Experimental Study on the Evolution Trend of the Pore Structure and the Permeability of Coal under Cyclic Loading and Unloading

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ABSTRACT: In the deep mining process of coal seams, the mechanical environment of the coal body is complex and in the state of cyclic loading and unloading. The change in the stress state leads to the change in the pore characteristics and the permeability. To investigate the effects of cyclic loading and unloading on the pore characteristics and the permeability of coal, the seepage experiment was carried out for the coal samples using the self-developed triaxial permeation instrument. By pressure confining and continuous cyclic loading and unloading, the evolution of the porosity and the permeability of the coal samples was investigated. Under the condition of the experiment, the influences of the initial value of the confining pressure and the cyclic load amplitude on the evolution of the permeability and the pore structure characteristics of the coal samples were clarified. The experimental results showed that the porosity and the permeability decreased exponentially with an increase in the number of loading and unloading cycles, and this decreasing trend gradually weakened until the porosity and the permeability became relatively stable. When the cyclic load amplitude was the same and the confining pressure increased, the effective porosity of the coal body and the bound porosity decreased. When the confining pressure was the same and the cyclic load amplitude increased, the effective porosity of the coal body decreased and the bound porosity increased. The loss rate of the permeability of the coal samples increased gradually with an increase in the cyclic load amplitude. The same tendency was observed when the cyclic load amplitude was the same, and the confining pressure was different, while the increasing trend was not so obvious. By analyzing the relationship between the porosity and the permeability of the coal samples under different cyclic loading and unloading paths, it was found that the effective porosity and the permeability of the coal samples conformed to the power-law relationship in the process of cyclic loading and unloading, and the change in the cyclic load amplitude had a significant effect on this relationship. The influences of the cyclic load amplitude and the confining pressure on the stress sensitivity of the coal samples were considered, and the change factor of the stress sensitivity was introduced into the relationship between the porosity and the permeability. This relationship was established considering cyclic loading and unloading.

1. INTRODUCTION

With an increase in the coal mining depth, the influence of high in-situ stress and high osmotic pressure on the pore structure and the permeability of surrounding rocks of the coal body in working faces has been increasingly investigated. For deep underground engineering, due to the action of severe disturbances such as mining, the stress of the coal body is often the dynamic load that changes constantly. In other words, cyclic loading is exerted on the coal body. There are significant differences between the mechanics and the permeability characteristics of the coal and rock mass under cyclic loading and unloading paths and conventional loading paths. Different cyclic paths have different influences on the mechanics and the permeability characteristics of the coal mass.

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Wang et al.\(^6\) found that when the confining pressure was fixed, the peak of the axial pressure gradually increased during cyclic loading and unloading. Weak damage was caused in the pre-peak coal, and then, this damage was recovered. Jiang et al.\(^5\) found in the experiment that when the axial pressure changed, the confining pressure remained unchanged. The first cycle had the greatest impact on the failure of the shale specimen, while other cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^1\) found in the experiment that when the axial pressure changed, the confining pressure remained unchanged. The first cycle had the greatest impact on the failure of the specimen, while other cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen. Tang et al.\(^6\) found that under cyclic loading with a low frequency and cycles had little impact on the failure of the specimen.

The failure processes of intact coal samples and coal samples with different prefabricated fractures are dominated by different mechanical mechanisms and show different failure modes macroscopically. Although some researchers have conducted more studies on the mechanics and the permeability characteristics of coal under different cyclic loading and unloading paths,\(^7\) the systematic studies on the constant amplitude cyclic loading and unloading with the pre-peak confining pressure are not enough, and further research studies are necessary.

Coal is a kind of complex heterogeneous organic matter composed of pores and fractures.\(^8\) The change in the coal permeability is closely related to the change in the porosity, and even a small change in the porosity may cause an order change in the permeability of coal rocks.\(^9\) Therefore, it is necessary to study the changing trend of the porosity in the changing process of coal permeability. Studies showed that for different coal rock samples, the relationship between the porosity and the permeability was different, and different correlations such as an exponential law or power law might be applicable.\(^10\) It was also found that these correlations were only applicable under simple loading and unloading paths.\(^11\) However, there are relatively few studies on the relationship between the porosity and the permeability under complex loading and unloading paths, and further studies are required on this topic.

In terms of the research methods for the porosity measurement, the traditional liquid nitrogen adsorption method and mercury injection method\(^12\) are usually combined to analyze the pore and the fracture structure of coal rock. With the development of science and technology, more common pore analysis methods in recent years include the scanning electron microscope method,\(^13\) the CT scanning method,\(^14\) and the nuclear magnetic resonance (NMR) method.\(^15\) The scanning electron microscope method and the CT scanning method mainly take the advantage of the visualization of the pore structure and combine the macro–micro analyses of the coal body. However, the NMR method can measure the T2 spectrum curve and the porosity of rock pores. It can quantitatively analyze the changes in the number and scale of pores of different sizes inside rocks under the action of external forces.\(^16\) It is helpful to analyze the influence of the coal pore characteristics on the permeability under cyclic loading and unloading conditions.

Given this, this paper adopted the triaxial permeation instrument and the MR-60 NMR core analyzer as experimental equipment. According to the relaxation characteristics of the fluid in the pores of coal, by analyzing the change in the coal porosity and permeability, the changing trend of the permeability and the porosity of the coal samples under the constant amplitude cyclic loading and unloading with the pre-peak confining pressure and their correlation were studied. By changing the stress path mode, the influence of cyclic loading and unloading of the pre-peak confining pressure on the coal seepage characteristics and the porosity was studied in depth. This research provided an experimental basis for further improvement in the gas migration law in coal undermining disturbances.

2. EXPERIMENTAL EQUIPMENT AND EXPERIMENTAL SCHEME

2.1. Experimental Equipment and Principle. The seepage experiment adopted the self-developed triaxial permeation instrument, which was mainly composed of the triaxial stress loading system, the temperature control system, the pore pressure loading system, the flow monitoring system, the coal deformation measurement system, and the stress–seepage–desorption chamber. In the triaxial stress loading system, the maximum supplied pressure of the pump was 63 MPa, and the maximum value of the stable pressure in the accumulator was 31.5 MPa. This instrument could be used to measure the...
adsorption, desorption, and seepage processes of coal and coal deformation. It was mainly used in the percolation process in this article. The MR-60 NMR core analyzer manufactured by Suzhou Niumai Electronic Technology Co. Ltd. was selected as the coal porosity-measurement device. The main magnetic field of the device was 0.51 T, the RF pulse frequency was 1.0−49.9 MHz, and the RF power was 300 W. The main test parameters were as follows: the principal value of the RF signal frequency was 32 MHz, the magnet temperature (T) was 32 °C, the single sampling number (Td) was 1024, the cumulative sampling time (NS) was 32, the echo time (Te) was 0.233 ms, and the echo number (NECH) was 6000.

The principle of NMR is as follows \(^{(21)}\)

\[
\frac{1}{T_2} = \frac{1}{T_{2S}} = \frac{S}{\mu L} \frac{V}{V}
\]

(1)

where \(\rho_s\) is the surface relaxation, \(S\) is the pore surface area, \(V\) is the pore volume, \(T_s\) is the total relaxation time, and \(T_{2S}\) is the surface relaxation time.

Because coal is a kind of a porous medium, a gas flow in a coal seam can be roughly described by the linear seepage law. By normalizing the flow rate and pressure in Darcy’s permeability formula, the following calculation formula of the axial permeability of a compressible gas can be obtained \(^{(22)}\)

\[
K = \frac{2P_0Q_0dL}{A(P_1^2 - P_2^2)}
\]

(2)

where \(K\) is the permeability of coal (Md), \(Q_0\) is the gas flow rate (cm³/s), \(P_0\) is the atmospheric pressure (Pa), \(P_1\) is the cross-sectional area of the coal sample (cm²), and \(P_2\) are the gas pressures at the inlet and outlet of the coal sample (MPa), respectively.

The schematic drawing of the overall experimental device is shown in Figure 1.

### 2.2. Selection of Coal Samples

The coal samples were taken from the no. 15 coal seam of the no. 31030 working face in the Pingmei no. 12, mine. The buried depth of the working face was 3583 m, the single sampling number (T) was 1024, the cumulative sampling time (NS) was 32, the echo time (Te) was 0.233 ms, and the echo number (NECH) was 6000.

Typical rock samples are shown in Figure 2, and the ultrasonic test results are shown in Table 1. Before the test, the coal samples were dried in the drying chamber shown in Figure 2 at 110 °C for more than 12 h until the quality of the coal samples did not change. This procedure was repeated for each drying.

### 2.3. Experimental Scheme

With an increase in the mining depth, the in-situ stress of the coal seam increased, and the initial state of the confining pressure of the coal body also increased. With different mining disturbance intensities, loading and unloading stresses with different cyclic amplitudes also appeared. Combined with the above situation and the measured triaxial compressive strength of the coal rock, the confining pressure of the cyclic loading and unloading path was designed. During the experiment, it was found that the larger the amplitude of the cyclic load was, the larger the difference in the experimental data was. This was more conducive to the analysis of the experimental results. Considering the bearing capacity of the experimental device and the data reliability, the experimental cyclic confining pressure stress was fixed in the range of 5−20 MPa. Taking 5 MPa as a gradient, 6 stress paths of 5−10, 5−15, 5−20, 10−15, 10−20, and 15−20 MPa were designed. The axial compression was kept unchanged at 20 MPa.

The specific stress path of confining pressure is shown in Figure 3. The specific experimental steps are as follows:

1. A specimen was selected and placed in the −0.1 MPa vacuum chamber using the water filling and condensate water device for more than 12 h until the quality of the coal sample did not change. Then, it was taken out for the NMR test.

2. After the NMR test, the specimen was dried again and put into the triaxial permeameter to check the airtightness of the equipment.

3. Prestress loading was conducted. Experimental path 1 was selected to load the predetermined effective stress.

4. The gas cylinder was opened, and the \(N_2\) pressure-regulating valve was adjusted so that the pore pressure became the predetermined value. After the pore pressure stabilized, the flow rate of the percolating gas was measured. Time, the axial pressure, the confining pressure, the pore pressure, and other data were recorded.

5. The stress was adjusted according to the stress change in stress path 1. Step (4) was repeated until all the predetermined paths were completed.

6. Check valve 5 was closed, and check valves 4 and 6 were opened at the same time before conducting each NMR examination. Under the gas pressure, water was pushed into the sample by a piston for treating the saturation water. The indicator value (11) of the pressure gauge was kept near the predetermined pore pressure value. The specimen was taken out for NMR after stabilizing the pressure gauge reading. The specimen was dried again before the permeability was measured again.

7. The above steps were repeated, and the stress path was replaced.

### Table 1. Ultrasonic Test Results of the Coal Body

| number | 1 | 2 | 3 | 4 | 5 | 6 |
|--------|---|---|---|---|---|---|
| acoustic velocity (m/s) | 1.04 | 1.03 | 1.08 | 1.09 | 1.1 | 1.03 |
| sound interval (μs) | 96.27 | 97.47 | 94.3 | 91.43 | 90.8 | 97.33 |

### Table 2. Industrial Analysis Data of the Coal Sample

| apparent density (t/m³) | porosity (%) | temperature of coal seam (°C) | water content Mad (%) | ash content Aad (%) | volatile matter Vdaf (%) | gas pressure (MPa) |
|-------------------------|--------------|-------------------------------|-----------------------|---------------------|-------------------------|-------------------|
| 1.29                    | 3            | 20                            | 1.28                  | 8.77                | 32.63                   | 0.16−2.7          |
3. RESULTS AND DISCUSSION

3.1. NMR T2 Spectral Analysis. The T2 spectrum curve could reflect the information on the pore size and the number of pores with different pore sizes in the rock samples. The T2 value was positively correlated with the pore size. The smaller the T2 value was, the smaller the pore size was. The larger the T2 value was, the larger the aperture was. The peak value of the T2 spectrum was positively correlated with the number of pores. The larger the peak value was, the more pores were produced corresponding to each pore size.

Figure 4 shows the initial NMR results of the experimental samples. Combined with the ultrasonic results shown in Table 1, it could be found that except for the cracks in the no2 specimens, no ultrasonic monitoring was detected in the coal body. The pore structure characteristics of the specimens were all similar showing the reliability of the experimental analysis results.

Figure 5 shows the variation of the NMR results of the specimens under the confining pressure of 5 MPa and the cyclic load amplitude of 15 MPa as a function of the number of loading and unloading cycles. Analysis results showed that with an increase in the number of cycles, the peaks of the T2 spectra of the specimens with saturated water gradually decreased. This decreasing trend became smaller, and the overall phenomena showed a slight left shift. However, the peaks of the T2 spectra of the centrifuged specimens gradually increased indicating that with an increase in the number of loading and unloading cycles, the total porosity of the coal body gradually decreased, while the bound porosity gradually increased. This was because, in the process of loading and unloading, the pores in the coal body were compressed, and the pore channels were gradually closed resulting in the reduction of the total porosity. On the other hand, some mesopores and macropores were compressed and reduced to small pores, which were not connected with the pore channels and became adsorption pores increasing the bound porosity.

![Figure 2. Standard test specimen and its maintenance.](image)

![Figure 3. Stress path diagram of the confining pressure.](image)

![Figure 4. T2 spectra of different specimens. Left: saturated, right: centrifuged.](image)
3.2. NMR Porosity Analysis. Due to the wettability difference between water and gas on the rock together with the action of the capillary force, it is impossible for the migrated gas to completely drive out the water in the rock pores when the gas migrates to the coal reservoir. Therefore, there will be a certain amount of water remaining in the rock pores. Because of its special state of existence and distribution, this part of the water is almost immobile and is called immobile water. The existence and distribution of this part of water are affected by the properties of solids. Therefore, it is also called bound water or residual water. The corresponding porosity is called the bound water porosity. For the same reason, the part of the water that flows is called the effective porosity. The sum of the bound water porosity and the effective porosity is the total porosity of the coal rock.

In NMR, the test results of the specimen in the saturated state are used to calculate the total porosity of the specimen. The test results of the specimen in the centrifuged state were used to calculate the bound porosity of the specimen. The bound porosity and the effective porosity constitute the total porosity of the specimen, and the relationship among these three porosities is as follows: \[ \varphi_{NB} = \varphi_N \times \frac{BVI}{BVI + FFI} \] \[ \varphi_{NE} = \varphi_N \times \frac{FFI}{BVI + FFI} \]

where \( \varphi_{NB} \) is the bound porosity of the specimen, \( \varphi_{NE} \) is the effective porosity of the specimen, \( \varphi_N \) is the total porosity of the specimen, BVI is the bound fluid coefficient, and FFI is the free fluid coefficient. Because the porosity of the specimen was constantly changing during loading and unloading, to effectively analyze the changing trend of the porosity of the specimen during the experiment, the porosity change rate (\( \Delta \varphi \% \)) was introduced to represent the porosity change degree during the experiment. The expression of this rate is as follows:

\[ \Delta \varphi \% = \frac{\varphi_{cv} - \varphi_i}{\varphi_i} \]

where \( \varphi_{cv} \) is the porosity under the current loading and unloading condition, and \( \varphi_i \) is the porosity under the initial loading condition.

Figure 6 shows the variation trend of the porosity of the coal body before and after five cycles of loading and unloading under different cyclic load amplitudes when the confining pressure was 5 MPa. It was found that the maximum porosity appeared at the initial loading stage under the cyclic load amplitude of 10 MPa, which was mainly because the initial confining pressure was all 5 MPa, and the porosity under the initial loading was mainly related to the original porosity of the coal body. The cracks in no. 2 specimens were relatively developed, and the original porosity was large. With an increase in the cyclic load amplitude, the total porosity and the effective porosity of the coal samples decreased. This indicated that an increase in the cyclic load amplitude increased the compaction rate of the coal body. Then, the pore closure in the coal body increased, the pore and the channel decreased, and the plastic deformation became larger. On the other hand, with an increase in the cyclic load amplitude, the change rate of the total porosity of the coal body increased from 11.4 to 31.56%. However, the change rate of the effective porosity increased from 11.47 to 44.81%, and the changing trend was the opposite. The explanation of this reason needs to start from the change in the bound porosity. Combined with Figure 5, it can be seen that cyclic loading and unloading increased the bound porosity of the coal body. The analysis of Figure 6a–c showed that this trend was also applicable when the cyclic load amplitude increased.

When the coal body was compressed under the action of the stress, not only the plastic deformation occurred but also the recoverable elastic deformation occurred. The larger the cyclic load amplitude was, the lower the recoverable deformation degree was. This led to a decrease in the overall pore size and an increase in the bound porosity. The change in the bound porosity led to an increase in the change quantity of the effective porosity and the change rate in the effective porosity.

Figure 7 shows the porosities of the coal samples before and after 5 cycles under different confining pressures at the cyclic load amplitude of 5 MPa. It was found that the variation trends of the coal porosity under different confining pressures were similar to those under different cyclic load amplitude values. That is, with an increase in the confining pressure, both the total...
porosity and the effective porosity of the coal samples showed a decreasing trend. With an increase in the confining pressure, the change rate of the total porosity of the coal samples decreased slightly after cyclic loading and unloading, while the change rates of the effective porosity with the confining pressures of 5, 10, and 15 MPa were 19.99, 16.04, and 15.24%, respectively, which significantly decreased with an increase in the confining pressure. This was mainly because the degree of coal compression increased during the initial loading, and the effective porosity and the permeability that could be compressed at the initial state of the coal samples were greatly reduced. This led to a decrease in the change rate of the effective porosity after cyclic loading and unloading, and the greater the confining pressure was, the more obvious this phenomenon was.

According to the analysis results shown in Figure 7a–c, it could also be found that with an increase in the confining pressure, the porosity components of mesopores and macropores in the coal samples under cyclic loading and unloading became lower and lower, and the change rates of the bound porosity with the confining pressures of 5, 10, and 15 MPa were 5.93, 4.34, and 4.06%, respectively, which also showed a decreasing trend. This indicated that the effect of the confining pressure on the coal body was the effect on the total pore size resulting in the overall decrease in the number of small pores, medium pores, and large pores rather than the transformation of medium pores and large pores into micropores.

3.3. Permeability Analysis of the Coal Samples. First, the variation trend of the permeability with the change in the pore pressure under the loading and unloading conditions was discussed. The experimental results are shown in Figure 8. It was found that with an increase in the pore pressure, the permeability first decreased and then increased, and there was a slippage effect. The minimum permeability was observed when the pore pressure was 3 MPa during both loading and unloading. Also, the permeability changed with the change in the pore pressure regardless of the loading and unloading processes. This indicated that the selection of one pore pressure for the follow-up research can reflect the trend under other pore pressures.
pressure conditions. At the same time, as the Pingmei no. 12 mine was a high-gas mine, the maximum gas pressure reached 2.7 MPa, and the gas pressure in the Ji no. 15 coal seam was 1.89 MPa. This pressure was close to 2 MPa, so a pore pressure of 2 MPa was selected for the subsequent permeability study.

Considering the ultrasonic test results and the NMR test results, the coal samples with small anisotropy were selected. Loading was carried out according to the stress path in the test procedure, and the variation trend of the permeability of the coal body under different paths was obtained. The permeability of the coal body decreased exponentially with an increase in the confining pressure in the pre-stress loading stage. After the pre-stress was loaded, the set stress path was cyclically loaded on the coal body. The experimental results are shown in Figure 9. The results showed that with an increase in the number of cycles of pressure confining, the overall permeability of the coal body decreased. The permeability variation of the first loading and unloading was the largest. With an increase in the number of loading and unloading cycles, the permeability variation gradually decreased and tended to be stable. This showed that the first loading and unloading was the main stage of the permeability change.

To further study the relationship between cyclic loading and unloading with the pre-peak confining pressure and the permeability, nonlinear regression fitting was conducted for the variation trend of the coal permeability by changing the number of loading and unloading cycles under different paths. Generally, the relationship between the permeability and the confining pressure is an exponential function. When we analyzed it, we found that the commonly used permeability-confining pressure relationship was quite different from the permeability-load/unload time relationship. With an increase in the cyclic loading and unloading times of the confining pressure before the peak, the permeability of coal decreased and tended to be stable. Therefore, with an increase in the loading and unloading time, theoretically, there was the permeability $y_0$ so that the permeability did not change. Because the relationship between the loading and unloading time and the permeability was mainly

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**Figure 7.** Variation trend of the coal porosity under cyclic loading and unloading at different confining pressures. (a) Confining pressure of 5 MPa, (b) confining pressure of 10 MPa, (c) Confining pressure of 15 MPa, and (d) variation trend of the porosity.
considered in the experiment, a single exponential function was adopted to fit the permeability and the loading and unloading time. As a result, eq 6 was obtained which could well explain the meaning of each parameter. The fitting results are shown in Table 3.

$$y = A_1 \times e^{-t/t_1} + y_0$$  \hspace{1cm} (6)$$

where $A_1$ is the pre-exponential factor representing the maximum permeability loss, $t_1$ is the relaxation time, and $y_0$ is
the final permeability of the coal body when the cyclic loading and unloading time increased. There was a good correlation between the permeability variation and the stress cycle number regardless of the stress path selected. It could reflect the trend of the permeability variation when the coal sample was loaded at the peak value and unloaded at a low value. Among different coal samples, the permeability under stress path 2 was larger because there were obvious cracks not detected by ultrasonic waves in the coal body. The existence of fissures increased the permeability of the coal.

### Table 3. Fitting Curve Expressions for the Coal Permeability

| specimen number | confining pressure cycle range | fit the confining pressure value | fitting formula | $R^2$  |
|-----------------|--------------------------------|---------------------------------|----------------|--------|
| no. 1           | 5–10                           | 5                               | $y = 0.24^*\exp(-x/1.65) + 0.51$ | 0.998 |
| no. 2           | 5–15                           | 5                               | $y = 0.23^*\exp(-x/0.78) + 0.19$ | 0.999 |
| no. 3           | 5–20                           | 5                               | $y = 0.51^*\exp(-x/1.21) + 0.75$ | 0.997 |
| no. 4           | 10–15                          | 10                              | $y = 0.26^*\exp(-x/1.37) + 0.10$ | 0.991 |
| no. 5           | 10–20                          | 15                              | $y = 1.39^*\exp(-x/0.44) + 0.38$ | 0.999 |
| no. 6           | 15–20                          | 20                              | $y = 0.01^*\exp(-x/4.75) + 0.07$ | 0.990 |

Figure 10. Curves of the permeability loss rate under different cyclic load amplitudes.

Figure 11. Influence of cyclic loading and unloading under different confining pressures on the permeability loss rate.
body but did not affect the trend of the permeability decrease with an increase in the number of cycles. In different paths, the peak-stress permeability was always lower than the low-stress permeability, and with an increase in the stress difference, the percentage of the difference between the peak-stress permeability and the low-stress permeability increased.

Due to anisotropy among different coal bodies, the permeability was not the same under the same confining pressure. To obtain the loss trend of the permeability of the coal body under the action of pre-peak cyclic loading and eliminate the influence of the coal body anisotropy on the experimental results, the permeability loss rate equation for the coal body was established, whose expression is as follows

\[
D = (1 - \frac{D_S}{D_0}) \times 100%
\]

where \(D_0\) is the permeability when the coal sample first reached the predetermined stress value, \(D_S\) is the permeability at the time of the S cycle and restored to the predetermined stress value, and \(D\) is the permeability loss rate at the time of the S cycle and restored to the predetermined stress value.

Because \(D\) is the permeability loss rate of the coal samples in different loading and unloading stages, we analyzed the permeability loss rate of the coal samples under the same stress level with the different number of loading and unloading cycles. Figures 10 and 11 show the curves of the permeability loss rate of the coal samples with different initial confining pressures, different numbers of loading and unloading cycles, and different cyclic load amplitudes.

According to Figure 10, when the confining pressure remained constant, the permeability loss rate of the coal samples showed a trend of gradual increase with an increase in the number of cycles. With an increase in the cyclic load amplitude, the initial permeability loss rate gradually increased. This was because the number of large and small pores in the coal samples decreased more with an increase in the cyclic load amplitude. With an increase in the number of cycles and the cyclic load amplitude, an increase in the permeability loss rate became smaller. This was quite different from the results of cyclic loading and unloading of axial compression. During the constant amplitude cyclic loading and unloading of axial compression, the pores of the coal body often increased gradually and even produced secondary cracks leading to an increase in the permeability and even the destruction of the coal body. The main reasons for such differences could be divided into two points. On one hand, the axial load direction was the principal stress direction of the standard test piece which easily caused the coal body to be damaged in the form of tension. However, the confining pressure was the pressure acting on the direction of the coal body which caused the coal body to be further squeezed or relaxed. On the other hand, such differences were related to the selection of the stress path. Because the purpose of the present study was to investigate the influence of the cyclic loading and unloading on the permeability characteristics of undamaged rock mass, the selected axial compression pressure was small, and the damaging effect on the coal mass was small. The number of new pore fractures generated during the cycle was less than the number of opening and closing of pore fractures under the confining pressure, so the trend was opposite to that in the axial compression cycle. At the same time, with an increase in the cyclic load amplitude, the degree of compression and reduction of the coal porosity during cyclic loading and unloading of the primary confining pressure increased. However, the porosity of the coal sample could not be reduced infinitely, so an increase in the permeability loss rate became smaller during the second cycle. This resulted in a greater increase in the permeability loss rate during the second cycle for the coal samples with a lower cyclic load amplitude than for the coal samples with a higher cyclic load amplitude.

According to the analysis results shown in Figure 11, when the cyclic load amplitude of the coal body was the same and the confining pressure was different, the permeability loss rate of the coal body increased with an increase in the number of cycles, while the increasing trend became smaller and smaller. The lower the confining pressure was, the smaller the overall permeability loss rate became. When the cyclic load amplitude was 5 MPa and the confining pressures were 5, 10, and 15 MPa, the permeability loss rates of the coal body in the second cycle were 9.77, 16.21, and 18.61%, respectively. In the 5th cycle, the load rates increased by 97.03, 51.82, and 51.53%, respectively, compared with the 2nd cycle. This indicated that when the cyclic load amplitude was the same, the smaller the confining pressure was, the greater the change in the loss rate became with an increase in the number of cycles. It could be predicted that with a continuous increase in the number of cycles, the permeability loss rate with low confining pressure will continue to increase until the total loss rate will become larger than that of the coal sample with a high confining pressure.

3.4. Sensitivity Analysis of the Permeability and the Porosity Stress under Cyclic Loading and Unloading Conditions. The permeability and the porosity of the coal body are usually more sensitive to stress, and the influence of the complex stress conditions of cyclic loading and unloading on the porosity and the permeability of the coal body is also complex. The relationship among the permeability, the porosity, and the stress change in the coal body and other tight reservoirs can be expressed from an exponential function

\[
k = k_0e^{-\gamma(p-p_f)}
\]

\[
\phi = \phi_0e^{-\alpha(p-p_f)}
\]

where \(k_0\) is the permeability in the initial state \((m^2)\), \(\gamma\) is the permeability stress sensitivity coefficient \((Pa^{-1})\), \(\phi_0\) is the porosity, \(p_f\) is the porosity at the reference stress, \(\alpha\) is the stress sensitivity coefficient of the porosity \((Pa^{-1})\), \(p_f\) is the overburden pressure \((Pa)\), and \(p\) is the formation pressure \((Pa)\).

David et al. emphasized that the stress sensitivity factor \(\gamma\) is the product of the porosity sensitivity index \((\alpha)\) and the pore compressibility factor \((C_\phi)\), thus

\[
\gamma = \alpha C_\phi
\]

The porosity-permeability variation relationship caused by the further loading process can be expressed as

\[
k = \left(\frac{\phi}{\phi_0}\right)\alpha
\]

The exponent \(\alpha\) is sensitive to materials and their evolution, and there is no "universal" \(\alpha\) value for all materials.

To further explore the relationship between the porosity and the permeability of coal and the evolution of the stress sensitivity under cyclic loading and unloading conditions, the variation trends of the effective porosity and the permeability of the coal samples under different cyclic loading and unloading conditions were fitted, as shown in Figures 12 and 13. Figure 12 shows the
Effect of the initial value of the cyclic confining pressure on the relationship between the effective porosity and the permeability of the coal samples when the cyclic load amplitude was 5 MPa. It was found that the variation trend of the porosity and the permeability during cyclic loading and unloading conformed to the exponential-law relationship.

Under different confining pressures, the fitting index $\alpha$ of the effective porosity and the permeability in the initial pre-stress loading stage was the largest indication that the stress in the pre-stress loading stage had the greatest influence on the porosity and the permeability. That is, the stress sensitivity was the most obvious in this stage. When the initial confining pressure remained unchanged during cyclic loading and unloading, the total changes in the effective porosity and the permeability of the coal body were less than those when the confining pressure was directly changed. This indicated that the pores in the coal body were further compressed during cyclic loading and unloading. At the same time, the fitting index $\alpha$ decreased slightly with an increase in the initial confining pressure. This indicated that the change in the initial value of the cyclic confining pressure had a weak influence on the stress sensitivity of the coal sample in the process of cyclic loading and unloading.

Figure 13 shows the relationship between the effective porosity and the permeability of the coal samples with different cyclic load amplitudes and numbers of loading and unloading cycles when the initial value of the cyclic confining pressure was 5 MPa. It can be seen that the effective porosity and the permeability of the coal samples also conformed to the exponential-law relationship under different cyclic load amplitudes. Because the initial confining pressure was the same, the initial permeability of the coal body mainly depended on its initial effective porosity and pore connectivity. It can be seen from the above results that the proportion of the initial mesopores and macropores in the no. 2 specimen was large, and clear fractures might exist in the coal body. Therefore, the initial permeability and the porosity of the coal body were both large when the cyclic load amplitude was 10 MPa. On the whole, the exponential $\alpha$ of the fitting function decreased with an increase in the cyclic load amplitude. This indicated that the stress sensitivity of the coal samples was significantly affected by the cyclic load amplitude, and the greater the cyclic load amplitude was, the weaker the stress sensitivity was. When the cyclic load amplitude increased from 5 to 15 MPa, the $\alpha$ index decreased by 69.23% indicating that the relationship between the effective porosity and the permeability of the coal body was greatly affected by the cyclic load amplitude. The results shown in Figure 14 also verified this discussion.

As can be seen from the above results, in the complex stress path of cyclic loading and unloading, repeated stress action led to constant changes in the stress sensitivity of the permeability and the porosity of the coal body. A single equation could not effectively reflect the relationship among the permeability, the porosity, and the stress change in the process of cyclic loading and unloading. Under the condition of the same initial confining pressure and the cyclic load amplitude, the stress sensitivity of the porosity and the permeability of the coal samples decreased gradually with an increase in the number of cycles. However, the degree of reduction decreased gradually, which conformed to the exponential-law relationship. The initial value of the confining pressure determined the initial value of the stress sensitivity change during loading and unloading and had good compatibility with the relationship among the original permeability, the porosity, and the stress change. The cyclic

![Figure 12](https://example.com/fig12.png)

**Figure 12.** Relationship between the effective porosity and the permeability under cyclic loading and unloading with different initial confining pressures.

![Figure 13](https://example.com/fig13.png)

**Figure 13.** Relationship between the effective porosity and the permeability during cyclic loading and unloading with different cyclic load amplitudes.
the porosity, and the stress change in the cyclic loading and unloading process. The change factor can be expressed as

\[ \eta = e^{\alpha a} \] (13)

where \( \zeta \) is the fitting index related to the change degree of the coal stress sensitivity, and \( a \) is the cyclic load amplitude. Therefore, the porosity–permeability change relationship can be expressed as

\[ \frac{k_i}{k_{i0}} = \left( \frac{\phi_i}{\phi_{i0}} \right)^{\eta \alpha} \] (14)

4. CONCLUSIONS

In this research, we have obtained the following conclusions:

1. In the process of cyclic loading and unloading, with an increase in the number of cycles, each peak value of the T2 map of saturated water in the coal samples decreased gradually. Each peak value of the centrifuged T2 map gradually increased. When the initial value of the confining pressure was the same and the cyclic load amplitude was different, with an increase in the cyclic load amplitude, the total porosity and the effective porosity of the coal samples decreased after cyclic loading and unloading, while the bound porosity increased. With an increase in the confining pressure, the effective porosity and the bound porosity decreased when the peak cyclic load amplitude was the same.

2. With an increase in the number of loading and unloading cycles, there was a negative exponential correlation with the overall permeability of the coal mass, and the permeability change in the first loading and unloading period was the largest. With an increase in the number of loading and unloading cycles, the permeability change gradually decreased and tended to be stable.

3. The variation trend of the coal permeability with the change in the cyclic load amplitude under different initial confining pressures was analyzed. The results showed that the permeability loss rate of the coal samples increased gradually with an increase in the number of cycles, and the initial permeability loss rate increased gradually with an increase in the cyclic load amplitude. The same trend was observed when the cyclic load amplitude was the same, and the initial confining pressure was constant, but there was no obvious increasing trend.

4. The relationship between the porosity and the permeability of the coal samples under different cyclic loading and unloading paths was analyzed. It was found that the relationship between the effective porosity and the permeability in the process of cyclic loading and unloading conformed to the exponential function relationship. The influence of the cyclic load amplitude on the stress sensitivity of the coal body was further analyzed, and the change factor of the stress sensitivity was introduced into the relationship between the porosity and the permeability of the coal body. As a result, the relationship between the porosity and the permeability of the coal body considering cyclic loading and unloading was established.
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Notes
The authors declare no competing financial interest.

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