Deformation Failure and Gas Seepage of Raw Coal in Alternate Loading and Unloading by Stages

Bang-an Zhang

Chongqing University

Yang yushun (✉ cqyysh@126.com)

Huaiyin Institute of Technology <https://orcid.org/0000-0002-9318-339X>

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Deformation failure and gas seepage of raw coal in alternate loading and unloading by stages

Bang-an Zhang¹, Yu-shun Yang^{2,3}

¹ School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China;

² State and Local Joint Engineering Laboratory for Gas Drainage & Ground Control of Deep Mines, Henan Polytechnic University

³ Faculty of Architecture and Civil Engineering, Huaiyin Institute of Technology, Jiangsu 223001, China

* Correspondence: cqyys@126.com

Abstract: In this paper, the cyclic loading and unloading confining pressure tests of raw coal samples were carried out by using the "Triaxial seepage test device of thermal fluid solid of coal and rock" developed by Chongqing University. The conclusions are as follows: (1) The axial strain change rate ε_1' , the radial strain change rate ε_3' and the permeability change rate k' under unit stress state are used to represent the sensitivity of axial stress and confining pressure to deformation and permeability characteristics of samples under unit stress state. (2) At the initial stage of unloading the confining pressure, the confining pressure has a greater influence on the permeability of the sample. At the initial stage of loading confining pressure, the confining pressure has a greater influence on the radial strain of the specimen. During the subsequent loading and unloading process, the confining pressure of loading and unloading has a greater influence on the permeability of the sample, and a smaller influence on the axial strain. The loading axial stress has a greater influence on the axial strain of the sample, and a smaller influence on the permeability of the sample. (3) When the axial stress is constant, the increase range of sample permeability increases with the increase of unloading confining pressure range, and the decreasing range of sample permeability increases with the increase of loading confining pressure range, and the increase range of sample permeability under unloading confining pressure is higher than that under increasing confining pressure. (4) In the process of loading axial stress and loading confining pressure, the permeability of samples decreases nonlinearly with the increase of principal stress difference, while the permeability of samples increases nonlinearly with the decrease of principal stress difference in the process of unloading confining pressure.

Keywords: alternate loading-unloading, raw coal, deformation failure, gas seepage, strain rate

1 Introduction

The mining of underground coal resources breaks the original stress balance, which will inevitably cause the redistribution of the internal stress field of the surrounding coal and rock masses, thus making the coal and rock masses in front of the work face a complex loading and unloading process, which is often accompanied by surrounding rocks. The conversion of energy within the body, especially the outflow of gas, has always threatened the safety of underground production. Once these disasters occur, they will cause huge economic losses to the mine and seriously threaten the lives of mine workers.

At present, scholars at home and abroad have carried out many studies on the permeability of coal and rock under loading and unloading conditions, and have achieved many beneficial results. Some scholars use coal briquette to carry out research (Li, et al. 2010; Xu, et al. 2014; Wang, et al. 2016). Briquette has the characteristics of being easier to obtain than raw coal samples, with less dispersion of results and

strong repeatability. However, this is quite different from the complex conditions on site, and the test results cannot be applied well on site. Therefore, many scholars have used raw coal samples to carry out related research. Liu (2019) carried out research on the evolution of coal permeability under the control of cyclic loading, which has theoretical support for explaining the anisotropic characteristics of coal permeability under complex stress fields. Jia et al. (2020) comparatively studied the permeability response characteristics of coal briquette samples and raw coal samples under the influence of mining. Xiao et al. (2012) studied the law of gas migration in the process of coal and rock deformation and fracture. Xu et al. (2012) carried out coal loading and unloading tests using the stress control method of adding axial pressure and unloading confining pressure, and analyzed the evolution law of coal and rock deformation characteristics and permeability characteristics under loading and unloading conditions. Yuan and Zhang (2017) revealed the deformation and seepage characteristics of coal samples under the staged unloading confining pressure through gas seepage tests of briquette under different paths. Li et al. (2019) conducted isotherm adsorption tests and seepage tests with increased pore pressure under different water-bearing conditions, constructed a permeability model considering the influence of water, and then analyzed the changes in coal and rock adsorption and seepage under different water-bearing conditions. Zhang et al. (2017) simulated coal seam excavation by unloading confining pressure, carried out a triaxial seepage test of gas-containing raw coal, and clarified the three-stage characteristics of gas seepage characteristics of raw coal. Yin et al. (2018) developed the mechanical properties and permeability evolution of raw coal under true triaxial loading and unloading stress paths. Duan et al. (2018) conducted a staged loading-unloading test of gas-containing raw coal, analyzed and discussed the deformation, permeability characteristics and energy consumption characteristics of coal and rock, and established a damage variable equation based on the energy consumption characteristics. Zhao et al. (2019) carried out gas flow characteristics tests under different conditions on pure coal samples, samples containing single-layer gangue, and samples containing two-layer gangue. Zhu et al. (2020) studied the influence mechanism of gas pressure and mining stress on coal and rock deformation and gas flow. Zhao et al. (2016) analyzed and studied the mechanical properties and seepage evolution laws of raw coal under different loading and unloading rates. Liu et al. (2014) conducted an experimental study on the effect of helium on the permeability of coal samples under the condition of changing the effective stress (4MPa~12MPa), and showed that the permeability of the sample decreased exponentially with the increase of effective stress. Xin et al. (2018) conducted mechanical and permeability tests of gas-bearing coal under different stress paths (conventional triaxial compression, staged variable speed triaxial compression, unloading of confining pressure and staged variable speed unloading of confining pressure). Zuo et al. (2016) studied the effect of effective stress and gas slippage effect on the permeability of coal samples under cyclic loading conditions, and believed that the slippage effect has a significant impact on the permeability of coal samples, especially in the low pore pressure range. The slippage effect is greater than the effective

stress. Ye et al. (2017) simulated the response characteristics of pore pressure to the permeability of raw coal under different loading and unloading paths of ground stress. Ju et al. (2017) conducted the methane permeability characteristics of fractured coal under different excavation stress paths and its dependence on the internal fracture network of fractured coal.

Previous studies mostly studied the deformation and permeability characteristics of coal and rock samples by loading and unloading axial pressure and confining pressure, and did not focus on the characteristics of grading, discontinuous, and variable loading and unloading strengths of the coal seam under actual mining conditions. Related research. In order to more realistically simulate the changes in the pressure of the coal seam during mining, and to further understand the deformation and failure of coal samples and the law of gas seepage under the conditions of staged loading axial pressure and loading and unloading confining pressure, the classification under the same loading rate was carried out this time. Research on the influence of loading axial pressure and loading and unloading confining pressure on the deformation and failure of gas-bearing coal and gas seepage characteristics.

2 Test device and scheme

2.1 Test device

The test device is a coal rock thermal fluid solid coupling triaxial servo seepage system developed by Chongqing University, as shown in Figure 1. The device consists of stress loading system, specimen clamping system, pore pressure control system, data acquisition system, vacuum extraction system and constant temperature water bath control system. It can simulate the gas permeability characteristics of coal samples under different pore pressure, confining pressure and temperature. The maximum axial load is 1000 kN, the radial confining pressure can be added to 60 MPa, and the maximum gas pressure can be 6 MPa. The maximum axial deformation is 60 mm and the radial deformation is 6 mm. The deformation accuracy is controlled within $\pm 1\%$.

Fig. 1 Tri-axial stress thermal-hydrological-mechanical Coal Gas Permeameter

Assuming that the gas flow in the coal sample conforms to Darcy's law, the permeability value can be obtained according to the gas pressure at both ends of the coal sample, gas flow rate, coal sample size and other parameters (Xu, et al. 2012; Zhang, et al. 2017):

$$k = \frac{2\mu P_2 QL}{A(P_1^2 - P_2^2)} \quad (1)$$

Where, k is permeability (mD); μ is gas dynamic viscosity coefficient at measured temperature, taking $1.08 \times 10^{-5} \text{ pa} \cdot \text{s}$; L is sample length (cm); A is sample cross-sectional area (cm^2); P_1 is gas inlet pressure (MPa); P_2 is gas outlet pressure (MPa); Q is gas flow under standard condition (cm^3/s).

2.2 Coal sample preparation

The test samples are taken from the No. 2+3# coal seam of Shanmushu Coal Mine, which is a coal and gas outburst coal seam. The gas pressure of the coal seam is 0.8 MPa~1.7 MPa, the average is 1.32 MPa, the inclination angle of the coal seam is $2^\circ \sim 6^\circ$, and the average thickness is about 3.1m. Select lump coal with a size greater than 200 mm×200 mm×200 mm on site, seal the lump coal with plastic wrap and transport it back to the laboratory, and drill it in accordance with the "Method for Determination of Physical and Mechanical Properties of Coal and Rocks" (GB/T23561.7-2009) Processed into a standard cylindrical raw coal sample with a size of $\varnothing 50\text{mm} \times 100\text{mm}$, the samples are shown in Figure 2.

Fig. 2 Raw coal sample

2.3 Test plan

This test mainly studies the permeability evolution law of raw coal samples under alternately staged loading axial stress and loading and unloading confining pressure. The details are as follows: (1) First, load the axial stress and confining pressure of the raw coal sample at the same rate $\sigma_1 = \sigma_3 = 7.0 \text{ MPa}$, vacuumize the coal sample, introduce 99.99% methane gas, and adjust the inlet pressure to $p_1 = 2.0 \text{ MPa}$, and make the coal absorb

gas for 24 h. (2) Open the valve at the gas outlet side, and perform alternate axial stress loading and unloading confining pressure tests after the flow is stable. The axial stress loading rate is 0.05 kN/s, and the confining pressure loading and unloading rate is 0.02 MPa/s. (3) After the alternate loading and unloading of axial stress and confining pressure is completed, the confining pressure shall be kept constant, and the axial stress shall be loaded at a rate of 0.1 mm/min under displacement control until the specimen is broken. At the end of the test, the coal sample was replaced and the confining pressure was changed to 6.0 MPa, 7.0 MPa, 8.0 MPa and 9.0 MPa respectively. During the loading and unloading process of axial stress and confining pressure, each level is maintained for five minutes. The loading and unloading steps of each sample are as follows:

a. Sample a₁, the loading and unloading step are ①~⑩

σ_1 /MPa	7.0	7.0	② →	10.63	④ →	14.25	⑥ →	17.88	⑧ →	21.5	⑩ →	peak intensity
σ_3 /MPa	7.0	① →	6.0	③ →	4.0	⑤ →	6.0	⑦ →	4.0	⑨ →	6.0	

b. Sample a₂, the loading and unloading step are ①~⑨

σ_1 /MPa	7.0	① →	10.63	③ →	14.25	⑤ →	17.88	⑦ →	21.5	⑨ →	peak intensity
σ_3 /MPa	7.0	② →	4.0	④ →	7.0	⑥ →	4.0	⑧ →	7.0		

c. Sample a₃, the loading and unloading step are ①~⑩

σ_1 /MPa	7.0	7.0	② →	10.63	④ →	14.25	⑥ →	17.88	⑧ →	21.5	⑩ →	peak intensity
σ_3 /MPa	7.0	① →	8.0	③ →	4.0	⑤ →	8.0	⑦ →	4.0	⑨ →	8.0	

d. Sample a₄, the loading and unloading step are ①~⑩

σ_1 /MPa	7.0	7.0	② →	10.63	④ →	14.25	⑥ →	17.88	⑧ →	21.5	⑩ →	peak intensity
σ_3 /MPa	7.0	① →	9.0	③ →	4.0	⑤ →	9.0	⑦ →	4.0	⑨ →	9.0	

3 Test results analysis

3.1 Stress sensitivity analysis

Figure 3 shows the deviatoric stress-strain-permeability curve of each sample during loading and unloading under different confining pressure conditions.

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140

(a) sample a₁

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142

(b) sample a₂

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(c) sample a₃

(d) sample a4

Fig. 3 Deviatoric stress-strain-permeability curves of each sample during loading and unloading

It can be seen from Figure 3 that in the process of unloading confining pressure under constant axial stress, the specimen presents axial compression deformation and radial expansion deformation, and the sample permeability increases nonlinearly with the unloading of confining pressure. In the process of axial compression under constant confining pressure, the specimen continues to show compression deformation in axial direction and expansion deformation in radial direction. In the process of loading confining pressure under constant axial stress, the axial deformation of the sample is almost constant, and compression deformation in radial direction. The permeability of the sample decreases nonlinearly with the confining pressure. In order to more clearly analyze the sensitivity of axial stress and confining pressure to the deformation parameters of samples during the loading and unloading process, the axial strain change rate $\mathcal{E}_1$, radial strain change rate $\mathcal{E}_3$ and permeability change rate $\mathcal{K}$ of samples under unit stress condition are proposed in this paper, as shown in equations (2), (3) and (4).

$$\mathcal{E}_1' = \frac{\Delta \varepsilon_1}{\Delta \sigma} \quad (2)$$

$$\mathcal{E}_3 = \frac{\Delta \varepsilon_3}{\Delta \sigma} \quad (3)$$

$$\mathcal{K} = \frac{\Delta k}{\Delta \sigma} \quad (4)$$

Which, $\Delta \varepsilon_1 = \varepsilon_{1i+1} - \varepsilon_{1i}$, $\Delta \varepsilon_3 = \varepsilon_{3i+1} - \varepsilon_{3i}$, $\Delta \sigma = |\sigma_1 - \sigma_3|$.

According to the test results in Figure 3, the axial strain change rate, radial strain change rate and permeability change rate of sample a₁ corresponding to different stress conditions during loading and unloading are calculated, as shown in Table 1.

Tab. 1 Test results of sample a₁ alternate loading and unloading

σ_1/MPa	7.0	7.0	10.63	10.63	14.25	14.25	17.88	17.88	21.5	21.5
σ_3/MPa	7.0	6.0	6.0	4.0	4.0	6.0	6.0	4.0	4.0	6.0
$\varepsilon_1'/\%$	-	0.30	3.14	0.63	3.39	-0.05	2.94	0.60	2.88	-0.02
$\varepsilon_3'/\%$	-	-0.84	-0.25	-1.19	-0.41	1.00	-0.28	-1.15	-0.47	0.93
$k'/\%$	-	2.30	-0.36	4.83	-0.67	-3.67	-0.56	2.79	-0.22	-2.54

Note: in the axial strain change rate, "+" represents axial compression and "-" represents axial expansion; in radial strain change rate, "+" represents radial compression and "-" represents radial expansion; in permeability change rate, "+" represents permeability increase and "-" represents permeability decrease.

It can be seen from Table 1 that the constant axial stress is 7.0 MPa, the confining pressure is unloaded from 7.0 MPa to 6.0 MPa, the corresponding sample axial strain change rate is 0.3%, radial strain change rate is 0.84%, and permeability change rate is 2.30%. At this time, the permeability change rate is relatively large, while the axial strain change rate is relatively small; When the constant confining pressure is 6.0 MPa and the axial stress is loaded from 7.0 MPa to 10.63 MPa, the sample axial strain change rate is 3.14%, the radial strain change rate is 0.25%, and the permeability change rate is 0.36%. When the constant confining pressure is 6.0 MPa and the axial stress is loaded from 14.25 MPa to 17.88 MPa, the sample axial strain change rate is 2.94%, the radial strain change rate is 0.28%, and the permeability change rate is 0.56%. It can be seen that during the constant confining pressure of 6.0 MPa and the loading axial compression, the sample axial strain change rate is larger, and the radial strain change rate is smaller, and the axial strain change rate of the sample under high axial stress is smaller than the change rate value under low axial stress, while the radial strain change rate and permeability change rate of the sample are larger than the change rate of each parameter under low axial compression. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 10.63 MPa to 14.25 MPa, the sample axial strain change rate is 3.39%, the radial strain change rate is 0.41%, and the permeability change rate is 0.67%. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 17.88 MPa to 21.5 MPa, the sample axial strain change rate is 2.88%, the radial strain change rate is 0.47%, and the permeability change rate is 0.22%. It can be seen that the axial strain change rate of the sample is larger, the radial strain change rate of the sample is smaller when the axial stress is low, and the permeability change rate of the sample is smaller when the axial stress is high. Moreover, the axial strain change rate and the permeability change rate of the sample under high axial stress are lower than the value of change rate under low axial stress, while the radial strain change rate of the sample is opposite. When the constant axial stress is 10.63 MPa and the confining pressure is unloaded from 6.0 MPa to 4.0 MPa, the sample axial strain change rate is 0.63%, the radial strain change rate is 1.19%, and the permeability change rate is 4.83%. When the constant axial stress is 17.88 MPa and the confining pressure is unloaded from 6.0 MPa to 4.0 MPa, the sample axial strain change rate is 0.60%, the radial strain change rate is 1.15%, and the permeability change rate is 2.79%. When the constant axial stress is 14.25 MPa and the confining pressure is loaded from 4.0 MPa to 6.0 MPa, the sample axial strain change rate is 0.05%, the radial strain change rate is 1.0%, and the permeability change rate

is 3.67%. When the constant axial stress is 21.5 MPa and the confining pressure is loaded from 4.0 MPa to 6.0 MPa, the sample axial strain change rate is 0.02%, the radial strain change rate is 0.93%, and the permeability change rate is 2.54%. It can be seen that in the process of constant axial stress and loading-unloading confining pressure, the permeability change rate of the sample is larger, the axial strain change rate of the sample is small, and the change rate value of each parameter under high axial stress is smaller than that the change rate value of each parameter under low axial stress.

It can be seen from the above analysis that constant axial stress and loading-unloading confining pressure have a great influence on the permeability change rate of the sample, while less impact on the radial strain change rate. Constant confining pressure and loading axial stress have a great influence on the axial strain change rate of the specimen, but have little effect on the radial strain change rate.

From the test results in Figure 3(b), the axial strain change rate, radial strain change rate and permeability change rate of sample a_2 corresponding to different stress states during the loading and unloading process can be calculated, as shown in Table 2.

Tab. 2 Test results of sample a_2 alternate loading and unloading

σ_1/MPa	7.0	10.63	10.63	14.25	14.25	17.88	17.88	21.5	21.5
σ_3/MPa	7.0	7.0	4.0	4.0	7.0	7.0	4.0	4.0	7.0
$\varepsilon_1'/\%$	-	3.01	0.52	3.62	0.07	3.01	0.66	3.95	0.03
$\varepsilon_3'/\%$	-	-0.19	-1.28	-0.45	0.91	-0.23	-1.37	-2.02	1.16
$k'/\%$	-	-0.42	3.83	-0.75	-3.11	-0.72	2.20	-0.04	-2.00

Note: in the axial strain change rate, "+" represents axial compression and "-" represents axial expansion; in radial strain change rate, "+" represents radial compression and "-" represents radial expansion; in permeability change rate, "+" represents permeability increase and "-" represents permeability decrease.

It can be seen from Table 2 that when the constant confining pressure is 7.0 MPa and the axial stress is loaded from 7.0 MPa to 10.63 MPa, the axial strain change rate is 3.01%, the radial strain rate is 0.19%, and the permeability change rate is 0.42%. When the confining pressure is 7.0 MPa and the axial stress is loaded from 14.25 MPa to 17.88 MPa, the axial strain rate is 3.01%, the radial strain rate is 0.23%, and the permeability change rate is 0.72%. It can be seen that with a constant confining pressure of 7.0 MPa and loading axial stress, the change rate of axial strain is larger and that of radial strain is smaller. The radial strain change rate and permeability change rate of sample under high axial stress are higher than those under low axial stress, but the axial strain change rate is unchanged. When the confining pressure is 4.0 MPa and the axial stress is loaded from 10.63 MPa to 14.25 MPa, the axial strain rate is 3.63%, the radial strain rate is 0.45%, and the permeability change rate is 0.75%. When the confining pressure is 4.0 MPa and the axial stress is from 17.88 MPa to 21.5 MPa, the axial strain rate is 3.95%, the radial strain rate is 2.02%, and the permeability change rate is 0.04%. It can be seen that the axial strain change rate is larger, and the higher the axial stress, the greater the axial strain change rate. Due to the anisotropy of samples, the radial strain rate and permeability change rate are different.

When the axial stress is 10.63 MPa and the confining pressure is unloaded from 7.0 MPa to 4.0 MPa, the axial strain change rate is 0.52%, the radial strain change rate is 1.28%, and the permeability change rate is 3.83%. When the axial stress is 14.25 MPa and the confining pressure is loaded from 4.0 MPa to 7.0 MPa, the axial strain change rate is 0.07%, the radial strain change rate is 0.91%, and the permeability change rate is 3.11%. When the axial stress is 17.88 MPa and the confining pressure is unloaded from 7.0 MPa to 4.0 MPa, the axial strain change rate is 0.66%, the radial strain change rate is 1.37%, and the permeability change rate is 2.20%. It can be seen that in the process of constant axial stress and loading-unloading confining pressure, the permeability change rate is larger and the axial strain change rate is smaller, and the change rate of each parameter under high axial stress is less than that under low axial stress.

According to the above analysis, under constant confining pressure and loading axial stress, the axial strain change rate of the sample is larger than that of the radial strain change rate. In the process of constant axial stress and loading-unloading confining pressure, the permeability change rate is larger, and the axial strain change rate is smaller, and the change rate of each parameter under high axial stress is less than that under low axial stress.

According to the test results in [Figure 3\(c\)](#), the axial strain change rate, radial strain change rate and permeability change rate of sample a_3 under different stress states during loading and unloading can be calculated, as shown in [Table 3](#).

Tab. 3 Test results of sample a_3 alternate loading and unloading

σ_1/MPa	7.0	7.0	10.63	10.63	14.25	14.25	17.88	17.88	21.5	21.5
σ_3/MPa	7.0	8.0	8.0	4.0	4.0	8.0	8.0	4.0	4.0	8.0
$\varepsilon_1'/\%$	-	0.19	3.16	0.53	3.30	0.15	2.81	0.49	2.74	0.02
$\varepsilon_3'/\%$	-	1.09	-0.16	-1.03	-0.37	1.01	-0.21	-1.09	-0.43	0.93
$k'/\%$	-	-0.41	-0.02	3.29	-0.13	-2.78	-0.31	1.42	-0.21	-1.34

Note: in the axial strain change rate, "+" represents axial compression and "-" represents axial expansion; in radial strain change rate, "+" represents radial compression and "-" represents radial expansion; in permeability change rate, "+" represents permeability increase and "-" represents permeability decrease.

It can be seen from [Table 3](#) that the constant axial stress is 7.0 MPa, the confining pressure is loaded from 7.0 MPa to 8.0 MPa, the sample axial strain change rate is 0.19%, the radial strain change rate is 1.09%, and the permeability change rate is 0.41%. It can be seen that at the initial stage of constant axial stress and loading confining pressure, the radial strain change rate of the specimen is larger, and the axial strain change rate is smaller. When the constant axial stress is 14.25 MPa and the confining pressure is loaded from 4.0 MPa to 8.0 MPa, the sample axial strain change rate is 0.15%, the radial strain change rate is 1.01%, and the permeability change rate is 2.78%. When the constant axial stress is 21.5 MPa and the confining pressure is loaded from 4.0 MPa to 8.0 MPa, the sample axial strain change rate is 0.02%, the radial strain change rate is 0.93%, and the permeability change rate is 1.34%. It can be seen that with constant axial stress and loaded confining pressure,

the permeability change rate of the sample is larger, and the axial strain change rate is smaller, and the change rate of each parameter under high axial stress is smaller than that under low axial stress. When the constant axial stress is 10.63 MPa and the confining pressure is unloaded from 8.0 MPa to 4.0 MPa, the sample axial strain change rate is 0.53%, the radial strain change rate is 1.03%, and the permeability change rate is 3.9%. When the constant axial stress is 17.88 MPa and the confining pressure is unloaded from 8.0MPa to 4.0 MPa, the sample axial strain change rate is 0.49%, the radial strain change rate is 1.09%, and the permeability change rate is 2.79%. It can be seen that with constant axial stress and unloaded confining pressure, the permeability change rate of the sample is larger, and the axial strain change rate is smaller, and the change rate of each parameter under high axial stress is smaller than that under low axial stress. When the constant confining pressure is 8.0 MPa and the axial stress is loaded from 7.0 MPa to 10.63 MPa, the sample axial strain change rate is 3.16%, the radial strain change rate is 0.16%, and the permeability change rate is 0.02%. When the constant confining pressure is 8.0 MPa and the axial stress is loaded from 14.25 MPa to 17.88 MPa, the sample axial strain change rate is 2.81%, the radial strain change rate is 0.21%, and the permeability change rate is 0.31%. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 10.63 MPa to 14.25 MPa, the sample axial strain change rate is 3.30%, the radial strain change rate is 0.37%, and the permeability change rate is 0.13%. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 17.88 MPa to 21.5 MPa, the sample axial strain change rate is 2.71%, the radial strain change rate is 0.43%, and the permeability change rate is 0.21%. It can be seen that under constant confining pressure and axial stress, the axial strain change rate is large, and the variation rate of radial strain and permeability is different due to the anisotropy of specimen.

According to the above analysis, under constant axial stress and loading confining pressure, the permeability change rate is larger and the axial strain change rate is smaller, and the change rate of each parameter under high axial stress is smaller than that under low axial stress. Under constant confining pressure and axial stress, the change rate of axial strain is large, and the change rate of radial strain and permeability is different due to the anisotropy of specimen.

According to the test results in Figure 3(d), the corresponding change rate of axial strain, radial strain and permeability of sample a₄ under different stress states during loading and unloading can be calculated, as shown in Table 4.

Tab. 4 Test results of sample a₄ alternate loading and unloading

σ_1/MPa	7.0	7.0	10.63	10.63	14.25	14.25	17.88	17.88	21.5	21.5
σ_3/MPa	7.0	9.0	9.0	4.0	4.0	9.0	9.0	4.0	4.0	9.0
$\varepsilon_1'/\%$	-	0.48	3.31	0.52	3.69	0.04	2.73	0.54	3.00	0.00
$\varepsilon_3'/\%$	-	0.90	-0.16	-1.12	-0.46	1.03	-0.21	-1.18	-0.73	1.00
$k'/\%$	-	-2.24	-0.30	3.55	-0.60	-3.34	-0.34	2.17	-0.54	-1.98

Note: in the axial strain change rate, "+" represents axial compression and "-" represents axial expansion; in radial strain change rate, "+" represents radial compression and "-" represents radial expansion; in permeability change rate, "+" represents permeability increase and "-" represents permeability decrease.

It can be seen from Table 4 that the constant axial stress is 7.0 MPa, the confining pressure is loaded from 7.0 MPa to 9.0 MPa, the axial strain change rate of the sample is 0.48%, the radial strain change rate is 0.90%, and the permeability change rate is 2.24%. When the axial stress is 14.25 MPa and the confining pressure is loaded from 4.0 MPa to 9.0 MPa, the axial strain change rate is 0.04%, the radial strain change rate is 1.03%, and the permeability change rate is 3.34%. When the axial stress is 21.5 MPa and the confining pressure is loaded from 4.0 MPa to 9.0 MPa, the axial strain change rate is 0.0%, the radial strain change rate is 1.0%, and the permeability change rate is 1.98%. It can be seen that under constant axial stress and loading confining pressure, the permeability change rate is larger and the axial strain rate is smaller; When the constant confining pressure is 9.0 MPa and the axial stress is loaded from 7.0 MPa to 10.63 MPa, the sample axial strain change rate is 3.31%, the radial strain change rate is 0.16%, and the permeability change rate is 0.30%. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 10.63 MPa to 14.25 MPa, the sample axial strain change rate is 3.69%, the radial strain change rate is 0.46%, and the permeability change rate is 0.60%. When the constant confining pressure is 9.0 MPa and the axial stress is loaded from 14.25 MPa to 17.88 MPa, the sample axial strain change rate is 2.73%, the radial strain change rate is 0.21%, and the permeability change rate is 0.34%. When the constant confining pressure is 4.0 MPa and the axial stress is loaded from 17.88 MPa to 21.5 MPa, the sample axial strain change rate is 3.0%, the radial strain change rate is 0.73%, and the permeability change rate is 0.54%. It can be seen that with constant confining pressure and loaded axial stress, the sample axial strain change rate is larger, and the radial strain change rate is smaller; When the constant axial stress is 10.63MPa and the confining pressure is unloaded from 9.0 MPa to 4.0 MPa, the sample axial strain change rate is 0.52%, the radial strain change rate is 1.12%, and the permeability change rate is 3.55%. When the constant axial stress is 17.88 MPa and the confining pressure is unloaded from 9.0 MPa to 4.0 MPa, the sample axial strain change rate is 0.54%, the radial strain change rate is 1.18%, and the permeability change rate is 2.17%. It can be seen that, with constant axial stress and unloaded confining pressure, the permeability change rate of sample is larger, and the axial strain change rate is smaller.

The above analysis shows that with constant axial stress and loading-unloading confining pressure, the permeability change rate of the sample is larger, and the axial strain change rate is smaller. With constant confining pressure and load axial stress, the sample axial strain change rate is larger, and the radial strain change rate is smaller.

3.2 Analysis of coal gas seepage by loading-unloading

According to the test results in Figure 3, the deviatoric stress-permeability curve of each sample under different confining pressures are plotted, as shown in Figure 4.

Fig. 4 Permeability-deviatoric stress curve of samples during alternate loading and unloading under different confining pressure

It can be seen from Figure 4 that during the alternate loading and unloading process, the deviatoric stress of the sample gradually increases under the condition of constant axial stress and unloading confining pressure, and the permeability of the sample increases nonlinearly with the increase of the deviatoric stress, this is because the axial stress is constant, and with the unloading of the confining pressure, the internal micropores and cracks in the sample slowly open, and the gas passing capacity is enhanced. Under the condition of constant confining pressure and axial stress, the deviatoric stress of the sample increases gradually, and the permeability of the sample decreases nonlinearly with the increase of the deviator stress. This is because the confining pressure is constant, the micropores and cracks inside the sample are slowly closed with the loading of the axial stress, the gas passing capacity is weakened, and the permeability of the sample is reduced. Under the condition of constant axial stress and loading confining pressure, the deviator stress of the sample further decreases, and the permeability of the sample decreases nonlinearly with the decrease of the deviator stress. This is because of the constant axial stress, with the loading of the confining pressure, the internal micropores and fissures of the sample are further compacted and closed, the gas permeability channel is blocked, and the gas passing capacity

is weakened, resulting in the decrease of the sample permeability. Subsequently, during the process of constant confining pressure and displacement controlled axial stress, the permeability of the sample decreases nonlinearly with the increase of the deviator stress. When the stress is loaded to the yield stage, cracks appear in the sample, and the permeability of the sample increases slowly. When the sample reaches the ultimate load-bearing capacity, the sample will be destabilized and destroyed, forming a through crack, and the permeability of the sample will increase rapidly, but the permeability of the sample has not reached the initial permeability of the sample under the action of the confining pressure.

The increase and decrease range of the sample permeability under the action of alternate loading and unloading under different confining pressure conditions is shown in Table 5. In the table, "+" means increase, and "-" means decrease. It can be seen that under the condition of constant axial stress, the increase range of sample permeability gradually increases with the increase of unloading confining pressure range, and the increase range of sample permeability after unloading confining pressure at 17.88 MPa is lower than that after unloading confining pressure at 10.63 MPa. Similarly, under the condition of constant axial stress, with the increase of the loading confining pressure range, the decrease range of sample permeability also gradually increases, and the decrease range of sample permeability after loading confining pressure at 21.5 MPa is lower than that after loading confining pressure of 14.25 MPa. Compared with that under the unloading confining pressure, the increase range of permeability is higher than the decrease range of the sample permeability under the increase of confining pressure.

Tab. 5 Increase and decrease range of permeability under loading and unloading

σ_1 /MPa	10.63MPa	17.88MPa	σ_1 /MPa	14.25	21.5
σ_3 /MPa	6→4	+70.54%	4→6	-35.03%	-31.11%
	7→4	+76.65%	4→7	-39.34%	-32.99%
	8→4	+265.04%	4→8	-62.90%	-51.74%
	9→4	+194.51%	4→9	-67.65%	-63.35%

Table 6 and Table 7 show the decrease range of permeability under axial the condition of loading axial stress, and the "-" in the table indicates decrease. It can be seen from Table 6 that when the confining pressure is constant and the axial stress is loaded to 17.88 MPa, the permeability reduction range of the sample is greater than that of the axial stress loading to 10.63 MPa, and with the increase of confining pressure, the decrease range of the sample permeability increases during the loading process. It can be seen from Table 7 that when the constant confining pressure is 4 MPa and the axial stress is loaded from 10.63 MPa to 14.25 MPa, with the increase of the loading and unloading range of the confining pressure, the decrease range of the permeability of the sample shows an increasing trend with the increase of the loading and unloading range of the confining pressure.

Tab. 6 Increase and decrease range of permeability under loading and unloading					
σ_3/MPa		6MPa	7MPa	8MPa	9MPa
σ_1/MPa	7→10.63	-8.67%	-9.24%	-1.32%	-10.54%
	14.25→17.88	-15.03%	-18.25%	-17.06%	-15.58%

Tab. 7 Increase and decrease range of permeability of sample under loading and unloading					
σ_3/MPa		4(6MPa)	4(7MPa)	4(8MPa)	4(9MPa)
σ_1/MPa	10.63→14.25	-10.31%	-10.29%	-2.64%	-8.13%
	17.88→21.5	-4.68%	-0.75%	-6.94%	-11.12%

In the process of loading axial stress and loading confining pressure, the permeability of the sample decreases nonlinearly with the increase of deviatoric stress. During the process of unloading confining pressure, the permeability of the sample increases nonlinearly with the decrease of deviatoric stress.

The relationship between the permeability and the principal stress difference of the fitting sample is in accordance with the negative exponential function, see equation (5):

$$k = a \cdot \exp(-b\sigma') + c \quad (5)$$

Among them, a, b, c are the fitting parameters, which are limited in space. In this paper, the relationship between permeability and principal stress difference of sample a₁ is analyzed, and the fitting curve is shown in Figure 5.

Fig. 5 Relationship curve between permeability of sample a₁ and deviatoric stress during loading-unloading

4. Conclusion

In this paper, the cyclic loading and unloading confining pressure tests of raw coal samples were carried out by using the "Triaxial seepage test device of thermal fluid solid of coal and rock" developed by Chongqing University, the conclusions are as follows:

1) The axial strain change rate ϵ_1' , the radial strain change rate ϵ_3' and the permeability change rate k' under unit stress state are used to represent the sensitivity of axial stress and confining pressure to deformation and permeability characteristics of samples under unit stress state.

2) At the initial stage of unloading the confining pressure, the confining pressure has a greater influence on the permeability of the sample. At the initial stage of loading confining pressure, the confining pressure has a greater influence on the radial strain of the specimen. During the subsequent loading and unloading process, the confining pressure of loading and unloading has a greater influence on the permeability of the sample, and a smaller influence on the axial strain. The loading axial stress has a greater influence on the axial strain of the sample, and a smaller influence on the permeability of the sample.

3) When the axial stress is constant, the increase range of sample permeability increases with the increase of unloading confining pressure range, and the decreasing range of sample permeability increases with the increase of loading confining pressure range, and the increase range of sample permeability under unloading confining pressure is higher than that under increasing confining pressure.

4) In the process of loading axial stress and loading confining pressure, the permeability of samples decreases nonlinearly with the increase of principal stress difference, while the permeability of samples increases nonlinearly with the decrease of principal stress difference in the process of unloading confining pressure.

Data Availability

The data used to support the study is available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' contributions.

Y.Y. conceived the original idea for this study. B. Z. and Y.Y. prepared all samples for analysis. B.Z. collected and analysed the data. Y.Y. wrote the manuscript. All the authors gave their final approval for publication.

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Figures

Figure 1

Tri-axial stress thermal-hydrological-mechanical Coal Gas Permeameter

Figure 2

Raw coal sample

Figure 3

Deviatoric stress-strain-permeability curves of each sample during loading and unloading

Figure 4

Permeability-deviatoric stress curve of samples during alternate loading and unloading under different confining pressure

Figure 5

Relationship curve between permeability of sample a1 and deviatoric stress during loading-unloading