Study on the permeability characteristics of coal containing coalbed methane under different loading paths

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Abstract
During the degassing process of coalbed methane, the external loads could change the permeability of the coal seam by means of transient and permanent deformations, which dramatically influence the production efficiency of coalbed gas. Due to the ignorance of irreversible deformation of coal permeability, the gas extraction efficiency and the prediction of gas disaster in underlying mining need to be improved. Thus, it is better to clarify the permeability change characteristics with irreversible deformation of coal. In this paper, the influence of different loading paths on the permeability of gas-containing coal was studied, and six loading paths were studied by employing a self-designed triaxial cyclic loading system. The results of this study show that the permeability of gas-containing coal samples would significantly change with different loading paths. Corresponding to the variation of mining pressure or periodic geo-stress varying in the excavation of roadways, both an increase in the axial pressure and an increase in the confining pressure would cause a decrease in gas permeability. In addition, the permeability of gas-containing coal would be damaged even when the external loads are removed. When given a constant strain loading, the permeability shows a “V”-shaped change with increased strain, and the transversal point of permeability locates between the yield point and the peak intensity. Therefore, it can be concluded that external loads less than the maximum strength of coal would lead to permeability loss in the coal seam, vice versa, the permeability will be increased. Hence, research results contributes to improving the gas permeability and increasing the gas production from coalbed by imposing effective loads on original coal seams through mining speed control.

Keywords
gas-containing coal, loading path, permeability, permeability damage rate

1 | INTRODUCTION

Coalbed methane mainly consists of CH₄ and is regarded as one of the sources of coal-gas outburst and explosions in underground coal mining.¹⁻⁴ It has been considered a typical unconventional natural gas since the 20th century, and the total amount of coalbed methane gas is estimated to be more than 89.4 × 10¹² m³ worldwide, which is comparable...
to the conventional natural gas reserves. However, coal is a typical pore-fracture dual medium, and the physical behavior is entirely consistent with coal being viewed as a dual porosity-dual permeability-dual stiffness continuum. The gas flow in coal seam is a very complex transportation process, including gas desorption, diffusion, sorption, and seepage processes. The permeability of gas-containing coal is the most important physical property, which is usually employed to estimate the capacity of coalbed gas drainage from the coal seam. The transient permeability in a fractured porous medium is primarily determined by the geometry and interconnectedness of the pores and the fractures as well as by the stress state. The permeability also shows strong correlations with burial depth, stress, and physical properties. In addition, the connection between fine pores and fractures is also beneficial to the permeability of the coal seam.

However, the pore and fracture structures of the coal are sensitive to external loads applied on the coal seam. On the one hand, external loads would lead to the closure of the original fracture, which decreases the permeability of the coal seam. On the other hand, external loads may facilitate the growth of new fractures, thus increasing the permeability of the coal seam. Furthermore, the desorption of coalbed methane is accompanied by the coal matrix shrinkage, resulting in the increase of the net permeability. With the extension of mining into deeper coal seams, the coal seam will encounter high geo-stress and high gas pressure. Both mining activities and coalbed methane drainage would break the balance of geo-stress, thus causing coal and rock deformation and changing the permeability of the coal seam. It is extremely significant to investigate the effect of multiple loading rates on the crack propagation of brittle material. Therefore, predicting the permeability change tendency under external loading is important for coalbed methane exploitation. Considering the factors of geo-stress, gas and coal physical and mechanical properties, the interaction between coal and gas is the trend and key point of current research.

To determine the permeability in coal specimens, a series of core-flooding experiments has been conducted for CO$_2$ flow under various effective stress conditions. Although permeability uncertainty still exists in different stresses conditions, the cause of permeability variation in coal samples has been tested by experiments at various confining stresses and pore pressures. Under uniaxial strain condition, Feng et al. have measured the permeability variation of coal by using the pressure pulse delay method. Likewise, the gas permeability of natural brown coal and reconstituted coal specimens has been tested in different effective stress and coal swelling. In addition, a number of permeability models have been developed for coal seams with methane gas. Due to the reversible deformation and irreversible extension of fractures in coal, cyclic loading of coals impacts permeability. It has been concluded that the whole stress-strain curve of the coal sample shows a reduced linear relationship with the seepage velocity in the triaxial gas seepage test process.

Allowing for the internal actions between coal fractures and matrices, a more accurate approach with various mechanic conditions has been developed to characterize the evolution of coal permeability, and the change in coal permeability has been successfully obtained by total “push back” strain. Moreover, the study of seepage-flow coal samples with cyclic loading under conditions of constant gas pressure and varying confining pressures shows that both the elastic modulus and the permeability of coal samples tend to decrease with an increased number of cycles, besides the decline is most obvious in the first cycle. Although a number of previous studies were conducted based on the elastoplastic constitutive relationship, the influence of nonmonotonic changes in load on the permeability of gas-containing coal has not been considered; thus, the influence of irreversible deformation on permeability has been essentially neglected. Through an experimental study under different stress paths, this paper attempts to explore the permeability variation characteristics of gas-containing coal to improve the gas permeability and increase the gas production by imposing effective loads on original coal seams through mining speed control, which contributes to providing a scientific basis for theoretical control of gas disasters in underground mining.

2 | EXPERIMENTAL PROCEDURES

2.1 | Experimental apparatus and preparation of coal samples

A self-developed triaxial servo fluid-solid coupling system was employed in this study, which allows the testing of permeability under different conditions. The system mainly includes a confining pressure system with a maximum loading pressure of 25 MPa, a gas supply and acquisition system with a maximum supplied pressure of 6 MPa, a triaxial infiltration system with a maximum pressure of 70 MPa, a gas-measuring system with a measuring range of 100 sccm (standard cubic centimeter per minute), 15 slm and 2 slm (standard liter per minute), and a constant temperature water bath system with a temperature range of −25°C to 95°C. All the data in the system were automatically recorded by the computer, as shown in Figure 1.

Coal samples were obtained from the Luban Northern Coal Mine in South Sichuan Coal Luzhou Co., Ltd., which locates in Yibin of Sichuan Province, China. The coal mine contains several minable coal seams. In order to avoid uncertain disturbance on the measured coal samples, all the coal samples were drilled parallel to the coal seam #2 with an inclined angle of 25 degrees, which facilitates to reducing the
compaction and shrinkage of the prepared coal samples. The coal mine has been defined to have the risk of coal-gas outburst since the in situ pressure of the coal seam is 1.61 MPa and the coal hardness coefficient is 0.492. The in situ temperature of coal seam #2 is 35°C. According to industrial analysis results, the basic parameters of coal seam #2 are shown in Table 1.

The original integrity of the raw coal was recovered by employing a core barrel with a diameter of 50 mm, and each core was cut to a length of 100 mm. All prepared coal samples were dried and saved in a drying oven at constant temperature. An ultrasonic measurement system was employed to ensure that all samples were under the same condition. Typically, prepared coal samples are shown in Figure 2.

### 2.2 | Test procedures

Methane gas with a purity of 99.99% was used for seepage flow of gas-containing coal under different stress-loading paths. Before the loading experiments, all coal samples were numbered and covered with a sample rubber. A layer of silicone was employed to seal the annulus between the coal sample and the sample rubber. Once the experimental apparatus was installed, first, the confining pressure was loaded to the predetermined value. Then, a predetermined axial pressure was applied to the coal sample, and the device was filled with gas to a certain pressure to check its airtightness. After the airtightness inspection was done, the gas valve was opened, and gas was injected into the coal sample to a preset pressure. The initial gas flow was recorded when the gas flow rate stabilized. Afterward, seepage tests were performed under different stress paths.

### 2.3 | Stress path setting

Permeability tests of gas-containing coal under the following six paths were conducted. Each path was named “Path” followed by a roman numeral, with details as follow:

- **Path I:** The confining pressure was maintained at 2 MPa and the gas pressure at 0.5 MPa during the whole-loading process. The axial pressure was then increased to 10 MPa with a gradient of 2 MPa. Each step of axial pressure was kept constant until the gas flow rate stabilized.

- **Path II:** At the end of path I, the axial pressure was maintained at 10 MPa, and the confining pressure was increased to 10 MPa with a gradient of 2 MPa. Each step of confining pressure was kept constant until the gas flow rate stabilized.

- **Path III:** After the loading phase of paths I and II, both the axial pressure and confining pressure were maintained at 10 MPa. The gas pressure was increased to 2.5 MPa with a gradient of 0.5 MPa, and each step of gas pressure was kept constant until the gas flow rate stabilized.

### Table 1 Basic parameters of coal seam #2

| Items                                      | Value |
|--------------------------------------------|-------|
| True density (g/cm³)                       | 1.62  |
| Ash content (%)                            | 9.07  |
| Volatile matter (%)                        | 6.29  |
| Total sulfur (%)                           | 0.65  |
| Carbon content (%)                         | 92.52 |
| Reflectance of vitrinite (%)               | 3.03  |
| True density (g/cm³)                       | 1.59  |
| False density (g/cm³)                      | 1.56  |
Path IV: After the completion of the loading test in paths I-III, a new coal sample was placed, and the gas permeation test was carried out under the thorough stress-strain conditions with a constant confining pressure and a gas pressure of 2 and 0.5 MPa, respectively. A strain control load of 0.2 mm/min was applied until the coal sample was damaged under quasi-static conditions.

Path V: A new coal sample was tested, presetting the gas pressure and axial pressure to 0.5 and 2 MPa, respectively. The confining pressure was increased to 10 MPa with a gradient of 2 MPa and then decreased with a gradient of 2 MPa after reaching 10 MPa. Each step of gas pressure was kept constant until the gas flow rate stabilized.

Path VI: Without changing the coal sample after conducting the loading in path V, the gas permeation test under complete stress-strain conditions with a strain control load of 0.2 mm/min was directly conducted.

3 TEST RESULTS AND DISCUSSIONS

A total of nine gas-containing coal samples were tested under various stress conditions. All of the coal samples were divided into three groups, and each group of sample tests was conducted by following different loading paths. During the experiment, the gas migration in a coal seam was basically in accordance with the rule of linear infiltration—Darcy’s law, and the permeability of coal containing methane gas can be calculated by equation 1 as:

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

where \( k \) is the coefficient of permeability, \( Q_e \) is the exit flow rate of the gas, \( P_e \) is the exit pressure of the gas, \( L \) and \( A \) are the length and cross-sectional area of the coal sample, \( P_i \) is the entrance pressure of the gas, and \( \mu \) is the viscosity of the gas at the tested temperature.

After completing the experimental tests, the permeability under the different stress paths of gas-containing coal samples was calculated by using Equation (1). The tests results are shown in Figures 3-8.

3.1 Relationship between the permeability and stress of gas-containing coal

Figures 3-5 show the test results obtained following by Path I to Path III, in which the permeability of the gas-containing coal sample deceases nonlinearly both with increasing axial stress and confining pressure, but it increases with increasing gas pressure. The relationships of the axial pressure and the confining pressure with the permeability of the gas-containing coal sample are logarithmic functions, and the relationship between the gas pressure and the permeability of a gas-containing coal sample shows a quadratic function change that is consistent with the result of the study conducted by Yin et al.\textsuperscript{30} It can be attributed to the effective stress change in the loading process.\textsuperscript{14} Meanwhile, the effective stress of the coal sample can be calculated as:

\[ \sigma' = \sigma - P, \]

where \( \sigma' \) is the effective stress, \( \sigma \) is the total stress supported by the coal sample, and \( P \) is the gas pressure.
While conducting the experiment following Path I and Path II, increasing the axial pressure and confining pressure would cause an increase in the effective stress in the axial direction and radial direction, respectively. Nevertheless, increasing the gas pressure would decrease the effective stress in both the axial and radial directions. It is known that the permeability of rocks depends on the effective flow cross-sectional area, which consists of connected pores and fractures. However, the original fractures in the rock body are sensitive to stress, and the increased effective stress would close the narrow fractures, thus decreasing the effective flow cross-sectional area. Furthermore, the coal sample is compressed more densely with an increase in effective stress. The pore diameter of the coal sample becomes smaller, which also would reduce the effective flow cross-sectional area. The increased gas pressure would reduce the effective stresses in both the axial and radial directions, thus enlarging the effective flow cross-sectional area and improving the permeability of gas-containing coal samples.

Meanwhile, the transient permeability of coal matrix is decreasing with the increased bulk stress, which results from the continuous compaction of coal with constant increasing level of axial pressure and confining pressure. According to the permeability variation curve of measured coal sample, it can be concluded that the closure of fractures is unrecoverable during the compaction of coal matrix, thereby the hysteresis loop exists between the permeability and axial stress, which is concluding in accord with the research results of Li.29

With respect to the variation of gas pressure on the permeability of coal samples, the formation and through-going expansion of fractures play significant roles, as shown in Figure 5. It can be inferred that the increase of coal permeability results from the accumulation and connection of microfractures inside the coal matrix, and the maximum
3.2 | Relationship between the permeability and strain of gas-containing coal

Figures 6 and 8 show the testing results obtained following Path IV and Path VI, in which the permeability of the gas-containing coal samples first decreases with the increase in strain, and then reverses when the strain of the coal samples reaches a critical value. The relationship between the permeability and strain of gas-containing coal shows a “V”-shaped change.

It can be illustrated that the effective stress of the coal sample would increase with the increasing strain, and the coal sample would experience microcrack closure and the elastic deformation stage; therefore, the permeability of coal samples decreases with increased stress. With the continuous increase in strain, the coal sample would enter the yielding stage. The permeability of the coal sample would be the minimum value before reaching the peak intensity, and then, the microcracks inside the coal sample would begin to expand, and the expansion of the microcracks would increase in the gas seepage channel. When the coal sample enters the peak-stress and the post-peak-stress zones, formation and expansion of the macrocracks caused by the microcrack expansion will occur inside, causing the permeability of gas-containing samples to naturally show a trend of a “V”-shaped change. Therefore, the trend of this “V”-shaped change is a macroscopic reflection of the change in the effective stress of the coal sample and the continuous expansion of internal cracks in the coal sample. However, the coal samples are always in a condition of compaction. Thus, the micro- and macrocracks caused by stress would experience generative and closing processes, and the increase in permeability caused by these generated micro- and macrocracks would be limited.

3.3 | Damage rate of the permeability

Figure 7 shows the changes in the permeability of a gas-containing coal sample under cyclic loading following Path V. The relationship between the permeability and the confining pressure can be described by a logarithmic function for each loading step, which can be expressed as:

\[ k = a + b \ln (\sigma_3), \]

where \( a \) and \( b \) are the fitting constants and correlation coefficients for each loading step following Path V, which are shown in Figure 7. With the process of cyclic loading, the difference in the fitting constants between two adjacent steps decreases significantly. It means that the permeability of the coal samples under cyclic loading would gradually tend to
stabilize, which is the same result obtained in the study by Li et al. 29

There are significant differences in the permeability-confining pressure curves between two loading steps, and the coal sample permeability during the process of decreasing the confining pressure is smaller than that during the process of increasing the confining pressure. It can be implied that the permeability of the coal sample cannot be recovered in the loading process, and the permeability of the coal samples would be damaged in the cyclic loading. As shown in Figure 7, the permeability-confining pressure curves do not overlap after three cycles of loading and unloading. Moreover, the pore space inside coal sample will be reduced with each single loading and unloading process, and the adjacent cracks will be spontaneously compacted to constant volume, thereby the permeability of coal sample is decreasing. Besides, the decreased permeability of coal samples can usually be assessed by employing the permeability damage rate. 31 The permeability damage rate of coal sample can be calculated as follows:

\[ D_k = \frac{k_0 - k_1}{k_0} \times 100\% \]  

(4)

where \( D_k \) is the permeability loss of coal samples, \( k_0 \) is the coal sample permeability measured at the first stress point during the rise in confining pressure, and \( k_1 \) is the permeability of the coal sample measured at the last stress point during the drop in confining pressure. The greater the permeability damage rate is, the worse the recovery of the permeability of the rock sample will be.

In addition, the amplitude of the reduction of the permeability of a coal sample under loading can be assessed by the maximum permeability damage rate. The greater the maximum permeability damage rate is, the greater the decrease of the permeability of coal samples will be. In addition, the damage under stress loading can be assessed by the maximum permeability damage rate:

\[ D_{\text{max}} = \frac{k_0 - k_{\text{min}}}{k_0} \times 100\% \]  

(5)

where \( D_{\text{max}} \) is the maximum permeability damage rate of the coal sample, and \( k_{\text{min}} \) is the coal permeability measured at the maximum effective stress point.

Table 2 shows the damage rate and maximum damage rate of the coal sample while loading as according to Path V. For the first loading and unloading cycle, the maximum permeability damage rate of gas-containing coal samples is 58.33%, and the permeability damage rate is 27.08%. It can be shown that the permeability of coal samples will be reduced to 72.92% once the first cycles of loading and unloading stress have been completed in terms of the confining pressure. In respect to the calculation data of the permeability damage of a coal sample in Table 2, the maximum permeability damage rate of the coal sample gradually decreases with the increase of the confining pressure and unloading frequency. The permeability damage rate of coal samples is also gradually reduced with the loading and unloading of the confining pressure.

While the confining pressure and unloading frequency are increasing, the internal particles inside the coal matrix will be damaged due to the failure of fracture connection. It can be analyzed that the fractures are closed to fall off the coal matrix, then will be thoroughly compacted to block the seepage path of methane gas; thus, the permeability of coal samples will be eventually decreased, likewise the maximum permeability damage rate of measured coal seam will be reduced.

The damage rate of the first loading is the largest. With the increase in the confining pressure and the cycles of loading and unloading, the coal permeability damage rate decreases gradually. The permeability changes of the coal samples can also reflect changes in the effective porosity of coal samples during the test, that is, the decrease in permeability indicates the decrease in effective porosity. The porosity of the coal sample is also damaged after one loading-unloading cycle of the confining pressure is completed, and its damage rate is equal to the permeability damage rate, namely, 27.08%, which is in accordance with the theory of recompaction of coal samples under cyclic loading.

In summary, it can be concluded that various loading paths have significant influence on the permeability of coal seam, and the permeability of coal can accordingly be damaged due to the frequent loading. However, corresponding activities will damage the stress status, such as the underlying excavating and mining, presplitting and blasting, hydraulic fracturing, and other methods for improving the permeability of coal seam. The loading and unloading effects will occur during those process, which can dramatically change the original permeability of coal seam, especially mining with protective roof. Therefore, research results contribute to providing theoretical supports for choosing the efficient protective roof and outstanding suggestions to improve the permeability of gassy coal seams.

### Table 2 Permeability damage rate of tested coal sample under cyclic loading

| Loading cycle         | \( D_{\text{max}} \) (%) | \( D_k \) (%) | \( D \) (%) |
|-----------------------|--------------------------|---------------|-------------|
| Loading and unloading 1 | 58.33                    | 27.08         | 27.08       |
| Loading and unloading 2 | 54.29                    | 25.71         | 45.83       |
| Loading and unloading 3 | 51.92                    | 23.08         | 58.33       |

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

### 4 CONCLUSIONS

With the drainage of coalbed methane from the coal seam, the external loads resulting from the loss of gas pressure in
the coal seam or the coal mining activities in deeper coal mines would change the permeability characteristics of the coal seam. In the present paper, the influence of different loading paths on the permeability variation of gas-containing coal was studied, and six loading path experiments were conducted by employing a self-designed three-axis cyclic-loading system. According to the experimental results, the following conclusions can be drawn:

1. The permeability of gas-containing coal samples will significantly change with different loading paths. Increase in both the axial and confining pressures would reduce the gas permeability due to the increased effective stress caused by the increasing axial and confining pressure. In addition, the relationship between them follows the logarithmic function.

2. The relationship between gas pressure and permeability follows a quadratic function, and the permeability increases with increasing gas pressure, which is attributed to the reduced effective stress caused by the increased gas pressure. The permeability of gas-containing coal would remain damaged even after the external loads are removed.

3. When given a constant strain loading, the permeability tends toward a “V”-shaped change with increased strain, and the transversal point of permeability is located between the yield point and the peak intensity. Therefore, it can be concluded that external loads less than the maximum strength of coal would lead to the loss of permeability in coal seams, and employing effective methods to damage the original coal structure can improve the gas permeability of the coal seams, which contributes to increasing the coalbed gas production.

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CONFLICT OF INTEREST
The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my coauthors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. Meanwhile, the founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHOR CONTRIBUTIONS
Fakai Wang and Yunpei Liang conceived and designed the experiments; Yongjiang Luo and Lei Li performed the experiments; Jiangfu He and Zhiwei Liao analyzed the data; Yongjiang Luo and Jiangfu He wrote the paper.

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