Research Article

Effect of Stress and Moisture Content on Permeability of Gas-Saturated Raw Coal

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Hydraulic fracturing and premining gas drainage are important to safe mining and coalbed methane extraction. These technical processes cause the redistribution of in-situ stress and the regional variation of moisture contents within the affected zone. Therefore, we investigated the coupled effect of variable stresses (from 9 MPa to 27 MPa) and moisture contents (from 0.22% to 4.00%) on the permeability evolution of gas-saturated raw coal. The results show that (1) the relationship between the mean effective stress and the permeability can be described by a power function according to the permeability evolution model of the porous matrix established in this study. Besides, the influence mechanisms of moisture on fitting coefficients in the function were analyzed. (2) The permeability decreases with the increase of in-situ stress (e.g., confining pressure or volumetric stress) in a negative exponential manner. (3) The curves of permeability variations with moisture content are not always linear, and the permeability is more sensitive to the moisture content than the volumetric stress in the test range. Moreover, the sensitivity of permeability varies in different regions. These results would be beneficial for permeability prediction and surface well parameters design.

1. Introduction

Coalbed methane (CBM) is an abundant valuable resource in underground coal mines. It is estimated that China bears approximately 36.8 trillion m³ of CBM in its reservoirs shallower than 2 km, ranking the third country in the world [1]. Qinshui Basin whose CBM reserve accounts for 1.08% of the total CBM reserve in China is one of the largest CBM reservoirs [2]. However, the reservoir is generally characterized by low permeability, which seriously inhibits efficient CBM extraction [3]. In-situ surface well extraction is a technique for enhancing the permeability and relieving the pressure of coal seams. Permeability is a key parameter for surface well design, and its temporal and spatial variations remarkably

affect the occurrence state, migration, and extraction of CBM [4]. Scholars have conducted extensive researches on the factors influencing permeability, including in-situ stress field [5], gas pressure [6], Klinkenberg effect [7], geothermal field [8], geoelectric field [9], acoustic field [10], and physical properties [11]. These findings have allowed the mechanics of permeability evolution to be deliberated and also provided an adequate data volume and dimension for machine learning which has been proven to be a powerful tool for permeability prediction [12, 13]. Specifically, the process of fracturing, drainage, and gas extraction in surface wells destroys the original stress distribution balance and results in the existence of stress concentration or relief region [14]. Besides, the large amount of fracturing fluids leads to

TABLE 1: Proximate analysis results and adsorption constants of coal samples.

Proximate analysis			True density (t/m^3)	Bulk density (t/m^3)	Porosity (%)	Absorption constant	
$M_{ad}(\%)$	$A_{ad}(\%)$	$V_{daf}(\%)$				a ($\text{cm}^3/\text{g}_{\text{daf}}$)	b (MPa^{-1})
0.49	10.31	16.01	1.46	1.43	2.05	34.14	0.80

regional differences in water-bearing conditions. Therefore, special attention needs to be paid to in-situ stress and moisture content of coal seam for the sake of permeability evolution investigation and prediction, gas flow simulation around the wells, and parameter design of CBM surface wells.

The development of uniaxial and triaxial loading devices has actively promoted the knowledge of permeability evolution characteristics under different stress conditions [15, 16]. The permeability-strain curve of coal corresponds well to its full stress-strain curve. To be specific, the permeability drops first and then rises as a coal sample gets loaded, deformed, and destructed [5]. The peak value of coal permeability lags behind that of stress and strain, suggesting that the characteristics of CBM flow are closely related to the evolution of coal damage generated in the loading process. In addition, scholars have carried out abundant researches on seepage tests under complex loading/unloading paths and loading/unloading rates and on the establishment of permeability models in the case of multifield coupling [17], but these researches are mostly focused on dry coal. The permeability evolution of water-bearing coal in the case of moisture-stress coupling is rarely reported.

The influence of moisture on the permeability of CBM reservoirs is primarily reflected in coal deformation, gas desorption, and migration [18]. Pan et al. [19] believed that moisture in the coal matrix would cause coal swelling/shrinkage and mechanical property alteration that would impact on coal permeability under reservoir conditions. Zhao et al. [20] and Gai et al. [21] investigated the desorption law of coal subjected to high-pressure water injection and made a comparison with the natural desorption state. Guo and Su [22] conducted laboratory tests on the starting pressure gradient and permeability under different water saturation conditions. The test results showed that the permeability gradually declined and the starting pressure gradient gradually rose with the increase of water saturation degree. Nie et al. [23] explored the microscopic mechanism of gas adsorption on coal samples with different moisture contents in light of molecular thermodynamics and surface physicochemical theories. Wang et al. [24] probed into the relationship among moisture content, porosity, and permeability of fractured coal. Yin et al. [25], Liu et al. [26], Wei et al. [27], and Yuan and Jiang [28] analysed the seepage characteristics of gas-bearing coal with different moisture contents and found that the moisture content and permeability shared a linear negative relationship or negative exponential variation law. Hao et al. [29] performed axial and radial gas seepage experiments and revealed that the axial and radial permeabilities of coal first increased and then decreased with the rise of moisture content. Nevertheless, these researches failed to achieve a unified understanding, and the varied research results imply

the difficulty in clearly explaining the effect of coupling terms on gas adsorption, diffusion, and seepage.

This study is focused on investigating the permeability evolution of gas-saturated raw coal samples with different moisture contents under varying stresses. Firstly, the experimental conditions were simplified by setting constant temperature and gas pressure, unidirectional loading path, and resaturated adsorption after the break of balance, so as to avoid irrelevant factors. Then, the relationship between effective stress and permeability was described by a new function that has a clear physical meaning based on the established permeability evolution model of the porous matrix. Furthermore, the mutual effect of moisture content and volumetric stress on permeability were obtained, and conclusions different from the abovementioned ones were drawn. Finally, a sensitivity analysis was performed in the test region.

2. Materials and Methods

2.1. Engineering Background. Yuwu Coal Mine is located in the south of Qinshui Basin, China. The buried depth of S2107 working face of the mine lies in the range of 480–543 m. No. 3 coal seam that is being mined belongs to a high-gas and low-permeability coal seam with a gas content of $7.71 \text{ m}^3/\text{t}$, a gas emission initial volume from a 100-meter-long borehole of $1.42 \text{ m}^3/\text{min} \cdot \text{h}$, and a permeability coefficient of $0.28\text{--}0.42 \text{ m}^2/(\text{MPa}^2 \cdot \text{d})$. The proximate analysis results and adsorption constants of coal samples from the No. 3 coal seam are listed in Table 1.

Surface wells #1-52 and #1-54 were constructed for conducting permeability-enhancing fracturing on S2107 working face before gas extraction. No. 1-No. 12 gas extraction drilling sites were arranged along the tailentry, and the single-hole gas flow rate was recorded within 50 d. During this period, the drilling sites were not affected by mining activities. The analysis results show that the influence radii of surface wells #1-52 and #1-54 are 85–100 m and 39–42 m, respectively. Coal samples YW1-YW4 were taken from the affected zone in Figure 1.

2.2. Coal Sample Preparation. The steps of coal sample preparation are shown in Figure 2. (1) Standard raw coal samples with the size of $\phi 50 \times (100 \pm 2) \text{ mm}$ were prepared with the aid of a wire cutting machine (Figure 2(a)), and relative homogeneity of the samples was ensured through density measurement and wave velocity measurement (PDS-SW ultrasonic detector). Samples YW1-YW3 almost bear no cracks (wave velocity range 1921.8–2050.8 m/s), while Sample YW4 owns obvious cracks on its surface (wave velocity range 1826.8–2033.8 m/s). (2) Preparation of coal samples with different moisture contents Φ : YW1 ($\Phi = 1.98\%$), the samples that

FIGURE 1: Affected zone of surface wells where samples were taken.

FIGURE 2: Coal sample preparation: (a) wire cutting; (b) drying oven; (c) pressure container.

had experienced hydraulic measures, did not receive any treatment; YW2 ($\Phi = 0.22\%$), the samples with an ultra-low moisture content (lower than the original moisture content 0.49%), were prepared by controlling the drying time of drying oven (Figure 2(b)); YW3 ($\Phi = 3.24\%$), the samples with a high moisture content, were prepared by controlling the pressure holding time of pressure container (Figure 2(c)); YW4 ($\Phi = 4\%$) were the crack-containing sample with a high moisture content.

2.3. Testing Apparatus. The testing apparatus is mainly composed of a loading frame, a servo hydraulic station, an air path system, a triaxial chamber, a constant-temperature oil bath, and a data acquisition system. The schematic diagram of the apparatus is displayed in Figure 3. The main technical parameters are as follows: axial stress range 10-800 KN,

confining pressure range 0-15 MPa, gas pressure range 0-15 MPa, and temperature range from room temperature to 260°C . The chamber equipped with a temperature sensor (PT100, $\pm 0.01^\circ\text{C}$) and a circumferential extensometer (Epsilon 3544, made in USA) was placed in the constant-temperature oil bath for maintaining a constant temperature.

2.4. Experimental Contents and Procedures. The experimental conditions were simplified by setting constant temperature and gas pressure. The temperature was maintained at 20°C . In the process of gas pressure determination, the Klinkenberg effect needs to be avoided, because a small gas pressure difference can cause gas slippage. More specifically, the Klinkenberg effect refers to the slip phenomenon that the gas flow velocity at the wall does not equal zero when the average molecular free path of gas approximates the pore size

FIGURE 3: Schematic diagram of the testing apparatus. 1. Loading frame; 2. Axial loading hydro-cylinder; 3. Displacement sensor; 4. Stress sensor; 5. Servo hydraulic station; 6. Triaxial compression chamber; 6-1. Coal sample; 6-2. Heat shrinkable tube; 6-3. Circumferential extensometer; 6-4. Temperature sensor; 7. Constant-temperature oil bath; 8. Data acquisition system; 9. Gas cylinder; 10. Gas mass flow meter; 11. Vacuum pump;

FIGURE 4: Influence of gas pressure on raw coal permeability: (a) Guandi Coal Mine in Qinshui Coalfield; (b) Malan Coal Mine in Qinshui Coalfield.

of a porous medium. It is manifested in varying ways under different effective stresses [5, 6, 30, 31], moisture contents [27, 28, 32], and temperatures [33, 34]. In view of this fact,

the permeabilities of coal samples from Qinshui coalfield were tested at 20°C under variable gas pressures. As presented in Figure 4, the Klinkenberg effect disappears when

FIGURE 5: The loading path of the prepared samples with different moisture contents.

the gas pressure exceeds 1.0-1.5 MPa, and its influence on the permeability becomes weaker with the rise of moisture content or volumetric stress.

Therefore, considering the in-situ stress value of No. 3 coal seam and the test results of Klinkenberg effect inflection point, the volumetric stress range and gas pressure were set as 9-27 MPa and 1.5 MPa, respectively, in this experiment. The prepared samples with different moisture contents were loaded in accordance with the path in Figure 5, which can ensure that the axial pressure is higher than the confining pressure and the applied unidirectional external stress is lower than the peak strength. Gas pressure at the outlet was 0.1 MPa. Saturated adsorption treatment was conducted on the samples when the stress condition was altered, in order to prevent the adsorption/desorption process from entangling the result analysis.

Experimental procedures: (1) Sample installation: First, the side of the sample was coated with 704 silicone rubber. Then, the sample was wrapped in a heat-shrinkable tube and placed in the chamber. Afterwards, the chamber was put in the 20°C oil bath. (2) Initial adsorption and seepage test: The in-situ stress was raised to the initial value, and 1.5 MPa of CH₄ was injected. Next, the outlet valve was closed to allow the sample to adsorb CH₄ until the equilibrium state was reached, i.e., until gas pressure in the chamber ceased changing. Finally, the outlet valve was opened to record the steady flowrate. (3) The sample was allowed to readsorb CH₄ for 2 h under an altered stress, after which the steady flowrate was recorded. Step (3) was repeated along the loading path. (4) Steps (1)-(3) were repeated for another sample.

3. Permeability of Coal Samples: Theoretical Backgrounds

3.1. Calculation Method for Permeability. According to the theory of geotechnical mechanics, the mean effective stress (MES) can be calculated by Eq. (1) [35, 36]:

$$\sigma_0 = \frac{1}{3}(\sigma_1 + 2\sigma_2) - \frac{1}{2}(P_1 + P_2), \quad (1)$$

where σ_0 is the MES, MPa; σ_1 is the axial stress, MPa; σ_2 is the confining pressure, MPa; P_1 is the gas pressure at the inlet, MPa; P_2 is the gas pressure at the outlet, MPa, and it takes the value 0.1 MPa.

Regardless of the starting pressure gradient, the permeability of the coal sample is calculated by Eq. (2) according to Darcy's law [37, 38]:

$$K = \frac{2QP_a\mu L}{A(P_1^2 - P_2^2)}, \quad (2)$$

where K is the permeability of coal sample, $10^{-3} \mu\text{m}^2$; Q is the gas flow rate at the outlet, cm^3/s ; P_a is the atmospheric pressure, 0.1 MPa; μ is the dynamic viscosity coefficient of gas, $\text{Pa}\cdot\text{s}$; L is the length of deformed coal sample, cm; A is the area of deformed coal sample, cm^2 ; P_1 is the gas pressure at the inlet, Pa.

$$L = L' - l_1, \quad (3)$$

$$A = \frac{1}{4}\pi \left(d + \frac{l_2}{\pi} \right)^2, \quad (4)$$

where L and A are the length and area of deformed coal sample; L' and d are the original height and diameter of coal sample, mm; l_1 is the axial deformation of coal sample after the force loading, mm; l_2 is the radial deformation of coal sample after the force loading, mm.

3.2. Permeability Evolution Model of Porous Matrix. The Warren-Root model of coal is presented in Figure 6 [39]. The porous matrix, which comprises pore clusters supported by skeletons, is the main gas storage space of coal (Figure 6(a)), while cracks, which completely separate the matrix, are the primary gas migration channel [40]. Figure 6(b) shows the seepage model of pores, in which the matrix is equivalent to parallel capillary tubes with equal diameter and skeletons.

Space of cracks or pores will be significantly reduced if deformation or stagnant water exists. Effective porosity is not only a key indicator for measuring the size of the space, but also an important factor that determines the adsorption/desorption and permeability of coal. The effective porosity of coal is related to its structural deformation and bulk deformation. Structural deformation refers to compression deformation of the skeleton caused by external stress, or the relative dislocation between tubes which make the tubes more closely arranged. It is usually unrecoverable. Bulk deformation refers to tube expansion caused by thermal stress or adsorption swelling, or compression deformation of tubes under the action of gas pressure [41]. Such elastic deformation caused by internal stress can be recovered.

In this study, the permeability evolution model of porous matrix considering moisture is established because Samples YW1-YW3 contain few cracks. Since the matrix will undergo

FIGURE 6: The Warren-Root model of coal: (a) pore clusters in porous matrix; (b) seepage model of pores comprising capillary tubes and skeletons.

structural deformation (external stress compression) and bulk deformation (adsorption swelling and gas pressure extrusion) under the condition of constant temperature and gas pressure, the dynamic evolution model of porosity φ_d of the dry matrix is [14, 41–44]:

$$\begin{aligned}\varphi_d &= 1 - \frac{1 - \varphi_0}{1 + e} \left(1 + \frac{\varepsilon_p}{1 - \varphi_0} - K_Y \Delta P_1 \right) \\ &= \frac{\varphi_0 + e - \varepsilon_p + K_Y \Delta P_1 (1 - \varphi_0)}{1 + e},\end{aligned}\quad (5)$$

where φ_d is the porosity of dry matrix, %; φ_0 is the initial porosity of matrix, %; e is the volumetric strain, of which the value is negative under compression; ε_p is the adsorption expansion strain per unit volume of coal; K_Y is the volumetric compression coefficient, MPa^{-1} .

The $A * L_1$ unit in the matrix is taken and regarded to be equivalent to the capillary tubes (Figure 6(b)). Given the fact that water distributed in macropores (pore diameter $> 1 \mu\text{m}$) and mesopores (pore diameter $= 0.1 - 1 \mu\text{m}$) occupies the space, the porosity of the water-containing matrix is [14]:

$$\varphi_w = \varphi_d \left(1 - \frac{\rho_s w}{n \rho_w \pi r^2} \right), \quad (6)$$

where ρ_s is the density of matrix, kg/m^3 ; w is the moisture content of matrix pores; n is the number of capillary tubes per unit area A , tubes/m^2 ; ρ_w is the density of water in capillary tubes, kg/m^3 ; and r is the radius of a tube, m .

By integrating Eq. (5) with Eq. (6), the effective porosity evolution model of water-containing matrix can be obtained:

$$\varphi_w = \left(1 - \frac{\rho_s w}{n \rho_w \pi r^2} \right) \left(\frac{\varphi_0 + e - \varepsilon_p + K_Y \Delta P_1 (1 - \varphi_0)}{1 + e} \right), \quad (7)$$

The relationship between permeability and porosity is given in the Kozeny-Carman equation established on the basis of the capillary tubes model [44]. Ignoring the change in the total surface area of coal particles per unit volume, a permeability evolution model that takes into account the moisture content in pores can be obtained:

$$K = \frac{K_0}{1 + e} \left(1 + \frac{e - \varepsilon_p + K_Y \Delta P_1 (1 - \varphi_0)}{\varphi_0} \right)^3 \left(1 - \frac{\rho_s w}{n \rho_w \pi r^2} \right), \quad (8)$$

where K_0 is the initial permeability of coal sample, $10^{-3} \mu\text{m}^2$.

4. Results and Discussion

4.1. Effect of Mean Effective Stress on Permeability. Changes in flow rates Q and permeabilities K of coal samples with moisture contents of 0.22%, 1.98%, and 3.24% under mean effective stress (MES) values of 4.2–8.3 MPa are disclosed in Figures 7(a)–7(c). The flow rates of coal samples decrease nonlinearly at a reduced rate with the increase of MES, and the relationship between flow rate and MES can be expressed by a quadratic function $Q = a_1 \sigma_0^2 + b_1 \sigma_0 + c_1$ where a_1 , b_1 , and c_1 are fitting coefficients.

The permeabilities and flow rates of samples with different moisture contents vary in similar trends (Figure 7(d)). The variation trend of permeability with MES can be fitted by the power function $K = a \cdot (1 + b \sigma_0)^3 / (1 + c \sigma_0)$ which agrees with the form of Eq. (8). In the function, a , b , and c are the fitting coefficients with clear physical meanings (see Table 2 for their values), and the influence mechanisms of moisture on the values of a , b , and c differ.

The fitting coefficient a is related to the initial permeability of the matrix with specified moisture content. The value of a drops sharply with the rise of moisture content, and the effect of water on the value of a is mainly reflected in the

FIGURE 7: $K - \sigma_0$ and $Q - \sigma_0$ curves of samples with different moisture contents: (a) moisture content 0.22%; (b) moisture content 1.98%; (c) moisture content 3.24%; (d) total trend.

TABLE 2: Fitting coefficients of K - σ_0 curves.

Value Φ	a	b	c	R^2
0.22%	231.3	-0.09	-0.08	0.99
1.98 %	69.8	-0.08	-0.08	0.99
3.24 %	15.9	-0.11	-0.11	0.99

FIGURE 8: Volumetric stress Θ -strain ϵ curves of samples with different moisture contents.

following two nondeformation aspects of matrix: (1) Free water, adhered water, and film water in macropores and mesopores occupy the gas flow channel, thus lowering the effective porosity of coal. In addition, a water film formed on the pore surface generates a certain vapor pressure, thus raising the viscous resistance of gas migration [45, 46]. (2) Within the main space for CH_4 adsorption and desorption, namely, micropores (0.01-0.1 μm) and molecules structural pores (<0.01 μm), capillary resistance formed by water hinders gas desorption and exhibits a water-locking effect.

The fitting coefficient b is related to the bulk deformation, structural deformation, and initial porosity of the coal matrix. By conducting wave velocity measurement, the initial permeabilities ϕ_0 of Samples YW1-YW3 are considered to be consistent, so the variation of b value is mainly affected by structural deformation (external stress) and bulk deformation (adsorption swelling and gas pressure extrusion) of the matrix in this test. As the moisture content increases, the volumetric compressive strain $|e|$ goes up (Figure 8); the volumetric compression coefficient K_V grows [47]; and the adsorption expansion strain ϵ_p does down [26, 42, 43, 48], because water molecules possess stronger adsorption competitiveness on the coal matrix surface compared with CH_4 molecules [49, 50]. Thereby, with the rise of moisture content, the effective adsorption sites of gas on the pore surface decrease, so does the adsorption expansion strain ϵ_p . As revealed by the analysis on the values of $|e|$, ϵ_p , K_V , and b

with the change of moisture content, with the rise of moisture content, the effective porosity of matrix increases in terms of bulk deformation, but meanwhile the existence of external stress makes the structural deformation of the matrix with a high moisture content more obvious. As a result, the effective porosity is reduced because of the larger structural deformation.

The fitting coefficient c is related to the structural deformation of the coal matrix caused by external stress. Figure 8 displays the curves of volumetric strain variation measured in the test. It can be seen that as the moisture content rises, the absolute value of volumetric strain increases, so does the absolute value of c .

4.2. Effect of In-Situ Stress on Permeability. Figure 9(a) demonstrates the permeability variations of samples with moisture contents of 0.22%, 1.98%, and 3.24% under a constant axial pressure of 5.5 MPa and confining pressures of 3.9, 4.1, 4.3, 4.5, and 4.7 MPa. Figure 9(b) shows the permeability variations of samples with moisture contents of 0.22%, 1.98%, and 3.24% under volumetric stresses of 13.3-27.3 MPa.

Obviously, permeability K goes downward nonlinearly at a reduced rate with the increase of in-situ stress (e.g., confining pressure σ_2 or volumetric stress Θ). The above downward trend can be fitted with a negative exponential function $K = a \cdot \exp(-bx)$ where a and b are the fitting coefficients and a is related to the initial permeabilities of coal samples with different moisture contents. This finding corresponds to previous research results [27, 35, 51]. The reason can be explained as follows. The initial permeabilities of coal samples with different moisture contents differ. Specifically, the higher the moisture content is, the lower the initial permeability is. First, the stagnant water and the seal off the effect of water reduce the effective porosity of coal [29]. Second, with the increase of external stress, the structural deformation of coal brings about further shrinkage of gas seepage channel.

Sample YW4 ($\Phi = 4\%$) contains evident microcracks (Figure 6). The test result shows that its permeability is up to 60% higher than the value in Figure 9 under the same in-situ stress condition. The result fully proves that although the moisture content seriously weakens coal permeability, cracks, as the dominant factor affecting coal permeability [52], will effectively weaken the negative impact of water on coal permeability.

4.3. Mutual Effect of Moisture Content and Volumetric Stress on Permeability

4.3.1. Relationship between Permeability and Moisture Content under Applied In-Situ Stress. Figure 10 exhibits the variation of permeability K with the moisture content Φ and the volumetric stress Θ . The $K - \Phi$ curves are not always linear. In the whole region ($\Phi = 0.22\text{--}3.24\%$), under low volumetric stresses ($\Theta < 15$ MPa), K decreases nonlinearly with the increase of Φ ; as the volumetric stress grows (e.g., $\Theta = 18$ MPa), it becomes linearly correlated with Φ , which agrees with the conclusions of Liu et al. [26], Yin et al. [25, 53], and Yuan and Jiang [28]; under high volumetric stresses

FIGURE 9: Effect of in-situ stress on permeability: (a) confining pressure; (b) volumetric stress.

FIGURE 10: Effect of moisture content and volumetric stress on permeability.

($\Theta > 18$ MPa), it is no longer linearly correlated with Φ , the slope of $K - \Phi$ curve altering evidently in the vicinity of $\Phi = 1.98\%$. Moisture occupies pores and external stress causes structural deformation of the pore, both reducing the effective porosity of matrix and thus resulting in a decrease in permeability.

In different regions ($\Phi = 0.22 - 1.98\%$ and $\Phi = 1.98 - 3.24\%$), the slope of $K - \Phi$ curve decreases with the increase of Θ , because influence of Φ on K weakens with the increase of Θ . It is noteworthy that in Zone I-1 where Φ is high and Θ is low, the slope of $K - \Phi$ curve remains basically constant with the increase of Θ ; in Zone II-1 where Φ is low and Θ is high, the slope of $K - \Phi$ curve remains basically unchanged with the increase of Φ . The variation trend reflects the differences in permeability sensitivity to volumetric stress and moisture content in different regions.

4.3.2. Sensitivity Analysis of the Test Regions. To determine the influence degrees of moisture content Φ and volumetric stress Θ on permeability K , the sensitivity coefficients of permeability to moisture content and volumetric stress were defined as C_Φ and C_Θ , respectively. The meanings of $C_{\Phi 1,2}$ and $C_{\Theta 1,2}$ were defined in the same way as above.

First, the correlation between variables was analysed. The Pearson correlation coefficient $\rho_{X,Y}$ (PPMCC) shown in Eq. (9), which is the quotient of the product of covariance and standard deviation of two variables [54], is widely used for measuring the correlation between two variables. Through calculation, the correlation between the moisture content Φ and the permeability K is -0.782 (highly significant, $P < 0.01$), while that between the volumetric stress Θ and the permeability K is -0.470 (significant, $P < 0.05$). In addition, Φ and Θ are two independent variables.

$$\rho_{X,Y} = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)} \sqrt{E(Y^2) - E^2(Y)}}, \quad (9)$$

where cov is the covariance; and E is the mathematical expectation.

TABLE 3: Calculation results of regression coefficients.

Coefficient	Value	Standard error	T value	$P > T $	Confidence interval
β_1	-0.782 ($P < 0.01$)	0.084	-9.35	0	[-0.95, -0.61]
β_2	-0.470 ($P < 0.01$)	0.084	-5.63	0	[-0.64, 0.30]
β_0	-0.001	0.082	0	1	[-0.17, 0.17]

TABLE 4: Calculation results of regression coefficients.

Coefficient	Value	Standard error	T value	$P > T $	Confidence interval
β_1	-52.679 ($P < 0.01$)	2.120	-24.85	0	[-57.06, -48.29]
β_2	-6.287 ($P < 0.01$)	0.250	-25.1	0	[-6.8, -5.77]
β_3	1.909 ($P < 0.01$)	0.114	16.74	0	[1.67, 2.14]
β_0	175.984	4.655	37.81	0	[166.36, 185.61]

(1) *Sensitivity analysis in the whole test region.* Based on the correlation analysis, a multiple regression model was established to calculate the sensitivity coefficients C_Φ and C_Θ . The data in Figure 10 were subjected to Z-Score standardization via Stata software and then substituted into the regression equation $Y_K = \beta_0 + \beta_1 X_\Phi + \beta_2 X_\Theta + \mu_I$ where β_0 , β_1 , and β_2 are the regression coefficients and μ_I is the error term.

The permeability K is more sensitive to the moisture content Φ in the whole test region. The overall sensitivity coefficients $C_{\Phi 1} = dY_K/dX_\Phi = \beta_1$ and $C_{\Theta 1} = dY_K/dX_\Theta = \beta_2$ were defined. Their values $C_{\Phi 1} = -0.782$ (highly significant, $P < 0.01$) and $C_{\Theta 1} = -0.470$ (highly significant, $P < 0.01$) can be found in Table 3. In the whole test region, $|C_{\Phi 1}| > |C_{\Theta 1}|$, that is, permeability is more sensitive to moisture content on the whole.

(2) *Sensitivity analysis in different regions.* The interaction variable [55–57] $\beta_3 X_\Phi X_\Theta$ was added into the regression equation $Y_K = \beta_0 + \beta_1 X_\Phi + \beta_2 X_\Theta + \beta_3 X_\Phi X_\Theta + \mu_2$ for comparing the values of C_Φ and C_Θ in different regions. The regional sensitivity coefficients $C_{\Phi 2} = dY_K/dx_\Phi = \beta_1 + \beta_3 * X_\Theta$ and $C_{\Theta 2} = dY/dx_\Theta = \beta_2 + \beta_3 * X_\Phi$ were defined.

As given in Table 4, the interaction term coefficient is 1.909 (highly significant, $P < 0.01$), suggesting that although moisture content and volumetric stress are independent variables, they exert a mutual effect on permeability. $C_{\Phi 2} = -52.679 + 1.909 * X_\Theta$ and $C_{\Theta 2} = -6.287 + 1.909 * X_\Phi$ demonstrate that the sensitivity coefficient $C_{\Phi 2}$ decreases gradually with the increase of volumetric stress while $C_{\Theta 2}$ decreases gradually with the increase of moisture content (Figure 11). Therefore, the sensitivity coefficient $C_{\Phi 2}$ decreases with the increase of volumetric stress Θ so that the slope of $K - \Phi$ curve becomes smaller and smaller in the ranges of $\Phi = 0.22 - 1.98\%$ and $\Phi = 1.98 - 3.24\%$ (Figure 10), which indicates the weakening influence of moisture content on permeability.

Figure 12(a) is a three-dimensional diagram of the data in Figure 10. As can be observed in Figure 12(b), $|C_{\Phi 2}| > |C_{\Theta 2}|$ in Zone I ($X_\Theta < 24.37 + X_\Phi$), that is, permeability is more

FIGURE 11: Calculation of sensitivity coefficient of each experimental condition.

sensitive to moisture content in this region; $|C_{\Phi 2}| < |C_{\Theta 2}|$ in Zone II ($X_\Theta > 24.37 + X_\Phi$), that is, permeability is more sensitive to volumetric stress in the region. The constant slopes of $K - \Phi$ curves in Zone I-1 and Zone II-1 in Figure 10 indicate the absolute influence of high volumetric stress or high moisture content on permeability.

The value of $C_{\Phi 2}$ is larger than that of $C_{\Theta 2}$ when the volumetric stress is lower than 15 MPa (Figure 11). At this time, coal permeability is not simply linearly correlated but shares a negative exponential relationship with moisture content (Figure 12(a)). This finding differs from the research results of Yin et al. [25, 53], probably because the briquette samples used by Yin et al. possess a homogeneous internal structure while the complex pore structure of raw coal samples used in this test decides the more complex influence mechanism

FIGURE 12: Division of sensitive regions under the test conditions: (a) Three-dimensional diagram of Figure 10; (b) Top view.

of moisture on raw coal permeability. Under a low volumetric stress, the pores in coal are slightly affected by stress, and the coal is strongly hydrophilic. As a result, the increased water adsorbs on the pore surface easily and meanwhile occupies the effective gas seepage channel. Since the porosity of coal is an important parameter affecting gas permeability, the permeability of coal falls rapidly with the rise of moisture content under a low volumetric stress. With the increase of volumetric stress, the sensitivity of permeability to moisture content decreases, so that permeability becomes linearly correlated with moisture content. After volumetric stress continues to increase to 24 MPa, the coal sample gets more sensitive to volumetric stress (Zone II in Figure 12(b)), which is reflected by the phenomenon that the increase of moisture content fails to notably lower permeability under a low moisture content.

5. Conclusions

In this study, a series of experiments were performed for grasping the permeability evolution of gas-saturated raw coal under the coupled influences of moisture contents and in-situ stress. The main conclusions reached are as follows.

- (1) A permeability evolution model of a porous matrix was established. On the basis of this mode, it is found that the power function $K = a \cdot (1 + b\sigma_0)^3 / (1 + c\sigma_0)$ can be used to describe the relationship between MES σ_0 and permeability K . In this function, the fitting coefficient a is related to the initial permeability with specified moisture content; b is related to the bulk deformation, structural deformation, and initial porosity of coal matrix; and c is related to the structural deformation of coal matrix caused by external stress. The influence mechanisms of moisture on these coefficients were analysed according to the experimental results afterwards

- (2) Permeability decreases nonlinearly with the increase of in-situ stress (e.g., confining pressure σ_2 or volumetric stress Θ), which can be fitted by a negative exponential function $K = a \cdot \exp(-bx)$, where a is related to the initial permeabilities of coal samples with specified moisture content Φ
- (3) The mutual influences of moisture content and volumetric stress on permeability were analysed. In different regions, the slope of $K - \Phi$ curve decreases with the increase of Θ , because the increase of Θ would weaken the influence of Φ on K . Overall, the $K - \Phi$ curves are not always linear. The variation reflects the differences in permeability sensitivity to volumetric stress and moisture content in different regions

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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