Experimental Study on the Porosity and Permeability Change of High-Rank Coal under Cyclic Loading and Unloading

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ABSTRACT: It is of great significance to study the evolution law and change characteristics of the porosity and permeability of coal under cyclic disturbance to efficiently exploit coal-bed methane (CBM). In this paper, the GCTS rock mechanics experimental system is applied, the unsteady gas seepage test under cyclic loading and unloading is carried out with high-grade coal samples from Zhijin County, Guizhou Province, as the research object, and the mathematical formula of the dynamic change of porosity during loading and unloading is established. The results show that (1) the porosity and permeability parameters of coal are negatively correlated with confining pressure, and all decrease with the increase in confining pressure; (2) the change rate of the porosity and permeability of bedding coal decreases gradually with the increase in stress, and the porosity and permeability under high stress decrease gradually with the increase in cycle times; (3) during cyclic loading and unloading, the permeability loss \( D_k \) of coal mainly occurs in the first loading (>90%), and \( D_k \) gradually decreases with the increase in cyclic times; (4) under the same test conditions, the evolution law of the porosity and permeability of parallel bedding coal and vertical bedding coal is similar but the stress sensitivity of vertical bedding coal is higher; (5) the circumferential strain of parallel bedding coal is higher than that of vertical bedding coal, and the porosity change and permeability loss show a specific bedding effect; and (6) under the action of cyclic stress, the change of strain—permeability of coal is abnormal after it is destroyed. With the increase in strain before the sample is destroyed, the permeability drops sharply, and after the sample is destroyed, the strain decreases and the permeability never recovers. The research results can provide favorable theoretical guidance and technical support for pressure relief exploitation of coal-bed methane, such as multibranch horizontal wells.

1. INTRODUCTION

China is relatively rich in high-rank coal-bed methane resources. The high-rank coal-bed methane enrichment areas are mainly distributed in Qinshui Basin, Ordos Basin, Qianxi-South Sichuan, and other regions. Coal-bed methane exploitation in the Qinshui Basin has entered the commercial model. Other coal-bed methane enrichment blocks have made positive progress in exploration and development in recent years. According to the research report of Zhu et al., the production of high coal rank coal-bed methane (CBM) has accounted for more than 90% of the total production of CBM in China.\(^1,2\) However, due to the complex occurrence conditions of CBM\(^3–5\) and the high metamorphic degree and generally low permeability of high-rank coal, it is difficult for its exploration and development to achieve the expected results. With the rapid growth of CBM mining technology, the current mining technologies such as hydraulic fracturing and multibranch horizontal well drainage have become the focus of CBM development.\(^6–8\)

Received: May 27, 2022
Accepted: August 11, 2022
Published: August 20, 2022
According to the evaluation of unconventional oil and gas by the Ministry of Land and Resources in 2015, it is predicted that the geological resources of CBM in the East Yunnan and West Guizhou gas-bearing basin group are 3.12 trillion m$^3$. The recoverable resources of CBM are 1.38 trillion m$^3$, and the average recoverable coefficient of CBM resources reaches 44.29%. The application prospect of multibranch horizontal well mining technology in Guizhou is good. Currently, a multibranch horizontal well has been applied to coal-bed methane mining in Guizhou. Multibranch horizontal well mining technology integrates drilling, completion, and stimulation and is suitable for low permeability CBM mining.\textsuperscript{9−12} This mining technology can reduce the pressure of the coal reservoir, promote the change of the in situ stress field and fracture field of the coal seam,\textsuperscript{13,14} and form a favorable channel for desorption and seepage of CBM to improve gas production. It is suitable for thick coal seams with simple structural and hydrogeological conditions. During drilling and completion, the coal seam around the wellbore is disturbed by stress, and the change of the stress field and fracture field affects the subsequent drainage and production work. The bedding features of high-rank coal are obvious. The expansion of cracks in coal with different beddings is quite different,\textsuperscript{15,16} which leads to significant differences in permeability changes after disturbance, which greatly influences CBM productivity. Some studies have shown that coal’s mechanics and damage properties are anisotropic due to bedding angles, and scholars have conducted many related experimental studies on this problem.

Mu et al.\textsuperscript{17,18} obtained coal’s failure situation and acoustic emission characteristics with different beddings through a uniaxial compression test combined with an auditory emission response. Hao et al.\textsuperscript{19} obtained the influence of the bedding angle on coal deformation and failure through uniaxial and triaxial compression tests. They analyzed the cracking and failure of coal with different bedding angles. Duan et al.\textsuperscript{20} studied the crack growth and confining pressure’s restriction on the crack propagation in the cyclic process based on the crack propagation on the test coal surface through conventional triaxial and cyclic loading tests. Zhang et al.\textsuperscript{21} investigated the deformation characteristics of coal subjected to the influence of the unloading
rate through unloading tests. Zeng et al.\textsuperscript{22} analyzed the impact of fracture on permeability, the control of maximum principal stress, and the bedding direction on permeability through the triaxial test. Yang et al.\textsuperscript{23} established a relationship between coal permeability and hydrostatic pressure through cyclic loading and unloading tests and quantified the relationship between permeability and stress. Through cyclic loading and unloading and permeability tests under different stresses, Li et al.\textsuperscript{24} found that with the increase in cyclic times and effective strain, the sensitivity of coal permeability to stress decreased. Ji et al.\textsuperscript{25} analyzed the relationship between effective stress and permeability and revealed the influencing mechanism. Liu et al.\textsuperscript{26} obtained the evolution law of permeability by studying the permeability of intact and fractured coal samples under different geological conditions.

According to the previous studies, the deformation, the evolution of porosity, and permeability of coal are complex in the cyclic test process, and there exists a rare analysis of the seepage characteristics of layered coal under the conditions of cyclic loading and unloading. Therefore, studying the change characteristics of porosity and permeability of different layered coal is essential. In this paper, the GCTS rock mechanics test system is used to study the change laws of porosity and permeability of high-rank coal during the process of cyclic loading and unloading, and the influence of confining pressure on the porosity, permeability, and strain of bedding coal and its mechanism were also analyzed. The research results can provide significant support for the efficient exploitation of CBM.

2. MATERIALS AND METHODS

2.1. Laboratory Apparatus. To simulate the change in the porosity and permeability of coal under different confining pressures, this experiment was carried out on the GCTS Rock Mechanics Test System of the State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University. The schematic diagram of the test system is shown in Figure 1 below. The GCTS test system can simulate the stress state and environmental conditions of deep underground rock mass and has the characteristics of stable performance and high precision. The system is mainly composed of a triaxial pressure chamber, an oil pump, a water pump, a hydraulic pump station, and a gas tank. It can be used for uniaxial/triaxial, true triaxial, and seepage experiments under complex stress conditions. During the investigation, a radial displacement meter is used to measure the radial deformation, and the computer automatically collects the data, which can accurately record the changes in various rock parameters during the whole experiment.

2.2. Sample Preparation and the Experimental Scheme. All of the test samples are obtained from the high-grade coal in Zhijin County, Guizhou Province, Southwest China, with a depth of about 200–800m. The coal samples have good surface integrity, high metamorphism, and strong hard brittleness. Due to the difference in primary fractures of coal, coal has strong anisotropy and a slightly high porosity difference. The obtained coal samples are processed into a standard cylindrical piece with a size of 50 × 100 mm\textsuperscript{2} by wire cutting to ensure that the flatness of the end surface is within 0.02 mm. For ease of differentiation, the bedding orientation parallel to the axial stress direction is defined as the parallel bedding samples (0°), and perpendicular to the axial stress direction as the vertical bedding samples (90°), as shown in Figure 2. The obtained parameters of coal samples are shown in Table 1. After the completion of sample processing, computed tomography (CT) scanning was performed to determine the distribution of primary fractures in the model for the subsequent analysis of the influence characteristics of prior fractures on porosity and permeability (Table 2).

According to the research on the adsorption capacity of various gases in coal, the adsorption capacity of nitrogen in coal is extremely low.\textsuperscript{27–29} To reduce the interference of gas adsorption and desorption on the experimental results and ensure the reliability of the experimental results, nitrogen (N\textsubscript{2}) was selected as the seepage gas in this experiment. During the test, the confining pressure (\(\sigma_a\)) is controlled within the range of 2–10 MPa, and the relationship between axial stress (\(\sigma_a\)) and confining pressure is \(\sigma_a - \sigma_a = 2\) MPa. The loading condition of the coal samples is shown in Figure 3, and the loading and unloading cycles are carried out three times. During the test, the upstream gas pressure (\(H_a\)) was set to be 0.5 MPa and the downstream air pressure (\(H_d\)) was set to be 0.2 MPa to ensure the continuous gas flow in the coal samples and shorten the upstream and downstream seepage balance time. The loading and unloading path and seepage balance conditions are shown in Figure 4. After the sample’s confining pressure loading and unloading are completed, manually the gas valve is adjusted to ensure that the upstream and downstream gas pressures reach the set value and start seepage. After the upstream and downstream gas pressures become balanced, the next loading and unloading cycles are completed by computer control, and the operation is repeated until the end of the cycling experiment. After the test, the real-time porosity and permeability under this confining pressure will be calculated by the difference between upstream and downstream gas pressure and volumetric strain during seepage.

2.3. Transient Pulse Method. The principle and test method of the short pulse method is as follows: when testing, the coal sample is installed between the upper and lower gas buffer chambers, and under the condition that the gas pressure at both ends of the coal sample is controlled to be equal, the upstream gas pressure is increased through the control panel, and a pressure pulse is applied to the sample. When the gas enters the downstream buffer pressure chamber along the seepage channel in coal under pulse pressure, the downstream pressure increases and the upstream and downstream pressures are gradually balanced. At this time, the gas permeability of the sample can be calculated by the curve of gas pressure difference with time.

Table 1. Parameter Table of Samples

| test number | bedding angle (degree) | diameter (mm) | length (mm) | weight (g) | density (g·cm\textsuperscript{-3}) | \(\phi\) (%) |
|-------------|------------------------|--------------|-------------|------------|-------------------------------|-------------|
| 0–1         | 0                      | 49.07        | 100.07      | 293.94     | 1.55                          | 6.37        |
| 0–2         | 0                      | 49.10        | 100.10      | 275.78     | 1.45                          | 5.48        |
| 90–1        | 90                     | 49.69        | 100.18      | 279.75     | 1.44                          | 2.83        |
| 90–2        | 90                     | 49.37        | 100.22      | 278.61     | 1.45                          | 3.56        |

Figure 2. Different bedding samples.
The change rule in the gas pressure difference during the transient pulse test is as follows

$$\Delta H(t) = (\Delta H_0) e^{-\alpha t}$$  \hspace{1cm} (1)

where $\Delta H(t)$ is the upstream and downstream gas pressure difference (MPa), $t$ is the test time (s), and $\alpha$ is a constant determined by sample and experimental conditions ($s^{-1}$).

As the gas flows through the internal cracks of the sample, the pressure difference between the upstream and downstream ($\Delta H = H_a - H_b$) will gradually decrease and maintain a stable value. After the pressure in this system reaches equilibrium, the permeability of the samples can be calculated by the following formula\textsuperscript{23}

$$H_i = H_b + \frac{V_0 \Delta H}{V_a + V_b}$$ \hspace{1cm} (2)

$$K = \frac{\mu L}{AH_i} \left( \frac{V_a V_b}{V_a + V_b} \right)$$ \hspace{1cm} (3)

where $V_a$ is the sum of the volumes of the upstream chambers $V_1$ and $V_2$, $V_b$ is the sum of the volumes of the downstream sections $V_3$ and $V_4$, $K$ is the permeability ($m^2$), $A$ is the cross-sectional area of the coal sample ($m^2$), $L$ is the length of the coal sample (m), and $\mu$ is the dynamic viscosity of nitrogen at room temperature (Pa·s).

Permeability loss ($D_k$) caused by stress sensitivity of coal during the test can be defined as the ratio of the difference between permeability before loading ($K_i$) and permeability after loading ($K_{i+1}$). It can also be used to characterize the damage degree of stress sensitivity of the coal sample,\textsuperscript{30–34} and the formula is given as follows

$$D_k = \frac{K_i - K_{i+1}}{K_i}$$ \hspace{1cm} (4)

### 3. EXPERIMENTAL RESULTS AND ANALYSIS

Porosity is a parameter closely related to permeability. However, porosity is a scalar, while permeability is a tensor. Porosity cannot reflect the direction and size of cracks and pores, so the directionality of pores and cracks should also be considered when analyzing the relationship between porosity and permeability. This is an essential guide for studying the recoverability of the original coal reservoir, that is, pay close attention to the development degree and the direction of pores and cracks in the original reservoir, then judge the correlation between them and CBM extraction, and then make use of the characteristics of the initial cracks and pores to serve for increasing the production and efficiency of CBM development.

The volume of rock will change in the loading and unloading process. But generally speaking, the strength of the mineral itself is extremely high, and the changes in cracks and pores mainly cause the volume change. Therefore, the change in the coal volume reflects the change in its internal cracks and pores, and the numerical value reflects the change in its porosity.

During the experiment, the porosity of the sample is calculated by the change in the crack volume of the coal sample, and the porosity can be calculated by the volumetric strain $\varepsilon$ of the coal sample. The initial volume of the coal sample is $V_0$ and the crack volume $V_c$ is

$$V_c = \phi_0 \times V_0$$ \hspace{1cm} (5)
During the experiment, the cracks of the coal sample were closed, and elastic deformation and plastic deformation were produced simultaneously, thus causing the change of porosity. The function of the volume change with time after loading is

\[ V(t) = v_0 \times c_0 - \Delta V(t) \]

where \( \Delta V(t) \) is the function of the crack volume of the sample with time and \( \varepsilon(t) \) is the volume strain function.

\[ V(t) = \phi_0 \times V_0 - \varepsilon(t) \times V_0 \]

where \( \phi_0 \) is the initial porosity and \( V_0 \) is the initial volume.

In this process, the calculation formula of the porosity change with time is given as

\[ \phi(t) = \frac{V(t)}{V_0} = \phi_0 - \varepsilon(t) \]

3.1. Evolution Result of Porosity and Permeability under Loading and Unloading Cycles. The pore-permeability evolution process of coal samples under cyclic loading and unloading conditions is shown in Figure 5.

(c) Average value of porosity and permeability evolution of two bedding layers

During the test, the changing trends of the porosity and permeability of different bedding coals in cyclic loading and unloading tests are basically the same. The porosity and permeability are negatively correlated with stress. Porosity decreases with increasing pressure and increases with decreasing stress; permeability decreases during loading and increases during unloading. The porosity and permeability during loading are higher than those during unloading under the same cycle and the same confining pressure. During the loading or unloading process, the difference between the porosity and permeability of the samples decreases gradually with the increase in confining pressure. The changes in the porosity and permeability of samples under high stress are relatively low.

The difference between the initial permeability and the initial porosity of the sample is quite significant, and this difference is always maintained during the test. Porosity and permeability decrease sharply at the first loading, and permeability even changes on the order of magnitude. In the process of the first loading, the porosity and permeability change of the coal sample is the largest; when the confining pressure first reaches 10 MPa, the porosity changes of parallel bedding samples are 0.586 and
0.612%, while the porosity changes of vertical bedding sample are 0.482 and 0.519%. Permeability changes on the order of magnitude at this time:

- The permeability of sample 0–01 is $2.32 \times 10^{-15}$ m$^2$, and $D_k$ is 91.38%.
- The permeability of sample 0–02 is $1.13 \times 10^{-16}$ m$^2$, and $D_k$ is 97.84%.
- The permeability of sample 90–01 is $3.03 \times 10^{-17}$ m$^2$, and $D_k$ is 99.41%.
- The permeability of sample 90–02 is $1.34 \times 10^{-17}$ m$^2$, and $D_k$ is 99.39%.

At this time, the porosity and permeability of the coal samples show obvious differences, and the porosity variation of the vertical bedding sample is relatively large, while $D_k$ is relatively small. It can be seen that the porosity variation value and $D_k$ of each coal sample gradually decreased in the subsequent tests. Still, the porosity variation and $D_k$ always showed the characteristics of larger variation in the porosity of parallel bedding and higher variation in vertical bedding. It can be seen from the analysis that the evolution of porosity and permeability in the cyclic process shows an obvious bedding effect.

It can be seen from the CT scanning pictures (Figure 6) that the distributions of internal cracks are different among the coal samples. The cracks in sample 0–01 and sample 90–01 are mainly along the bedding direction. The main cracks inside the sample 0–02 intersect with the bedding direction at a large angle. The cracks along the bedding direction and vertical bedding cracks are contained inside sample 90–02. The difference in the permeability of vertical bedding samples is small, and the influence of the sample crack on the initial permeability is insignificant. Combined with Figure 5b, the crack of parallel bedding sample 0–01 is along the bedding plane, and the coal gangue and the coal interface contact effect is bad; by the CT scan, it can be observed to have no contact part, and other samples of coal and the coal gangue interface contact effect are relatively good. Therefore, the permeability of sample 0–02 is higher than that of other samples. After the test, most of the samples have small microcrack deformation and limited CT accuracy, so the CT scanning images of the samples after the test are not compared.

In the loading or unloading section of the test, the porosity does not decrease monotonically with the increase in cycle times under the same confining pressure. As shown in Figure 5a, the porosity of sample 0–02 and 90–01 increased obviously when the confining pressure of the third cycle was unloaded to 2 MPa. According to the porosity calculation formula eq 7, the sample volumetric strain decreases, and the sample volume expands. At the end of the test, sample 90–02 was subjected to local failure, and the other samples were not subjected to macroscopic failure. Porosity changes and $D_k$ behavior differed from other samples due to local failure in sample 90–02. The porosity of the loading section of the sample without macroscopic failure decreases with the increase in the cycle times, and the permeability always decreases negatively and exponentially with increasing stress and increases exponentially with the decrease in the stress. While the porosity of sample 90–02 increased during the third loading, permeability increased during the second loading. In the third loading, the permeability drops sharply, and $D_k$ increases obviously in the loading process. The permeability recovery during the third unloading is relatively poor, and the permeability does not recover obviously like other samples at 2 MPa.

According to Figure 5d, $D_k$ during the cycle decreases gradually with the cycle time increase, and the reducing rate becomes gradually slow. However, the $D_k$ value is still very high, and the stress sensitivity of bedding coal is extremely strong. It can be seen that the law of permeability loss curves of the parallel bedding samples and the vertical bedding samples is about the same. Still, the law of the $D_k$ curve of sample 90–02 is relatively poor, and $D_k$ increases obviously in the third cycle. It can be seen from the combination of Figure 5b,d that the permeability evolution law of the failure sample under stress is relatively poor.

To sum up, the evolution law of the porosity and permeability of the coal sample with stress is affected by factors such as the bedding direction (parallel bedding and vertical bedding), the crack direction (along the bedding direction), the failure condition, and cycle times.

### 3.2 Porosity and Permeability Evolution Analyses

In engineering practice, the coal seam is damaged by engineering disturbance, so it is of great significance to deeply analyze the evolution of porosity and permeability under cyclic loading and unloading of coal for applying pressure relief mining technology in multibranch horizontal wells.

In the cyclic loading–unloading seepage test of high-rank coal, the pore permeability decreases gradually with increasing confining pressure-compression deformation of coal under confining pressure and axial pressure during the loading stage.
damaged during the first loading from the perspective of strain. However, in the subsequent loading and unloading stages, nearly coincident “hysteresis loops” appeared, all of which were above the strain curve. This fully shows that the sample produced irreversible plastic deformation in the first loading stage. In contrast, the subsequent loading and unloading showed significant elastic deformation characteristics (close to the coincident hysteresis loop). After several times of loading and unloading, most of the internal cracks in the samples did not expand and penetrate and formed obvious damage, so the porosity and permeability of the samples in the last two cycles changed less. However, according to previous research, increasing the number of cycles will gradually increase the hysteresis loop area and damage the degree of coal, and with the increase in the number of cycles, coal will be unstable and destroyed. Under the long-term cycle, it will benefit the development of microcracks, and coal will be more broken during instability failure. Therefore, to implement pressure relief mining in this kind of coal seam, in addition to forming pressure relief conditions by drilling a borehole, the deviation stress of the branch borehole wall and the disturbance of drilling stress also need to be considered. Therefore, further strengthening of pressure relief conditions should be considered in the follow-up research.

The strain of sample 0–02 during the third unloading is lower than during the previous two unloadings, indicating that the deformation changes from compression to expansion and leads to increased sample porosity. On the other hand, sample 90–02 suffered local failure due to its low strength. Still, the failure surface of coal in the failure area was damaged, rearranged, and compressed under the stress action, and no significant volume expansion occurred. Therefore, the strain development was similar to that of other samples. However, the fracture surface is damaged and deformed, and the fracture recombination of the original seepage channel decreases permeability. There is no significant increase in the permeability during unloading, increasing $D_k$. According to the stress–strain diagram, the strain will grow slowly with the increase in cycles under the same stress condition. In this process, the microcracks close and open repeatedly. In this process, the coal rock (90–02) with low strength develops into macroscopic cracks until it is destroyed. Therefore, the influence of engineering disturbance should be reduced as much as possible during the CBM mining to prevent the coal seam from being damaged, leading to the blockage of seepage channels and affecting the branch CBM drainage and mining.

4. EFFECT OF THE INTERNAL STRUCTURE ON THE POROSITY AND PERMEABILITY

The influence of bedding on coal during the test is mainly reflected in deformation and permeability recovery. Bedding, as a weak structural plane in the coal matrix, obviously influences the porosity and permeability of coal. The volumetric strain can reflect the overall deformation of the sample but cannot reflect the deformation and porosity change characteristics in all directions of the sample. According to the porosity calculation formula $eq\ 7$, the contribution of deformation in all directions of coal to porosity and permeability change can be obtained through radial and axial strain. The strain changes of coal during the cycle are shown in Figure 8. The radial strain changes within the range of 0.05–0.22%, and the axial strain fluctuates within the range of 0.02–0.57%. It can be seen from the figure that the
axial strains of middling during the cycle are similar, and the radial strains show obvious differences.

For porosity, according to the porosity calculation formula eq 7, the radial porosity change is 2 times the radial strain, and the axial porosity change is the axial deformation. According to Figure 8, the porosity variation difference in two directions of parallel bedding coal is small, and the porosity of vertical bedding coal is mainly affected by axial strain. The internal crack of bedding coal is shown in Figure 9; the bedding plane of parallel bedding coal is vertical to the direction of the confining pressure, axial fracture and the axial structure weak surface is abundant, and the compression deformation caused by confining pressure is higher. The bedding plane of the vertical bedding coal seam is parallel to the confining pressure direction. The confining pressure mainly acts on the coal matrix, and the deformation of the coal matrix is relatively low under the same confining pressure. Therefore, the radial deformation shows significant bedding differences with a ratio of 1.33, resulting in a difference in the porosity variation in the direction.

For permeability, in the test process, the gas seepage channel is mainly the internal cracks and the bedding matrix, and the gas permeability in the matrix is low. Therefore, coal crack and bedding have an important influence on permeability. It can be seen from Figure 5c,d that there are significant differences in the permeability change loss during the loading and unloading of the two kinds of bedding coals. Vertical bedding coal permeability changes more under the same stress condition. In the cyclic loading and unloading experiments, the radial deformation of coal varies greatly, and Figure 10 below shows the relationship between the radial strain and permeability.

In the test process, the internal fractures of coal undergo repeated compression and opening, which affect the deformation of coal and further affect the evolution of porosity and permeability. There is an obvious exponential relationship between circumferential strain and permeability ($y = y_0 + ae^{bx}$). Fitting the strain–permeability of the sample at each loading and unloading stage, the $R^2$ value is as high as 0.99 (0.88 only when sample 90–02 is unloaded for the third time). Combining Figures 9 and 10, it can be seen that the regularity of the strain–permeability curve of coal containing only bedding cracks is better, and the relationship between strain and permeability of samples containing cracks intersecting bedding planes is more complicated. According to the pretest CT scanning (Figure 6 and Figure 9), samples 0–01 and 90–01 only have cracks parallel to the bedding direction. The strain–permeability curves of the two samples gradually decrease with the increase in cycle times and monotonically decrease with the increase in strain. However, the regularity of other samples is poor, and the curve does not move down with the increase in the cycle.

The difference in internal cracks in coal leads to the difference in the initial permeability of coal with the same bedding. There is a large size through fracture-filled with a dirt band along the seepage direction in sample 0–01; the permeability is high.

Figure 8. Axial and radial strain in tests.

Figure 9. Three-dimensional (3D) diagram of the coal internal structure.
Sample 0–02 also has large angle intersecting cracks with the bedding plane, and sample 90–02 has vertical bedding plane cracks. According to the research, the fracture angle will affect the fracture expansion and peak strength during the loading process. Sample 0–02 has cracks intersecting with a large angle axial stress direction, and its expansion deformation will affect permeability recovery. Therefore, the volumetric strain decreases with little change in the permeability during the third unloading. The vertical bedding plane crack in sample 90–02 intersects with the parallel bedding plane crack, resulting in the local failure in the area where the crack is located. The strain of the coal body affected by the stress is not significantly reduced but the original seepage channel is damaged. Therefore, the strain of sample 90–02 recovers after unloading but the permeability does not recover. According to the deformation curve, the difference in the axial deformation of bedding coal is low but the same axial deformation has different effects on the permeability of different bedding coal.

When the seepage direction is parallel to the bedding plane (parallel bedding coal), bedding and fractures serve as the main seepage channels, and the bedding plane of the parallel bedding coal is parallel to the seepage direction, so the permeability is higher. It can be seen from CT that most of the fractures in the coal with parallel bedding intersect with the bedding at a parallel or large angle, and the fractures serve as the main channels for seepage. When the axial stress is parallel to the fracture direction, the fracture surface is affected by tensile action, and the closure effect of seepage fractures is relatively poor. Therefore, the permeability of the parallel bedding coal is higher than that of the vertical bedding coal, and $D_k$ is relatively low during the test.

Now, the cracks and bedding of coal with parallel bedding undergo a large deformation under the influence of confining pressure (compared with that of vertical bedding coal). Therefore, the permeability of coal with parallel bedding is mainly affected by radial deformation, while the impact of axial deformation on permeability is limited.

**Figure 10.** Radial strain–permeability relationship.
When the seepage direction is vertical to the bedding plane (vertical bedding), the axial deformation of the vertical bedding coal is much higher than that of the parallel bedding coal in the radial direction, and during the test, the closure degrees of the bedding plane and bedding fracture of the vertical bedding coal are higher than those of the parallel bedding coal. When the axial stress is low, the seepage is mainly through the cracks and matrix, so the relative parallel bedding seepage is more difficult, the seepage channel is tortuous, and the seepage velocity is slow. When the axial stress increases, the vertical bedding coal along the bedding plane cracks closed; at this time, the gas seepage mainly through the coal matrix. After loading, the matrix of coal is the main channel of seepage. The primary fracture has little effect on seepage. The gas permeability in the coal matrix is much weaker than in the fracture and bedding. Under the same experimental conditions, the permeability loss during the loading process of vertical bedding coal is higher, and the axial deformation has a greater effect on the vertical bedding coal.

In circulation, the porosity and permeability of parallel and vertical beddings are similar but their influencing mechanisms are different. This situation is also verified by the directionality of the strain of coal with other bedding in the test process. The angle between stress and bedding and fracture affect strain development, and the directionality of strain also affects the change in permeability and porosity.

5. CONCLUSIONS AND PROSPECTS

In practical engineering, the stress field of the coal seam changes during the drilling process. During this process, the internal bedding and cracks of coal rock are deformed due to the load change. This paper simulates the disturbance of underground coal rock through cyclic loading and unloading experiments and studies the changes in the porosity and permeability of coal during this process. According to the study on the evolution laws of porosity and permeability in the test process, the following conclusions can be obtained:

(1) In the cyclic loading and unloading experiment, the porosity and permeability decrease with increasing confining pressure. The initial porosity and permeability of bedding coal are quite different, which always keeps this difference under stress. During the test, the plastic deformation mainly occurred in the first loading period. During cyclic loading and unloading, the axial direction of coal rock should be increased. The degree of crack and joint closure of vertical bedding coal under axial compression is higher than that of parallel bedding coal. The permeability loss of multiple cycles is higher than 92%, and the stress sensitivity of vertical bedding coal is stronger.

(2) Under cyclic loading and unloading, the change in circumferential porosity is determined by circumferential strain, and the strain of parallel bedding coal under confining pressure is higher than that of vertical bedding coal. When loading to 10 MPa, the circumferential deformation ratio of parallel bedding coal to vertical bedding coal is about 1.33, and the porosity change value of parallel bedding coal is higher during loading.

(3) Based on the evolution of strain–permeability in the cyclic process, it can be known that the evolution law of strain–permeability was obvious before coal failure. After the local damage of coal, the strain does not drop significantly but the permeability is no longer restored.

Therefore, in the actual engineering, it is necessary to pay attention to the stability of the branch shaft wall, and the collapse of the coal wall affects the production of coal-bed methane drainage.

Due to the limitation of test conditions and practical engineering considerations, the number of coal-rock cycles in the test is small, and the research on the evolution of coal-rock porosity and permeability in multiple cycles is insufficient. Further research is needed on the influence of multiple disturbances on coal.

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Notes
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Acknowledgments
The authors would gratefully like to acknowledge the financial support from the National Natural Science Foundation of China under grants 52074046 and 51834003 and the Guizhou Geological Exploration Fund Project [208-9912-JBN-UTS0, 52000021MGQSE7SK6PRP].

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