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Research Article

Effect of Clay Mineral Content and Confining Pressure on Energy Dissipation Characteristics of Basalt with Different Overburden Depths

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With the deepening of coal mining in China, dynamic disasters occur with the release of energy. In this study, in order to study the difference between shallow rock and deep rock, conventional triaxial compression tests were carried out on basalts with different overburden depths. The mechanical properties and energy evolution characteristics of basalts with different overburden depths were analyzed. The results show that the strength parameters increase with increasing depths, while the deformation parameters exhibit the opposite phenomenon. The strength and peak strain of basalt with the same depth increase with increasing confining pressure. However, the elastic modulus almost remains unchanged. The prepeak total input energy and dissipation energy decrease with increasing depths, and total elastic energy increases with increasing depths which indicates that the deep rock releases more energy than shallow rock when failure occurs. The input energy, elastic energy, and dissipation energy increase with increasing confining pressure. However, elastic energy ratio decreases with increasing confining pressure. The strength parameters and elastic energy increase with increasing density and deformation parameter, while the dissipation energy decreases. This phenomenon has the opposite law when clay mineral content is increased. The conclusions of this study may provide theoretical reference to dynamic disasters induced by energy in deep coal mines.

1. Introduction

With the gradual reduction of shallow coal resources in China, coal mines in the central and eastern regions have gradually entered the state of deep mining, resulting in frequent occurrence of dynamic disasters such as rock burst [1–3]. Regarding the definition of deep part, according to the present situation of coal mining technology and the requirements of safe mining, the concept of deep part is proposed as 700~1000 m [4]. From shallow to deep, the physical and mechanical properties of rocks are constantly changing, reflecting obvious nonlinear characteristics, which is the research focus and a challenge of deep rock mechanics investigation. Under deep mining conditions, surrounding rock accumulates much elastic energy, and the elastic energy release (up to 10^9 J) will cause equipment damage, and even casualties [2, 4]. Rock (coal) is a complex geological material. Under the action of external load, its deformation and failure process is accompanied by energy absorption, storage, dissipation, and release [5–8]. In underground coal mine, with the deepening of buried depth, the principal stress showed a gradual upward trend and tomography of the dynamic stress coefficient in sedimentary rocks decreased significantly with the increase of vertical distance [9, 10]. Li et al. [11] found that the longer the mining advance distance, the greater the tensile stress on the regenerated roof. Therefore, in order to explore the difference of mechanical properties and energy evolution between shallow rock and deep rock, it is necessary to carry out rock mechanics tests at different overburden depths.

The failure of rock has been studied from the perspective of energy. The main relationships covered are that between energy dissipation and damage of rock element, that between energy dissipation and rock constitutive, and that between released strain energy in rock element and failure or rupture of rock element [8]. Tsoutrelis and Exadaktylos [12] studied the influence of failure energy parameters on rock strength for the failure behavior of jointed rock mass. Hua and You [13] studied the energy release characteristics during unloading confining pressure. Li et al. [14] studied the strain rate effect of energy evolution of coarse-grained marble and found that the absorbed strain energy before peak, damage strain energy, and elastic strain energy increased with the increase of strain rate. Peng et al. [15] conducted conventional triaxial compression tests on coal samples with a buried depth of 600 m and studied the energy transfer in the process of coal failure. It was found that the failure energy ratio β and stress drop coefficient α were approximately linear with the fractal dimension of the coal block, and a higher failure energy ratio corresponded to larger fractal dimension and more serious failure. Wang et al. [16] analyzed the law of energy dissipation and energy conversion of rock under cyclic loading and unloading and the stress-energy mechanism inducing rock failure. They also established the constitutive model and multicriteria model of rock failure and revealed the law of energy release and dissipation through stress in the process of rock failure from the perspective of energy. Meng et al. [17] studied the energy accumulation, evolution, and dissipation characteristics of 30 sandstone specimens under uniaxial cyclic loading-unloading compression at six different loading rates. The experimental results showed that the input energy causes the irreversible initiation and propagation of microcracks in rock mass. Additionally, elastic energy release leads to sudden instability of rock mass and drives rock mass failure. Through uniaxial and biaxial compression tests, Xie et al. [18] observed that only a small proportion of total input energy dissipated in hard rock before peak load, while a large proportion of energy dissipated in soft rock. Gong et al. [19] defined the ratio of elastic strain energy density to dissipative strain energy density corresponding to peak compressive strength of rock specimens as the peak strength strain energy storage index, so as to estimate and classify the impact tendency of rock materials. Meng et al. [20] and Gong et al. [21] conducted cyclic loading-unloading uniaxial compression tests, revealing the evolution law of energy accumulation and dissipation in rocks. Deng et al. [22] carried out dynamic uniaxial compression tests of granite and sandstone under five different impact velocities by using a split Hopkinson pressure bar (SHPB) device. It was found that with the increase of energy consumption density, the average size decreased significantly, and the fracture surface area increased accordingly. Meng et al. [23], Zhang et al. [24], and Li et al. [25] studied the influence of confining pressure on the evolution characteristics of rock energy and found that the confining pressure could increase the elastic energy density in the prepeak stage. Wang et al. [26] decomposed the target waveform into multiple intrinsic mode function (IMF) components by Hilbert-Huang transform (HHT) method and found that the energy was mainly concentrated in the C_1-C_4 IMF components.

The above studies are mostly based on the same depth of rock, without considering the influence of different overburden depth on the energy evolution of rock failure. Most gently inclined coal seams are difficult to sample with the same lithology and hundreds of meters of shallow and deep span. The basalt selected in the present study is igneous eruption rock, which is steeply inclined. The sampling depth range is 510–1010 m, which basically covers the variation range from shallow to deep. In addition, different depths affect rock mineral composition and density. The influence of depth on rock mechanical properties is in fact the influence of physical parameters such as mineral composition and density on rock mechanical properties. On this basis, this paper discusses the influence of overburden depth, clay content, and density on the energy release and energy dissipation of basalt according to the differences in mechanical properties of basalts at varying depths, so as to provide theoretical reference for the dynamic disasters caused by energy in deep coal mining.

2. Test Results

The mechanical properties of the basalt were previously investigated by Zhou et al. [27] and Zuo et al. [28]. The triaxial compression test results of basalts at different depths are shown in Table 1 [27, 28]. In Table 1, B510-1 represents the first sample of the overburden depth of 510 m, σ_3 is confining pressure, $(\sigma_1 - \sigma_3)_p$ is the peak differential strength, E is the elastic modulus (slope of the linear elastic stage of the stress-strain curve), and ε_{1p} is the peak strain. Figure 1 is the axial stress-axial strain curve of basalt under different depths and confining pressures. It can be seen from Figure 1 that, under axial load, most of the stress-strain curves of basalt show a type II curve phenomenon, which is mainly related to the uneven distribution of samples, rigidity of the testing machine, and loading control conditions [29, 30].

Figure 2 shows the variation trend of mechanical parameters of basalt with different occurrence depths and confining pressures. Combining with Table 1 and Figure 2(a), it can be seen that the peak strength of basalt gradually increases with the increase of overburden depth. Compared with sample B510-1, the depth of sample B1010-1 increased by 500 m, and the strength increased by about 24.5%, for an increase of nearly 25%. The elastic modulus increases slightly with the increase of the overburden depth. Compared with the overburden depth of 510 m, the elastic modulus of basalt with the overburden depth of 1010 m increases by 19.9 GPa. It can be seen that the strength parameters (peak strength and elastic modulus) of basalt increase significantly under the same confining pressure. In addition, with the increase of overburden depth, the peak strain of basalt exhibits a decreasing trend. That is to say, the greater the overburden depth is, the less basalt damage the deformation will cause. The reason for this difference in mechanical parameters is mainly related to the geostress of basalt. Following the magma intrusion and consolidation, under the action of high geostress, the density of deep basalt increases, the porosity decreases, peak strength and elastic

Table 1: Results of triaxial compression tests of basalt.

No.	σ_3/MPa	$(\sigma_1-\sigma_3)_p$/MPa	E/GPa	$\varepsilon_{1p}/10^{-3}$
B510-1	0	213.5	139.8	2.15
B510-2	5	244.6	135.9	2.91
B510-3	15	273.8	124.2	2.98
B510-4	25	287.7	125.9	3.67
B510-5	35	336.6	121.2	4.36
B710-2	5	260.8	127.0	3.11
B810-2	5	273.5	137.4	2.65
B910-2	5	278.4	124.7	2.28
B1010-2	5	304.5	141.1	2.43

modulus increase, and peak strain decreases. Combining Table 1 and Figure 2(b), it can be seen that when the overburden depth is 510 m, with the increase of confining pressure, the peak strength and peak strain of the basalt gradually increase, while the elastic modulus remains basically unchanged.

3. Energy Evolution Characteristics of Rock Deformation and Failure

The process of rock deformation and failure is accompanied by the dissipation of energy. Reference [6] considered that the unit volume of rock unit deforms under the action of external force. Assuming that there is no heat exchange between the physical process and the outside world, the total input energy generated by external force is U. According to the first law of thermodynamics, the following can be obtained:

$$U = U^{\mathrm{d}} + U^{\mathrm{e}}, \tag{1}$$

where U^{d} is the element dissipation energy, which reflects the unidirectionality and irreversibility of thermodynamics in the process of rock deformation and failure, and U^{e} is the element release elastic strain energy.

Under normal triaxial compression, the total input energy U at a certain stress level is as follows [6].

$$U = \int_0^{\varepsilon_{1i}} \sigma_{1i} d\varepsilon_{1i} + 2\int_0^{\varepsilon_{3i}} \sigma_{3i} d\varepsilon_{3i}, \tag{2}$$

where σ_{1i} and σ_{3i} are the axial stress and hoop stress at a certain time and ε_{1i}, ε_{3i} are corresponding axial strain and radial strain.

Since the circumferential elastic strain energy is small relative to the axial direction, it can be ignored. Therefore, under triaxial loading conditions, for the calculation of the released elastic strain energy U^{e}, the elastic modulus E of the elastic segment at the front of the rock peak is usually used to replace the unloading elastic modulus E_i, and then, the released elastic strain energy is as follows:

$$U^{\mathrm{e}} = \frac{\sigma_{1i}^2}{2}. \tag{3}$$

Combining Equations (1), (2), and (3), the dissipation energy at a certain stress level σ_{1i} is calculated as follows:

$$U^d = \int_0^{\varepsilon_{1i}} \sigma_{1i} d\varepsilon_{1i} + 2\int_0^{\varepsilon_{3i}} \sigma_{3i} d\varepsilon_{3i} - \frac{\sigma_{1i}^2}{2}. \tag{4}$$

3.1. Energy Evolution Characteristics of Basalt at Different Depths

3.1.1. Stress-Strain Curves. Samples B510-1 and B710-2 are selected as examples, and the energy evolution curves are shown in Figure 3. It can be seen from Figure 3 that with the continuous increase of axial load, the total input energy continues to increase, and the elastic energy begins to decrease after reaching the peak value. The dissipation energy first remains basically unchanged near 0, then begins to increase rapidly.

In order to facilitate the analysis, the energy evolution process is divided into two stages, with the dissipation energy beginning to increase as the boundary point. In the first stage, with the increase of axial load, the axial stress and axial strain increase linearly, as shown in the orange solid line in Figure 3. At this time, most of the energy absorbed by basalt samples is converted into elastic energy. The main reason for this is that the basalt is very dense and there are few internal microcracks. The energy applied is absorbed by the matrix and converted into elastic energy for storage. In the second stage, with the continuous increase of the axial load, the stress-strain curve of basalt begins to deviate from the orange solid line. At this time, the microcracks in basalt begin to initiate, then propagate. Some of the energy absorbed by the specimen is stored in the form of elastic energy, and the rest is dissipated due to the initiation and propagation of cracks.

The relationship among the prepeak total input energy, elastic energy, and dissipation energy of basalts with different overburden depths is shown in Figure 4. It can be seen from the figure that, with the deepening of overburden depth, the total input energy and dissipation energy before the peak gradually decrease. Under the same confining pressure, the energy required for deep basalt failure is less than that for shallow basalt failure. This can be seen from the variation rule of overburden depth and energy in Figure 4. For example, with the increase of overburden depth, the input energy decreases. The prepeak dissipation energy reflects the crack propagation of rock. The smaller total dissipation energy before peak leads to smaller crack propagation, which reflects the strong brittleness of the rock from another perspective, that is, less crack propagation causes rock failure. The stored elastic energy begins to release after the rock has been damaged, which is one of the important causes of rock burst. It can be seen from Figure 4 that the total elastic energy released before peak increases with the increase of overburden depth. Under the same conditions, deep rock stores elastic energy more easily. When the rock mass is excavated, the elastic energy released by the deep rock is greater, then the dynamic disasters such as rock burst or rock burst occur frequently.

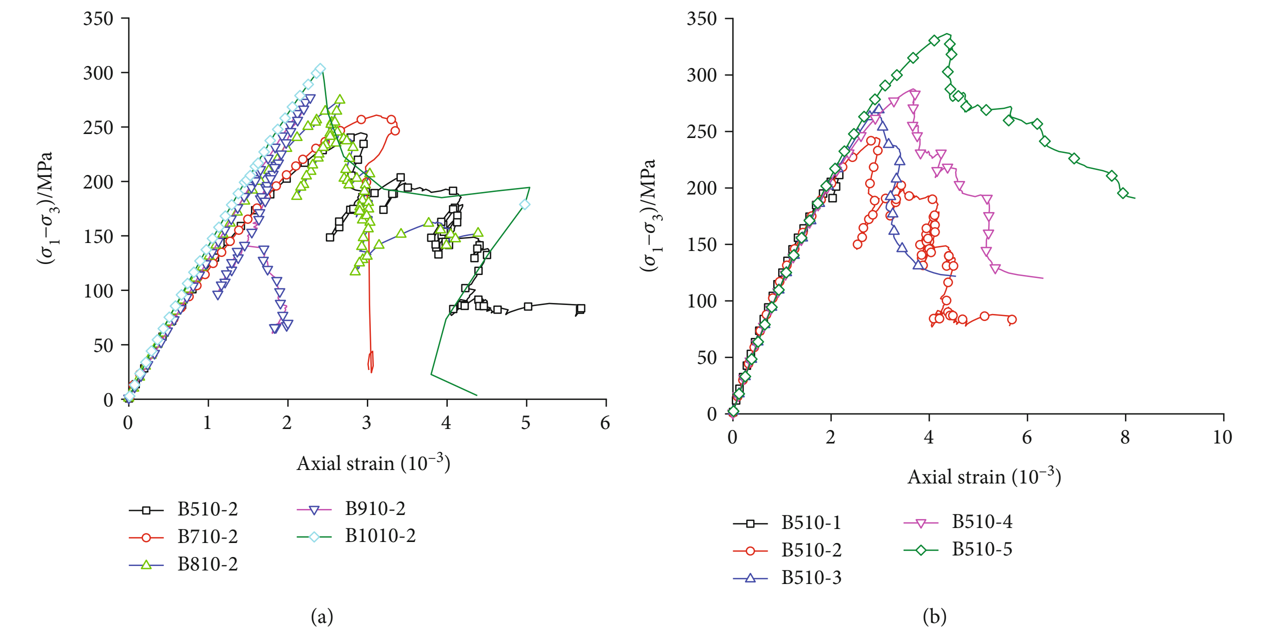

Figure 1: The complete stress-strain curves of basalt with different depths and confining pressure. (a) Different overburden depths. (b) Different confining pressures.

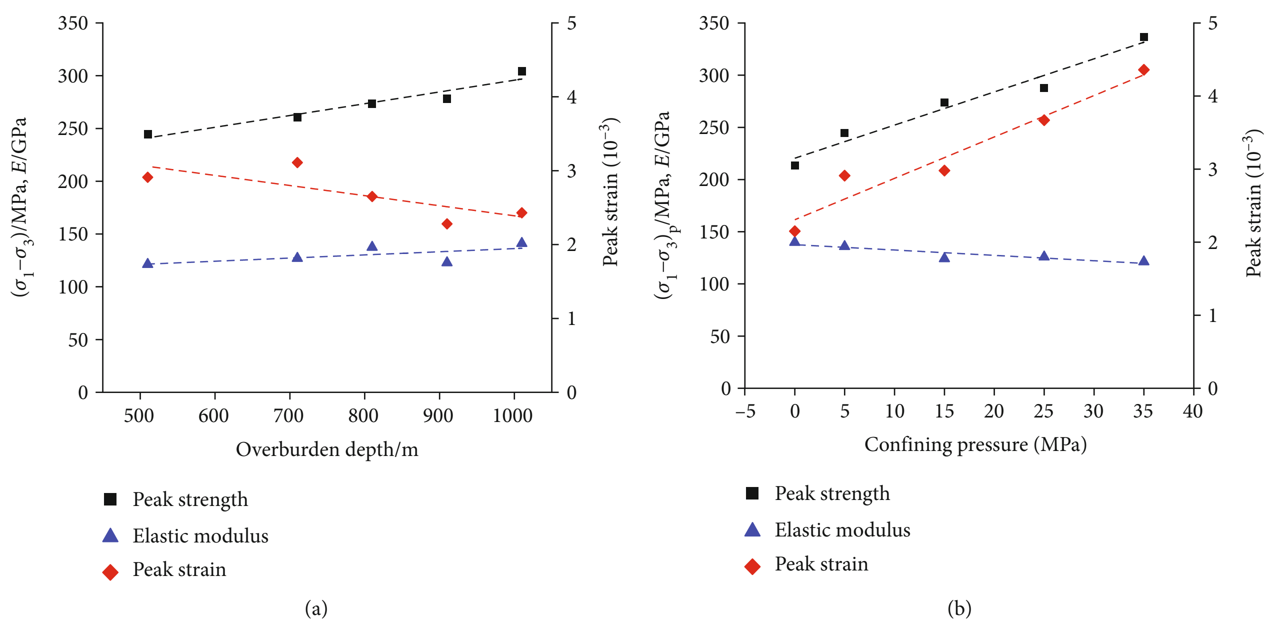

Figure 2: Mechanical parameters of basalt with different overburden depths and confining pressure. (a) Different overburden depths. (b) Different confining pressures.

The energy ratios of basalts with different overburden depths are shown in Figure 5. It can be seen that, as the overburden depth increases, the elastic energy ratio gradually increases, and the dissipation energy ratio gradually decreases. The elastic energy proportion of sample B910-2 is the largest, and the dissipation energy proportion is the smallest. The main reason for this is that B910-2 has very strong brittleness characteristics. There is no obvious yield stage before the peak, while there are obvious type II curve characteristics after the peak.

3.1.2. Relationship between Energy Dissipation Rate and Depth of Basalt. The increment of energy per unit time reflects the energy conversion rate in the loading process. Taking the energy dissipation of basalt as an example, the increment of unit dissipated energy is the energy dissipation rate, which reflects the speed of deformation and damage rate of basalt. The calculation formula is as follows:

$$\dot{U}_i^d = \frac{U_i^d - U_{i-1}^d}{t_i - t_{i-1}}, \tag{5}$$

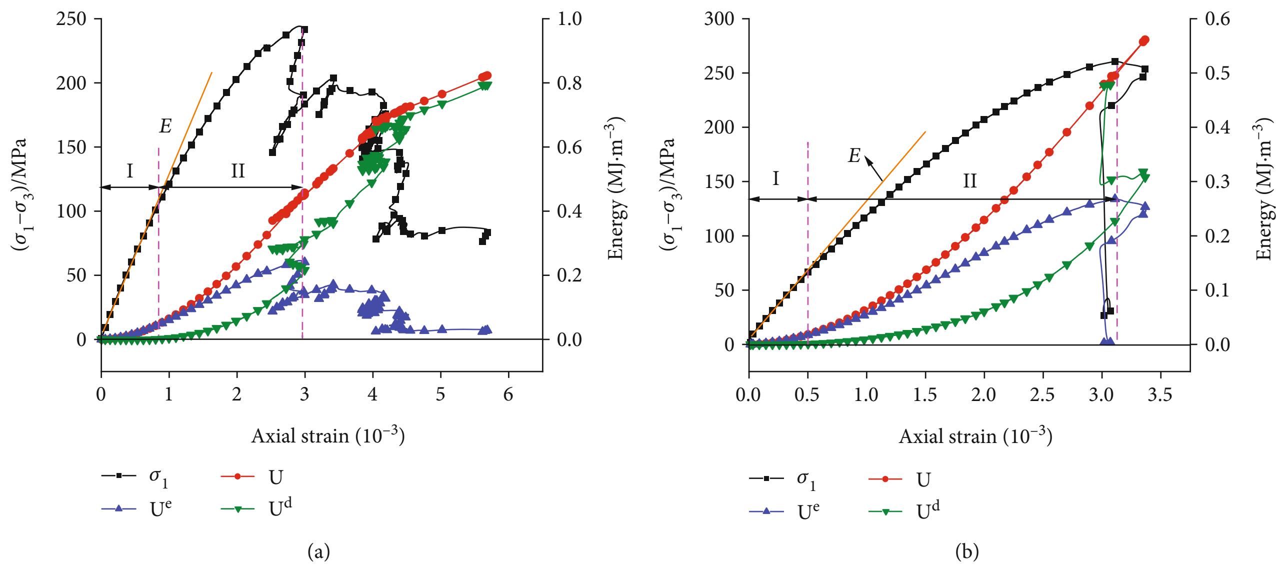

Figure 3: Energy evolution curves of basalt with different depths. (a) B510-2, (b) B710-2.

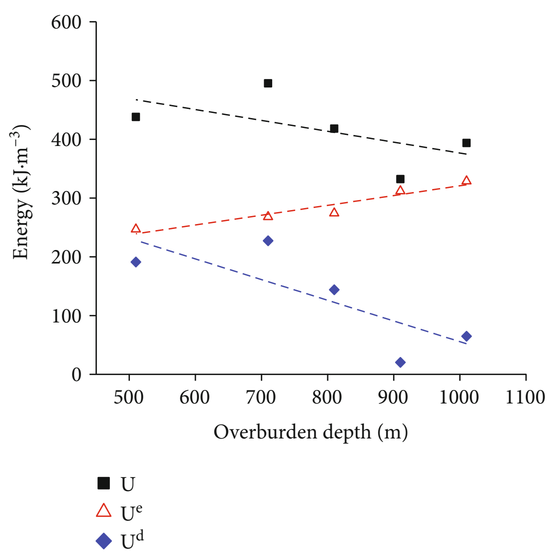

Figure 4: Relation between energy and overburden depths.

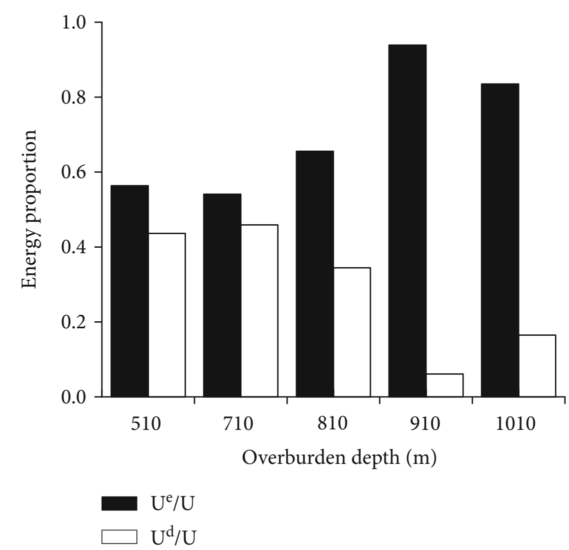

Figure 5: Relation between overburden depths and energy ratio.

where $\dot{U}_i^{\mathrm{d}}$ is the rate of energy dissipation, t_i, t_{i-1} is a certain loading time, U_i^{d} is the dissipation energy of t_i, and U_{i-1}^{d} is the dissipation energy of t_{i-1}.

The relationship between the energy dissipation rate of basalt and the loading time is shown in Figure 6. Due to space limitations, sample B910-2 is selected for illustration.

From Figure 6, it can be seen that with the extension of loading time, the energy dissipation rate is basically maintained near 0, and the differential stress-time curve is also linearly increased. When the basalt is damaged, the differential stress drops suddenly for the first time, the crack begins to form, and the dissipation energy conversion rate increases suddenly. This indicates that the deformation damage of basalt is the greatest. The differential stress-time curve falls for the second time, and the transformation rate of dissipated energy increases sharply. Then, the crack propagates stably, and the energy dissipation rate remains basically unchanged, i.e., the increment of dissipation energy remains basically unchanged. Statistics show that the sudden increase of energy dissipation rate generally occurs when the differential stress drops.

Figure 7 shows the relationship between the peak energy dissipation rate and overburden depth. The peak energy dissipation rate is the energy dissipation rate when the basalt reaches the peak stress. It can be seen from Figure 7 that with the increase of overburden depth, the maximum energy dissipation rate gradually decreases, indicating that the energy dissipation rate is faster when the failure and instability of shallow basalt occurs, as is the deformation and damage rate. In a certain time, the dissipated energy is more

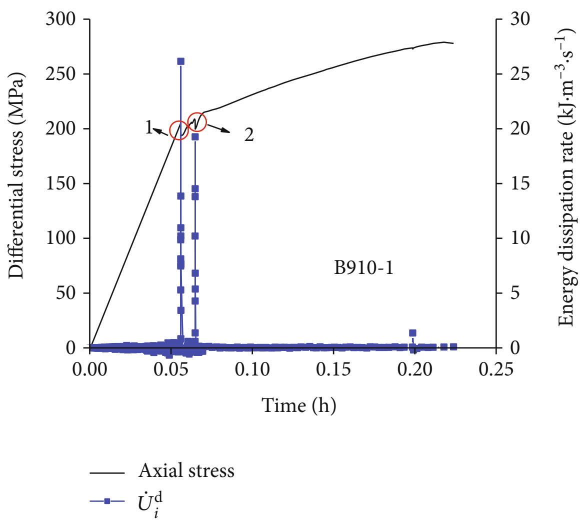

Figure 6: Change of energy dissipation rate.

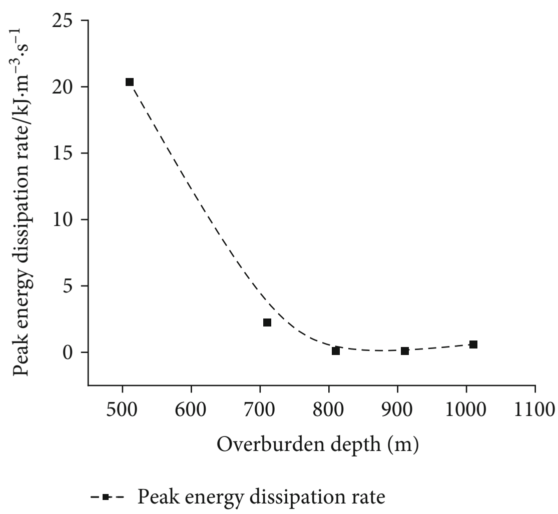

Figure 7: Relation between peak energy dissipation rate and overburden depths.

than that of deep basalt. Combining these observations with Figure 5(a), it can be seen that the deeper the depth is, the greater the released elastic energy will be. In addition, the energy dissipation rate is small; thus, the basalt is prone to rock burst.

4. Discussion

4.1. Relationship between Clay Content and Mechanical Parameters. The rock used in this study was taken from the volcanic basalt stratum in Datai coal mine. After magma intrusion and consolidation, under the action of tectonic stress, the ground stress of deep basalt is large, and the density of basalt increases with the increase of depth. After magma intrusion, from shallow to deep, the mineral composition of basalt is different, which affects the basalt's change of macroscopic mechanical parameters. Different overburden depths affect the density and mineral composition of basalt, while density and mineral composition can indirectly reflect different overburden depths. Reference [27] gave the law of density increasing with depth deepening. Reference [28] elucidated the relationship between clay minerals and overburden depth, as shown in Figure 8. It can be seen that, with the increase of overburden depth, the clay minerals gradually decrease.

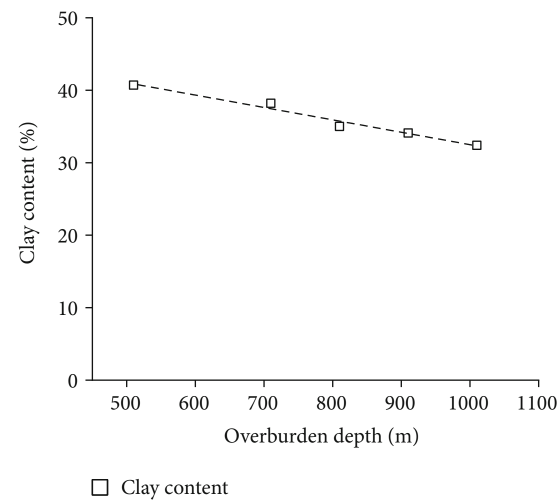

Figure 8: Change of clay mineral content with overburden depths.

Figure 9 shows the relationship among density, clay content, and mechanical parameters. It can be seen from Figure 9(a) that the greater the density is, the greater the strength parameters (peak strength, elastic modulus) of basalt will be, exhibiting a positive correlation. Additionally, the peak strain decreases with the increase of density. In the case of the same size, the greater the density is, the denser the rock will be, and the fewer internal cracks there will be, thus resulting in higher strength. However, when the cracks begin to initiate, the fewer cracks can cause the rock failure, reflecting strong brittle characteristics. It can be seen from Figure 9(b) that the higher the clay content is, the lower the strength parameters (peak strength and elastic modulus) of the basalt will be. The peak strain increases with the increase of clay content, which reflects the large deformation characteristics of clay.

4.2. Relationship between Clay Content and Energy Dissipation. Figure 10 illustrates the relationship between the total elastic energy and dissipation energy of basalt before peak, density, and clay content. It can be seen from Figure 10(a) that the higher the clay content is, the greater the dissipation energy will be and the smaller the elastic energy will be. The main reason for this is that clay minerals do not store energy, and have large deformation. The deformation of clay minerals mainly dissipates energy, resulting in the phenomenon that the higher the clay content is, the greater the dissipation energy will be.

Different depths affect the mineral composition, density, and other physical parameters of the rock. The different physical parameters affect the change of mechanical parameters of the rock. Under the same loading conditions, the released elastic energy of deep basalt is higher than that of

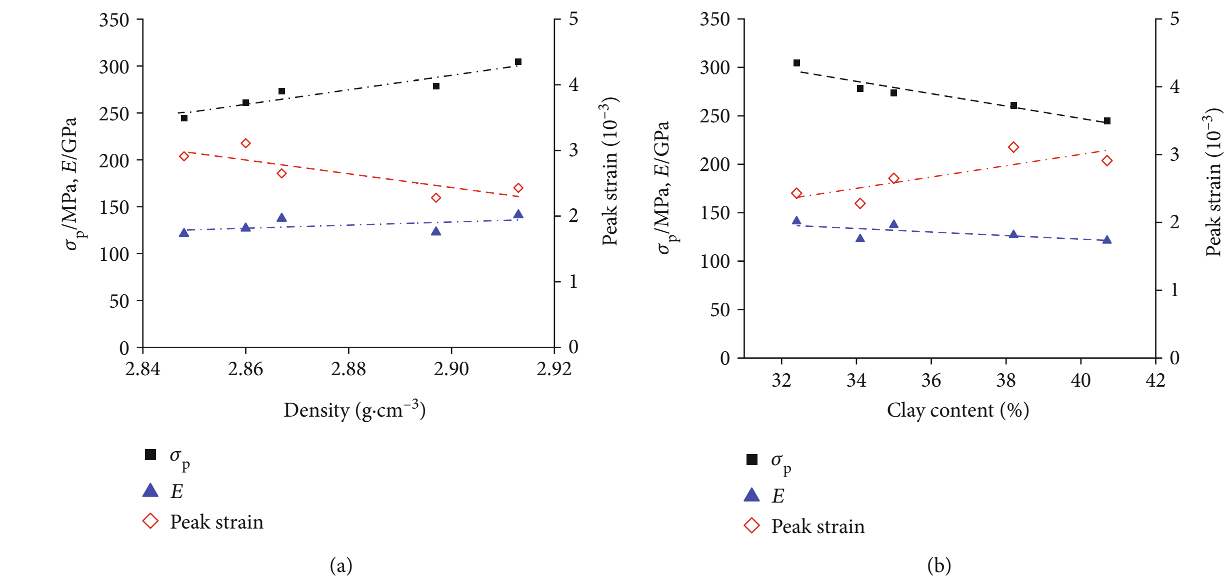

Figure 9: Change of mechanical parameters with density and clay mineral content. (a) Relationship between density and mechanical parameters, (b) relationship between clay content and mechanical parameters.

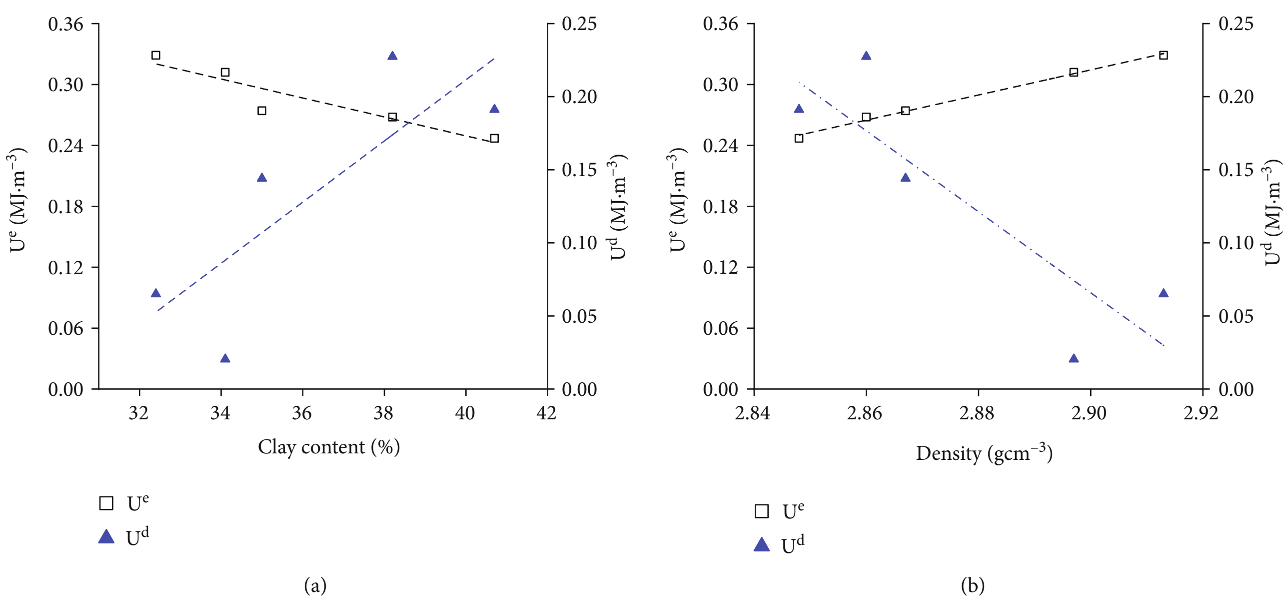

Figure 10: Change of energy with density and clay content. (a) Relationship between clay content and energy. (b) Relationship between density and energy.

shallow basalt. During tunneling or working face mining, the elastic energy accumulated in deep rock is more than that in shallow rock, and less energy is dissipated prior to rock failure. In the case of mining disturbance, the energy released by rock failure is greater than that in shallow rock, which easily leads to rock burs. From the perspective of mineral composition and density, the lower the clay mineral content is, the less the dissipated energy of the rock will be. In addition, the higher the density is, the greater the released elastic energy of rock will be. Under the influence of high ground stress, deep rock is denser than shallow rock, and the damage caused by rock burst is greater than shallow rock.

4.3. Energy Evolution Characteristics of Basalt under Different Confining Pressures. In this study, two samples are selected to illustrate the energy evolution characteristics of the basalt, namely, B1010-1 and B1010-5, which are shown in Figure 11. It can be seen from Figure 11 that the prepeak energy conversion is mainly divided into two stages. In the first stage, before the initiation and propagation of microcracks, the basalt exhibits obvious elastic characteristics. In this stage, the energy absorbed by the basalt is mainly converted into the releasable elastic strain energy, which is stored in the matrix of the sample and exhibits the elastic deformation of the sample. If it is unloaded in this stage,

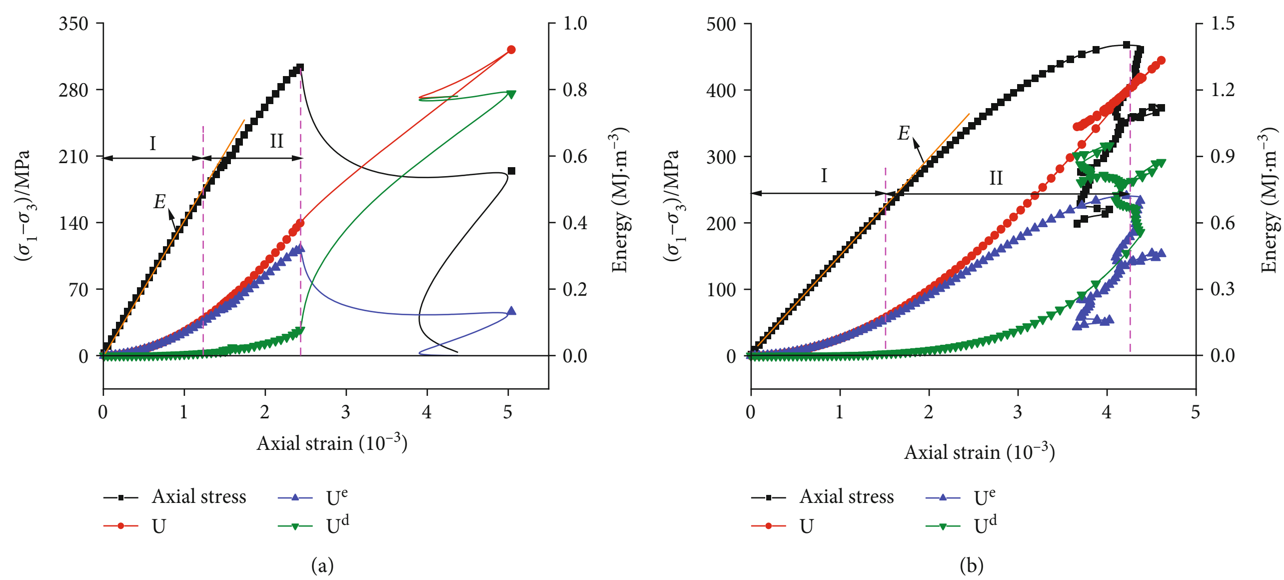

FIGURE 11: Energy evolution curves of basalt with different confining pressure. (a) B1010-1. (b) B1010-5.

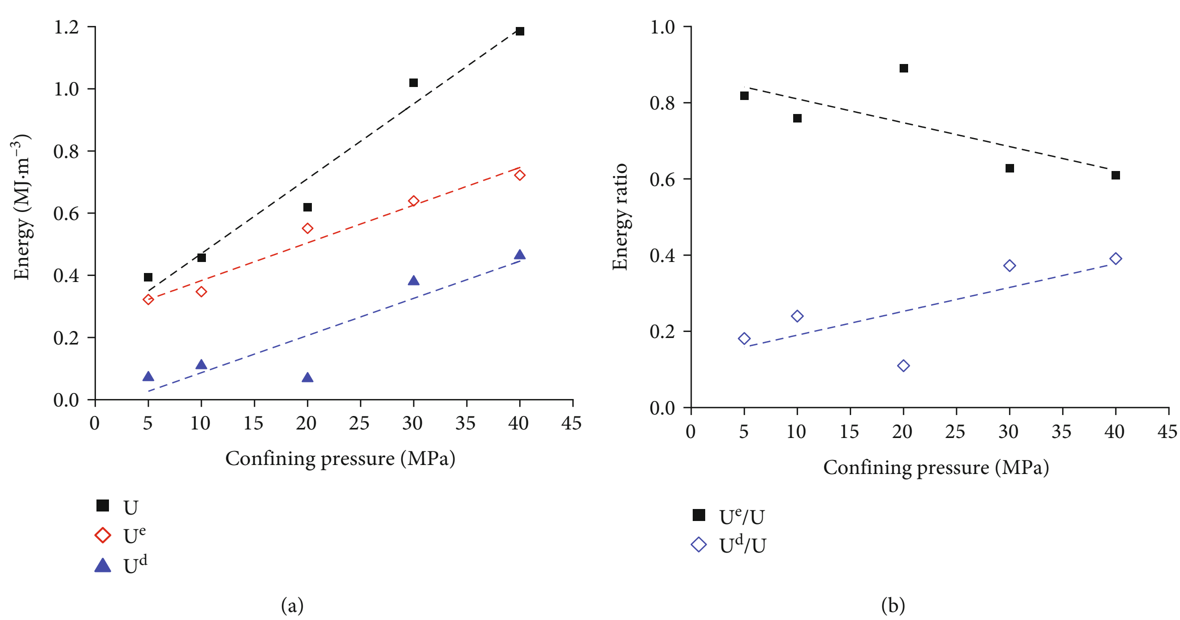

FIGURE 12: Change of energy (ratio) with confining pressure. (a) Relationship between energy and confining pressure. (b) Relationship between energy ratio and confining pressure.

then the elastic deformation can be restored. When the orange line in Figure 11 of the differential stress-strain curve (the slope is the elastic modulus) enters stage II, then the dissipation energy begins to gradually increase. The dissipated energy in stage II is mainly used for the initiation and propagation of internal cracks in basalt.

The relationship among the prepeak total input energy, elastic energy, dissipation energy, elastic energy ratio (total elastic energy/total input energy), dissipation energy ratio (total dissipation energy/total input energy), and confining pressure of basalt at the same depth is shown in Figure 12. It can be seen from Figure 12(a) that the input energy, elastic energy, and dissipation energy increase with the increase of confining pressure. Taking the total input energy as an example, the total input energy is 0.39 MJ·m^{-3} when the confining pressure is 5 MPa, and 1.2 MJ·m^{-3} when the confining pressure is 40 MPa, for an increase by nearly three times. The larger the confining pressure is, the greater the energy will be. The main reason for this is that the confining pressure inhibits the crack initiation and propagation of rock. The higher the confining pressure is, the greater the friction force between the rock fracture surfaces will be, and in turn the rock becomes more difficult to damage. Therefore, the input of large energy can cause damage to it. Under the action of high confining pressure, in the hydrostatic pressure stage, the microcracks inside the rock are closed, so that the rock can store more energy. Therefore, the greater the confining pressure is, the greater the elastic energy will be. Additionally, the greater the confining pressure is, the more cracks will be needed to lead to the rock failure, and thus the more energy will be dissipated.

Figure 12(b) is the relationship between energy ratio and confining pressure. It can be seen from Figure 12 that, with the increase of confining pressure, the elastic energy ratio of the basalt gradually decreases, and the dissipation energy ratio gradually increases. The elastic energy ratio decreases from 82% to 61%. In addition, the dissipation energy ratio increases from 18% to 39%. This shows that when the confining pressure is low, the energy consumption of crack initiation, propagation, and coalescence is less significant, and the rock is destroyed. The initiation, propagation, and coalescence of cracks under high confining pressure require more energy to destroy the rock.

The greater the confining pressure is, the greater the required input energy will be when the rock is damaged, thus indicating that the rock under high confining pressure needs high energy input to be damaged. Therefore, in deep coal mining, it is necessary to transfer the concentrated stress acting on the surrounding rock of the roadway to the distant rock mass for the rock in the distant three-dimensional stress state to carry greater more mining disturbance force. Consequently, that the surrounding rock of the roadway is less disturbed, and the purpose of the stability of the surrounding rock of the roadway is achieved.

5. Conclusions

In this paper, triaxial compression tests were carried out on basalts with different overburden depths, and the relationship between different overburden depths and confining pressures and mechanical parameters and energy evolution of basalts was discussed. The main conclusions are as follows:

(1) The peak strength and elastic modulus of basalt increase with the deepening of depth, and the peak strain gradually decreases. This reveals that the deformation of deep rock is smaller than that of shallow rock, and the brittleness of deep rock is stronger. Under confining pressure, the peak strength and peak strain of the basalt at the same depth increase with the increase of confining pressure, and the elastic modulus remains basically unchanged

(2) The total input energy and dissipation energy before the peak of the basalt at different overburden depths decrease with the deepening of the depth, and the elastic energy released increases with the deepening of the depth. This shows that when the deep rock is destroyed, the released energy is more than that of the shallow rock, resulting in more hazards and occurrence times of rock burst

(3) The relationship between density and clay content, mechanical parameters and energy evolution was discussed. The greater the density is, the greater the strength parameters and elastic energy of basalt is, the smaller the deformation parameters and dissipation energy will be. In addition, the greater the clay content is, the smaller the strength parameters and elastic energy will be, and the larger the deformation parameters and dissipation energy will be

(4) The sudden drop of stress leads to the sudden increase of energy dissipation rate. The greater the depth is, the smaller the peak energy dissipation rate will be. In unit time, the energy dissipation of deep rock failure is small, and most of the energy is released in the form of elastic energy, which easily causes rock burst or rockburst disaster

(5) The greater the confining pressure is, the greater the total input energy, elastic energy and dissipation energy before the peak of basalt at the same depth will be. This indicates that the higher the confining pressure is, the more energy is needed to input to destroy the rock. Additionally, the larger the confining pressure is, the more cracks are needed for rock failure, resulting in a greater proportion of dissipated energy, and the proportion of elastic energy exhibits a downward trend

Data Availability

The data used to support the finding of this study are available from the corresponding author on reasonable request.

Conflicts of Interest

No potential conflict of interest is reported by the authors.

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