Experimental Study on the Variation Mechanism of Permeability and Seepage Characteristics of High-Rank Coal with Different Bedding

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ABSTRACT: In order to understand the variation mechanism of permeability and seepage characteristics of high-rank coal with different bedding, we prepared cylindrical raw coal samples according to the bedding angles of 0, 30, 45, 60, and 90° and conducted permeability tests under two stress paths (stress path 1, unloading confining pressure under constant axial pressure; stress path 2, simultaneous loading axial pressure and unloading confining pressure). The results show that the relationship between the permeability and effective stress of high-rank coal with different bedding in the two stress paths conforms to an exponential function, and the permeability increases gradually with an increase in differential stress. Under the two stress paths, the initial permeability of different bedding under the loading axial pressure and confining pressure shows a pattern of a maximum for parallel bedding coal samples, followed by oblique bedding coal samples, and a minimum for vertical bedding coal samples. Under path 1, the increase in the permeability of the oblique bedding is 21.4 times that of the vertical bedding and 14.94 times that of the parallel bedding, and under path 2, the increase in the permeability of the oblique bedding is 26.45 times that of the vertical bedding and 142.11 times that of the parallel bedding; the coal samples of the oblique bedding suffer the greatest damage. The increase in the permeability of parallel bedding coal samples, oblique bedding coal samples, and vertical bedding coal samples under path 2 is 1.47 times, 13.96 times, and 11.3 times the increase in the permeability of the corresponding coal samples under path 1, respectively, and the damage produced by coal samples under path 2 is greater than that under path 1.

1. INTRODUCTION

The most important factor affecting the permeability of coal is the stress environment to which the coal is subjected, such as the contraction strain and the effective stress.1,2 Conducting research on the influence of the stress environment on the permeability of different bedding coals is critical to coal seam gas production and provides an effective theoretical basis for the design of gas extraction in coal mines and other aspects of safety production.

Nowadays, the experiments on the seepage characteristics of coal are mainly carried out from different stress loading conditions, different types of coals, different seepage media, etc.3−5 Among them, most of the experiments that study the relationship between coal permeability and stress6−11 Such as triaxial seepage tests can be carried out to reveal the seepage characteristics of coal under triaxial stress.12−14 It can also study the evolution mechanism of coal permeability by controlling the cyclic load;15−18 different loading conditions can also be designed to study the seepage characteristics of coal under different stress environments.19,20 In addition to the stress experimental study, there are experimental studies that analyze the relationship between the water saturation of coal and the effective stress coefficient and stress sensitivity by controlling the different water saturation of coal and comparative seepage experimental studies that control different seepage media.21,22 These experimental studies can reveal the seepage characteristics of coal. However, it can be seen that these experiments are all based on the external environment of coal. Whether it is the stress condition or the seepage medium, they involve the influence of the external environment on coal while ignoring the influence of different bedding structures unique to coal on the seepage characteristics of coal.

In addition to the experimental research method, the permeability model can also be established through COMSOL, ANSYS, and other simulation software to study the evolution of...
mechanism of coal strain and permeability under different gas pressures. For example, the effective stress model can analyze the relationship between coal permeability and effective stress; the fluid solid coupling model can study the seepage mechanism of gas in coal seams; the damage constitutive model of coal under the conditions of thermal mechanical coupling and the permeability model of coal considering thermal damage and adsorption effect can reveal the relationship between temperature and permeability. Although model research can overcome the limitations of time and space, the results of simulation are often not as accurate as those of experimental research, so this paper mainly describes the experimental research.

To sum up, the current research on the gas seepage characteristics of coal is mainly aimed at the relationship between the permeability of coal and the confining pressure, the effective stress, and the temperature, while there is no relevant report on the permeability characteristics of high-rank coal with different bedding. Therefore, this paper investigates the influence of different bedding structures on the permeability of coal samples by using the triaxial adsorption–desorption–seepage experimental system of coals, which further reveals the seepage characteristics of coals and provides a theoretical basis for the safe production of coal mines.

2. SAMPLES AND METHODS

2.1. Coal Triaxial Adsorption–Desorption–Seepage Experimental System. The coal triaxial adsorption–desorption–seepage experimental system mainly consists of gas cylinder, gripper, axial pressure pump, confining pressure pump, data acquisition system, pressure sensor, temperature sensor, pipe and valve parts, etc. The coal triaxial adsorption–desorption–seepage experimental system can load the axial and confining pressures on the coal samples mounted in the gripper, and change the stress environment to which the coal samples are subjected by changing the axial and confining pressures. In addition, the system uses flexible heating wool for heating and temperature sensors to monitor whether the coal sample reaches the set temperature, better simulating the temperature environment in which the coal body is located in the mine.

The coal triaxial adsorption–desorption–seepage experimental system used in this experiment is shown in Figure 1.

The schematic diagram of the coal triaxial adsorption–desorption–seepage experimental system used in this experiment is shown in Figure 2.

From Figures 1 and 2, it can be seen that the coal triaxial adsorption–desorption–seepage experimental system mainly consists of a gas cylinder, a main control panel, a static strain tester, a data acquisition system, a confining pressure pump, an axial pressure pump, and a vacuum pump. The main control panel includes a gripper, a temperature control device, a flowmeter, a pressure gauge, pipe valve parts, etc.

2.2. Collection and Preparation of Coal Samples. First, fresh briquettes were collected from the Zhongmacun mine of the Jiaozuo Coal Industry Group, and then cylindrical raw coal samples of φ 25 mm × 50 mm were drilled according to bedding angles of 0, 30, 45, 60, and 90° with the coal, marked as ZM1, ZM2, ZM3, ZM4, and ZM5, respectively. The prepared coal samples were divided into three categories: a parallel bedding coal sample ZM1 (bedding angle 0°), a vertical bedding coal sample ZM5 (bedding angle 90°), and oblique bedding coal samples ZM2, ZM3, and ZM4 (bedding angles 30, 45, and 60°).
Finally, the prepared coal samples were sealed with cling film and set aside.

The process of making coal samples is shown in Figure 3.

### 2.3. Basic Parameters of Coal Samples

The basic parameters of the ZM1, ZM2, ZM3, ZM4, and ZM5 coal samples were tested and the results are shown in Table 1. The proximate analysis results of the coal samples are shown in Table 2.

### 2.4. Experimental Methods

The current methods for determining permeability are mainly steady-state and transient methods. In this paper, the steady-state method is used to test the permeability of coal samples. The experiment uses methane (99.99%) as the permeation medium, and the permeation rate is calculated by applying a pressure difference at both ends of the test sample, and the gas passes through the test sample. When the airflow is stable, the permeation rate is calculated by calculating the total amount of gas flowing through the test sample. The controlling equation for the steady-state determination of permeability is shown in eq 1.

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

Where \(Q\) is the gas flow rate, \(cm^3/s\); \(p_0\) is the standard atmospheric pressure, Pa; \(\mu\) is the gas dynamic viscosity, \(Pa\ s\); \(L\) is the length of the test sample, cm; \(p_1\) and \(p_2\) are the pressure at the inlet and outlet of the sample, Pa; and \(A\) is the cross-sectional area of the sample, \(cm^2\).

In this paper, the triaxial adsorption–desorption–seepage experimental system for coals is used for testing experiments on the permeability of high-rank coal with different beddings, and the following should be noted when conducting the experiments:

1. The confining pressure should always be kept greater than the gas pressure during the experiment to ensure that the gas does not flow out from the gap between the coal sample and the rubber sleeve of the gripper.
2. The gas tightness of the device should be checked and evacuated before the start of the experiment.
3. After the end of the experiment, the gas pressure should be removed first, and then the axial pressure and confining pressure, which ensures the safety of the experiment as well as the protection of the gripper rubber sleeve.

### 2.5. Experimental Scheme

In order to analyze the variation mechanism of permeability of high-rank coal with different bedding under different confining pressure and axial pressure, as well as the seepage mechanism between high-rank coal under different bedding, we designed two stress paths in this experiment: path 1 is unloading confining pressure under constant axial pressure, and path 2 is simultaneously loading axial pressure and unloading confining pressure. The effective stress on the coal sample in the experiment was calculated according to eq 2.

\[
\sigma_1 = \frac{1}{3}(\sigma_1 + 2\sigma_2) - p
\]

Where: \(\sigma_1\) is the effective stress, MPa; \(\sigma_1\) is the axial stress, MPa; \(\sigma_2\) is the confining stress, MPa; and \(p\) is the gas pressure, MPa.
The gas pressure was set at 1.47 MPa for this experiment, and the experimental temperature was controlled at 30 °C by a flexible heating jacket and a temperature sensor.

The two stress paths are shown schematically in Figures 4 and 5, respectively.

![Figure 4. Schematic diagram of the path 1 process.](image)

![Figure 5. Schematic diagram of the path 2 process.](image)

As shown in Figures 4 and 5, first, the confining pressure was loaded to 3 MPa, and then the axial pressure was also loaded to 3 MPa, and after the gas adsorption equilibrium, the loading and unloading permeability test experiment was carried out, and then each step would be carried out in accordance with the steps of adding 1 MPa to the confining pressure and then 1 MPa to the axial pressure on the basis of 3 MPa, until both the confining pressure and axial pressure were added to 12 MPa, and then the loading process was finished. Path 1 keeps the axial pressure unchanged after the loading is completed and unload the confining pressure to 3 MPa, while path 2 increases the axial pressure by 1 MPa and decreases the confining pressure by 1 MPa at each subsequent step after the loading is completed until the axial pressure increases to 21 MPa and the confining pressure decreases to 3 MPa.

The specific steps of the experiment are as follows:

1. Two sets of cylindrical raw coal samples with the bedding angle of 0, 30, 45, 60, and 90° were taken. The two groups of coal samples were put in 101 type electric blast dryer and the drying temperature was set to 80 °C. The coal samples were considered to be completely dried when the quality of coal samples no longer changed, and the dried coal samples were kept for experimental backup.

2. Connect the apparatus and equipment, fill the liquid (distilled water) used for pressurization in the confining pressure pump and axial pressure pump, and connect the apparatus gas line piping; check the gas tightness of the apparatus. Then, add the confining pressure to 3 MPa, and then add the axial pressure to 3 MPa. After the gas adsorption equilibrium, carry out the loading and unloading permeability test experiment, and then carry out each step in accordance with the steps of adding 1 MPa to the confining pressure and then 1 MPa to the axial pressure on the basis of 3 MPa, until both the confining pressure and axial pressure are added to 12 MPa, and then the loading process is completed. Then, reduce the confining pressure to 3 MPa while keeping the axial pressure unchanged after the loading is completed.

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device. Fill the gripper with a steel block equal in size to the coal sample, then install the plug of the gripper and ensure the stability of the screws at the connection; set the confining pressure to 3 MPa, start the confining pressure pump, then set the axial pressure to 3 MPa, start the axial pressure pump, wait until the axial pressure and confining pressure reach the set value of 3 MPa, open V\(_1\), V\(_2\), and V\(_3\) to close V\(_4\), open the valve of the gas cylinder to pass 1.47 MPa into the pipeline gas, close the V\(_1\) valve, make the gas in the pipeline stable at 1.47 MPa; then stop 30 min after recording the pressure value in the pipeline; if the change of gas pressure is less than 0.01%, it proves that the pipeline has good gas tightness.

(3) Turn on the heating button of the instrument, set the temperature to 30 °C, ensure that the flexible heating sleeve is closely attached to the external surface of the gripper, keep the gripper in the heating state for 12 h, and ensure that the temperature inside the gripper is constant at 30 °C.

(4) Load the measured coal sample into the gripper, set the confining pressure to 3 MPa, start the confining pressure pump, then set the axial pressure to 3 MPa, start the axial pressure pump, and after the axial pressure and confining pressure reach the set value of 3 MPa, open V\(_1\), V\(_2\), and V\(_3\) to close V\(_4\), open the vacuum valve, and use the vacuum pump to evacuate the pipeline for 30 min to remove the gas in the pipeline.

(5) Open the valve of gas cylinder and pass 1.47 MPa gas into the pipeline, close the valve of V\(_1\) to make the gas in the pipeline stable at 1.47 MPa; record the pressure of reference cylinder every 1 h during gas adsorption, if the pressure is less than 1.47 MPa, continue to pass gas into the pipeline for 12 h until the pressure of reference cylinder pressure no longer drops, indicating that the gas adsorption balance.

(6) Open the data acquisition system, open the permeability testing software, input the radius and height of the coal

(a) Loading axial and confining (b) Unloading confining and constant axial

Figure 6. Permeability variation of ZM1 under path 1: (a) loading axial and confining (b) unloading confining and constant axial.

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Figure 7. Permeability variation of ZM2 under path 1: (a) loading axial and confining, (b) unloading confining and constant axial.
sample and other parameters; open the gas cylinder and \( V_1 \) and \( V_4 \) valves at the same time to ensure that the gas pressure in the pipeline is maintained at 1.47 MPa during the permeability testing experiment. After the experiment is finished, close the valve of the gas cylinder, open the \( V_4 \) valve, and unload the axial pressure after all the gas in the pipeline is discharged into the air, and finally unload the confining pressure. Save the experimental data and remove the coal sample to prepare for the next experiment.

(7) ZM1, ZM2, ZM3, ZM4, and ZM5 of the first and second groups of coal samples were subjected to repeated experimental steps 2–6 under the above conditions of confining pressure relief under constant axial pressure and simultaneous addition of axial pressure to unload the confining pressure, and the changes in permeability of coal samples during the experiments were recorded.

3. RESULTS

In this paper, according to the experimental scheme, the gas seepage characteristics experiments of different bedding high-rank coal under two stress paths are carried out, the relationship between permeability and effective stress and differential stress are obtained, and the experimental results are fitted and analyzed.

3.1. Evolutionary of Permeability under Path 1. ZM1, ZM2, ZM3, ZM4, and ZM5 were subjected to permeability experiments according to the experimental scheme stress path 1, and the permeability changes during addition and removal are shown in Figures 6–10, respectively, panel a shows the loading axial and confining pressure and panel b shows the unloading confining pressure under constant axial pressure.

Analysis of Figures 6–10 shows that ZM1, ZM2, ZM3, ZM4, and ZM5 have similar patterns of permeability changes under stress path 1, all presenting a gradual decrease in permeability during the process of loading axial pressure and confining pressure, a gradual increase in permeability during the process of

![Figure 8. Permeability variation of ZM3 under path 1: (a) loading axial and confining, (b) unloading confining and constant axial.](image)

![Figure 9. Permeability variation of ZM4 under path 1: (a) loading axial and confining, (b) unloading confining and constant axial.](image)
unloading confining pressure under constant axial pressure, and a rapid decrease in permeability followed by a slow decrease during the process of loading axial pressure and confining pressure in stress path 1, and a slow increase in permeability followed by a rapid increase during the process of unloading confining pressure under constant axial pressure in stress path 1. The reason is that at the initial stage of loading, the pores of coal samples are rapidly closed under the action of external load, the gas flow channel is rapidly narrowed or even closed, and the permeability is rapidly reduced; when the load continues to increase, the coal matrix is already in a closely fitted state, and the closing effect of pore fissures is not obvious compared with the initial loading stage, so the rate of permeability reduction decreases. In the process of unloading the confining pressure under constant axial pressure, the holes without plastic deformation of coal samples at the beginning start to open slowly, so that the channels of gas flow gradually become wider and the permeability gradually increases, and after unloading the confining pressure under constant axial pressure to a certain value, the primary fissures start to extend through and thus form new fissures, so new channels of gas flow are formed, and the permeability increases rapidly at this time.

The relationship between permeability and effective stress during loading axial and confining pressure and unloading confining pressure under constant axial pressure for stress path 1 are shown in Figures 13 and 14, respectively. We also studied the effect of confining pressure and unloading confining pressure in stress path 1 on permeability. In order to further analyze the variation mechanism of permeability of high-rank coal with different beddings under the condition of constant axial pressure and unloading confining pressure in stress path 1. The results of the effect of confining pressure and differential stress on permeability under the condition of constant axial pressure and unloading confining pressure in stress path 1 are shown in Figures 13 and 14, respectively.

Analysis of Figures 13 and 14 shows that the high-rank coal with different beddings exhibit large differences in permeability under constant axial pressure and unloading confining pressure in stress path 1.
The permeability of the coal samples gradually increases with the decrease in the confining pressure; the decrease in the confining pressure during the process of constant axial pressure unloading of the stress path 1 is 72.72%, and the increase multipliers of the permeability of high-rank coal with different bedding are 0.48, 3.70, 9.31, 8.50, and 0.34, respectively. The
The average value of the increase in the permeability of the oblique bedding coal samples ZM2, ZM3, and ZM4 is the largest, the increase in the permeability of the parallel bedding coal samples ZM1 is the second, and the increase in the permeability of the vertical bedding coal samples ZM5 is the smallest.

Figure 12. Relationship between effective stress and permeability during confining pressure relief under constant axial pressure in path 1.
The permeability of the coal samples increased gradually with the increase of differential stress, and the differential stress increased by 10 MPa during the process of constant axial pressure and unloading confining pressure in stress path 1, and

Figure 13. Influence of confining pressure on the permeability of high-rank coal with different bedding in the confining pressure unloading process under constant axial pressure (path 1).
the increase multiples of permeability of high-rank coal with different bedding were 0.48, 3.70, 9.31, 8.50, and 0.34, respectively. The average values of increase of permeability of ZM2, ZM3, and ZM4 of oblique bedding coal samples were the largest in this process.

Figure 14. Relationship between differential stress and permeability during confining pressure relief under constant axial pressure (path 1).
3.2. Evolutionary of Permeability under Path 2. ZM1, ZM2, ZM3, ZM4 and ZM5 were subjected to permeability experiments according to the experimental scheme stress path 2, and the permeability changes during addition and removal are shown in Figures 15−19, respectively, where panel a is the loading axial pressure and confining pressure and panel b is the simultaneous loading axial pressure and unloading confining pressure.

Analyzing Figures 15−19, it can be seen that the permeability change mechanisms of ZM1, ZM2, ZM3, ZM4 and ZM5 under stress path 2 are similar to those under stress path 1. The permeability of high-rank coal with different beddings tested under stress path 2 all show the mechanism that the permeability decreases rapidly and then decreases slowly with the increase in effective stress in the loading process, and the permeability increases slowly and then increases rapidly with the decrease of effective stress in the unloading process. The reasons for such variation in permeability are similar to those described above for stress path 1 and will not be repeated here. The relationship between permeability and effective stress was fitted as a function of the stress path 2 loading axial and confining pressure and simultaneous loading axial pressure and unloading confining pressure processes. The fitting results of the relationship between permeability and effective stress for the process of loading axial and confining pressure in stress path 2 are shown in Figure 20.

As shown in Figure 20, the relationship between permeability and effective stress in the process of loading axial and confining pressure in stress path 2 is in accordance with the exponential function of $y = a \exp(bx)$ (where $a$ and $b$ are constants), and the fit degree $R^2$ is greater than 0.97, which is a good correlation of function fit. The permeability decreases sharply with the increase of effective stress in the process of loading axial and confining pressure in stress path 2. The reason is similar to that of the permeability change in the process of loading axial and confining pressure in stress path 1, and will not be repeated here.

The fitting results of the relationship between permeability and effective stress for the process of simultaneous loading axial and confining pressure in stress path 2 are shown in Figure 21.

![Graph](image1)

**Figure 15.** Permeability variation of ZM1 under path 2: (a) loading axial and confining (b) loading axial and unloading confining.

![Graph](image2)

**Figure 16.** Permeability variation of ZM2 under path 2: (a) loading axial and confining, (b) loading axial and unloading confining.
pressure and unloading confining pressure in stress path 2 are shown in Figure 21.

As shown in Figure 21, the relationship between permeability and effective stress during the simultaneous addition of axial pressure and removal of confining pressure under stress path 2 is in accordance with the exponential function $y = a \exp(bx)$ (where $a$ and $b$ are constants), and the fit $R^2$ is greater than 0.9, which is a good correlation of function fit. The permeability increases slowly as the effective stress decreases during the simultaneous loading axial pressure and unloading confining pressure under stress path 2. The reason is that the external stress on the coal sample gradually decreases during the process of simultaneous loading axial pressure and unloading confining pressure under the stress path 2, which makes the pore fissures slowly open, and the coal sample is plastically deformed under the external stress to produce new fissures, thus creating new channels for gas seepage; the gas flow rate is gradually accelerated, and the permeability of the coal sample becomes higher and higher. The increase in the axial pressure and the decrease in the confining pressure decreased the reduction of the effective stress but increased the differential stress, so the permeability of the coal sample increased when the axial pressure was added and the confining pressure was removed simultaneously under stress path 2. The relationship between the differential stress and the permeability under stress path 2 with simultaneous loading axial pressure and unloading confining pressure was further investigated, and the results are shown in Figure 22.

Analysis of Figure 22 shows that the high-rank coal with different bedding shows a large difference in permeability under the conditions of stress path 2 with simultaneous loading axial pressure and unloading confining pressure, and the permeability of coal samples gradually increases with the increase in differential stress. The differential stress increased by 20 MPa during the simultaneous loading axial pressure and unloading confining pressure in stress path 2, and the increase multipliers of high-rank coal with different bedding permeability were 0.71, 3.05, 166.2, 131.2, and 3.78, respectively. The mean values of the
increase in permeability of ZM2, ZM3, and ZM4 of the oblique bedding coal samples are the largest during this process.

4. DISCUSSION

In order to further analyze the variation mechanism of permeability of high-rank coal with different bedding under different stress paths and explore the influence of bedding structure on the permeability of coal samples, the experimental data of bedding structure and permeability of coal samples are summarized and analyzed and discussed in this paper.

4.1. Permeability Analysis of High-Rank Coal with Different Beddings under Stress Path 1. The results of the initial permeability of loaded axial and confining pressure coal samples \( (P_1) \), the end permeability of loaded axial and confining pressure coal samples (axial and confining pressure loaded to 12 MPa) \( (P_2) \), and the end permeability of unloading confining pressure under constant axial pressure coal samples \( (P_3) \) for high-rank coal with different beddings under stress path 1 are shown in Table 5, where \( \eta \) is the decrease in permeability of the loaded axial and confining pressure process and \( \gamma \) is the increase in permeability of the unloading confining pressure under a constant axial pressure process.

Analysis of Table 5 shows that under the experimental conditions of stress path 1, the initial permeability of the loaded axial and confining pressure of parallel bedding coal sample ZM1 is the largest, followed by the initial permeability of the loaded axial and confining pressure of oblique bedding coal samples ZM2, ZM3, and ZM4, and the initial permeability of loaded axial and confining pressure of vertical bedding coal sample ZM5 is the smallest. This is because under the initial conditions of 3 MPa axial pressure and 3 MPa confining pressure, the bedding direction of the parallel bedding coal sample ZM1 is consistent with the direction of gas flow to the coal sample holder, and gas passes through the coal sample along the fracture direction on the bedding surface, so the initial permeability of the loaded axial and confining pressure of the parallel bedding coal sample ZM1 is measured to be the largest. The direction of ZM5 gas flow in the vertical bedding coal sample is perpendicular to the direction of the laminated structure, which hinders the flow of gas in the coal sample to some extent, so the initial permeability of the vertical bedding coal sample is measured to be the smallest.

In the process of loading axial pressure and confining pressure in stress path 1, the decrease in the permeability of high-rank coal with different bedding is larger, and all of them reach more than 78%. The average value of the decrease in permeability during loading axial pressure and confining pressure of ZM2, ZM3, and ZM4 of oblique bedding coal samples is larger than that of permeability during loading axial pressure and confining pressure of ZM1 of parallel bedding coal samples and ZM5 of vertical bedding coal samples. This is because there are developed pores and fissures distributed on the laminae, and the number of holes on the laminae of oblique bedding is more than that of vertical bedding and parallel bedding coal samples according to the Pythagorean theorem and calculus, under the action of external load, the closing effect of pores is more obstructive to the flow of gas in the coal samples, so the average value of the decrease in permeability of oblique bedding coal samples is the largest.

The average increase in the permeability of ZM2, ZM3, and ZM4 of the oblique bedding coal samples is 21.4 times higher than the increase in permeability of ZM5 of the vertical bedding coal samples during the constant-axis pressure and unloading confining pressure process, and 14.94 times higher than the increase in permeability of ZM1 of the parallel bedding coal samples during the constant-axis pressure and unloading confining pressure process. The reason is that the permeability increases with the decrease of the effective stress during the unloading confining pressure process of constant axial pressure, and when the unloading reaches a specific value, the rate of the increase in permeability has a significant increase, and it is inferred that new fractures are generated in the coal sample at this time. The damage of the diagonal laminated coal samples is along the shear damage of the laminae, a large number of fractures are generated, and the fractures on the laminae are interconnected, so the average increase in the permeability of the diagonal laminated coal samples is the largest in the process of constant axial pressure and unloading confining pressure.

4.2. Permeability Analysis of High-Rank Coal with Different Beddings under Stress Path 2. The results of the initial permeability of loaded axial and confining pressure coal samples \( (P_1) \), the end permeability of loaded axial and confining pressure coal samples (axial and confining pressure loaded to 12 MPa) \( (P_2) \), and the permeability of coal samples at the end of
simultaneous axial pressure and unloading confining pressure ($P_3$) for high-rank coal with different beddings under stress path 2 are shown in Table 6, where $\eta$ is the decrease in the permeability of the loaded axial and confining pressure process and $\gamma$ is the increase in the permeability of the constant axial pressure and unloading confining pressure process.

**Figure 20.** Relationship between effective stress and permeability during axial compression confining process under path 2.
Analysis of Table 6 shows that under the experimental conditions of stress path 2, the initial permeability of loaded axial pressure confining pressure of parallel bedding coal sample ZM1 is the largest, followed by the initial permeability of the loaded axial and confining pressure of oblique bedding coal samples ZM2, ZM3, and ZM4, and the initial permeability of loaded axial pressure confining pressure of parallel bedding coal sample ZM1.

Figure 21. Relationship between effective stress and permeability during confining pressure relief with axial pressure at the same time in path 2.
During stress path 2 loading axial and confining pressure, the high-rank coal with different bedding permeability decreases are all larger, all reaching more than 81%. During the process of confining pressure relief with axial pressure simultaneously (path 2), the permeability of vertical bedding coal sample ZM5 is the smallest.

Figure 22. Relationship between differential stress and permeability during confining pressure relief with axial pressure simultaneously (path 2).
and ZM4 for oblique bedding coal samples, and the increase in permeability of ZM5 for vertical bedding coal samples, are 13.96 times, and 11.3 times that under the constant-axis pressure and unloading confining pressure process, respectively.

Table 5. Permeability Results of High-Rank Coal with Different Bedding Path 1

| coal sample no. | $P_1$ (mD) | $P_2$ (mD) | $\eta$ (%) | $P_3$ (mD) | $\gamma$ |
|-----------------|------------|------------|------------|------------|--------|
| ZM1             | 0.09214    | 0.019940   | 78.36      | 0.02951    | 0.48   |
| ZM2             | 0.06711    | 0.006340   | 90.55      | 0.02981    | 3.70   |
| ZM3             | 0.08743    | 0.000059   | 99.93      | 0.00061    | 9.31   |
| ZM4             | 0.03737    | 0.000112   | 99.67      | 0.00106    | 8.50   |
| ZM5             | 0.01702    | 0.000749   | 95.60      | 0.00100    | 0.34   |

Table 6. Permeability Results of High-Rank Coal with Different Bedding Path 2

| coal sample no. | $P_1$ (mD) | $P_2$ (mD) | $\eta$ (%) | $P_3$ (mD) | $\gamma$ |
|-----------------|------------|------------|------------|------------|--------|
| ZM1             | 0.08624    | 0.01557    | 81.95%     | 0.02654    | 0.71   |
| ZM2             | 0.04870    | 0.00574    | 88.21%     | 0.02322    | 3.05   |
| ZM3             | 0.08453    | 0.00300    | 96.45%     | 0.05147    | 166.20 |
| ZM4             | 0.00698    | 0.00010    | 98.57%     | 0.01322    | 131.20 |
| ZM5             | 0.01504    | 0.00024    | 98.39%     | 0.00116    | 3.78   |

The effective stress decreased by 28.49% during stress path 2, which keeps the axial pressure unchanged to unload the confining pressure, and the damage to the coal samples is greater.

5. CONCLUSIONS

(1) The relationship between the permeability and the effective stress of high-rank coal with different bedding under both stress paths is consistent with the exponential function of $y = a exp(bx)$. Under constant axial pressure, the permeability gradually increases with the decrease of confining pressure or the increase of differential stress. Under simultaneous loading axial pressure and unloading confining pressure, the permeability gradually increases with the increase of differential stress.

(2) Under the two stress paths, the initial permeability of different bedding at the stage of loading axial pressure and unloading confining pressure shows that the parallel bedding coal sample ZM1 is the largest, the inclined bedding coal sample ZM2, ZM3, and ZM4 is the second, and the vertical bedding coal sample ZM5 is the smallest.

(3) The permeability change in oblique bedding coal samples under stress loading is greater than that of other bedding. The permeability increase in the oblique bedding is 21.4 times that of the vertical bedding, 14.94 times that of the parallel bedding under the constant-axis pressure and unloading confining pressure process, 26.45 times that of the vertical bedding, and 142.11 times that of the parallel bedding under the simultaneous loading axial pressure and unloading confining pressure process.

(4) The effect of simultaneous loading axial pressure and unloading confining pressure on the permeability of coal is greater than that of constant-axis pressure and unloading confining pressure, and the damage to coal is also greater. The increase in the permeability of parallel bedding, oblique bedding and vertical bedding coal samples under the simultaneous loading axial pressure and unloading confining pressure process is 1.47 times, 13.96 times, and 11.3 times that of the constant-axis pressure and unloading confining pressure process, respectively.

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Notes

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