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Experimental Study on Gas Permeability Characteristics of Coal-Mudstone Composites

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Abstract

To investigate the gas permeability characteristics of coal-mudstone composites, helium seepage tests were conducted under different confining pressures and inlet gas pressures using a triaxial testing system. The effects of gas pressure and confining pressure on permeability were examined, and the Klinkenberg and negative exponential models were used to evaluate gas slippage and stress sensitivity, respectively. The results show that permeability generally decreases with increasing inlet gas pressure, although the reduction varies under different confining pressures. The Klinkenberg model describes the overall trend, while the fitted slippage factor shows a nonmonotonic variation with confining pressure. Permeability also decreases markedly as confining pressure increases, with a rapid reduction at lower confining pressures followed by a slower decline. The relationship between permeability and confining pressure is well described by a negative exponential model, with R2 values exceeding 0.998. The stress sensitivity coefficient increases with inlet gas pressure, indicating different responses to confining pressure under varying gas-pressure conditions. These findings provide experimental evidence for understanding pressure-dependent gas transport in coal-mudstone composites.

Keywords

Coal-Mudstone Composite; Permeability; Confining Pressure; Gas Pressure; Klinkenberg Effect; Stress Sensitivity

1. Introduction

Coal-bearing strata are generally composed of coal seams and surrounding rocks, such as mudstone and sandstone. The permeability of these rocks plays an important role in gas migration and coalbed methane extraction. Under different stress conditions, changes in pore and fracture structures can affect gas flow through coal-bearing formations[1]. Therefore, investigating the permeability characteristics of coal-rock composites is important for understanding gas transport and improving gas extraction efficiency.

Previous studies have examined the effects of coal–rock interfaces[2], confining

pressure[3], and mechanical loading[4] on the permeability of coal–rock composites. Due to differences in mechanical properties and pore–fracture structures, coal and mudstone may exhibit different deformation responses under loading. Increasing confining pressure tends to compress pores and fractures, leading to a reduction in permeability[5]. Meanwhile, variations in gas pressure may affect the apparent permeability through gas slippage. However, the permeability response of coal–mudstone composites to changes in gas pressure under different confining pressures remains insufficiently understood, particularly with regard to gas slippage and stress sensitivity.

In this study, gas seepage tests were conducted on a coal-mudstone composite under different confining pressures and gas pressures using a triaxial seepage testing system. The variations in permeability were analyzed to determine the effects of confining pressure and gas pressure on gas transport. The Klinkenberg model was used to evaluate the gas slippage effect, while an exponential model was employed to characterize the stress sensitivity of permeability. The results provide experimental data for understanding the seepage characteristics of coal-mudstone composites and offer a reference for gas migration in coal-bearing strata.

2. Experimental Materials and Methods

2.1. Sample Preparation

The coal and mudstone samples used in this study were collected from the Yongcheng mining area in Henan Province, China. The collected samples were processed into cylindrical specimens with a diameter of 50 mm and a height of 50 mm. The coal and mudstone specimens were then combined along the axial direction to form coal-mudstone composite specimens with a diameter of 50 mm and a total height of 100 mm. The prepared composite specimens were used for gas seepage tests under different pressure conditions, as shown in Figure 1.



Figure 1. Coal-mudstone composite specimen.

2.2. Experimental Apparatus

Gas seepage tests were conducted using a rock triaxial rheological testing system

jointly developed by Luoyang Institute of Science and Technology and Nantong Yanchuang Petroleum Technology Co., Ltd., China. The experimental system mainly consists of a loading system, a confining-pressure control system, a gas pressure control system, a specimen chamber, and a data acquisition system. High-purity helium (He), a non-adsorbing gas, was used as the seepage medium to minimize the influence of gas adsorption on permeability measurements. The loading system was used to apply axial and confining pressures, while the gas pressure was controlled by the gas supply system. During testing, the confining pressure, inlet gas pressure, outlet gas pressure, and gas flow rate were continuously monitored and recorded. The experimental apparatus is shown in Figure 2.



Figure 2. Rock triaxial seepage testing system.

2.3. Experimental Scheme and Procedure

To investigate the effects of confining pressure and gas pressure on the permeability of coal-mudstone composites, gas seepage tests were designed under different pressure conditions. Considering the low permeability of mudstone and the differences in gas flow capacity under different confining pressures, the initial inlet gas pressure was set at 0.6 MPa based on preliminary tests. Four confining-pressure levels of 3, 6, 9, and 12 MPa and five inlet gas-pressure levels of 0.6, 0.9, 1.2, 1.5, and 2.0 MPa were adopted. The experimental conditions are listed in Table 1.

Before testing, the composite specimen was installed in the triaxial pressure chamber and sealed to prevent gas leakage. Axial and confining pressures were then applied to establish the required stress conditions. Helium was introduced into the specimen through the inlet, and the gas pressure was varied during the seepage test. The inlet pressure, outlet pressure, and gas flow rate were recorded by the data acquisition system. The seepage behavior of the composite was analyzed under different confining-pressure and gas-pressure conditions.

Table 1. Experimental Pressure Conditions for Coal-Mudstone Composites.

Group	Actual Confining Pressure (MPa)	Inlet Gas Pressure (MPa)
Group 1	3	0.6, 0.9, 1.2, 1.5, 2.0
Group 2	6	0.6, 0.9, 1.2, 1.5, 2.0
Group 3	9	0.6, 0.9, 1.2, 1.5, 2.0
Group 4	12	0.6, 0.9, 1.2, 1.5, 2.0

3. Results and Discussion

3.1. Effect of Gas Pressure on Permeability

Figure 3 shows the variation in permeability with inlet gas pressure under different confining pressures. The permeability of the coal-mudstone composite decreased with increasing gas pressure, although the variation differed among the four groups. At 3 MPa, permeability decreased slightly and remained relatively stable, whereas a more pronounced decline was observed at 6 MPa. At 9 MPa, the reduction was mainly concentrated in the low-pressure range of 0.6-0.9 MPa, followed by a gradual stabilization. In contrast, only minor changes were observed at 12 MPa. This pressure dependence is consistent with the Klinkenberg effect, in which gas slippage contributes to higher apparent permeability at low pressures[6]. As gas pressure increases, the relative contribution of slippage decreases, leading to a reduction in measured permeability. Changes in pore pressure and effective stress may also influence the permeability response.

To examine the gas slippage effect, the permeability data were fitted using the Klinkenberg model[7], with the results presented in Table 2. The fitting coefficients (R2) ranged from 0.829 to 0.988, with the highest value obtained at 6 MPa. The relatively lower R2 at 9 MPa was associated with the sharp permeability reduction in the low-pressure range. The fitted slippage factor increased from 0.0237 MPa at 3 MPa to 0.2869 MPa at 9 MPa, but decreased to 0.0622 MPa at 12 MPa. Unlike the intrinsic permeability, which decreased across the four groups, the slippage factor showed no consistent trend with confining pressure. This nonmonotonic variation may be related to differences in gas flow through the pore-fracture network under different loading conditions, although the influence of effective stress cannot be excluded.

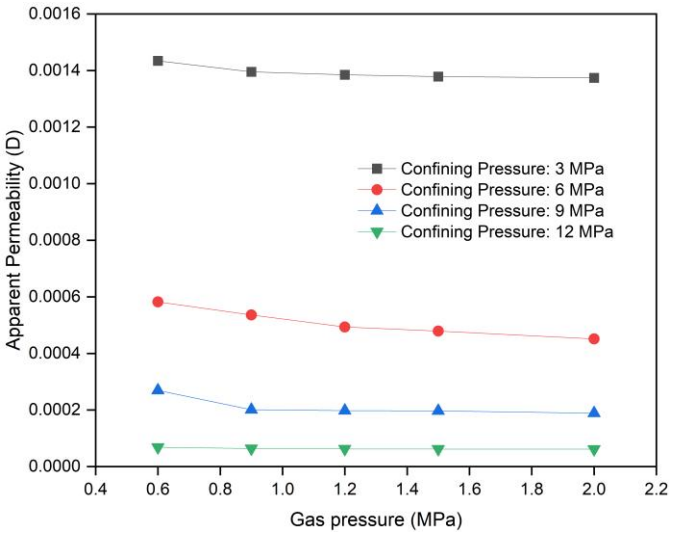


Figure 3. Permeability variation with inlet gas pressure under different confining pressures.

Table 2. Klinkenberg Fitting Results under Different Confining Pressures.

Confining Pressure (MPa)	Fitting Equation	R^2	Slippage Factor b (MPa)	Intrinsic Permeability (D)
3	k=0.001339(1+0.0237/pm)	0.958	0.0237	0.001339
6	k=0.000390(1+0.1762/pm)	0.988	0.1762	0.000390
9	k=0.000141(1+0.2869/pm)	0.829	0.2869	0.000141
12	k=0.0000576(1+0.0622/pm)	0.922	0.0622	0.0000576

3.2. Effect of Confining Pressure on Permeability

Figure 4 shows the variation in permeability with confining pressure at different inlet gas pressures. The permeability of the coal-mudstone composite decreased continuously as confining pressure increased from 3 to 12 MPa. A marked reduction occurred between 3 and 6 MPa, followed by a progressively smaller decrease at higher confining pressures. At an inlet gas pressure of 0.6 MPa, permeability decreased from 0.001434 D to approximately 0.000069 D, representing a reduction of about 95%. Similar trends were observed at other gas pressures, with only small differences among the five groups. The initial rapid decrease can be attributed to the compression and closure of pre-existing pores and fractures, which reduces the available gas flow paths. As confining pressure increases further, the remaining flow paths become less compressible, resulting in a slower decrease in permeability. The response may also be influenced by deformation at the coal-mudstone interface[8].

The relationship between permeability and confining pressure was fitted using an exponential model, and the results are listed in Table 3. The coefficients of determination ranged from 0.9984 to 0.9998, showing good agreement between the fitted curves and experimental data. The stress sensitivity coefficient increased from 0.29647 MPa-1 at an inlet gas pressure of 0.6 MPa to 0.35561 MPa-1 at 2.0 MPa.

This increase reflects a greater relative reduction in permeability with confining pressure at higher inlet gas pressures within the tested range. The exponential relationship describes the stress-dependent permeability of the composite, although the fitted coefficients may also be affected by changes in pore pressure and gas flow conditions[9].

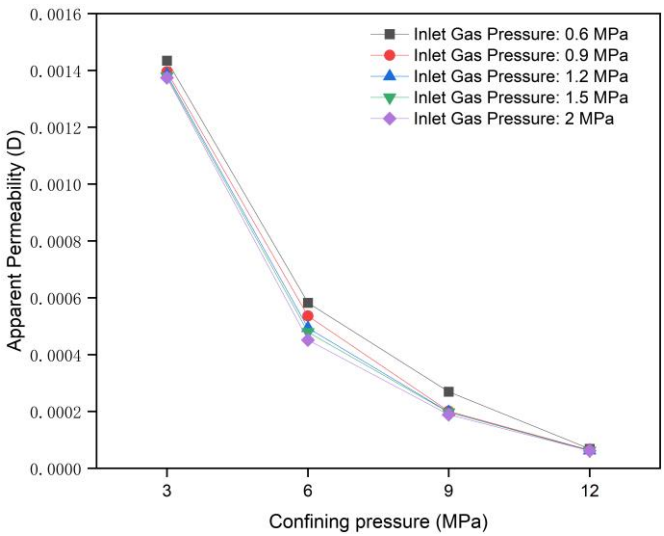


Figure 4. Permeability variation with confining pressure under different inlet gas pressures.

Table 3. Exponential Fitting Results of Permeability under Different Gas Pressures.

Gas Pressure (MPa)	Fitting Equation	R^2	Stress Sensitivity Coefficient (MPa-1)
0.6	k=0.003489e^{-0.29647σ3}	0.9984	0.29647
0.9	k=0.003680e^{-0.32289σ3}	0.9998	0.32289
1.2	k=0.003804e^{-0.33719σ3}	0.9997	0.33719
1.5	k=0.003840e^{-0.34211σ3}	0.9994	0.34211
2	k=0.003983e^{-0.35561σ3}	0.9989	0.35561

4. Conclusions

In this study, gas permeability tests were conducted on coal-mudstone composites under different confining pressures and inlet gas pressures. The main conclusions are as follows:

- The permeability of the coal-mudstone composite generally decreased with increasing inlet gas pressure, although the reduction varied under different confining pressures. The decrease was more pronounced at 6 and 9 MPa, while relatively small changes were observed at 3 and 12 MPa. This behavior is consistent with the weakening of gas slippage as gas pressure increases.
- The Klinkenberg model provided a reasonable fit to the permeability data, with R2 values ranging from 0.829 to 0.988. The fitted slippage factor initially increased and then decreased with increasing confining pressure, reaching a maximum of 0.2869 MPa at 9 MPa. The results indicate that the gas-pressure dependence of permeability varies with the confining conditions.

- The permeability decreased markedly with increasing confining pressure, with the greatest reduction occurring between 3 and 6 MPa. The relationship between permeability and confining pressure was well described by a negative exponential model, with R2 values ranging from 0.9984 to 0.9998. The stress sensitivity coefficient increased from 0.29647 to 0.35561 MPa-1 as the inlet gas pressure increased from 0.6 to 2.0 MPa.

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