Research Article

Study on Damage Law of Raw Coal Based on Different Characterization Methods

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The different damage variables equation based on strain, energy dissipation, acoustic emission (AE), and permeability characteristics under tiered cyclic loading were defined. The damage variables based on different characteristics were compared, analyzed, and found that there are similarities and differences between them. The results show that: (1) the law curve of single cycle damage based on residual deformation and permeability is the same. With the increase of cycle times, it decreases first and then gently increases, increased sharply before the failure. However, the law curve of single cycle damage based on energy dissipation and AE ring count shows that it first increases slowly and the adjacent failure increases rapidly. (2) The cumulative damage evolution law based on residual deformation and permeability show an obvious three-stage pattern; that is, first accelerates, then slows down, and then accelerates again. However, the cumulative damage evolution law based on energy dissipation and AE ring count shows an obvious two-stage pattern, that is, first gently increases, and increased sharply before the failure.

1. Introduction

In the process of deep coal mining, it often suffers from a variety of cyclic mining stress, such as the effect of blasting stress wave on support, excavation and support of chamber, geological structure movement, and so on [1–5]. As a product of complex geological structure, there are a large number of irregular microcracks in coal and rock, whose structure is very uneven and presents complex nonlinear mechanical characteristics. Under the action of external load and environment, the internal microcracks of coal and rock continue to derive and expand, causing continuous damage of coal and rock, and finally forming macro cracks, leading to failure [6, 7]. The deformation and failure process of coal and rock under cyclic loading is essentially the process of cumulative damage development of coal and rock [8–10].

Therefore, it is of great significance to study the damage evolution law of coal and rock for further revealing the deformation and failure characteristics of mining rock mass.

The key to study the damage characteristics of coal and rock mass is to answer two questions: first, what is the characterization of damage? Second, what kind of variables can be used as damage variables? In view of these two problems, scholars at home and abroad have done a lot of research on the damage of various types of rocks, and also proposed a variety of characterization methods of rock damage [11–14]. For example, based on the equivalent strain hypothesis, Lemaitre proposed the classical damage definition "elastic modulus method" [11], and its damage variable formula was as follows:

$$D = 1 - \frac{E^d}{E},\tag{1}$$

where E is the elastic modulus of the material without damage; E^d is the elastic modulus of the material with damage, i.e., unloading modulus.

The classical definition of damage variable was modified by Ju and Xie and an elastic-plastic damage definition coupled with plastic deformation and damage deformation mechanism was proposed [12].

$$D = 1 - \left(1 - \frac{\varepsilon_p}{\varepsilon}\right)\left(\frac{E^d}{E}\right), \tag{2}$$

where ε_p and ε are the residual strain after unloading and the total strain during unloading, respectively.

Based on the Weibull distribution of material fracture limit at the meso scale, the relationship between loading/unloading response ratio Y and damage variable D was established by Zhang et al. [13].

$$D = 1 - \exp\left(\frac{1 - Y_E}{m_{Wei} Y_E}\right), \tag{3}$$

where Y_E is loading/unloading response ratio and m_{Wei} is Weibull index.

Li et al. [14] assumed that the fatigue damage is related to the microplastic strain, and established the high cycle fatigue damage equation expressed by cycle number:

$$D = 1 - \left(1 - \frac{N}{N_F}\right)^{1/1+b}, \tag{4}$$

where N_F is the number of cycles when the rock reaches fatigue failure, and b is the experimental parameter.

Based on the theory of energy consumption and the influence of cumulative dissipated energy on the damage of specimens, Deng proposed the relationship between energy consumption and damage [15].

$$D = \sum_{i=1}^{n} D(i) = \frac{\sum_{i=1}^{n} U^d(i)}{U}. \tag{5}$$

Liu et al. established the damage variable expression based on AE cumulative ringing count [16].

$$D = \sum_{i=1}^{n} D(i) = \frac{\sum_{i=1}^{n} N^e(i)}{N}. \tag{6}$$

Dong et al. established a damage evolution model of the frozen sandstone reflecting the temperature effect using a power function to fit the cumulative AE count [17]. Wu et al. studied the damage characteristics of materials under laser shock strengthening by AE [18]. Zhao et al. defined damage variable based on the relative variation of AE parameters [19].

To sum up, the common damage characterization methods were listed. They reflected the damage evolution process of rock during loading by some variables, such as elastic modulus, plastic deformation, energy dissipation, and AE. Although it indirectly represents the evolution of damage variables from different aspects, there are still many controversies and phenomena that are not consistent with the reality. At the same time, they did not compare and analyze damage variables based on different characteristics parameter. It is difficult to obtain some of the damage characterization parameters mentioned above in the field or experiment.

Therefore, in this study, coal was used to carry out tiered cyclic loading test, and the characteristics of energy dissipation, AE, permeability, and residual strain were used to comprehensively reflect the damage evolution characteristics of raw coal tiered cyclic loading process. A new damage variable equation based on permeability change rate was defined and compared with the damage characteristics based on energy dissipation, AE, and residual strain. The damage characterization based on permeability change is easy to measure and can reflect the law of coal damage evolution from the side.

2. Test Equipment and Scheme

2.1. Test Equipment. The triaxial stress thermal-hydro-mechanical coal containing gas permeameter system [20] was used in the experiment, which can simulate and study the gas seepage test of coal and rock under different in situ stress fields (confining and axial pressures), different gas pressures, and different in situ temperature fields, as shown in Figure 1. The cracking process was recorded by the PCI-2 AE system. The preamplifier gain was 40 dB. The AE sensors were arranged in the horizontal and vertical directions of the coal samples [3].

2.2. Coal Samples. The coal samples used in the experiment were taken from $K1$ coal seam in the west wing of the Nanchuan Hongneng coal mine. The coal seam is rich in gas and has coal dust explosions. The basic physical parameters of sample are shown in Table 1. The large coal blocks taken on-site were drilled along the vertical bedding direction, and then cut and polished to make the size of $\Phi 50 \times (100 \pm 0.25 \, mm)$, and the actual coal sample is shown in Figure 2.

2.3. Experimental Scheme. In this experiment, the axial pressure and confining pressure were loaded to 3 MPa hydrostatic pressure at the speed of 0.05 MPa/s at the same time, and then 1 MPa gas was injected. After adsorption equilibrium, the confining pressure and gas pressure were kept unchanged. The axial pressure continued to load at the speed of 0.05 MPa/s, then unloaded to the target value, and then unloaded to 5 MPa before the next loading. The specific loading paths are shown in Figure 3.

3. Experiment Results and Analysis

In this experiment, the loading and unloading tests of three raw coals (RC-1, RC-2, and RC-3) were carried out under the same conditions, and the damage change amount and cumulative damage change law of each cycle before the failure of raw coal were studied. The total damage variable was defined as 1 and the initial damage was defined as 0. Based on the characteristics of residual strain, energy dissipation, AE, and permeability of raw coal during the staged cyclic loading and unloading process, the characterization methods of different damage variables were defined, and the damage variable laws based on different parameters were compared and analyzed. Taking RC-1 as an example, in the
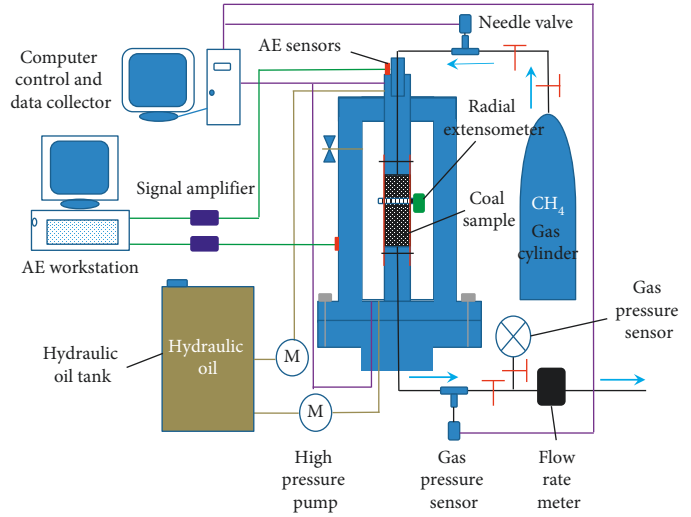
FIGURE 1: Triaxial stress thermal-hydro-mechanical coal containing gas permeameter [20].

TABLE 1: Main physic parameter of the sample [3].

Mad (%)	Aad (%)	Vad (%)	FCad (%)	v (cm/s)	Density (g/cm^3)
0.75	12.31	13.01	73.93	1659	1.385

Mad—moisture content on air dried basis; Aad—ash content on air dried basis; Vad—volatile content on air dried basis; FCad—fixed carbon content on air dried basis; v—wave velocity of coal sample.

process of tiered cyclic loading, from the corresponding relationship diagram of stress-strain, permeability, and AE, it can be seen that with the increase of stress, the damage of coal increases continuously, and the damage can be expressed by different variables (residual strain, permeability, and AE). Next, different variables used to characterize the damage characteristics were discussed.

3.1. Damage Variable Based on Residual Deformation Characteristics.

The continuous and irreversible fatigue damage of rock will be produced under the action of external force, and the residual deformation can precisely reflect the plastic deformation characteristics and the irrecoverable degree of cracks of rock under the action of external force. Therefore, the residual deformation can better reflect the characteristics of rock fatigue damage. Based on the residual strain produced during cyclic loading and unloading, the single cycle damage variable $D_p(i)$ and cumulative damage variable D_p were defined as follows:

$$D_P(i) = \frac{\varepsilon_P(i)}{\varepsilon_P^{\max}}, \tag{7}$$

$$D_P = \sum_{i=1}^{n} D_P(i), \tag{8}$$

where $\varepsilon_P(i)$ is the residual strain of the ith cycle; that is, $\varepsilon_P(i) = \varepsilon(i) - \varepsilon(i-1)$; $\varepsilon(i)$ is the strain when the cyclic loading and unloading i times, the axial stress is unloaded to the

5 MPa, as shown in Figure 4. $\varepsilon_P^{\max}$ is the total amount of all cyclic residual strains before failure.

According to equations (7) and (8), single cycle damage variable $D_p(i)$ and cumulative damage variable D_p based on residual deformation characteristics can be obtained. As shown in Figures 5(a) and 5(b), the change trend of damage variables of three coal samples with the increase of cycle times is roughly the same, while the change trend of single cycle damage and cumulative damage is quite different. During the loading and unloading process, the single cycle damage firstly decreases and then increases with the increase of the number of cycles. The damage of raw coal in the initial compaction stage and near failure stage is larger than that in the middle elastic deformation stage. The cumulative damage variable can be divided into three stages: the first stage is the initial accelerated damage stage, in the initial cycle stage, a large number of pores and fissures of raw coal are compressed, the second stage is the elastic gentle damage stage, and the third stage is near the rapid damage stage. This reflects the damage evolution process of raw coal under tiered cyclic loading.

3.2. Damage Variable Based on Energy Dissipation Characteristics.

Rock damage is the deterioration of rock properties caused by the development of internal defects, and energy is the driving force of the generation and expansion of rock defects and damage development. Therefore, the deformation and fracture process of rock must be accompanied by the transformation of energy [21–26]. It is feasible to analyze the energy transformation characteristics of rock deformation and fracture process, and find the appropriate energy transformation related features to describe the damage characteristics of rock. It is of great significance to further analysis and evolution of rock damage. Based on the energy dissipation during cyclic loading and unloading, the single cycle damage variable $D_U(i)$ and cumulative damage variable D_U are defined as follows:
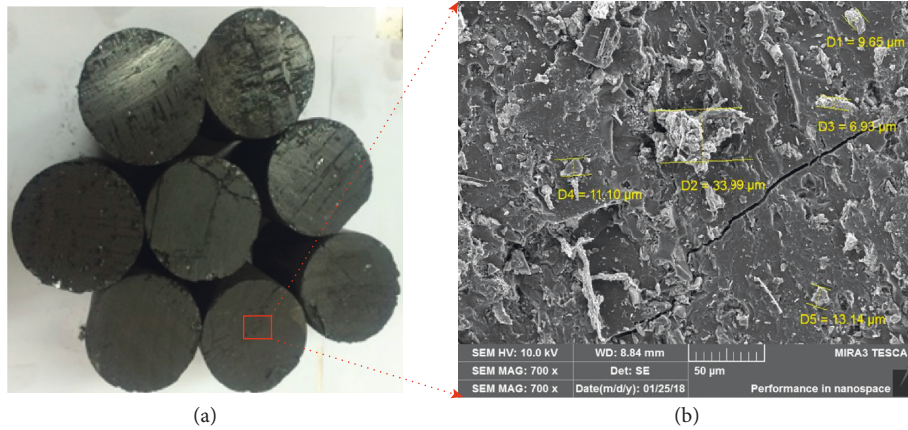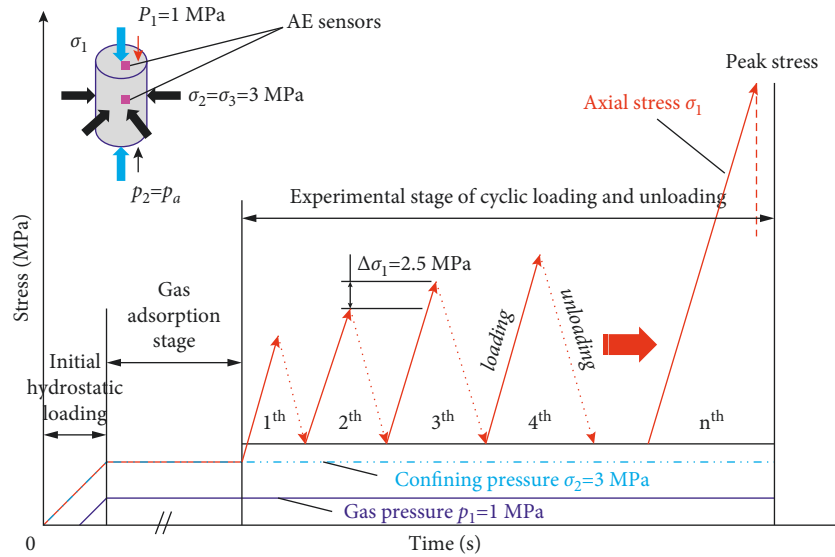
FIGURE 2: Standard raw coal samples and SEM of coal.

FIGURE 3: The loading paths for tests [1].

$$D_U(i) = \frac{U^d(i)}{U}, \tag{10}$$

$$D_U = \sum_{i=1}^{n} D_U(i), \tag{11}$$

where $U^d(i)$ is the energy dissipation of the ith cycle, as shown in Figure6. U is the total amount of all cyclic energy dissipation before failure. The specific calculation method of energy dissipation can refer to the previous research literature [22].

According to equations (10) and (11), single cycle damage variable $D_U(i)$ and cumulative damage variable D_U based on energy dissipation characteristics can be obtained. As shown in Figures 7(a) and 7(b), the variation trend of single cycle damage and cumulative damage is also quite different, and it is different from the damage variable calculated based on the residual deformation characteristics, but the trend is basically the same. The single cycle damage has some fluctuation. The cumulative damage increased with the increase of the number of graded cycles, and there were

no obvious three stages. The general rule of damage variable based on energy consumption characteristics is the same as that based on residual deformation, but there are differences. Therefore, whether the characteristics of damage variables can better characterize the fatigue mechanical properties of rock under cyclic loading is related to the selection of appropriate characterization methods. To further illustrate that the damage variables obtained by selecting different parameters are not only the same, the damage variables based on AE signal and permeability characteristic parameters were selected for analysis in this experiment.

3.3. Damage Variable Based on AE Characteristics. AE is a phenomenon where rock materials produce strain energy and release elastic waves under loading. As a nondestructive monitoring method, the AE monitoring technology is widely used in the study of material damage characteristics [27–29]. The relationship between AE characteristic parameters and mechanical parameters
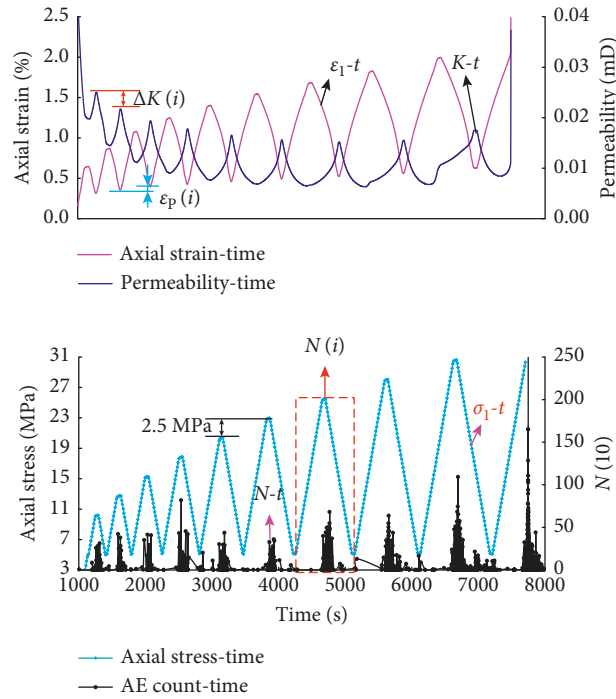
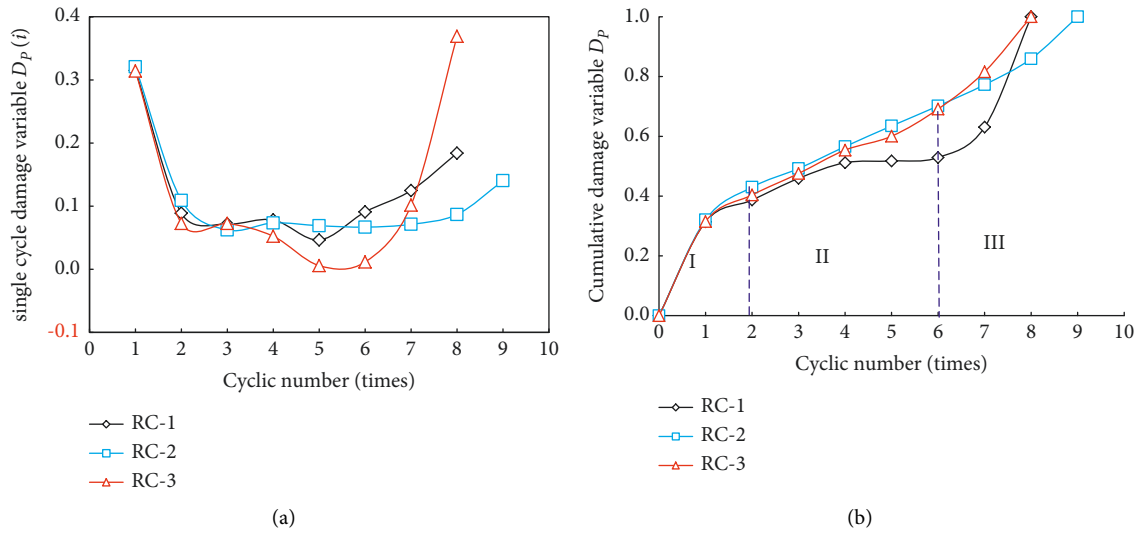FIGURE 4: The corresponding relationship diagram of stress-strain, permeability, and AE of RC-1.

(a)

(b)

FIGURE 5: Damage variable curve based on residual deformation: (a) $D_P(i)$ and (b) D_P.

contains the damage information of materials [30]. The change of AE characteristic parameters indicates the damage evolution process of materials. Therefore, this study selects AE ringing count to describe the damage process of raw coal under cyclic stress. Based on the AE ringing count, the single cycle damage variable $D_A(i)$ and cumulative damage variable D_A were defined as follows:

$$D_A(i) = \frac{N(i)}{N}, \tag{12}$$

$$D_A = \sum_{i=1}^{n} D_A(i), \tag{13}$$

where $N(i)$ is the AE ringing count of the ith cycle, as shown in Figure 4, N is the total AE ringing count of all cycles before failure.

According to equations (12) and (13), single cycle damage variable $D_A(i)$ and cumulative damage variable D_A based on AE characteristics can be obtained. As shown in Figures 8(a) and 8(b), with the increase of the number of cycles, the damage evolution law of the three coal samples based on the AE characteristics is roughly the same. The damage amount of a single cycle increases significantly before the failure and remains stable in the early stage. The cumulative damage increases slowly in the early stage and rapidly before failure,
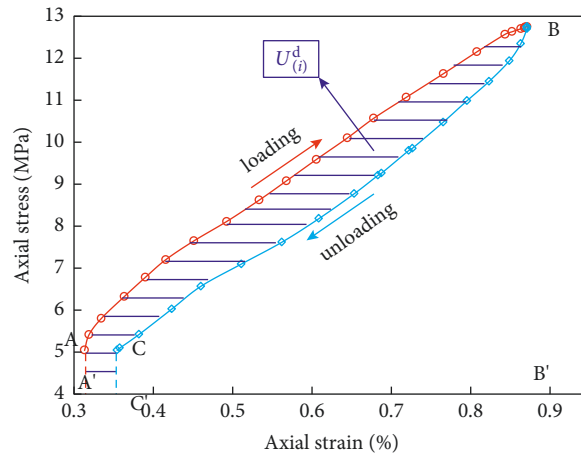
FIGURE 6: Calculation area of coal energy dissipation under tiered cyclic loading.
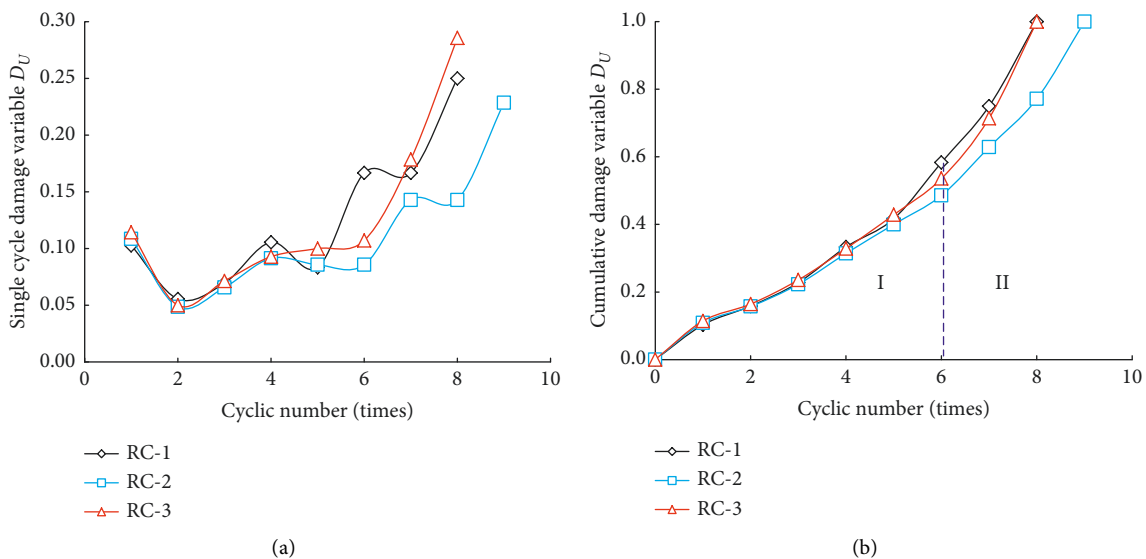

(a)

(b)

FIGURE 7: Damage variable curve based on energy dissipation. (a) $D_U(i)$. (b) D_U.

which can be divided into two stages: the first stage is stable period and the second stage is rapid deterioration period.

There are some differences between the damage evolution law based on AE characteristics based on residual strain and energy consumption characteristics, which may be related to the data collected by AE. Because the AE acquisition needs to set a certain threshold value in order to avoid the influence of the noise of the testing machine when the cyclic stress is low, the intensity of the AE signal generated is weak, and it does not reach the threshold value of the acquisition signal and is not collected, so it shows the phenomenon of less AE ringing count and low damage at the initial stage of the cycle.

3.4. Damage Variable Based on Seepage Characteristics.
The damage variables based on residual deformation, energy consumption, and AE characteristics are more traditional parameter variables to characterize the damage, but these are not easy to measure in situ. However, the measurement of coal seam gas is more convenient, so it is considered whether there is coal permeability to characterize the damage. The closure, development, expansion, and connection of coal internal fractures are the fundamental reasons for the change of coal permeability [31–35]. Under the action of external load, the change of internal pore structure and fracture morphology is also the fundamental cause of coal rock damage. For the relationship between seepage and damage evolution, some studies have been carried out by scholars. Based on micromechanics, Shao et al. proposed the damage model of granite and established the coupling relationship between damage tensor and seepage characteristics [36, 37]; Sheng et al. put forward the expression of permeability tensor of fractured rock mass considering fracture damage effect [38–40]. Therefore, it is feasible to characterize the damage change of coal mass by permeability change.
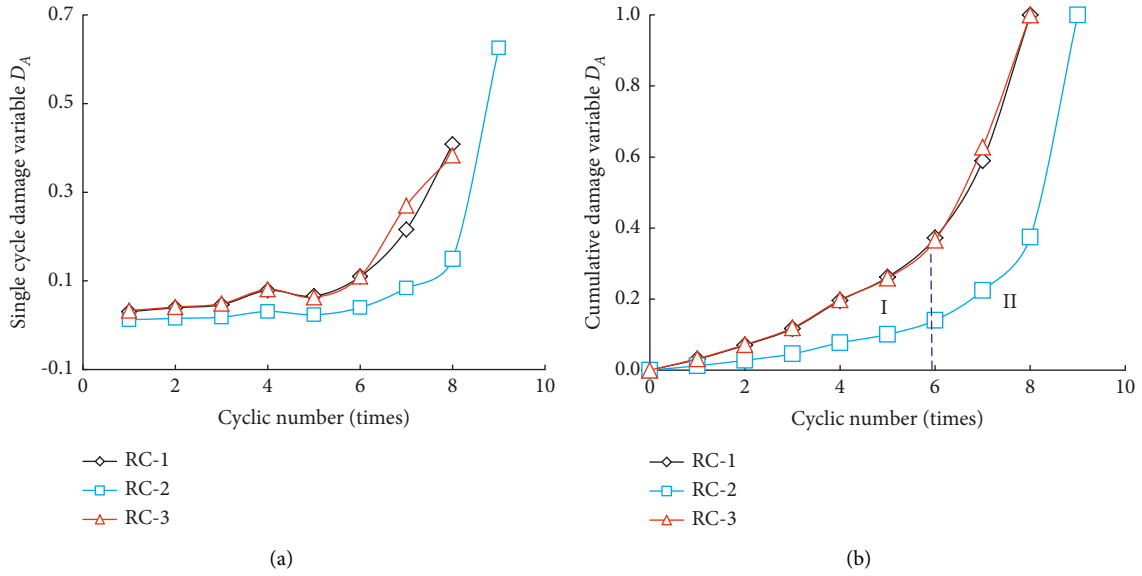
(a)

(b)

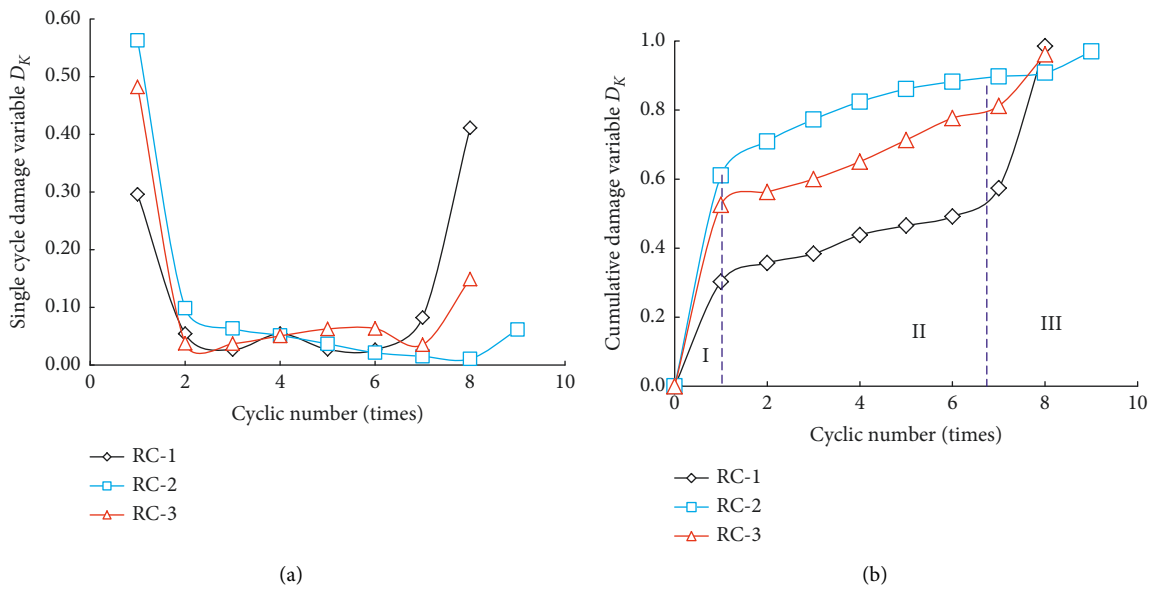FIGURE 8: Damage variable curve based on AE characteristics. (a) $D_A(i)$. (b) D_A.

(a)

(b)

FIGURE 9: Damage variable curve based on seepage characteristics: (a) $D_K(i)$; (b) D_K.

Loading and unloading experiments were carried out in this experiment. The axial pressure was loaded and unloaded step by step, and the confining pressure was kept constant. A certain amount of damage was produced in each cycle. The change of permeability could indirectly reflect the amount of damage. Therefore, based on the permeability change during cyclic loading and unloading, a new damage characterization method can be defined; that is, the single cycle damage variable $D_K(i)$ and cumulative damage variable D_K are as follows:

$$\Delta K(i) = \left| K_- - K_+ \right|, \tag{14}$$

$$D_K(i) = \frac{\Delta K(i)}{\Delta K}, \tag{15}$$

$$D_K = \sum_{i=1}^{n} D_K(i), \tag{16}$$

where $\Delta K(i)$ is the change of permeability K_+ at the beginning of cyclic loading and K_- at the beginning of cyclic unloading during the ith cycle, as shown in Figure 4. ΔK is the cumulative permeability change of all cycles before failure.

According to equations (15) and (16), single-cycle damage variable $D_K(i)$ and cumulative damage variable D_K based on seepage characteristics can be obtained. As shown in Figures 9(a) and 9(b), the damage evolution law based on permeability change is similar to that based on residual strain. The damage amount of a single cycle is
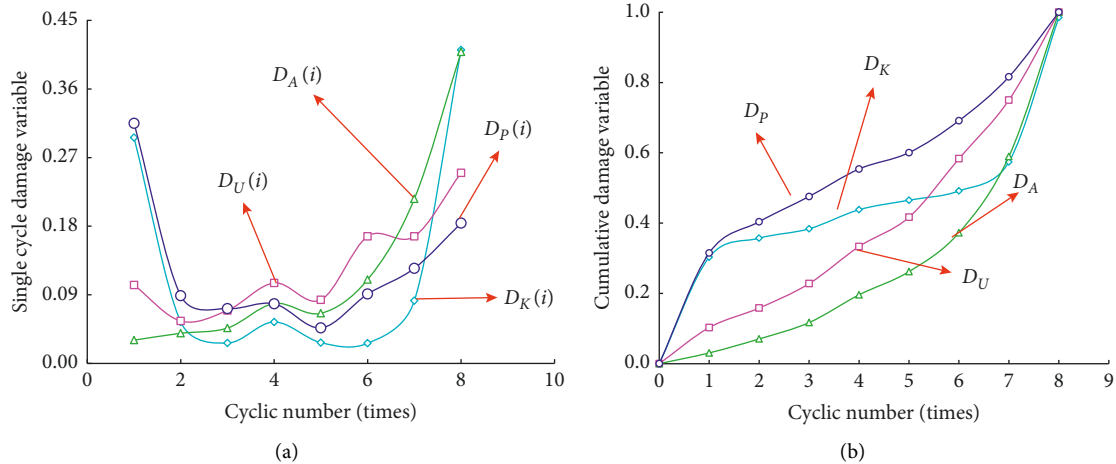
(a)

(b)

FIGURE 10: Damage variable curve based on different characteristics: (a) single cycle damage variable and (b) cumulative damage variable.
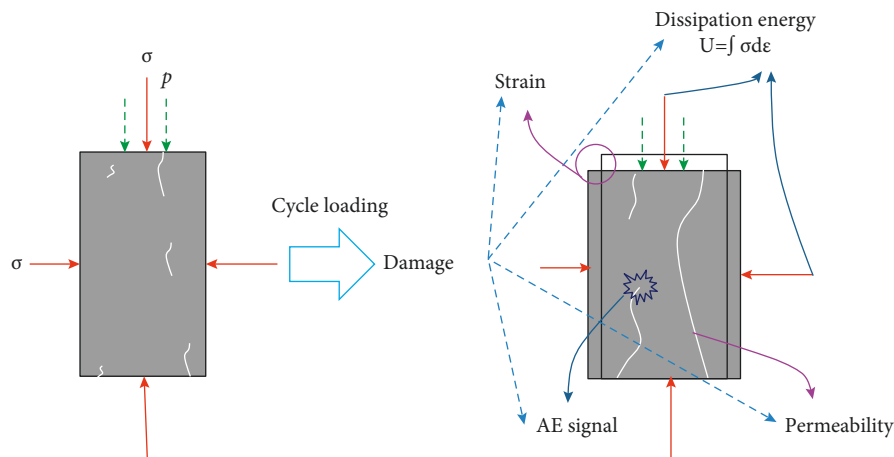

FIGURE 11: The damage of coal characterized in the form of different variables under cycle loading.

larger in the first cycle loading and unloading, smaller and stable in the second cycle, and increases significantly in the near failure. The cumulative damage amount also presents in three stages, which is the same as the change rule of damage amount based on residual strain.

4. Discussion

The damage variable is introduced according to the characteristics of microdefects in the studied material, which is a measure of the degree of damage and deterioration in the material. However, in engineering practice, more attention is paid to the deterioration evolution of macro physical and mechanical properties during the damage process [24, 27, 41–43]. Therefore, macro quantity is often used to define the damage variable, and the macro quantity as the damage variable must have clear physical meaning, easy to measure (determine), and the variation law is consistent with the evolution process of material fatigue mechanical properties. In this paper, the residual strain, energy dissipation, AE ringing count, and permeability change all meet the above conditions, which can be used to characterize the

damage evolution law of coal. However, by comparing the single cycle damage and cumulative damage in Figures 5 and 7–9, it can be found that the damage evolution law calculated by different parameters has the same trend, However, the damage paths are different.

To compare the similarities and differences between the damage variables based on different parameter characteristics, the single cycle damage variables and cumulative damage variables of RC-1 coal sample calculated based on different parameters are plotted in the same figure, as shown in Figures 10(a) and 10(b). It can be seen from Figure 10(a) that the trend of single cycle damage amount based on residual deformation and permeability change is the same, which first increases and then increases gently with the increase of graded cycles, and then increases with the increase of adjacent failure. However, the trend of single cycle damage amount based on energy dissipation and AE ringing count is obviously different, showing a slow increase at first and a rapid increase of adjacent failure. Figure 10(b) shows that the evolution law of cumulative damage based on residual deformation and permeability change is the same, showing an obvious three-stage pattern, first accelerating, then

slowing down, and then accelerating the near failure, while the evolution law of cumulative damage based on energy dissipation and AE ringing count is the same, showing an obvious two-stage pattern; that is, first, increasing gently, and the near failure increases sharply. This may be due to the residual strain and permeability changes are the comparison of physical quantities between unloading point and loading point, while energy dissipation and AE ringing count are the comparison of physical quantities in the whole loading and unloading process. Both energy dissipation and AE signals are the macroscopic manifestation of energy in driving rock damage. Therefore, the damage evolution trend of the two groups is shown, but the cumulative damage of the two groups increases with the increase of the number of cycles. The path does not match, but forms a good complementary.

Coal is damaged under the action of stress cycle, and the damage can be shown from different aspects. In this study, strain, energy dissipation, AE signal, and permeability change are selected to characterize the damage degree. The damage of coal based on different characterization methods was mutually verified. The essence of damage is the deformation of coal caused by stress, which affects the coal to produce cracks and release AE signals. The change of cracks directly affects the change of permeability. The damage of coal needs to consume energy. The energy dissipation of coal under stress is mainly used for the damage and failure of coal (see Figure 11). Although there are some differences in the damage represented by different parameters, the overall law is similar, which shows that different parameters can reflect the damage of coal from the side.

5. Conclusions

The different damage variables equation based on strain, energy dissipation, AE, and permeability characteristics under cyclic loading and unloading were defined. The damage variables based on different characteristics were compared and analyzed, and found that there are similarities and differences between them. The results show that

(1) The law curve of single cycle damage based on residual deformation and permeability is the same. With the increase of cycle times, it decreases first and then gently increases, increased sharply before the failure. However, the law curve of single cycle damage based on energy dissipation and AE ring count shows that it first increases slowly and then the adjacent failure increases rapidly.

(2) The cumulative damage evolution law based on residual deformation and permeability shows an obvious three-stage pattern, that is, first accelerates, then slows down, and then accelerates again. However, the cumulative damage evolution law based on energy dissipation and AE ring count shows an obvious two-stage pattern; that is, first gently increases, and increased sharply before the failure.

Data Availability

All data are presented in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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