Permeability Response Characteristics of Primary Undeformed Coal and Tectonically Deformed Coal under Loading—Unloading Conditions in Huainan Coalfield, China

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1. INTRODUCTION

Tectonically deformed coal (TDC) can be produced by brittle, shear/transitional, ductile deformations, and tectonic stress from primary undeformed coal (PUC) in actual geology processes. TDC reservoirs are prevalent in China and badly affect the coal mining production safety and efficient extraction of coalbed methane (CBM). On the one hand, the tectonic deformation (including brittle fracturing, broken or ductile deformation, or superimposed destruction) damages the intact coal matrix, changes the fissure system, and results in a much lower permeability of TDC reservoirs under in situ stress compared to PUC, which is normally less than 0.01 millidarcy. In the meantime, the coal particles undergo secondary formation under geostress to a coal body, making the TDC exhibit a low strength and weakly cohesive feature. The main characteristics of low permeability and low strength resulting in the conventional reservoir stimulation methods, such as fracturing and drainage, are not suitable for the TDC reservoir. Although some new CBM fracturing methods are attracting more attention, such as liquid nitrogen fracturing and supercritical carbon dioxide fracturing, they have not been applied in large-scale engineering.

Reservoir permeability is the key issue in CBM extraction and is determined by the pore−fissure geometry and connectivity. The pore−fissure systems of coal reservoirs have ternary features that consist of cleats, microcracks, and pores. The change in the stress field state during the mining process, including the axial and radial loading−unloading, affects the pore−fissure structure and permeability. The in situ stress compresses the coal matrix and pore−fissures, and the coal permeability decreases exponentially with the increase of effective stress. Nevertheless, the failure deformation formed in TDC reservoirs when stress is released can help to expand fissures and improve reservoir permeability. In fact, the engineering practices of...
reservoir depressurization and permeability enhancement are widely applied for CBM extraction in TDC reservoirs, such as Huainan coalfield and Tiefa coalfield in China.19–21

Since the stress field has a significant effect on coal seam permeability, many theories and models have been proposed to quantitatively investigate the relationship between effective stress and permeability, such as the Palmer—Mansoori (PM) model,22 Shi—Durucan (SD) model,23 Cui—Bustin (CB) model,24 and Robertson—Christiansen (RC) model.25 Most of these studies were based on the assumption that the coal matrix skeleton undergoes elastoplastic deformation under in situ stress and fluid pressure. However, the coal matrix has a dual porosity system instead of an absolute elastic body, and mining stress has a more complicated effect on the coal body and permeability. Zhao et al. (2004) discussed the influence of coal matrix deformation on gas seepage in coal under triaxial stress and put forward the nonlinear permeability model;26 Xie et al. (2013) established four theoretical models for the permeability enhancement during the comming of coal and CBM;27 Liu et al. (2011) investigated the comprehensive influence of coal seam deformation and adsorption swelling on permeability during the CBM exploitation based on non-Darcy flow;28 Pan and Connell (2012) established an anisotropic coal matrix adsorption swelling model.

More importantly, the structural difference between TDC and PUC affects their permeability response to stress. For instance, the TDC matrix was secondary reconstituted by coal particles after tectonic stress,3 which has poor integrity compared with PUC and exhibits varying strain behavior and pore—fissure morphology under in situ stress. In addition, PUC can be brittlely deformed under stress conditions and form some new cracks when the stress is released.29 However, the microcracks in TDC can be badly dislocated and tightly compressed, and the coal matrix experiences obvious strain hardening behavior under extreme stress, leading to the residual strain of the coal body after the pressure is released.30,31

As the depth of coal mining increases and the demand for CBM extraction in the TDC reservoir, the effective stress changes and coal structure progressively become important factors affecting the permeability evolution. The change in the mechanisms of fissure deformation caused by axial and radial stress loading—unloading and their influence on the permeability evolution of PUC and TDC still require in-depth study. Consequently, the PUC and TDC cores were used for permeability experiments during the triaxial stress loading—unloading in this study in order to offset inadequate understanding of the permeability response to the stress loading–unloading process and provide some clarifications for the TDC reservoir depressurization and permeability enhancement for CBM extraction.

2. EXPERIMENTS AND METHODS

2.1. Sample Collection and Preparation. 2.1.1. Sample Information. The coal samples were collected from the same coal seam called no. 11-2 of Shihezi Formation in the Permian at Zhangji coal mine in Huainan coalfield, China (Figure 1), which is a typical area for TDC mining and exploration.32 The coal samples were collected from the same coal seam to minimize the effects of coal rank and composition. The collection, transportation, storage, and preparation of coal samples were strictly conducted according to the Chinese standard (GB/T 16773-2008).

Judging by the mechanical property, morphology, and shape,32 these coal samples were divided into PUC (blocky, complete, and hard), cataclastic coal (brittle deformed coal, broken and loose), and mylonitic coal (ductile deformed coal, loose, weak, and easily crushed into powder), defined as C1, C2, and C3, respectively, as shown in Table 1.

2.1.2. Coal Core Preparations. The sample specification for the experimental platform was a standard core (diameter = 50 mm, length = 100 mm) in this study. The PUC could be directly drilled using a coring machine in the vertical stratification direction carefully at the China University of Mining and Technology (CUMT), as shown in Figure 2.

However, there are many insuperable difficulties in cutting the highly tectonically damaged coal into a standard size, and the reconstituted coal cores were provided as a substitute for natural coal samples in previous investigations.33–35 In this study, the TDC mass was sieved using a milling machine and weighed based on the original particle size. Then the coal particles were weighed proportionally and mixed with water and packaged with breathable gauze, which was compacted using a specially designed steel mold (diameter = 50 mm). The applied axial model stress was set to 25 MPa with a molding time of 168 h. Finally, the reconstituted coal cores were extruded from the steel mold, and the two ends were carefully cut to a length of 100 mm.

The natural PUC cores and reconstituted TDC cores were wrapped carefully to prevent breakage and vacuum-dried at 30 °C for 24 h. Although the coal seam has a certain degree of water saturation under the in situ condition,36 the reconstituted TDC cores compressed by coal particles have a loose structure and its water saturation is much higher than that of the intact TDC core and the origin TDC seam after the equilibrium moisture experiment. Besides, part of the water will enter the coal particles during the TDC core preparation, which may affect the mechanical properties of coal samples. Therefore, all coal cores were dried to minimize the moisture errors in this study. These cores possess a nearly coherent appearance size and scale, which can be carried out in the control experiment.

2.2. Experimental Setup. The schematic diagram of the strain and permeability test apparatus for coal cores under triaxial stress conditions is shown in Figure 3, which is similar to the mature testing methods adopted in previous research.37,38 The coal cores were wrapped in heat-shrink tubing to ensure gas tightness and prevent hydraulic oil intrusion. Two strain extensometers were attached to the core sample device, parallel and perpendicular, respectively, as recommended by the International Society for Rock Mechanics (ISRM). The resistance signals were converted to microstrain and stored in

Figure 1. Stratigraphic distribution of sampling location, coal seam, and sample morphology.
the data acquisition device. The axial plug was used to fix the coal core and adjust axial pressure, and the confining pressure was provided by filling hydraulic oil in the triaxial cell.

The gas flow rates of upstream and downstream were measured by a mass flow controller and recorded by a computer. The permeability testing followed the gas industry standards of China (SY/T 6385-2016). Even if the airflow is dynamic at the early stage, the gas flow in the test reaches stability within 10 min. Once the flow variation is stable, the experimental condition is adjusted to the next target value. Assuming that the gas flow in the coal seam obeys the steady-state isothermal seepage condition, the permeability of the coal cores can be calculated by modified Darcy’s law: 50

\[
K = \frac{2Q \rho L}{A(P_{\text{in}} - P_{\text{out}})}
\]

(1)

where \(K\) is the gas permeability of coal at mean pressure \(P_{\text{m}} = (P_{\text{in}} + P_{\text{out}})/2\), mD; \(P_0\) is the standard atmospheric pressure, MPa; \(\mu\) is the gas kinetic viscosity, Pa·s; \(L\) is the length of the cubic coal sample in the gas flow direction, cm; \(A\) is the cross-sectional area of the cubic coal sample in the vertical gas flow direction, cm²; and \(P_{\text{in}}\) and \(P_{\text{out}}\) are the inlet and outlet gas pressures, respectively, MPa.

2.3. Pore-Feature Structure Analysis. Nuclear magnetic resonance (NMR) provides a fast, convenient, and non-destructive tool for characterizing complex porous media, particularly the petroleum reservoir rocks, which has been widely used in the petrophysical characterization of sandstones, carbonates, and coal. 13 The NMR test method was used in this study because it can characterize full-scale pore structures of coal cores with no destruction and avoid the shortcomings of other methods, such as mercury intrusion and liquid nitrogen, which can only analyze the pore structure of coal particles. The principle of NMR has been introduced in detail in previous studies, 13, 41, 42 which can be summarized in brief as the transverse relaxation time (\(T_2\)) distribution reflecting the pore size distribution of coal cores, and the hydrogen protons in smaller pores relax faster than that in larger pores. The relaxation characteristics can be expressed as eq 2. 13, 40

\[
\frac{1}{T_2} = \frac{S}{V} \approx \frac{S}{V} = \frac{\rho S}{r}
\]

(2)

where \(T_2\) represents transverse relaxation time, ms; \(S\) represents the pore surface area, nm²; \(V\) is the pore volume, nm³; \(\rho\) denotes

### Table 1. Basic Information of Coal Samples

| Coal Type                  | Sample ID | Depth (m) | \(R_{\text{o,max}}\) (%) | \(\rho_T\) (g/cm³) | \(M_{\text{ad}}\) (wt, %) | \(A_{\text{ad}}\) (wt, %) | \(V_{\text{daf}}\) (wt, %) | \(FC_{\text{ad}}\) (wt, %) |
|----------------------------|-----------|-----------|--------------------------|-------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| primary undeformed coal    | C1        | −680      | 0.8                      | 1.46              | 1.63                     | 21.29                    | 37.26                    | 49.38                    |
| cataclastic coal           | C2        | −681      | 0.81                     | 1.47              | 1.72                     | 24.38                    | 38.7                     | 46.36                    |
| mylonitic coal             | C3        | −681      | 0.83                     | 1.43              | 1.41                     | 26.1                     | 38.3                     | 34.19                    |

Note: \(R_{\text{o,max}}\) is the mean maximum reflectance values of vitrinite, %; \(\rho_T\) is the true density, g/cm³; \(M_{\text{ad}}\) is the moisture content, wt, %; \(A_{\text{ad}}\) is the ash yield content, wt, %; \(V_{\text{daf}}\) is the volatile matter content, wt, %; \(FC_{\text{ad}}\) is the fixed carbon content wt, %; wt % is weight percent; the subscript “ad” means air-drying base and the “daf” means dry ash-free base.

Figure 2. Sample preparation methods and coal cores.

Figure 3. Schematic diagram of the experimental apparatus.
the transverse surface relaxation coefficient, nm/ms; \( r \) is the pore radius, nm; and \( F \) represents the geometry factor.

A Micro MR12-150H-I NMR equipment manufactured by NIUMAG was used in this study, with a resonant frequency of 12.952 MHz and a magnet temperature of 32.00 ± 0.01 °C. The diameter of the probe coil was 30 mm, and the size of the test core was 25 mm in diameter and 50 mm in length. Generally, NMR experiments have two sets: a saturated water condition and an irreducible water condition, which can be used to study the total pore-fractures’ characteristics and the pore-fractures’ irreducible space characteristics, respectively. The dried coal cores measured the \( T_2 \) relaxation time to get a background value. The coal cores were wrapped with permeable tape to prevent breakage, then saturated with ionized water for 72 h at a pressure of 2 MPa. The total porosity can be obtained by comparing the total magnetization of the sample in 100% water-saturated conditions by using the magnetization of a known volume of fluid as the standard.

Then, the water-saturated cores were centrifuged and subjected to NMR tests. The centrifugal pressure was 200 psi, and it corresponded to a pore-throat radius of 100 nm approximately according to the Washburn equation and the surface tension and contact angle between coal and water. Thus, the \( T_2 \) distribution characteristics under the water-saturated \( (S_w) \) and the irreducible water-condition \( (S_r) \) residual water can be used to investigate coal pore information. In addition, the \( T_2 \) distribution characteristics can also be used to get the scanned image of the coal core section, which helps visually describe the pore—fissure structures inside of the coal cores.

3. EXPERIMENTAL RESULTS AND ANALYSES

3.1. Pore—Fissure Distributions. The NMR method was used to analyze the distribution of pores—fissures in the coal core, which is the basis for exploring the difference in coal permeability. The higher the \( T_2 \) signal intensity, the larger the corresponding pore size. The \( T_2 \) distribution characteristics, including the number, area, and peak position, can be used to analyze coal pore-fracture types. It can be seen in Figure 4 that the PUC and cataclastic coal samples have two \( T_2 \) spectral peaks under water-saturated conditions, located in the transitional pores and macropore stages, while the mylonitic coal sample has only one \( T_2 \) peak. The distributions of \( T_2 \) spectra can reflect multiple coal pore types and volumes. The transitional pores and macropores of PUC are developed to form \( T_2 \) peaks, but the mesopore volume is relatively small. TDC samples have a loose structure, and the larger volume of each pore is conducive to the water intrusion to form the \( T_2 \) peak, the developed transitional pores in mylonitic coal even lead to the interconnection of \( T_2 \) peaks of transitional pores and macropores.

Comparing the NMR measurement under irreducible water to saturated water, the \( T_2 \) signals of the pores above 1000 nm are very weak or even disappear after centrifugation, indicating that the macropores and microfissures have good connectivity to form a fluid migration path. The better pore connectivity in cataclastic coal leads to a significant decrease in the \( T_2 \) peaks corresponding to pores smaller than 100 nm after centrifuging. The transitional pore volume of PUC and mylonitic coal samples is small, and the poor connectivity of micropores and mesopores causes more water to be retained inside the micro- and transitional pores to form \( T_2 \) peaks.

The scanned image of pore—fissure distribution in coal cores is shown in Figure 5 based on \( T_2 \) distribution characteristics, and
the stronger-signal-intensity regions indicate more pore space. It was difficult for moisture to enter the PUC core with a weak $T_2$ signal intensity; while the reconstituted TDC cores had a stronger $T_2$ signal. For example, the loose structure and intergranular pores of mylonitic coal cores formed communication internals, even when they had poor matrix pore connectivity. The coal permeability was controlled by these seepage channels and affected by the stress conditions of the coal reservoir. Therefore, the pore–fissure distribution of coal cores based on the NMR is more helpful than that of coal particles to analyze the effect of effective stress on permeability.

3.2. Mechanical Properties. The coal core samples were subjected to axial compression tests under different confining pressures, and their deviatoric stress–strain curves are shown in

![Figure 6. Stress–strain curves of coal samples under different confining stresses: (a) is the PUC; (b) is the cataclastic coal; (c) is the mylonitic coal.](https://doi.org/10.1021/acsomega.2c04267)
The PUC samples had a complete coal matrix and showed obvious elastic deformation characteristics. They had a long elastic deformation stage during the axial stress application, but the yield stages were short, and then the strength rapidly decreased. The plastic yield stage of TDC samples was relatively long and the elastic deformation gradually transitioned to the plastic deformation with the increase of axial stress. In this study, the maximum axial compression stress of samples before failure was set as the compressive strength under the confining pressure condition. It can be seen that the compressive strength of PUC (C1), cataclastic coal (C2), and mylonitic coal (C3) samples gradually decreased, and their compressive strength increased with the increase of confining pressure.

The cohesion and internal friction angle are calculated based on the widely used Mohr–Coulomb (M–H) failure law. The principal stress can be expressed as

\[ \sigma_1 = \psi + \xi \sigma_3 \] (3)
Table 3. Fissure Compressibility Coefficient ($C_f$) of Coal Samples before and after Absorption

| sample ID          | initial permeability ($k_0$) before | fitting coefficient ($b$) before | correlation coefficient ($R^2$) before | initial permeability ($k_0$) after | fitting coefficient ($b$) after | correlation coefficient ($R^2$) after |
|--------------------|-------------------------------------|---------------------------------|--------------------------------------|----------------------------------|---------------------------------|------------------------------------|
| PUC                | 0.7350                              | 0.4107                          | 0.375                                | 0.399                            | 0.9589                          | 0.9880                             |
| cataclastic coal   | 4.1926                              | 3.5357                          | 0.200                                | 0.187                            | 0.9726                          | 0.9865                             |
| mylonitic coal     | 4.2295                              | 1.8372                          | 0.344                                | 0.278                            | 0.9886                          | 0.9875                             |

where $\sigma_1$ and $\sigma_3$ are the maximum and minimum principal stresses, respectively; $\psi$ and $\xi$ are the functions of the cohesion ($C$) and internal friction angle ($\phi$), respectively

$$
\psi = \frac{2C \cos \phi}{1 - \sin \phi} \quad (4)
$$

$$
\xi = \tan^2(45^\circ + \phi/2) \quad (5)
$$

Meanwhile, Young's modulus ($\mu$) and Poisson's ratio ($E$) can be calculated using eqs 6 and 7 based on the test results during the elastic deformation stage.

$$
E = \Delta \sigma / \Delta \varepsilon_i \quad (6)
$$

$$
\mu = -\Delta \varepsilon_i / \Delta \varepsilon_i \quad (7)
$$

where $\Delta \sigma$ is the axial stress variation, MPa; $\Delta \varepsilon_i$ is the axial strain variation, mm/mm; $\Delta \varepsilon_i$ is the radial strain variation, mm/mm.

The mechanical parameters of the coal samples were calculated and are shown in Table 2. The larger cohesion ($C$) and internal friction angle ($\phi$) of PUC samples indicated that the cohesive force of the complete coal matrix in the PUC sample is significantly higher than that of TDC samples reconstituted by coal particles. Under uniaxial conditions, the compressive strength of TDC is much lower than that of PUC, while their smaller Young's modulus ($\mu$) and larger Poisson's ratio ($E$) mean better plasticity. Poisson's ratio of PUC samples increased as the confining pressure increased. However, the higher confining pressure limited the radial strain of TDC samples and extended their plastic yielding stage, resulting in a larger deformation before failure.

In addition, the original mechanical properties of coal particles lead to differences in the mechanical parameters of reconstituted TDC cores. Cataclastic coal particles still retained the coal matrix structure, and the formed reconstituted cores had higher mechanical properties compared to mylonitic coal. Meanwhile, the change range of Poisson's ratio in cataclastic coal was smaller than that of mylonitic coal when the confining pressure increased, indicating that cataclastic coal can maintain structural integrity, while mylonitic coal is easier to be compressed. The coal connectivity under in situ conditions is controlled by the pore–fissure structure. The transformation of the coal matrix and pore–fissure structure by stress changes will inevitably affect the gas migration characteristics and permeability of PUC and TDC reservoirs.

3.3. Permeability Stress Sensitiveness. 3.3.1. Effective Stress. In order to explore the influences of effective stress and adsorption swelling on the coal permeability, the permeability testing platform under triaxial stress conditions (Figure 3) was used to monitor the permeability and radial strain of coal cores before and after adsorption under different confining pressure conditions without axial stress; the test results are shown in Figure 7. Due to the relatively loose structure, the reconstituted TDC cores had a greater strain than the PUC cores under confining pressure. With the increase of confining pressure, the radial strains of PUC and cataclastic coal approximated a straight line, while the mylonite coal samples showed a tendency to yield deformation. In the meantime, the swelling stress of the coal matrix after adsorption weakened the compression by confining pressure and resulted in a smaller strain than before. Moreover, the permeability difference before and after adsorption gradually decreased with the increase of confining pressure, indicating that the main factor affecting permeability changed from matrix adsorption swelling to the fissure compressions of high confining pressure.

A large number of intergranular pores led to a significantly higher permeability of the reconstituted TDC cores than that of the PUC cores. Under low-pressure conditions, the compression of internal fissures resulted in a rapid decrease in permeability. With the increase of confining pressure, the gradual compaction of fissures weakened the influence of effective stress on permeability. Generally, the permeability shows an approximate negative exponential function with the change of effective stress, which can be expressed as

$$
k = k_0 \times e^{b \sigma} \quad (8)
$$

where $k$ is the permeability of the coal sample under different effective stresses, m$^2$; $k_0$ is the initial permeability m$^2$; $b$ is the fitting coefficient; and $\sigma$ is the effective stress, which is the difference between the total stress and the internal pore pressure.

The least-squares method was used to fit the relationship between effective stress and permeability based on experimental results. As shown in Table 3, the correlation coefficient ($R^2$) of eq 8 was very high, which means that the fitted equation is accurate and suitable for analyzing the experiment results. The widely used cubic model (or bundled matchstick model) considers that the coal permeability is a function of the pore–fissure system, which can be expressed as

$$
\frac{k}{k_0} = \left(\frac{\phi_f}{\phi_{f0}}\right)^3 \quad (9)
$$

where $\phi_f$ is the fissure degree under different confining pressure conditions, %; $\phi_{f0}$ is the fissure degree under the initial state, %.

The fissure compressibility coefficient ($C_f$) was used to describe the volume compressibility of coal cleats by effective stress and in turn led to permeability changes. The relationship between permeability and effective stress can be expressed as

$$
k = k_0 e^{-3C_f \times (\Delta \sigma_p - \beta \Delta p)} \quad (10)
$$

where $\Delta \sigma_p$ is the confining pressure variation, MPa; $\beta \Delta p$ is the fluid pressure variation, MPa, since the pore pressure was kept constant in this study, $\beta \Delta p = 0$; $\beta$ is the pressure coefficient.

Based on eq 10, $C_f$ can be obtained as

$$
C_f = \left(\frac{\Delta \varepsilon_p}{\Delta \sigma}\right) \quad (11)
$$

where $\Delta \varepsilon_p$ is the axial strain variation, mm/mm; $\Delta \sigma$ is the axial stress variation, MPa; $\Delta \sigma_p$ is the pressure coefficient.
The large fissure compressibility ($C_f$) value means that the coal permeability is more sensitive to stress changes. According to the test results (Figure 7), the $C_f$ values of PUC and TDC samples were calculated and are shown in Table 3.

The fissure compressibility coefficients ($C_f$) of PUC, cataclastic coal, and mylonitic coal samples gradually decreased, indicating that the effective stress changes had a stronger transformation effect on the coal permeability with a relatively complete structure. The $C_f$ of PUC increased slightly after adsorption, while it decreased in TDC samples after adsorption, which may be related to the adsorption swelling phenomenon of the coal matrix.

### 3.3.2. Permeability Response under Loading−Unloading Conditions

In order to explore the permeability response to the stress loading−unloading, the PUC and TDC cores were used to conduct permeability and strain test experiments under triaxial stress conditions.

#### 3.3.2.1. Axial Loading−Unloading When the Confining Pressure Is Fixed

The permeability test of coal samples during axial loading−unloading was conducted under different confining pressures. First, the confining pressure was loaded to set values, which are 4, 6, 8, 10, and 12 MPa. Then, the axial pressure began to load at a speed of 50 N/s. The set axial pressure change range was from 4 to 13 MPa, and the single increment was 1 MPa. When the permeability test of 13 MPa axial pressure was completed, axial stress was unloaded with a speed of 50 N/s to 0 Mpa and the single drop was 1 Mpa. Each time when the axial pressure became stable, unadsorbed helium was injected to test the permeability while keeping the axial and confining pressure unchanged.

As shown in Figure 7, there is a great difference in the absolute permeability value between PUC and TDC cores. That is, the absolute permeability value of PUC is between 0 and 0.4 mD while that of TDC is generally between 0 and 3 mD. In order to eliminate the influence of the absolute value of permeability, the permeability relative change rate ($P_a$) is introduced to quantitatively characterize the influence of stress change on permeability

$$P_a = \frac{P_{cp}}{P_0} \times 100$$

where $P_0$ is the initial permeability when the axial pressure is 0 Mpa and the confining pressure is 4 Mpa; $P_{cp}$ is the permeability under different axial and confining pressure conditions.

The permeability relative change rate ($P_a$) and the axial loading−unloading process of PUC and TDC samples during axial loading−unloading are shown in Figure 8, in which the solid line is the loading process and the dashed line is the unloading process.

The permeability variation with axial loading−unloading is relatively complex and affected by confining pressure. Generally speaking, the permeability of PUC and TDC samples first decreased and then increased with the increase of axial pressure under low confining pressure, while the permeability simply decreased as the axial pressure increased under high confining pressure. At the same time, the coal permeability increased during the axial unloading process. It is worth noting that the TDC permeability increased significantly during the initial axial unloading under the low-confining-pressure condition (4 Mpa), even exceeding the corresponding axial pressure of the pressurization process, which is related to the matrix volume expansion and the pore−fissure rapid recovery. As the axial

![Figure 8. Permeability changes with axial loading−unloading of different confining pressures: (a) is the PUC; (b) is the cataclastic coal; (c) is the mylonitic coal; (d) is the loading−unloading process of axial stress.](https://doi.org/10.1021/acsomega.2c04267)
stress decreased, the coal permeability gradually increased but it could not recover to the original value, indicating that the stress loading process may cause irreversible damage to coal connectivity. In addition, under the high confining pressure...
conditions (10 and 12 Mpa), the permeability of PUC and cataclastic coal samples was closer to their original value than that of mylonitic coal when the axial load was completely released.

3.3.2.2. Confining Pressure Loading—Unloading When the Axial Stress Is Fixed. Similarly, the permeability test was carried out under different axial pressures during confining pressure loading—unloading. The experimental procedure was similar to the previous test. The axial pressures were set to 0, 4, 6, 8, 10, and 12 MPa, and the confining pressure varied from 4 to 11 MPa. The permeability relative change rate \( P_a \) of these samples during the confining pressure loading—unloading process was calculated based on the test results and is shown in Figure 9, where the solid line is the loading process and the dashed line is the unloading process.

The increase in confining pressure compressed the coal matrix and internal fissures of the coal cores, and their permeability rapidly and then slowly decreased. During confining pressure unloading, the compressed fissures in the coal matrix were gradually recovered and expanded, resulting in an increase in permeability. However, the permeability after the confining pressure was completely released could not reach the initial value, especially for mylonitic coal, and the difference between the two was larger under a higher axial pressure. This indicated that the residual strain of the coal matrix when the confining pressure was released made it difficult for the pore—fissure system to recover completely, and the new microcracks in the coal matrix during the compression process can hardly form effective seepage channels. At the same time, the fissure compressibility \( C_f \) of mylonitic coal during the confining pressure unloading process without axial compression was calculated to be 0.0337, smaller than the initial value (Table 3), which means that the fissure sensitivity to stress was weakened after the coal matrix was compacted.

3.3.2.3. Simultaneous Loading—Unloading of Axial and Confining Pressure. The permeability test experiments of PUC and TDC cores were carried out under the axial and confining pressure simultaneously that changed. The axial and confining pressure gradually increased from 4 to 11 MPa and then decreased to 4 MPa. The single pressure change was 1 MPa. The permeability and strain of coal samples under different stress conditions were tested and are shown in Figure 10, where the solid line is the loading process and the dashed line is the unloading.

As the axial and confining pressure increased simultaneously, the permeability of coal samples decreased rapidly and then slowly, which is similar to the test results of confining pressure changes. During the stress unloading process, the coal permeability gradually recovered. The permeability of PUC and cataclastic coal after stress release were similar to the initial value, but the permeability of mylonitic coal increased slowly and was quite different from the initial value. In addition, there were some differences in the strain changes of these coal samples. The axial and radial strains of the PUC samples showed a linear trend during stress loading—unloading, while the relationship between the strain change and stress of TDC cores in the loading stage was not obvious, and the strain decreased slightly during the unloading stage.

4. DISCUSSION

4.1. Fissure Evolution under Stress. Coal permeability is a function of the pore—fissure system. Although there are some differences in the pore—fissure structure of PUC and reconstituted TDC cores, the internal effective seepage fissures are the key factor determining the permeability when the coal cores are treated as a whole system. Therefore, the transformation effect of stress on pores—fissures directly controls the coal permeability. Previous research and the permeability test results (Figure 7) have demonstrated that the permeability shows a changing trend of approximate negative exponential function with the increase of effective stress (perpendicular to the fluid direction).

In order to explore the transformative effect of axial pressure (stress parallel to the direction of airflow) on coal permeability, the fissure volume strain \( \epsilon_v^f \) is used to uniformly describe the fissure structure changes of the whole coal core, which can be expressed as the difference between the total volumetric strain \( \epsilon_v \) and the coal matrix skeleton strain \( \epsilon_v^s \): \( \epsilon_v = \epsilon_v^f \).

\[
\epsilon_v^f = \epsilon_v - \epsilon_v^s \tag{13}
\]

For the coal cores, the total volumetric strain \( \epsilon_v \) can be approximately expressed as

\[
\epsilon_v = \epsilon_1 + 2\epsilon_3 \tag{14}
\]

where \( \epsilon_1 \) and \( \epsilon_3 \) are the axial strain and radial strain, respectively.

The coal matrix skeleton can simply be regarded as an elastic—plastic structure so that the generalized Hooke’s law is used to calculate the volumetric strain of the coal matrix skeleton \( \epsilon_v^s \)

\[
\epsilon_v^s = \frac{1 - 2\mu}{E_3} (\sigma_1 + 2\sigma_3) \tag{15}
\]
where $\sigma_1$ is the axial stress, MPa; $\sigma_3$ is the confining pressure, MPa; $E$ is Young’s modulus, and $\mu$ is Poisson’s ratio

$$E = \frac{\sigma_1 - 2\mu\sigma_3}{\sigma_1}$$ (16)

$$\mu = \frac{\sigma_1(e_3/e_1) - \sigma_3}{2(e_1/e_1)\sigma_1 - \sigma_3 - \sigma_1}$$ (17)

In summary, the fissure volume strain ($\epsilon_f^v$) can be calculated

$$\epsilon_f^v = \epsilon_v^s - \epsilon_f^s = \epsilon_1 + 2\epsilon_3 - \frac{1 - 2\mu}{E_\varepsilon}(\sigma_1 + 2\sigma_3)$$ (18)

Taking the deviatoric stress–strain variation of the PUC samples under a confining pressure of 4 MPa as an example, we calculate its fissure volume strain ($\epsilon_f^v$) to analyze the fissure evolution process during the axial loading, as shown in Figure 11.

Generally speaking, the intact coal matrix and internal fissures will be compressed in the initial axial loading stage, thus reducing the coal permeability. As the axial stress increases, the coal body enters elastic deformation and gradually transforms into plastic yield deformation. During this process, the coal matrix undergoes radial deformation and generates microfissures. The development and expansion of microfissures can increase coal permeability. Based on the previous research of the coal body failure process, comprehensively analyzing the fissure volume strain ($\epsilon_f^v$) (Figure 11) and permeability (Figure 8) response of the PUC samples during the axial stress changes, the structure and permeability change process under the axial stress loading–unloading conditions is divided into the following five stages:

(I) Coal matrix compression stage (OA). At this stage, the coal volume strain and fissure strain values are both increased (where the value increase means that the coal matrix and fissures are compressed, while the decrease means the fissure expansion and coal body expansion). The coal matrix and primary fissures are gradually compacted, and the coal permeability decreases with the increase in pressure. The coal body undergoes elastic deformation, and the coal matrix fissure can recover when the stress is unloaded.

(II) Microcrack generation stage (AB). At this stage, the coal volumetric strain increases, while the fissure volume strain decreases. The inside structure of the coal matrix begins to be destroyed and generates microcracks. The coal sample is still in the compressed elastic deformation stage, and the microcracks generated are too weak to form a connected fissure network and affect the elastic strain. The deformation of the coal matrix can be recovered after the stress is unloaded.

(III) Microcrack development stage (BC). At this stage, the coal volume strain and the fissure strain both decrease, but the coal core is compressed as a whole. The microcracks develop rapidly along the direction of the maximum principal stress and cause irreversible structural damage to the coal matrix, which increases the coal permeability but is hard to recover to its original value during stress unloading.

(IV) Coal matrix yield stage (CD). At this stage, the coal volumetric strain and fracture strain continue to decrease and the expansion deformation of the coal body exceeds the compression deformation. At the same time, microcracks develop rapidly to form connected networks, and the coal matrix is damaged and shows damage expansion. However, the coal cores cannot retain an intact structure after stress unloading.

(V) Coal core failure stage (DE). At this stage, the coal volumetric strain and fracture strain both decrease rapidly, the coal body gradually breaks and radially expands to form a large number of failure surfaces, and the fissures develop significantly.

4.2. Permeability Response to Stress Loading and Unloading. 4.2.1. Coal Core Structure and Permeability Sensitivity. In order to explore the permeability change difference of PUC and TDC samples during stress loading–unloading in this study, based on the pore structure characteristics (Figures 4 and 5) and sample preparation (Figure 3) of coal cores, a structural schematic diagram of PUC and TDC core samples under axial stress conditions is established and shown in Figure 12.

![Figure 12.](https://doi.org/10.1021/acsomega.2c04267)

The coal matrix of the PUC sample is complete and hard. The axial loading compresses the coal matrix skeleton and internal fractures simultaneously. The coal matrix strain changes approximately linearly with the increase of axial pressure (Figure 6), and the compression of fractures reduces the coal permeability (Figure 8). As the axial pressure increases, the coal matrix may gradually yield and even result in failure (Figure 11), and the permeability increases instead (Figure 8). The TDC core samples are formed by the reorganization of coal particles (Figure 12). The coal particles support each other in the coal cores and the interconnected intergranular pores constitute the fracture system, which is the main factor determining permeability. At the beginning of stress loading, the coal particles are squeezed and displaced, resulting in the overall ductile deformation of coal cores (Figure 6). In the meantime, the movement of coal particles can block the intergranular pores and lead to a rapid decrease in permeability (Figure 8). As the axial stress increases, the coal particles gradually transition from point contact to surface contact and the pores/fissures inside the coal particles begin to be compressed, resulting in a slow decrease in coal permeability.

During stress unloading, the elastic recovery and fracture expansion of the coal matrix in PUC and TDC cores lead to a gradual increase in permeability. The TDC permeability at the initial unloading stage even exceeds that at the corresponding stress loading stage (Figure 8), which may be related to the microcracks formed by high axial stress in TDC particles. During stress unloading, the permeability of PUC cores gradually increases and is close to their original values, while the permeability of TDC cores is much smaller than their original values when the stress is released due to the blockage of intergranular pores by coal particle compaction and displacement.
4.2.2. Confining Pressure. The confining pressure conditions affect the failure mode of the coal body. Under low-confining-pressure conditions, the intact rock is mainly sheared failure with obvious fissure surfaces. With the increase of the confining pressure, the coal sample shows a ductile deformation trend, which is manifested as expansion damage and accompanied by a large number of conjugate shear joints (Figure 13). In this study, the PUC samples are mainly shear failure under the low-confining-pressure condition, and the toughness of the coal sample also increases with the increase of confining pressure. The TDC samples show a ductile deformation trend under low confining pressure, and the increase of confining pressure can limit the radial strain (Figure 6).

The confining pressure affects the coal permeability response to axial stress loading—unloading. The increase of confining pressure helps to improve the compressive strength of the coal body (Figure 6). Under low-confining-pressure conditions, the initial axial loading has an obvious effect on the coal matrix compression and microcrack formations. As shown in Figure 8, the permeability of PUC samples first decreased and then increased with the increase of axial pressure under the confining pressure of 4 MPa. The increase in confining pressure can strengthen the coal matrix and extend the range of elastic deformation stress. At the same time, the high confining pressure can limit the radial strain of the coal core, which further compacts the coal matrix and reduces permeability. In addition, it can be seen in Figures 8 and 9 that the change effect of confining pressure on permeability is greater than that of axial pressure. Under high confining pressures, the permeability change caused by axial pressure is relatively smaller, while the confining pressure change leads to a greater change in permeability under the high-axial-pressure condition.

The confining pressure conditions also lead to various permeability responses to axial unloading of PUC and TDC samples. As shown in Figure 8, under the condition of low confining pressure, when the axial pressure of primary structural coal is just reduced, the coal matrix begins to recover elastically and squeezes the fracture space inside the coal. At this time, the permeability of the sample decreases. Under low-confining-pressure conditions, the elastic recovery of the PUC matrix in the initial axial unloading stage squeezes the internal fracture space and reduces coal permeability. With the axial pressure reduction, the gradual recovery of internal fractures continually increases the permeability. The PUC permeability increases rapidly at the initial unloading stage due to the expansion of microcracks generated during the loading process. In the case of high confining pressure, the permeability of the coal body gradually increases with the decrease of axial pressure.

4.2.3. Adsorption Swelling. The adsorption swelling of the coal matrix affects the change in permeability. The adsorption swelling stress can be transformed into compression of the coal matrix and pores—fractures under the limitation of external pressure. As shown in Figure 7, the permeability of PUC and TDC samples generally decreases after adsorption. The permeability difference before and after adsorption gradually decreased with the increase of confining pressure, indicating that the higher confining pressure reduced the influence of adsorption expansion on permeability. Besides, the fissure compressibility coefficient ($C_f$) of PUC samples increases after adsorption, indicating that the adsorption swelling of the coal matrix will squeeze the pores—fractures inside the coal core, resulting in a more sensitive response of permeability to stress changes. However, the $C_f$ of TDC samples is slightly reduced after adsorption because the main factors determining the permeability of TDC cores are the intergranular pores instead of the endogenous fractures of the coal matrix. These intergranular pores provide free space for coal particle adsorption swelling to resist the compression of intergranular pores, leading to a smaller change in permeability with the increase of confining pressure, which also makes coal cores denser and reduces the permeability. At the same time, the adsorption swelling strain can also promote fissure expansion and increase coal permeability when stress is released.

4.3. Experimental Errors. Previous studies $^{31,39,49}$ have shown that when the in situ stress is close to or even exceeds the compressive strength of the coal body, or when the coal is deformed and damaged by mining stress, a large number of cracks will be generated in the coal matrix and lead to a rapid increase in permeability. However, even if the stress conditions of some PUC and TDC samples in this study have reached the ductile strain stage, the permeability after stress release was lower than the original value (Figures 8 and 9). On the one hand, the generated fissure during the loading process is not completely connected. On the other hand, high stress leads to plastic deformation and failure of the contact point between the coal matrix and fracture surface, and the generated pulverized coal particles block fissure channels and reduce the permeability. $^{49,50}$ Although some attempts were made to pressurize the sample to the crushing stress during the experiment, the huge deformation of the coal core caused the wrapped heat-shrinkable tube to rupture, resulting in the intrusion of hydraulic oil into the coal core and the inability to test the permeability accurately.

In addition, it is worth noting that the TDC samples in this experiment have undergone stress loading and release processes during sample collection and coal core preparation, respectively. Therefore, it is foreseeable that the volume expansion and fracture diffusion capacity of TDC samples are reduced during the simulation experiments of stress loading—unloading, which leads to some permeability test errors between the simulation experiments and theoretical analysis and hardly be avoided.

5. CONCLUSIONS

In this study, the pore—fissure structure analysis, mechanical property test, and permeability experiments under different stress loading—unloading conditions were carried out on the PUC and TDC samples to draw the following conclusions:

(1) Coal permeability shows an approximate negative exponential function with the change of effective stress.
The permeability change with the axial loading process can be divided into five stages: coal matrix compression stage, microcrack generation stage, microcrack development stage, coal matrix yield stage, and coal mass failure stage. Among them, the permeability is more sensitive to changes in confining pressure (perpendicular to airflow) than axial pressure (parallel to airflow).

(2) The structural difference between PUC and TDC samples affects the permeability response behavior to stress loading—unloading. The loaded stress can simultaneously compress the coal matrix and fractures of the PUC samples. The coal particles in the TDC cores undergo deformation and displacement first to block the pores during stress loading, and then the coal particles make contact with each other from point to the surface and compress the internal pore—fissure system of the coal matrix. At the initial stress unloading stage, the fissure recovery and expansion lead to a rapid increase in permeability, but the permeability cannot reach the original value when the axial stress is completely released.

(3) Except for the coal body structure, the coal permeability response to stress loading—unloading is affected by the confining pressure conditions and the coal matrix adsorption swelling.

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Notes
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