Research Article

Study on the Permeability Change Characteristic of Gas-Bearing Coal under Cyclic Loading and Unloading Path

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Using the self-developed three-axis servo fluid-solid coupling system with gas-solid coupling of gas-bearing coal, the variation law of the permeability of gas coal under the stress cycle loading and unloading path was studied. The qualitative and quantitative relationships between permeability, axial force, and radial stress of gas-bearing coals were established, and the variation law of permeability of gas-bearing coals was discussed. The results show that (1) different cyclic loading and unloading stress paths correspond to the permeability characteristics of different gas-bearing coals. (2) Permeability of gas-bearing coal decreases with the increase of axial stress and radial stress, and it has a logarithmic function with axial stress and radial stress. This shows that axial stress and radial stress are important factors affecting the permeability characteristics of gas-bearing coal. (3) Under the same stress loading and unloading conditions, the axial stress is less than radial stress on the permeability of gas-bearing coal. In the cyclic loading and unloading axial stress process, the permeability of the gas-bearing coal varies by a smaller extent than the cyclically unloaded confining force. (4) The cumulative damage rate of gas-bearing coal under axial stress gradually increases with the increase of the number of cycles of loading and unloading, and the rate of the cumulative damage rate of permeability is less than the corresponding rate of radial stress.

1. Introduction

Coal is buried deep in the stratum and is a typical dual medium of pore fissures. Gas associated with it is deposited in adsorbed and free states [1]. Gas flow in the coal seam includes adsorption, desorption, diffusion, and seepage. It is a very complicated migration process. The permeability of gas-bearing coal is an important indicator of the degree of seepage of gas in the coal seam, and it is a key parameter that determines the degree of gas drainage in the coal seam.

After the coal seam is mined, the overlying strata above the coal seam are usually divided into three zones from the bottom to the top, which are the falling zone, the fissure zone, and the curved subsidence zone [2, 3]. Falling zone, which is also called goaf, are composed of irregularly broken coal and rock bodies. The vertical height can reach 4-11 times to the mining height. It has high porosity and permeability, resulting in the storage of large amounts of gas. These gasses mainly come from the adjacent fissure coal seams and rock formations [4, 5]. With the continuous mining of the working face, the coal and rock blocks in the goaf are gradually compacted due to overburden pressure and self-gravity [6]. Overburden movement and surface subsidence are caused, which may result in the destruction of buildings [7, 8]. It causes a dynamic change in the permeability of adjacent coal seams. Considering factors such as in situ stress, gas, and
physical and mechanical properties of coal, it is a hotspot and
difficulty to explore the characteristics of permeability
changes in gas-bearing coal seams [9].

At present, the research on the permeability characteris-
tics of gas-bearing coal seams is mainly based on theoretical
analysis, laboratory tests, and numerical simulation methods.
Martin and Chandler established a relationship between
damage variables and cohesion and internal friction angles
by loading and unloading tests on granites [10]. Eberhardt
et al. studied the effect of prepeak microcracks on macro-
scopic crack propagation through cyclic loading and unload-
ing tests [11]. Xi et al. studied Young’s modulus, P-wave
velocity, and hysteresis loop movement with frequency vari-
ation when the loading amplitude is lower than the yield
point and higher than the yield point [12]. Liu et al. studied
the effect of stress amplitude and frequency on dissipative
energy, dynamic elastic modulus, and dynamic Poisson’s
ratio under dynamic loading conditions [13].

Tian et al. carried out simulation tests on coal slug under
cyclic loading and unloading under different confining forces
and analyzed the macroscopic parameters, crack propagation
processes, and the relationship between those under different
confining forces [14]. Wang et al. conducted conventional
triaxial permeation tests and controlled triaxial permeability
tests with axial strain and confining force rising first and then
decreased and discussed the relationship between the abso-
late value of the difference between the axial force and con-
fining force and the permeability [15]. Somerton simulated
the cyclic loading and unloading of particles in coal samples
under different confining forces and analyzed the macro-
scopic parameters, crack propagation, and the relationship
between them under different confining forces [16]. McKee
et al. studied the relationship between stress coal porosity
and permeability [17]. Harpalani studied permeability char-
acteristics of gas-bearing coal under load conditions [18].
Enever et al. studied the effect of effective stress of coal on
permeability and established the relationship between the
permeability rate and effective stress [19]. Hema et al. studied
the influence of the confining force on coal permeation char-
acteristics by using carbon dioxide as seepage gas [20].
Gawuga studied the flow law of gas under coal strata under
stress [21]. Sun et al. showed that the permeability and axial
stress of coal samples meet the negative exponential function
during loading and unloading [22]. Permeability
decreases during loading and recovers during unloading.

From an engineering point of view, the self-stress and
tectonic stress fields with gas-bearing coal seams can be con-
sidered approximately unchanged. However, in the mining
process, the disturbance generated by the production layer
breaks the original stress distribution balance within the pro-
tected layer coal body. Especially, coal mine that can recover
3 layers or more. The mining process of the protected layer
tends to produce cyclic stress concentration on the adjacent
recoverable coal seams, resulting in the presence of stress
concentration areas or stress anomalies within the adjacent
clay layers of the protected layer. In high gas or gas outburst
mines, mining disturbances constantly change the load of the
gas-rich coal seams in the affected area, resulting in elasto-
plastic phenomena of gas-bearing coal seams, and this
change has a significant impact on gas drainage. Ban and
MackinMOB pointed out that the elastoplastic phenomenon
has a significant influence on the seepage of coal and rock,
especially for weakly cemented porous media [23]. Although
many existing researches are based on the elastoplastic con-
stitutive relation, they do not consider the effect of cyclic
loading and unloading on the permeability of gas-bearing
coals, essentially ignoring the irreversible deformation and
permeability caused by stress cycle loading and unloading.
This paper attempts to study the permeability change charac-
teristics of gas-bearing coal under cyclic loading and unload-
ing stress conditions to explore the infiltration rules of gas-
bearing coal, in order to provide theoretical guidance for coal
mine gas drainage technology.

2. Experimental Research

2.1. Experimental Principle. During the experiment, the gas
flow in coal samples complies with gas seepage theory; that
is, gas migration in coal seam is basically in accordance with
the law of linear infiltration—law of darcy [3], and the per-
meability of gas containing coal gas is obtained according
to the flow of the coal sample and the osmotic pressure at
both ends of the coal sample. Calculate the coefficient of per-
meability, k, at each mean pressure, as follows: [24]

\[ k = \left[ \frac{2Q_e P_e \mu L}{(P_i^2 - P_e^2) A} \right], \]

where \( k \) is the coefficient of permeability, mD, \( Q_e \) is the
exit flow rate of air, m³/s, \( P_e \) is the exit pressure of air, Pa, \( L \)
is the length of specimen, m, \( A \) is the cross-section area of
specimen, m², \( P_i \) is the entrance pressure of air, Pa, and \( \mu \)
is the viscosity of air at temperature of test, Pa·s.

Compute the mean pressure of each test for each speci-
men in Pa (atmospheres) and then calculate the reciprocal
of each mean pressure, as follows:

\[ 2/(P_i + P_e). \]

Plot the coefficient of permeability versus the reciprocal
of the mean pressure for each test of a specimen, diagram-
matic sketch as shown in Figure 1.

Draw a straight line through at least three points (this will
be at the lower values of reciprocal mean pressure) and
eextrapolate the line to intersect the ordinate line at zero recip-
rocals mean pressure. The value of \( k \) at the intersection is the
equivalent liquid permeability of the specimen. If a straight
line cannot be established through the data points, another
test at a lower mean pressure may be required, or the com-
plete test should be repeated.

2.2. Experimental Equipment. A self-developed triaxial servo
fluid-solid coupling system was employed, which allowed to
test permeability under different stress conditions. The sys-
tem mainly includes a confining force system with maximum
loading pressure of 25 MPa, a gas supply and acquisition sys-
tem with maximum supplied pressure of 6 MPa, a triaxial
infiltration system with maximum pressure of 70 MPa, a
gas measuring system with a measuring range of 100 sccm
classi

Proximate analysis was determined in accordance with measured by the MDMDY-300 automatic density instru-
ters and proximate analysis of the N-2 coal were tested. The

that the N-2 coal seam has the risk of coal and gas outburst.

And, as shown in Table 1, the evaluation index test results

vention and Control of Coal and Gas Outburst

water bath system with a temperature range of -25°C to 95°C. All the data in the system are automatically collected

(standard-state cubic centimeter per minute), 15 slm (stan-
dard litre per minute), and 2 slm, and constant temperature
water bath system with a temperature range of -25°C to 95°C. All the data in the system are automatically collected
by the computer, as shown in Figure 2.

2.3. Preparation of Coal Samples. The coal samples were
obtained from the Luban Northern Coal Mine (LB) of South
Sichuan Coal Luzhou Co., Ltd., which is located in Sichuan
Province, China. The coal mine contains several minable coal
seams, whose geological conditions are simple. As shown in
Figure 3, the coal samples were collected from coal seam #2
and marked as N-2, respectively. Each raw coal samples
was taken from the same site and prepared according to
“Methods for determining the physical and mechanical prop-
erties of coal and rock –Part 1: General requirements for
sampling (GB/T23561.1-2009)” [25]. Besides, the gas pres-
sure and the temperature of the N-2 coal seam were also
measured.

The outburst danger of the N-2 coal seam of LB is evalu-
ated in accordance with “Specification for identification of
coll and gas outburst mine “ (AQ1024-2006) [26] and “Pre-
vention and Control of Coal and Gas Outburst”(2009) [27].
And, as shown in Table 1, the evaluation index test results
of the N-2 coal seam were satisfy with the outburst hazard
identification critical value. Then, come to the conclusion
that the N-2 coal seam has the risk of coal and gas outburst.

Besides, as shown in Table 2, some of the basic param-
ters and proximate analysis of the N-2 coal were tested. The
true relative density and the apparent relative density were
measured by the MDMDY-300 automatic density instru-
ment. Proximate analysis was determined in accordance with
“Proximate analysis of coal (GB/T 212-2008)” [28]. The coal
classification index (R’max) was conducted in accordance with
“Method of determining microscopically the reflectance of
vitrinite in coal (GB/T 6948-2008)” [29]. According to the
measured parameters as shown in Table 2, it can be con-
cluded that the N-2 coal is highly metamorphic, low-ash
and low-sulfur anthracite.

In the laboratory, preparing standard coal sample is in
accordance with “Method for preparation of coal sam-
ple“(GB 474-2008) [30]: firstly, selecting the large block and
good integrity raw coal. Second, coring the coal sample using
a Φ50 mm core barrel. Third, cutting the coal core samples
into standard length using a cut machine. The standard coal
samples size is Φ50 mm × 100 mm, as shown in Figure 4.
Fourth, the prepared coal samples were dried and placed in
a drying oven.

Due to the close wave speed characteristics of the stan-
dard coal samples, its internal crack development is similar
too [31]. So, in order to avoid different crack development
that affect seepage results, it is necessary to check the stan-
dard coal samples before the seepage test. Finally, using wave
speed detector HS-FSB4C to choose the standard coal sam-
ples with close wave speed.

2.4. Experimental Procedure. The methane with a purity of
99.99% is used in the seepage test of gas-bearing coal under
the cyclic loading and unloading stress path. And the exper-
imental procedure is as follows:

(1) Apply a layer of silicone rubber about 1 mm thick on
the surface of the standard coal sample
(2) The rubber sleeve, the coal sample, and the loading
head are installed together on the cylindrical lower
head in the sealed cylinder body of the gas seepage
device, keeping the coal sample axis always perpen-
dicular to the lower pressing head plane
(3) Tighten the external screws that seal the cylinder and
check and connect all the piping and instruments
(4) Start the manual pressure pump and inject the water
into the cylinder so that the true triaxial force cham-
ber reaches the desired confining force
(5) After the confining force is stabilized, apply 2 MPa
axial force to the coal sample. Then, inflate a certain
pressure gas to check the airtightness of the device
(6) After passing the airtightness inspection, open the
gas valve and inflate the methane with a predeter-
dined pressure into the coal sample. After the
methane flow is stabilized, record the initial gas
flow
(7) After the above six steps are completed, the seepage
test under the cyclic loading and unloading stress
path can be performed according to Figure 5

In order to investigate the infiltration law of gas-bearing
col under the cyclic loading and unloading stress path, the
following two paths were performed under the conditions
of preset initial axial force σ 1 which is 2 MPa, radial pressure
σ 3 which is 2 MPa, and gas pressure P which is 1 MPa. The
following penetration test is as follows:

(1) Path I: keep the radial pressure σ 3 (2 MPa) and the
gas pressure P (1 MPa) constant, increase the axial
force σ 1 from 2 MPa step to 10 MPa, and then step
down to 2 MPa, as shown in Figure 5(a)
(2) Path II: maintain the axial force $\sigma_1$ (2 MPa) and the gas pressure $P$ (1 MPa) unchanged, increase the radial pressure $\sigma_3$ from 2 MPa ladder to 10 MPa, and then step down to 2 MPa, as shown in Figure 5(b).

### 3. Experimental Results and Data Analysis

#### 3.1. Law of Permeability Change

According to the experimental procedure, maintain the gas pressure 1 MPa. Then, the test law of the permeability change of gas-bearing coal is carried out according to the design cyclic loading and unloading confining force path (I and II). At the end of the

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**Table 1: Comparison between evaluation index and identification critical value.**

<table>
<thead>
<tr>
<th>Contents</th>
<th>Degree of coal fracturing</th>
<th>$\Delta P$</th>
<th>$f$</th>
<th>$P$</th>
<th>$W$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria value</td>
<td>III, IV, V</td>
<td>$\geq 10$</td>
<td>$\leq 0.5$</td>
<td>0.74</td>
<td>$\geq 8$</td>
<td>/</td>
</tr>
<tr>
<td>N-2</td>
<td>V</td>
<td>20.5</td>
<td>0.492</td>
<td>1.61</td>
<td>15.6377</td>
<td>35</td>
</tr>
</tbody>
</table>

$P$ is the coal seam gas pressure, MPa; $f$ is the coal hardness coefficient, dimensionless; $\Delta P$ is the initial gas diffusion velocity of coal, mmHg; $W$ is the coal seam gas content, m$^3$/t; and $T$ is the coal seam temperature, °C; degree of coal fracturing is qualitative evaluation index.
first and then increases, but the value does not return to the initial permeability value of 4.8 mD. Similarly, the confining force is loaded and unloaded during the 2nd and 3rd cycles. With the increase of time, the permeability of gas-bearing coal showed a decrease and then an increase, but the increase did not return to the initial value of permeability at the beginning of the cyclic loading and unloading stress.

The variation of permeability of gas-bearing coal during cyclic loading and unloading axial stress is smaller than that of confining force. Therefore, it can be concluded that the confining force has greater influence on permeability of gas-bearing coal than the axial force.

### 3.2. Evolution of Permeability with the Axial Force

Under the conditions of cyclic loading and unloading stress path I, the experimental data of the coal sample permeability were fitted by regression, and the regression curve was shown in Figure 7. The optimal fitted expression formula is shown in Table 3. From Figure 7 and Table 3, it can be seen that the fitting formula is in good agreement with the experimental data, indicating that the permeability of gas-bearing coal decreases with the increase of the axial force and is a logarithmic function of the axial force.

Under the initial stress state, the permeability of coal samples varies significantly, sometimes by several times. In the process of stress loading, the permeability of coal sample decreases with the increase of axial stress. However, in the process of stress unloading, the permeability gradually recovers with the reduction of axial stress, but the closed loop curve cannot be formed, and the curves of loading and unloading do not coincide [22]. According to the research results of Li et al., the permeability of gas-bearing coal samples would tend to be constant under cyclic loading [32]. Therefore, the logarithmic function relationship should have a constant term. That is, the experimental data satisfy

\[ k = a + b \ln(\sigma_1), \]

Where \(a\) and \(b\) are all fitting constants, dimensionless.

From Table 3, it can be seen that formula (3) can well describe the variation law of gas permeability of gas-containing coal under loading and unloading axial stress path I. From Figure 7(a), it can be seen that as the axial force increases, the permeability of the coal samples decreases during the loading cycles, the permeability decrease the most during the 1st loading, and the permeability decrease the least during the 3rd loading. From Figure 7(b), it can be seen that the permeability of the coal sample increases to some extent with the decrease of the load in the axial force unloading process, the increase in the permeability of the 1st unloading process is the largest, and the 3rd unloading process penetrates. The rate of increase is the smallest.

According to the principle of effective stress proposed by Terzaghi [33], the effective stress of gas-bearing coal samples can be approximated as

\[ \sigma' = \sigma - P, \]**
where $\sigma'$ is the effective stress, and $\sigma$ is the total stress of the coal sample.

According to the force state of the coal sample, it is known $\sigma_1' = \sigma_1 - P$ in the axial direction, where $\sigma_1'$ is the effective stress and $\sigma_1$ is the total stress of the coal sample, respectively. It can be seen that the increase in axial stress corresponds to an increase in the axial effective stress while keeping the gas pressure constant. Therefore, the increase in effective stress causes the coal sample to be compressed more densely. The smaller pore diameter of the coal sample reduces the effective permeation path of the gas. The resistance of the migration of gas molecules is increased, and the seepage velocity of gas is reduced. As a result, the permeability of coal samples decreases, and the permeability of gas-containing coal gas decreases rapidly. This shows that coal samples are compressed and compacted under effective stress. When the force is unloaded, the effect is exactly the opposite of increasing the axial force. That is, the force unload will reduce the effective stress on the coal sample, and the reduction of the effective stress will cause the coal sample to change from compression to stress relaxation. Due to the elastic force of the coal, the pore diameter of the coal sample becomes larger. The effective percolation channel of gas is increased, and the effective percolation channel and the percolation velocity of gas are increased. This eventually led to an increase in the permeability of coal samples.

The definition of $k_r$ is the permeability difference between the beginning and end of each loading, the format of which is $k_r = k_0 - k_s$, where $k_0$ is the permeability at the beginning of loading, $k_s$ is the permeability at the end of loading. Similarly, define $k_m = |k_s - k_t|$, where $k_t$ is the value of the permeability when the axial stress is unloaded to the initial state. One can see from the experimental results that the values of $k_r$ and $k_m$ gradually decrease with the increase of the cycles of loading and unloading. And Table 3 shows the values of $k_r$ and $k_m$ for different coal samples are found to be relatively large.

It can be seen that the axial stress increases, and the permeability decreases, and when $\sigma_1'$ approaches to 0, $k$ equals to a. Thus, a can be considered as a quantity that is independent of the axial stress, and it indicates the relationship between the permeability and the coal structure. On the other hand, when $\sigma_1'$ approaches to $\infty$, $k$ equals to 0, which is the permeability of the coal body in no stress field. In this situation, $a$ represents the reduced permeability, and it is due to the closure of pores and cracks when the stress field changes, that is, the permeability of the coal being affected by stress changes. The value of $b$ reflects the stress sensitivity of the coal body, which is a scalar quantity of the changing degree of permeability when the axial stress changes, determining the changing law of the slope of the permeability curve.

### 3.3. Evolution of Permeability with the Confining Force.

Under the condition of cyclic loading and unloading of stress path II, the experimental data of the coal sample permeability were fitted by regression. The regression fitted curve is shown in Figure 8, and the best fitting expression is shown in

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**Figure 5:** Circulation loading and unloading path.

**Figure 6:** Experimental results under circulation loading and unloading path.
Table 3: Regression expressions of permeability of coal samples under paths I.

<table>
<thead>
<tr>
<th>Tension loading and unloading</th>
<th>$k_w$ (mD)</th>
<th>$k_f$ (mD)</th>
<th>Constants $a$</th>
<th>Constants $b$</th>
<th>Correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1</td>
<td>/</td>
<td>1.83</td>
<td>5.7909</td>
<td>-1.12</td>
<td>0.9928</td>
</tr>
<tr>
<td>Unload 1</td>
<td>0.74</td>
<td>/</td>
<td>4.2429</td>
<td>-0.479</td>
<td>0.991</td>
</tr>
<tr>
<td>Load 2</td>
<td>/</td>
<td>1.05</td>
<td>4.3008</td>
<td>-0.661</td>
<td>0.9772</td>
</tr>
<tr>
<td>Unload 2</td>
<td>0.55</td>
<td>/</td>
<td>3.6145</td>
<td>-0.343</td>
<td>0.9854</td>
</tr>
<tr>
<td>Load 3</td>
<td>/</td>
<td>0.70</td>
<td>3.6532</td>
<td>-0.42</td>
<td>0.9758</td>
</tr>
<tr>
<td>Unload 3</td>
<td>0.40</td>
<td>/</td>
<td>3.259</td>
<td>-0.248</td>
<td>0.992</td>
</tr>
</tbody>
</table>

Figure 7: Permeability regression curves of coal samples under I paths.

Table 4 from Figure 8 and Table 4, it can be seen that the fitting results are in good agreement with the experimental data. It shows that the permeability of gas-containing coal decreases with the increase of the confining force and is a logarithmic function with the confining force.

From Table 4, it can be seen that formula (3) can well describe the variation law of the permeability of gas-containing coal under loading and unloading axial stress path II. From Figure 8(a), it can be seen that as the axial force increases, the permeability of coal samples decreases during each loading cycle. The decrease in permeability was the greatest during the 1st loading, and the decrease in permeability was minimal during the third loading. As shown in Figure 8(b), it can be seen that as the load decreases, the permeability of the coal sample increases to a certain degree in the axial force unloading process. The permeability of the 1st unloading process increases the most, and the 3rd is the smallest.

When analyzing the origin of this change law, according to the effective stress principle [33], there are $\sigma_3' = \sigma_3 - P$ in radial directions, where $\sigma_3'$ is the effective confining force and $\sigma_3$ is the total confining force in the radial direction of the coal sample, respectively. It can be seen that the increase in the confining force corresponds to an increase in radial effective stress. Therefore, the loading of the confining force will lead to the increase of the effective stress of coal samples. The increase of effective stress will make the coal sample compressed more compactly, and the pore diameter of the coal sample will become smaller. The effective percolation channel of gas will be reduced, and the gas will increase. The molecular migration resistance reduces the gas flow rate of the gas and eventually results in a decrease in the permeability of the coal sample. When the confining force is unloaded, the effect is just the opposite of the effect of increasing the confining force. That is, the confining force unload will reduce the effective stress of the confining force of the coal sample, and the reduction of the effective stress will cause the coal sample to transform from compression to stress relaxation in the coal. Under the action of the elastic force, the pore diameter of the coal sample becomes larger, which increases the effective percolation channel of the gas, increases the effective percolation channel and the percolation velocity of the gas, and finally leads to the increase of the permeability of the coal sample.

Figure 8 and Table 4 show the change in permeability of the coal sample after loading under different confining forces. It can be seen that as the confining force increases, the permeability becomes smaller, and the increase in the number of loadings also makes the sensitivity of the permeability change to the confining force lower. During the unloading process, the permeability shows an increasing trend with the decrease of the effective stress. Because the pores and microcracks in the coal sample produce an irreversible deformation under the effect of effective stress, the partial permeability is irreversible after unloading.

With the radial stress increases, the permeability decreases. When $\sigma_3' \rightarrow 0$, $k = a$, where $a$ is considered to be a quantity that is independent of the axial stress and represents the relationship between the permeability and the structure of the coal itself. When $\sigma_3' \rightarrow \infty$, the permeability...
I and path II, it can be seen that the fi-

sion value at the time of loading [14]. From the test data regres-

unloading, the permeability cannot be restored to the initial

stress increases with the number of loadings. Simultaneous

and unloading, the sensitivity of the permeability to e-
tive stress are not a simple function. Under cycled loading

ing process, which means that the permeability and the e-
tive stress curves do not coincide during the loading and unload-

4. Discussion

4.1. Effect of Effective Stress on Permeability. From the experi-

mental data, it can be seen that the permeability and effective

stress curves do not coincide during the loading and unloading

process, which means that the permeability and the effective

stress are not a simple function. Under cycled loading and unloading, the sensitivity of the permeability to effective stress increases with the number of loadings. Simultaneous unloading, the permeability cannot be restored to the initial value at the time of loading [14]. From the test data regression fitting results of coal sample permeability under stress path I and path II, it can be seen that the fitting result is in good agreement with the experimental data, which shows that the permeability of gas-bearing coal decreases with the increase of the axial force and confining force and with the axial force and confining force logarithmically.

According to the force state of the coal sample, there is $\sigma'_1 = \sigma_1 - P$ in the axial direction, in which $\sigma'_1$ is the effective stress and $\sigma_1$ is the total stress in the axial direction of the coal sample, respectively. And there is $\sigma'_3 = \sigma_3 - P$ in the radial direction, where $\sigma'_3$ is the confining force and $\sigma_3$ is the total confining force of the coal sample, respectively. It can be seen that the increase of axial stress corresponds to the increase of axial effective stress, and the increase of the confining force corresponds to the increase of radial effective stress. Therefore, the increase of axial stress and confining stress will increase the effective stress of the coal sample. The increase of the effective stress makes the coal sample be compressed more compactly, and the pore diameter of the coal sample becomes smaller, which reduces the effective percolation channel of the gas. The resistance to the migration of gas molecules is increased, the permeation velocity of gas is reduced, and the permeability of coal samples eventually decreases. When gas pressure is increased, the effect is just the opposite of the effective percolation channel of the gas, and the permeability of coal samples increases. As a result, the absolute permeability of the coal is reduced.

Table 4: Regression expressions of permeability of coal samples under path II.

<table>
<thead>
<tr>
<th>Tension loading and unloading</th>
<th>$k_m$ (mD)</th>
<th>$k_e$ (mD)</th>
<th>Constants</th>
<th>Constants</th>
<th>Correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1</td>
<td>0</td>
<td>2.80</td>
<td>5.9378</td>
<td>-1.792</td>
<td>0.9809</td>
</tr>
<tr>
<td>Unload 1</td>
<td>1.50</td>
<td>/</td>
<td>4.0895</td>
<td>-0.951</td>
<td>0.9816</td>
</tr>
<tr>
<td>Load 2</td>
<td>1.90</td>
<td>4.1553</td>
<td>-1.197</td>
<td>0.9373</td>
<td></td>
</tr>
<tr>
<td>Unload 2</td>
<td>1.00</td>
<td>2.9601</td>
<td>-0.636</td>
<td>0.9447</td>
<td></td>
</tr>
<tr>
<td>Load 3</td>
<td>1.35</td>
<td>3.0488</td>
<td>-0.847</td>
<td>0.9281</td>
<td></td>
</tr>
<tr>
<td>Unload 3</td>
<td>0.75</td>
<td>2.2446</td>
<td>-0.476</td>
<td>0.9105</td>
<td></td>
</tr>
</tbody>
</table>

$k = 0$, which is the permeability of the coal body when there is no stress field, and $a$ reflects the part where the permeability is reduced due to the closure of pores and cracks when the permeability field changes, i.e., coal. The part of the body that is affected by stress changes. The $b$ reflects the stress sensitivity of the coal body, which is a scalar quantity of the degree of permeability change when the axial stress changes and determines the law of the slope of the permeability curve.

**Figure 8:** Permeability regression curves of coal samples under II paths.
The experimental data of the loading and unloading path and the mathematical analysis model were fitted, and the matching degree was good. Li et al. showed that the permeability and axial stress of coal samples can form hysteresis loops under cyclic loading, which similar to the results of this study [32]. During the stress loading process, the damage of pores and cracks closed in the compaction stage on the permeability is irreparable, especially for the coal samples with low strength. At the same time, the increase in the number of loading and unloading makes the elastic properties of the coal sample stronger, and it also leads to a one-to-one correspondence between permeability and effective stress [34].

4.2. Relationship between Stress and Permeability Damage. Since the permeability rate reflects the change of effective porosity within the coal sample during the experiment, the increase of permeability indicates the increase of effective porosity, and the decrease of permeability indicates the decrease of effective porosity. Therefore, the permeability and effective porosity have the same change rule during the deformation process of coal samples. Similarly, the degree of damage to the coal sample permeability is also reflected in the porosity. That is to say, for stress paths I and II, the porosity of the coal sample also suffers damage after the stress has completed the loading and unloading cycle, and the damage rate is equal to the damage rate of the permeability [35].

Under the stress paths I and II, the two circulation axial forces and confining forces are not coincident with the permeability curves of gas-bearing coals, and the permeability of the coal samples in the force unload process is smaller than that of the loading process. That is, after the stress loading and unloading, the permeability of the coal sample cannot be restored to its original value. This shows that the permeability has been damaged to a certain extent during 1st loading and unloading stress. After 3rd of loading and unloading stress, the cumulative damage of permeability gradually increases, but the rate of damage of permeability decreases gradually.

According to the results of Jing and Yuan, the change rate of permeability and the degree of recovery of permeability can be evaluated by using the maximum permeability change rate and the damage rate of coal samples [36]. It shows that the greater the rate of change in maximum permeability, the greater the decrease in permeability of coal samples. Similarly, it shows that the greater the rate of damage in permeability, the worse the degree of recovery of permeability. The maximum permeability change rate of coal samples can be calculated as follows: [22]

\[ D_{\text{max}} = \left( \frac{k_0 - k_{\text{min}}}{k_0} \right) \times 100\%, \]  

where \( D_{\text{max}} \) is the maximum permeability change rate of the coal sample, \( k_0 \) is the coal sample permeability measured at the first stress point during the confining force rise, and \( k_{\text{min}} \) is the coal sample permeability measured at the maximum effective stress point.

### Table 5: Permeability change rate and permeability damage rate.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Loading and unloading path</th>
<th>( D_{\text{max}} ) (%)</th>
<th>( D_k ) (%)</th>
<th>( D ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial force</td>
<td>Load and unload 1</td>
<td>36.65</td>
<td>21.8</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>Load and unload 2</td>
<td>26.92</td>
<td>12.82</td>
<td>31.83</td>
</tr>
<tr>
<td></td>
<td>Load and unload 3</td>
<td>20.59</td>
<td>8.82</td>
<td>37.84</td>
</tr>
<tr>
<td>Confining force</td>
<td>Load and unload 1</td>
<td>58.33</td>
<td>27.08</td>
<td>27.08</td>
</tr>
<tr>
<td></td>
<td>Load and unload 2</td>
<td>54.29</td>
<td>25.71</td>
<td>45.83</td>
</tr>
<tr>
<td></td>
<td>Load and unload 3</td>
<td>51.92</td>
<td>23.08</td>
<td>58.34</td>
</tr>
</tbody>
</table>

\( D \) is accumulated coal sample permeability damage rate, %.

The coal sample permeability damage rate can be calculated as follows:

\[ D_k = \left( \frac{k_0 - k_1}{k_0} \right) \times 100\%, \]  

where \( D_k \) is the permeation damage rate of the coal sample, and \( k_1 \) is the coal sample permeability measured at the last stress point during the confining force drop process.

According to Eqs. (5) and (6), the permeation damage rate of the gas-filled coal gas under loading and unloading under the stress paths I and II is calculated, see Table 5 for details. Under the stress path I, the maximum permeability change rate of the first cycle of loading and unloading gas-bearing coal samples was 36.65%, and the permeability damage rate was 21.8%. It can be seen that after the first stress loading and unloading cycle is completed, the permeability of the coal sample will be reduced to 78.2%. Similarly, after completing the 2nd and 3rd stress loading/unloading cycles in the axial direction, the permeability of coal samples will be reduced to 68.17% and 62.16%, respectively.

Under the stress path II, the maximum permeability change rate of the first cycle of unloading gas-bearing coal samples was 58.33%, and the permeability damage rate was 27.08%. It can be seen that after the confining force completes the 1st stress loading and unloading cycle, the permeability of the coal sample will be reduced to 72.92%. Similarly, after radial completion of the 2nd and 3rd stress loading/unloading cycles in the axial direction, the permeability of coal samples will be reduced to 54.17% and 41.67%, respectively.

The permeability damage rate of gas-bearing coal under various loading and unloading stress conditions is shown in Figure 9.

From Figure 9(a), it can be seen that under the condition of axial cyclic loading and unloading stress, the degree of reduction in the permeability damage rate of gas-bearing coal is the largest in the 1st cycle, and the degree of reduction in the loading and unloading stress conditions of cycles 2nd and 3rd is small. This trend of change is a macroscopic manifestation of the change in the effective stress of coal samples and the continuous expansion of internal cracks in coal samples. According to the principle of effective stress, in the stage of elastic deformation, along with the continuous increase of the axial stress of the coal sample, the internal microfractures of the coal sample are closed, and the effective seepage channel of the gas is reduced, resulting in a rapid decrease of the permeability of the coal sample. As the effective stress of
the coal sample continues to increase, the pore diameter of the coal sample suffers from compression deformation and shrinkage, and the permeability decreases. As the effective stress of coal samples continues to increase, the pore deformation resistance and shrinkage resistance of coal mines are getting larger and larger. It shows that under the condition of cyclic loading and unloading stress, the permeability damage rate gradually decreases with the increase of loading and unloading times.

From Figure 9(b), it can be seen that under radial cyclic loading and unloading stress conditions, the degree of damage reduction of gas-bearing coal gas permeability is the highest in the 1st cycle, and the degree of reduction in the loading and unloading stress conditions of the 2nd and 3rd cycles is relatively small. This trend of change is a macroscopic manifestation of the change in the effective stress of coal samples and the continuous expansion of internal cracks in coal samples. According to the principle of effective stress, in the stage of elastic deformation, along with the continuous increase of the axial stress of the coal sample, the internal microfractures of the coal sample are closed, and the effective seepage channel of the gas is reduced, resulting in a rapid decrease of the permeability of the coal sample. As the effective stress of the coal sample continues to increase, the pore diameter of the coal sample suffers from compression deformation and shrinkage, and the permeability decreases. As the effective stress of coal samples continues to increase, the pore deformation resistance and shrinkage resistance of coal mines are getting larger and larger. It shows that under the condition of cyclic loading and unloading stress, the permeability damage rate gradually decreases with the increase of loading and unloading times.

Comparing Figures 9(a) and 9(b), under the same stress loading and unloading conditions, the axial stress is less than the radial stress and the permeability of gas-bearing coal, and the cyclic stress on gas is added under the same stress cyclic loading and unloading conditions. The coal permeability damage rate is less than radial cyclic stress. Therefore, under the action of the radial force, the permeability damage rate is greater than its effect on the axial force. After the 1st cyclic stress is unloaded and unloaded, the permeability damage rate of gas-bearing coal under the action of axial force is 0.81 times to the radial force. Under the influence of the radial force, the permeability damage rate of the lower gas-bearing coal is 0.69 times. After the 3rd cyclic stress is unloaded and unloaded, the accumulation of the permeability damage rate under the axial force is 0.65 times to the radial force. It shows that the cumulative damage rate under the axial force increases with the increase of the cycle loading and unloading times and the accumulative rate of permeability damage rate is smaller than that of radial force, that is, the axial force acts less impact on permeability than the radial force.

From Eqs. (7) and (8), it can be seen that when the axial stress and the radial stress are equal, the standard test piece is subjected to a radial force that is 4 times that of the axial force. Therefore, under the action of the radial force, the permeability damage rate is significantly higher than the 2nd and 3rd cycle loading and unloading axial stress. Secondly, due to the small axial stress contact area, the axial force acting on the test piece is $F_A$ less than the radial force $F_C$, as shown below:

$$ F_A = \pi \sigma_1 \times 25^2, $$  \(7\)

$$ F_C = \pi \sigma_3 \times 25 \times 100, $$  \(8\)

where $F_A$ is the axial force, $N$, and $F_C$ is the radial force, $N$.

![Figure 9: Permeability damage rate under cyclic loading and unloading stress.](image-url)
5. Conclusion

In this paper, an independent design of the triaxial stress system is used to design two kinds of stress loading and unloading paths. The permeability of gas-bearing coal under loading and unloading paths with axial and radial stress is measured. And the maximum permeability change rate and the permeability damage rate data are used to analysis of the experimental data. Then, explored the law of the permeability of gas-bearing coal and obtained the following conclusions:

(1) The cyclic loading and unloading stress path has an important influence on the permeability characteristics. Different cyclic loading and unloading stress paths correspond to the different permeability characteristics. The permeability decreases with the increase of axial stress and radial stress, and it changes logarithmically with axial stress and radial stress. It shows that axial stress and radial stress are important factors affecting the permeability characteristics of gas-bearing coal.

(2) Under the same stress loading and unloading conditions, the axial stress is less than the radial stress on the permeability of gas-bearing coal. And the axial cyclic stress has less influence on the permeability damage rate of gas-bearing coal than the radial cyclic stress. The variation of permeability of gas-bearing coal during cyclic loading and unloading axial stress is smaller than that of radial cyclic stress. The permeability is affected by the number of cycles of loading and unloading. The degree of damage can be characterized by the maximum permeability change rate and the permeability damage rate.

(3) The accumulation of the permeability damage rate of gas-bearing coal under the axial force gradually increases with the increase of the number of cycles, and the accumulative rate of the permeability damage rate is smaller than the effect of the radial force.

Data Availability

The readers could obtain the data by contacting to the corresponding author.

Conflicts of Interest

The authors declared no conflicts of interest.

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