of confining pressure.

(3) The brittle fracture characteristics of shale have obvious anisotropy. The shale samples under different bedding angles show different brittle fracture characteristics. The results of brittleness evaluation show that with the increase of the bedding angle, the brittleness of shale shows a decreasing trend. This is consistent with the brittle change characteristics reflected by the fracture mode of the shale sample.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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