Mechanical response characteristics and permeability evolution of coal samples under cyclic loading

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Abstract
Understanding the stress-cracks-permeability evolution law inside coal body under cyclic loading is significant to optimize the gas extraction technology and gas disaster prevention technology. In order to explore the influence of mining cyclic stress on the mechanical behavior and permeability variation of gas-bearing seams, the experiments on permeability evolution, deformation law, and acoustic emission (AE) characteristics of coal samples under cyclic loading with different loading stress level and different loading frequency were carried out. These results indicate that the higher loading stress level, the shorter the fatigue life of coal sample. With the increase of the loading stress level, the change rate of permeability became higher and the relation curves between permeability and loading cycles developed from “U” to “V,” which can be defined and divided into three stages, for example, decrease stage, stable stage, and increase stage. And the permeability in the decrease stage can be modeled as a power function of the loading cycles, while the permeability in the increase stage can be modeled as an exponential function of the loading cycles. Besides, the loading stress level has a significant on the permeability, while the loading frequency has little impact on the permeability evolution. In the process of coal deformation under cyclic loading, the strain development of strain coal samples was in the shape of inverted “S,” while the variation of the peak values of corresponding AE ring counts presented “U” type. In addition, there was a good correlation between the permeability and the AE parameters of coal samples, which provide a new sight into the dynamic variation process of the stress-cracks-permeability evolution inside coal body under cyclic loading.

KEYWORDS
AE parameters, cyclic loading, permeability evolution, stress-cracks-permeability evolution
1 | INTRODUCTION

China is the largest coal producer and consumer globally.\textsuperscript{1,2} And coal reservoir is a typical double porosity medium.\textsuperscript{3,4} As a basic attribute of coal, the permeability determines coal and gas production, which is also sensitive to many factors, including swelling stress and shrinkage effect, coal matrix, gas pressure and among which in situ stress plays a predominant role.\textsuperscript{5-9} The effective stress mainly acts on the coal mechanical deformation; on the one hand, the original microcleats and fractures will close with the increase in effective stress, resulting in a drastic drop in coal permeability; on the other hand, external loads may facilitate the growth of new fractures, thus increasing the permeability.\textsuperscript{10} Related research results also showed that coal permeability strongly depended on stress changes and the orientations of the flow planes, in which the role of anisotropy was taken into consideration.\textsuperscript{11-13} The early relationship between the permeability and effective stress was established by Enever and Henning.\textsuperscript{14} Further research was carried out by McKeen et al\textsuperscript{15} and found that, with the increase of buried depth and effective stress of coal seam, the cleats decreased and permeability decreased exponentially. Wang et al\textsuperscript{16} derived the gas seepage equation of coal seam in the geophysical field based on the motion equation, continuity equation, gas state equation, and content equation of gas in coal seams. Besides, the gas adsorption and coal deformation had a significant influence on the gas seepage properties, and this was demonstrated by the work conducted by Zhao et al\textsuperscript{17} who showed that the permeability was mainly controlled by the volumetric stress, while the shear stress has little impact on the permeability.

In China, the underground mining method is currently employed in 95% of coal mines. And in the actual production, the coal seam will encounter the gravity of overlying strata, horizontal in situ stress, and tectonic stress, as well as the dynamic loadings from various mining operations, such as drilling, blasting, roadway heading, and other engineering activities. Different mining operations pose different loadings on the coal and rock mass, which also change the seepage characteristics of gas in coal seam.\textsuperscript{18} For instance, during driving roadways and normal mining process, the loading mode on coal body can be simplified as the cyclic loading and unloading process. Thus, the coal and rock mass are subjected to cyclic or even dynamic loads.\textsuperscript{19,20} Under cyclic loading, not only the mechanical property of the coal body is deteriorated, as well as the interior pore and fracture structure, resulting in uneven gas emission and over-limit in the mining area, which may cause major dynamic disasters such as coal and gas outburst.\textsuperscript{21} Moreover, the gas seepage characteristics of coal seams will also directly affect the occurrence of coal and gas outburst disasters during mining activities and the efficiency of coal-gas co-exploitation.\textsuperscript{22} Thus, there is an urgent need to investigate the mechanical response characteristics and permeability evolution of coal samples under cyclic loading, which would be helpful to understand the failure mechanisms of gas-containing coal seam and also significant for enhancing gas extraction efficiency and gas disasters prevention. Li et al\textsuperscript{23} conducted the seepage experiments of outburst coal samples under cyclic loading, revealing that plastic deformation of coal sample was produced under cyclic loading. The permeability variation was closely related to the damage deformation of coal samples. What's more, permeability rate was positively correlated with damage variable. Based on tests carried out on the deformation and permeability characteristics of outburst coal under step unloading conditions, Yuan and Zhang\textsuperscript{24} put forward to analyze the permeability variation of coal samples in the view of energy dissipation and found that the permeability increased exponentially with the energy dissipation rate. Jiang et al\textsuperscript{25} found that the absolute recovery of permeability first decreased gradually and then increased while the relative recovery rate of permeability gradually increased. Similar research conducted by Li et al\textsuperscript{26} shows that, after being subjected to stress unloading and loading, the permeability of coal samples gradually decreased and the permeability did not increase before the stress exceeded the yield stage of the coal samples. And with the increase of peak stress and the accumulation of damage in coal samples, the sensitivity of the permeability of coal samples to stress gradually declined.

In recent years, acoustic emission (AE) technology is increasingly used to investigate the damage characteristics of coal and rock under loading, because it can effectively reflect the degree of internal damage in the coal and rock to some extent.\textsuperscript{27-31} Yu et al\textsuperscript{32} further pointed out that there were certain correspondences among the permeability, AE parameters, stress, and bulk strain. Wang et al\textsuperscript{33} analyzed and discussed the permeability and AE characteristics of fine sandstone during the whole failure process, and found that that the abrupt change of transverse deformation corresponded to the abrupt change of permeability, which can effectively reflect the permeability variation characteristics. Li et al\textsuperscript{34} discussed the AE characteristics of the rock with water seepage and nonseepage under uniaxial compression and considered that the influence of water seepage on AE was more significant when rock was close to failure. In a word, a large number of related studies have been conducted to investigate the relationship between the seepage and AE characteristics, but few of them used the gas as the medium. Taking gas-containing coal sample as research objective, Zhao and Yin\textsuperscript{35} studied the AE variation laws in the process of triaxial compression and established the damage model of the gas-containing coal based on the AE parameters.

The main objective of this study was to investigate the deformation characteristics, permeability evolution, and AE characteristics of natural coal under cyclic loading process, and finally analyze the roles of loading stress level and
loading frequency in the process of loading and unloading. The main value of this work is to try to explore the relationship among the deformation, permeability, and AE parameters of coal samples in the process of cyclic loading, which may provide a new sight into the dynamic variation process of the stress-cracks-permeability evolution inside coal body under cyclic loading, and further laid the foundation for the reasonable gas extraction and gas disasters prevention.

2 | EXPERIMENTAL

2.1 | Coal samples preparation and selection

Coal is a kind of heterogeneous body containing original damage (pores and cracks) resulting from the coalification function and the strong tectonic movement. To study the failure mechanism and seepage characteristics of coal, raw coal samples which are more similar to the original structure should be selected. The coal samples were obtained from large coal blocks from Sihe coal mine, Shanxi province, China (Figure 1). In order to minimize the mining disturbance to the original structure of the coal body, the sampling site was selected to be far from the head and tail entry of the working face to avoid the advanced abutment pressure. Meanwhile, to reduce the experimental deviation caused by the heterogeneity of the coal body, the volume of the coal block cored from the sampling site should be as large as possible. After the coal block mined out, it should be lightly handled and then immediately packed and transported to the laboratory. The large coal block was cored parallel to the bedding planes to obtain the standard cores measuring 50 mm in diameter and 100 mm in length. During the coal sample processing, in order to reduce the damage of mechanical vibration to the primary structure of the coal, the wet dense core method was applied. Besides, the industrial grinding of the ends of the coal samples was needed to ensure their flatness, so that the flatness deviation is controlled within 0.005 cm, and the diameter deviation is <0.02 cm. The prepared coal samples were divided into several groups, and each group contained three coal samples. The coal samples before and after processing are shown in Figure 2. Table 1 lists the basic information of coal sample.

2.2 | Experimental apparatus

As can be seen in Figure 3, the triaxial seepage tests were conducted using the self-developed triaxial servo-controlled seepage equipment, which mainly contains a device clamp, a pressure chamber equipment, a loading system, a constant-stability pressure equipment, a hydraulic pressure transfer system, an automatic data collection system, etc. The loading and unloading of axial and confining pressures are controlled by oil pressure, which can achieve the automatic control of loading and unloading and the long-term pressure holding. Besides, the loading and unloading of axial pressure and confining pressure were independent and do not affect each other. The pressure control system firstly pressurizes the gas flowing to the buffer tank through the pressure booster and then reduces the gas pressure by the pressure reducing valve to a certain pressure. Then, the gas pressure is loaded and...
unloaded on the coal samples through the connected clamping device with a two-position two-pass valve. The temperature control system integrates PID temperature control device into the gripper to achieve the temperature control (Table 2).

In this equipment, the axial load can be controlled by force or displacement. The testing ranges for axial compression stress, confining stress, and axial deformation extensometer are 0-120 MPa, 0-60 MPa, and 0-100 mm, respectively. The testing range for gas pressure is 0-10 MPa, and a test temperature ranges from room temperature to 150°C. And

### Table 1 Primary physical and mechanical properties of the coal

| Mad (%) | Aad (%) | Vad (%) | Fcad (%) | $v$ (m/s) | Density (g/cm$^3$) | TCS (MPa) | EM  | $f$ |
|---------|---------|---------|----------|----------|-------------------|-----------|-----|-----|
| 2.15    | 16.56   | 6.84    | 74.45    | 1817     | 1.415             | 53.41     | 3.716| 1.48|

Abbreviations: Aad, ash content on air-dried basis; EM, elasticity modulus; $f$, firmness coefficient; Fcad, fixed carbon content on air-dried basis; Mad, moisture content on air-dried basis; TCS, triaxial compressive strength with confining pressure of 2 MPa; $v$, wave velocity of coal sample; Vad, volatile content on air-dried basis.

### Table 2 The fatigue life of coal samples under different stress levels

| $\sigma_{\text{max}}$ (MPa) | Peak stress ratio (%) | Loading cycles | Fracture |
|-----------------------------|-----------------------|----------------|----------|
| 50                          | 93.6                  | 14             | Yes      |
| 45                          | 84.24                 | 86             | Yes      |
| 40                          | 74.88                 | 247            | Yes      |
| 35                          | 65.52                 | 1000           | No       |
the cracking process of coal samples was recorded by the DS5-8B acoustic emission (AE) system (Beijing Softland Times Scientific & Technology Co. Ltd). Two AE sensors were symmetrically installed in the horizontal direction of the coal samples, and the acoustic emission signals were received by the DS5-8B acoustic emission system during the entire experimental process.

2.3 | Testing scheme

During the test, axial stress and confining pressure were applied to a hydrostatic pressure of 2 MPa at a speed of 0.05 MPa/s, and methane gas (concentration of 99.99%) pressure was kept at 1 MPa. The adsorption was maintained for 24 hours until reaching equilibrium. The axial stress was continuously loaded and unloaded alternately at a speed of 0.05 MPa/s to maximum and minimum value, while maintaining constant confining and gas pressure. Figure 4 shows the loading-unloading cycle path. Due to different stress paths have a significant impact on the fracture network and permeability of coal, this paper focused on the effect of stress levels and cycle frequencies on the mechanical response characteristics and permeability evolution characteristics of raw coal, in which the constant amplitude triangular wave cyclic loading path was adopted, as shown in Figure 4. The first loading procedure involved three maximum axial stress (50, 45, and 40 MPa) with a constant minimum axial stress of 20 MPa and a constant loading frequency of 0.05 Hz, while the second loading procedure involved three different loading frequencies (0.02, 0.05, and 0.1 Hz) with a constant maximum loading stress (45 MPa) and minimum loading stress (20 MPa). It should be noted that a constant confining pressure of 2 MPa was maintained during these tests. The gas temperature of tests was set as room temperature, that is, 25°C and a gas injection pressure of 1 MPa was applied.

2.4 | Permeability measurement

Under cyclic loading, the microstructure and mechanical properties of coal samples changed greatly, as well as the pore structure, resulting in the significant variation of the permeability. Thus, to explore the permeability evolution characteristics of coal samples under cyclic loading, the permeability tests of coal samples under cyclic loading with different stress levels and different loading frequencies were carried out.

In this paper, it is assumed that the gas flow through the coal samples subjected to cyclic loading obeys the Darcy's law:

\[ q = -\frac{kA}{\mu} \frac{dp}{dx}. \]  

Based on the Boyle's law, it can be obtained:

\[ p_2 q_2 t = p_1 q_1 t. \]  

Substituting 2 into 1 and integrating:

\[ kA \int_{p_1}^{p_2} dp = -\mu p_1 q_1 \int_0^L dx. \]

The permeability of porous media can be followed as:

\[ k = \frac{2q_1 \mu L}{A(p_2^2 - p_1^2)}. \]

where \( k \) is the permeability of coal sample, mD; \( q_2 \) and \( q_1 \) are the gas quantity flowing through the inlet and outlet ends of coal sample per unite time, mL/s; \( \mu \) is the gas viscosity, Pa·s; \( L \) is the height of coal sample, mm; \( A \) is the surface area of the two ends, mm²; \( p_2 \) and \( p_1 \) are the gas pressure of the inlet and outlet ends of coal sample, MPa.

3 | RESULTS AND DISCUSSIONS

3.1 | Mechanical response characteristics of coal samples under cyclic loading

3.1.1 | Deformation characteristics of coal samples under cyclic loading with different loading stress levels

In order to probe the effect of stress level on the deformation law of coal samples, three maximum axial stresses (50, 45,
and 40 MPa) with a constant minimum axial stress of 20 MPa and a constant loading frequency of 0.05 Hz were selected. The experimental results can be seen in Figure 5.

Obviously, the deformation law of coal samples under cyclic loading with different stress levels had certain similarity. In the loading stage of the first cycle, the deformation developed very fast, which was similar to that under the conventional triaxial compression. However, the curves of unloading stage and loading stage did not coincide, which indicated a certain plastic strain was produced. From the second cycle, the loading curve formed a hysteresis loop with the unloading curve of the previous cycle, resulting from the irreversible plastic deformation of coal sample under stress. Thereafter, the number of hysteresis loops increased with the number of loading cycles, and the overall variation presented “sparse-dense-sparse,” which was similar to the cyclic fatigue failure process of rock-like materials. Thus, the deformation of the coal sample under cyclic loading can be defined and divided into three stages: The first stage is the deceleration deformation stage, in which the deformation speed of the coal sample gradually decreases, and the hysteresis loop develops from sparse to dense; the second stage is stable stage, in which the deformation caused by a single loading cycle is small and stable, but accounts for a large proportion in the whole deformation; the third stage is the accelerated deformation stage, in which the strain rate is much larger than that in the previous two stages, and the deformation caused by the single loading cycle is also large, but the cycles experienced are less. After the above three stages of deformation, the gradual accumulation of deformation eventually leads to the instability failure of the coal sample.

Meanwhile, the deformation law of coal samples under cyclic loading with different stress levels also had certain differences. At higher stress levels, the amount of irreversible deformation produced by a single loading cycle was

**FIGURE 5** Stress-strain curves of coal samples under cyclic loading with different stress levels (A) 20-50 MPa (B) 20-45 MPa (C) 20-40 MPa
large, the hysteresis loop formed was sparse, and the number of cycles required for coal sample failure was less; while at lower stress levels, the amount of deformation produced by a single cycle was small, the hysteresis loop was denser, and the number of cycles required for coal sample failure was more. This was due to that the lower the stress level, the less plastic damage caused by the single loading cycle to the coal sample, and the lower the rate of deformation development. The fatigue life of coal samples under different stress levels is shown in Table 1.

From Table 1, it can be seen the coal sample was destructed after 14 cycles under the stress level of 20-50 MPa; while under the stress levels of 20-45 MPa and 20-40 MPa, the coal samples were destructed after 86 and 247 loading cycles, respectively. However, under the stress level of 20-35 MPa, the coal sample has not been destructed after 1000 cycles, which indicated that the fatigue failure process of coal samples is similar to that of rock materials under cyclic loading, where may exist a threshold value of fatigue failure.\(^{39}\)

3.1.2 | Deformation characteristics of coal samples under cyclic loading with different loading frequencies

In order to investigate the influence of loading frequency on the deformation characteristics of coal samples, three loading frequencies (0.02, 0.05, and 0.1 Hz) with a constant stress level of 20-45 MPa were selected. The experimental results are shown in Figure 6.

From Figure 6, it can be seen that the loading frequencies had a significance on the fatigue failure process of coal samples. That is, during the deformation process of coal samples under cyclic loading, the higher the loading frequency, the larger the proportion of the deceleration deformation stage, and the smaller the proportion of the acceleration deformation stage. It can be interpreted as:

In the initial stage of the fatigue failure process of coal sample under cyclic loading, the hysteretic curves developed from sparse to dense, and the mechanical properties were...
strengthened due to that the coal samples became more compact after cyclic loading. In this stage, the closure of pores and cracks of coal samples is dominant. Under cyclic loading with lower frequency, the time for single-cycle load on the coal sample was relatively long, and the pores and cracks of were closed quickly, and thus, it entered into the stable stage of fatigue failure after less loading cycles. On the contrary, the higher the loading frequency, the shorter the single-cycle loading time, and the pores and cracks would undergo a new round of loading cycle before closed, and thus, it took more loading cycle to enter into the stable stage. Thereafter, the hysteretic curves developed from dense to sparse, which is due to the degradation of the mechanical properties of coal samples resulting from the formation of plastic deformation and the cracks propagation.

3.2 | AE characteristics of coal samples under cyclic loading

Previous study has shown that the damage process of coal and rock can be effectively reflected by AE parameters.\textsuperscript{40-42} In this section, AE parameters were selected to characterize the damage characteristics of coal samples under cyclic loading. Figure 7 clearly illustrates the variation of AE ringing counts of coal samples under cyclic loading with different stress levels. Obviously, the variation characteristics of AE ringing counts have good cyclic characteristics and have a good correlation with the stress-strain curves of coal samples under the function of cyclic loading.

In a single loading cycle, initially, a small amount of AE signals was generated, which mainly originated from the closure of the original cracks and the dislocation of microstructural surfaces. As the loading stress increases, the coal sample entered the elastic stage, where the AE signals increased slightly. This phenomenon mainly attributed to the dislocation of the closed cracks from the last stage and the slippage of mineral grains. As the stress continued to increase, the coal sample entered the plastic stage, where new cracks were generated and began to expand, resulting in a large increase in AE signals. However, obviously, the AE ring counts decreased with unloading.

**FIGURE 7** Change of ringing count of coal sample under different stress levels (A) 20-50 MPa (B) 20-45 MPa (C) 20-40 MPa
During the entire loading process, the variation of the peak value of AE ringing counts was in the shape of “U,” which can also be defined and divided into three distinct stages, for example, decrease stage, stable stage, and increase stage.

1. At the decrease stage, the AE activities were relatively dense, and a small number of AE signals were generated during the initial loading and unloading. Moreover, with the increase of loading cycles, the AE activities tended to weaken.

2. After several loading cycles, the AE activities entered a stable stage, which accounted for a large proportion during the whole cyclic loading process. At this stage, the AE events in single cycle were stable and the peak values of AE ringing counts of each cycle were relatively close.

3. With the progress of the cyclic loading, the AE activities entered the increase stage. The AE activities at this stage increased significantly, as well as the peak values of AE ringing counts of single cycle. At the moment of coal sample destruction, the AE activities were most intense, and the AE ringing counts reached the maximum of which the values were obviously higher than that in previous two stages.

Combining with Figure 7A-C, it can be seen that the stress level has a significant effect on the AE activities, and there is a certain difference in the variation characteristics of AE ring counts under cyclic loading with different stress levels. The higher the loading stress level, the greater the damage degree of coal sample caused by a single loading cycle, and thus, the more intense the corresponding AE activities, as well as the AE ringing counts in each stage.

Figure 8 shows the variation of AE ringing counts of coal samples under cyclic loading with different loading frequencies. Obviously, the higher the loading frequency, the less the time needed for the destruction of coal samples, the more the AE ring counts generated per unit time. Under cyclic loading

![Figure 8](image-url)
with high frequency, the cracks have to undergo the next loading cycle before it is fully closed because of the previous short-term loading cycle, thus reducing the resistance of crack propagation and accelerating the crack propagation process, and leading to the significant increase of the corresponding AE ring counts. Especially in the plastic stage of coal samples, due to the further expansion and propagation of cracks, the corresponding AE ring counts increase exponentially.

### 3.3 Permeability evolution of coal samples under cyclic loading

#### 3.3.1 Permeability variation characteristics of coal samples under cyclic loading

Permeability evolution under cyclic loading is a continuous variation process. Thus, the permeability corresponding to the minimum and maximum loading stress during each single loading cycle was selected to investigate the influence of stress levels on the coal permeability. Figure 9 shows the variation characteristics of coal permeability under cyclic loading with different stress levels. It is noted that the graphs marked by “(a)” and “(b)” present the variation characteristics of coal permeability corresponding to the minimum and maximum loading stress of a single loading cycle during the cyclic loading process, respectively. Obviously, the permeability variation corresponding to the maximum or minimum loading stress was all in the shape of “U,” and three stages may be visualized in these plots: decrease stage, stable stage, and increase stage. Besides, with the increase of the stress level, the change rate of permeability became higher and the relation curves between permeability and loading cycles developed from “U” to “V.” With the increase of the amplitude values of cyclic loading, the permeability increases no matter in loading stage or unloading stage. However, on the whole, the permeability of unloading stage is higher than that of loading stage. In addition, the permeability tests of coal samples under cyclic loading with different loading frequencies have also been conducted, and the results indicate that the loading frequency has little influence on the permeability variation.

#### 3.3.2 Quantitative analysis of permeability evolution of coal samples under cyclic loading

In this section, the model simplification method and mathematical fitting method were employed to study the quantitative relationship between the permeability and loading cycles in detail. Since the permeability in the stable stage changed little, only the permeability values in the decreasing and increasing stages were fitted, as shown in Figure 10, and the other sets of data fitting results are shown in Table 3. The tests were divided into five groups according to the loading stress levels and loading frequencies, and each group contained three specimens to eliminate the dispersion.

It can be concluded that the permeability in the decrease stage can be modeled as a power function of the loading cycles, regardless of the loading stress, and can be expressed by:

\[ y = ax^{-b}. \]  

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**FIGURE 9** The relation curves of permeability and cycle number of coal samples under different stress levels (A) Permeability corresponding to the minimum stress (unloading stage) (B) Permeability corresponding to the maximum stress (loading stage)

**FIGURE 10** The fitting curves of the permeability corresponding to the minimum and maximum loading stress and loading cycles (A) The decrease stage of coal sample A-2 (B) The increase stage of coal sample A-2 (C) The decrease stage of coal sample B-2 (D) The increase stage of coal sample B-2 (E) The decrease stage of coal sample C-2 (F) The increase stage of coal sample C-2 (G) The decrease stage of coal sample D-2 (H) The increase stage of coal sample D-2 (I) The decrease stage of coal sample E-1 (J) The increase stage of coal sample E-1
Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-50 MPa, 0.05 Hz

\[ y = 0.331x^{0.130}, R^2 = 0.995 \]

Permeability (mD)
Cycle numbers

(A)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-50 MPa, 0.05 Hz

\[ y = 0.413x^{0.130}, R^2 = 0.961 \]

Permeability (mD)
Cycle numbers

(B)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-50 MPa, 0.05 Hz

\[ y = 0.346x^{0.112}, R^2 = 0.983 \]

Permeability (mD)
Cycle numbers

(C)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-50 MPa, 0.05 Hz

\[ y = 0.411x^{0.151}, R^2 = 0.992 \]

Permeability (mD)
Cycle numbers

(D)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-50 MPa, 0.05 Hz

\[ y = 0.078x^{0.144}, R^2 = 0.996 \]

Permeability (mD)
Cycle numbers

(E)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-45 MPa, 0.05 Hz

\[ y = 0.354x^{0.05}, R^2 = 0.992 \]

Permeability (mD)
Cycle numbers

(F)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-45 MPa, 0.05 Hz

\[ y = 0.0138x^{0.05}, R^2 = 0.971 \]

Permeability (mD)
Cycle numbers

(G)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-45 MPa, 0.1 Hz

\[ y = 0.39x^{0.02}, R^2 = 0.987 \]

Permeability (mD)
Cycle numbers

(H)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-45 MPa, 0.1 Hz

\[ y = 0.0127x^{0.05}, R^2 = 0.992 \]

Permeability (mD)
Cycle numbers

(I)

Permeability corresponding to the minimum loading stress
Permeability corresponding to the maximum loading stress
20-45 MPa, 0.02 Hz

\[ y = 0.386x^{0.02}, R^2 = 0.99 \]

Permeability (mD)
Cycle numbers

(J)
And the permeability in the increase stage can be modeled as an exponential function of the loading cycles, regardless of the loading stress, and can be expressed by:

\[ y = ce^{dx}, \]  

(6)

**TABLE 3** The fitting results of the permeability corresponding to the minimum and maximum loading stress and loading cycles

| No. | Variation stages | Loading stress (MPa) | Fitted equation | Square deviation \((R^2)\) |
|-----|------------------|---------------------|----------------|-----------------|
| A-1 | Decrease         | Maximum             | \(y = 0.293x^{-0.14}\) | 0.981           |
|     |                  | Minimum             | \(y = 0.37x^{-0.2}\)    | 0.971           |
|     | Increase         | Maximum             | \(y = 0.063e^{0.099x}\) | 0.985           |
|     |                  | Minimum             | \(y = 0.06e^{0.107x}\)   | 0.974           |
| A-3 | Decrease         | Maximum             | \(y = 0.366x^{-0.16}\) | 0.991           |
|     |                  | Minimum             | \(y = 0.466x^{-0.22}\)  | 0.994           |
|     | Increase         | Maximum             | \(y = 0.145e^{0.107x}\) | 0.985           |
|     |                  | Minimum             | \(y = 0.168e^{0.11x}\)  | 0.978           |
| B-1 | Decrease         | Maximum             | \(y = 0.385x^{-0.09}\) | 0.984           |
|     |                  | Minimum             | \(y = 0.454x^{-0.11}\)  | 0.992           |
|     | Increase         | Maximum             | \(y = 0.011e^{0.056x}\) | 0.96            |
|     |                  | Minimum             | \(y = 0.009e^{0.06x}\)  | 0.956           |
| B-3 | Decrease         | Maximum             | \(y = 0.316x^{-0.14}\) | 0.972           |
|     |                  | Minimum             | \(y = 0.412x^{-0.15}\)  | 0.994           |
|     | Increase         | Maximum             | \(y = 0.002e^{0.063x}\) | 0.938           |
|     |                  | Minimum             | \(y = 0.001e^{0.072x}\) | 0.942           |
| C-1 | Decrease         | Maximum             | \(y = 0.284x^{-0.10}\) | 0.988           |
|     |                  | Minimum             | \(y = 0.382x^{-0.11}\)  | 0.986           |
|     | Increase         | Maximum             | \(y = 7E-05e^{0.041x}\) | 0.944           |
|     |                  | Minimum             | \(y = 0.0028e^{0.045x}\) | 0.956           |
| C-3 | Decrease         | Maximum             | \(y = 0.408x^{-0.09}\) | 0.985           |
|     |                  | Minimum             | \(y = 0.453x^{-0.11}\)  | 0.95            |
|     | Increase         | Maximum             | \(y = 0.0008e^{0.029x}\) | 0.962           |
|     |                  | Minimum             | \(y = 0.001e^{0.032x}\) | 0.939           |
| D-1 | Decrease         | Maximum             | \(y = 0.383x^{-0.13}\) | 0.993           |
|     |                  | Minimum             | \(y = 0.418x^{-0.15}\)  | 0.993           |
|     | Increase         | Maximum             | \(y = 0.016e^{0.044x}\) | 0.922           |
|     |                  | Minimum             | \(y = 0.01e^{0.055x}\)  | 0.961           |
| D-3 | Decrease         | Maximum             | \(y = 0.316x^{-0.1}\)  | 0.991           |
|     |                  | Minimum             | \(y = 0.365x^{-0.11}\)  | 0.998           |
|     | Increase         | Maximum             | \(y = 0.00053e^{0.077x}\) | 0.931           |
|     |                  | Minimum             | \(y = 0.00055e^{0.08x}\) | 0.945           |
| E-2 | Decrease         | Maximum             | \(y = 0.397x^{-0.12}\) | 0.993           |
|     |                  | Minimum             | \(y = 0.438x^{-0.15}\)  | 0.995           |
|     | Increase         | Maximum             | \(y = 0.005e^{0.052x}\) | 0.963           |
|     |                  | Minimum             | \(y = 0.004e^{0.055x}\) | 0.97            |
| E-3 | Decrease         | Maximum             | \(y = 0.384x^{-0.08}\) | 0.985           |
|     |                  | Minimum             | \(y = 0.417x^{-0.11}\)  | 0.994           |
|     | Increase         | Maximum             | \(y = 0.007e^{0.052x}\) | 0.946           |
|     |                  | Minimum             | \(y = 0.007e^{0.054x}\) | 0.929           |
By comparing the fitting curves of the same coal sample, it can be seen that, in the decrease stage of permeability, the $b$ value of the fitting curve of the permeability corresponding to the minimum loading stress was larger, which indicated that, in the early loading cycles, the reduction rate of the permeability corresponding to the minimum loading stress was larger. Similarly, in the increase stage of permeability, the $d$ value of the fitting curve of the permeability corresponding to the minimum loading stress was larger, which indicated that, in the late loading cycles, the growth rate of the permeability corresponding to the minimum loading stress was larger.

By comparing and analyzing the fitting parameters of coal permeability under different stress levels, it can be seen that, in the decrease stage of permeability, when the loading stress level was 20-50, 20-45, and 20-40 MPa, the mean $b$ values of the fitting curves of the permeability corresponding to the minimum loading stress were 0.197, 0.133, and 0.113, while the mean $b$ values of the fitting curves of the permeability corresponding to the maximum loading stress were 0.143, 0.112, and 0.1, respectively. Thus, it can be concluded that, in the decrease stage, the $b$ value decreased with the loading stress, that is, the reduction rate of permeability was positively correlated with the stress level. In addition, in the increase stage of permeability, the mean $d$ values of the fitting curves of the permeability corresponding to the minimum loading stress were 0.115, 0.069, and 0.033, while the mean $d$ values of the fitting curves of the permeability corresponding to the maximum loading stress were 0.102, 0.061, and 0.035, respectively. Therefore, it can be concluded that, in the increase stage, the $d$ value decreased with the loading stress, that is, the growth rate of permeability was positively correlated with the stress level. Besides, under the same stress level, the $d$ values were almost equal.

However, by comparing the fitting parameters of permeability of coal samples under cyclic loading with different loading frequencies, it can be found that the fitting parameters changed little whether in the decrease stage or in the increase stage, indicating that the loading frequency had little

![Figure 11](image_url)  
**Figure 11** The relation curves between strain, the peak number of acoustic emission ringing counts, and cycle numbers under different stress levels (A) 20-50 MPa (B) 20-45 MPa (C) 20-40 MPa
influence on the variation of permeability values of coal samples under cyclic loading.

3.4 The stress-cracks-permeability evolution of coal samples under cyclic loading

Figure 11 shows the relationship between the peak values of AE ring counts and deformation of coal samples corresponding to the maximum loading stress in the whole process of cyclic loading with different stress levels. Clearly, the strain development of strain coal samples was in the shape of inverted “S,” while the variation of the peak values of corresponding AE ring counts presented “U” type. Though there was obvious difference of two curves in shape, but a good correspondence in terms of the variation trend. Apparently, in the decrease stage of the growth rate of strain, the peak values of AE ring counts decreased with the loading cycles; in the stable stage, the peak values of AE ring counts were relatively stable; in the increase stage, the peak values of AE ring counts rose abruptly. Thus, it can be concluded that, in the process of coal deformation under cyclic loading, the peak values of AE ring counts have a positive correlation with the growth rate of strain.

In addition, coal sample B-2 was taken as an example, and the 2nd, 30th, and 65th loading cycles were selected to investigate the relationship between the permeability evolution and coal deformation in a single loading cycle.

As can be seen from Figure 12, in the 2nd loading cycle, the pores and cracks inside coal samples gradually closed with the increase of loading stress from the minimum value to the elastic limit, resulting in the decrease of the permeability. As the loading stress increased from the elastic limit to the maximum value, the increase of stress would cause the plastic damage and cracks propagation of coal samples to a certain extent, thus increasing a small increase of permeability. Then, with stress unloading, the compressed cracks reopened, which directly increased the permeability. In this stage, the original cracks dominated the permeability variation. In this loading cycle, the stress-strain curves of loading and unloading did form an incomplete loop. This was due to

**FIGURE 12** The relation curves of stress-strain-permeability in a single loading cycle (A) the second loading cycle (B) the 30th loading cycle (C) the 65th loading cycle
that the generation of the irrecoverable plastic damage and the change of internal structure under the function of cyclic loading.

In the 30th loading cycle, the overall variation trend of stress-strain-permeability curves was similar to that in the second loading cycle. However, the strain development was stable, and less plastic damages occurred. Thus, the deviation strain of unloading and unloading was small. Besides, the permeability can also recover to the initial value after unloading.

In the 65th loading cycle, the stress-strain curve still formed an incomplete loop, but the residual strain further increased, that is, the strain value increased significantly after unloading. Meanwhile, the permeability-strain curve presented different variation characteristics. The permeability cannot recover to the initial value after unloading, but increased significantly. In the later stage of cyclic loading, a large number of secondary cracks were generated, and the microcracks inside the coal sample gradually converged to large flow channels. Thus, the compressed pores and cracks can expand under the action of gas pressure after unloading. As a result, the permeability increased gradually to a certain extent, which was greater than the initial value. It can be concluded that the crack growth dominated the permeability variation in this stage.

From aforementioned analysis, it can be concluded that, during the cyclic loading, there was a good correlation between the permeability and the AE parameters of coal samples. It is well known that AE parameters can well reflect the process of the crack's growth in coal samples, that is, the cracks development can be characterized by the variation of the AE parameters. In the initial stage, the original cracks were gradually compressed, and the mechanical property of coal samples was strengthened, resulting in the decrease of the permeability accompanied by less AE signals. In the middle (elastic) stage, the internal structure was stable, and the permeability and the AE parameters barely changed. In the later (plastic and failure) stage, with the cyclic loading, the internal structure changed greatly, and a large number of secondary and new cracks were generated and began to expand and converge, resulting in the continuous increase in permeability, accompanied by the strong AE activities.

1. The deformation of the coal samples under cyclic loading can be defined and divided into three stages, that is, the deceleration deformation stage, the uniform deformation stage, and the accelerated deformation stage. And the hysteresis loops of formed by stress-strain curves present “sparse-dense-sparse” with the loading cycles. The higher loading stress level, the shorter the fatigue life of coal sample.

2. During the entire cyclic loading process, the variation of the peak ringing counts was in the shape of “U,” which also can be defined and divided into three stages, for example, decrease stage, stable stage, and increase stage. The higher the loading stress level, the greater the damage degree of coal sample caused by a single loading cycle, and thus, the more intense the corresponding AE activities, as well as the AE ringing counts in each stage. In addition, the higher the loading frequency, the less the time needed for the destruction of coal samples, the more the AE ring counts generated per unit time.

3. The permeability variation corresponding to the maximum or minimum loading stress was all in the shape of “U,” and three stages may be visualized in these plots: decrease stage, stable stage, and increase stage. Besides, with the increase of the stress level, the change rate of permeability became higher and the relation curves between permeability and loading cycles developed from “U” to “V”. Besides, it can be concluded that the permeability in the decrease stage can be modeled as a power function of the loading cycles, while the permeability in the increase stage can be modeled as an exponential function of the loading cycles.

4. In the process of coal deformation under cyclic loading, there was a good correlation between the permeability and the AE parameters of coal samples. Although the quantitative relation between the permeability and the AE signals was still ambiguous, the qualitative relation was deduced and verified, which provide a new sight into the dynamic variation process of the stress-cracks-permeability evolution inside coal body under cyclic loading, and further laid the foundation for the reasonable gas extraction and gas disasters prevention.

**ACKNOWLEDGMENTS**

This work is financially supported by the Natural Science Foundation of China (Grant Nos. 51574280, 51774319, and 51874348), Tiandi technology Co. Ltd Special funds for scientific and technological innovation and entrepreneurship (2018-TD-QN062), the National Science and Technology Major Project of China (Grant No. 2016ZX05045004), and the Research Fund of the State Key Laboratory of Coal Resources and Safe Mining, CUMT (SKLCRSM19KF008), which are gratefully acknowledged. The authors also thank...
the editor and anonymous reviewers very much for their valuable advices.

CONFLICT OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. Meanwhile, the founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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**How to cite this article:** Yang X, Cao J, Cheng X, et al. Mechanical response characteristics and permeability evolution of coal samples under cyclic loading. *Energy Sci Eng*. 2019;7:1588–1604. [https://doi.org/10.1002/esce3.368](https://doi.org/10.1002/esce3.368)