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Experimental Investigation on the Influence of Water Content on Gas Permeability Characteristics in Tectonic Coal

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ABSTRACT

The flow behaviour of gas within water-bearing tectonic coal plays a crucial role in disaster prevention and mitigation under actual mining conditions. To investigate the evolution of gas permeability in tectonic coal with varying water content, a series of controlled laboratory experiments were conducted using a self-developed gas-bearing coal permeability testing apparatus. Tectonically tectonic coal from western Henan Province was selected as the test subject, while primary coal was employed as a comparative reference. The permeability of both coal types was measured under varying levels of water content, axial and confining stresses, and pore pressure. Experimental results indicated that both coal types exhibited similar trends in permeability reduction with increasing effective stress, pore pressure, and water content. However, the permeability of tectonic coal was found to be significantly more sensitive, with a reduction magnitude up to 60%, in contrast to only 20% observed in primary coal. Tectonic coal demonstrated greater responsiveness to variations in both effective stress and water content. Data analysis revealed that the relationship between permeability loss rate and effective stress can be well described by the Hill function. Furthermore, an exponential function was found to best represent the correlation between gas pressure and permeability loss. Under specific stress conditions, the relationship between permeability and water content exhibited a decaying exponential trend, whereas the permeability loss rate conformed to a negative exponential distribution. The observed disparity in permeability behaviour between the two coal types was attributed primarily to differences in mechanical strength and internal structure. Within the experimental range of stress, pore pressure, and water content, the pore and fracture systems in tectonic coal displayed a higher degree of stress sensitivity. In the presence of moisture, the closure of these pores and fractures under applied stress was enhanced, providing a plausible explanation for the limited effectiveness of hydraulic stimulation techniques in regions dominated by tectonic coal. The findings elucidate the moisture-induced sensitivity mechanisms governing gas permeability in tectonic coal, offering a theoretical basis for the observed inefficacy of hydraulic methods in such geological settings and contributing to improved engineering strategies for gas management in coal mines.

1. INTRODUCTION

Gas-related issues have always been one of the key factors restricting the efficient and safe mining of coal. Tectonic coal is characterized by high adsorption capacity and low permeability, and is classified as a difficult-to-extract coal seam, thus attracting continuous attention from researchers both domestically and internationally.

As a geological body, coal contains varying degrees of moisture, and during gas control processes, hydraulic measures also lead to different levels of changes in the coal's water content. Regarding the influence of moisture on coal and rock permeability [1], based on oil and gas seepage experiments, obtained a quantitative expression of rock permeability and water content; Yin et al. [2] simulated the influence of water content in coal seams on gas seepage during the mining process, and established a functional relationship between coal seam water content and effective gas permeability; Shi et al. [3] concluded from experiments that within a certain range, coal permeability changes linearly with the increase in water content, but once the water content exceeds a critical value, the permeability shows an accelerated attenuation trend; Li et al. [4-7] conducted multi-perspective studies on the variation of permeability under the influence of moisture in coal and rock, and obtained some meaningful results; Wang et al. [8] believed that as the water content in tectonic coal increases, porosity decreases and permeability reduces; some studies also suggest that borehole hydraulic fracturing can effectively improve the permeability of coal seams [9]; Jing et al. [10] obtained through experiments that

6% water content is the threshold for permeability variation; Liu et al. [11] found that with increasing water content in coal, the stress-sensitive point of coalbed methane seepage velocity gradually decreases; Chao et al. [12] found through experiments that the effective permeability of low-permeability rocks under moisture saturation conforms to a power function relationship, and permeability exhibits slippage effects. Wei et al. [13] obtained the permeability characteristics of gas-bearing coal affected by water content based on experiments. Review of research findings [14] that water saturation is a critical factor influencing gas diffusion. Higher water saturation may reduce the effective diffusion coefficient of gas in porous media, as water occupies a portion of the pore space, thereby limiting the diffusion pathways available for gas molecules. However, the magnitude of this effect depends on the pore structure of the rock and its water wettability.

In coal seam gas control, the application of hydraulic measures such as hydraulic slotting, hydraulic punching, and hydraulic fracturing is becoming increasingly common. However, the implementation effect in tectonic coal seams is not ideal. The underlying reason is believed to be the unclear understanding of the evolution characteristics of gas permeability in tectonic coal, resulting in a lack of targeted strategies. Why have hydraulic measures, which have performed well in hard coal, not achieved significant results in tectonic coal? To explore this issue, tectonic coal seams influenced by the Songshan geological structure in western Henan were selected as the research object, with primary structural coal used for comparison. Experimental research was conducted using a self-developed triaxial gas seepage system for coal and rock, aiming to improve the efficiency of gas extraction in coal seams and further promote the theoretical development of gas-bearing coal and rock permeability.

2. EXPERIMENTAL METHODS

2.1 Sample preparation

The coal samples were taken from the 12021 working face of the Dengfeng Jiaoxue No.3 Coal Mine. The target Coal Mine is located in Xuzhuang Township, Dengfeng, and is influenced by the Songshan geological structure, making it a typical tectonic coal seam. The coal has a simple structure, low strength, and is brittle under point pressure. The primary structural hard coal samples were obtained from the No. 3 coal seam of the Yangcheng Rundong Coal Mine of Shanxi Jincheng Group, which has high strength and good integrity. Table 1 shows the different physicochemical parameters of the two coal types.

Considering the difficulty in preparing the raw coal samples of tectonic coal, the preparation of shaped coal samples was carried out according to the MT/T752-1997 *Determine Method of Methane Adsorption Capacity in Coal*. The primary structural coal was processed directly according to the *Code for Rock Tests in Water and Hydropower Projects* (SL 264-2001) to obtain raw coal samples. Saturated water coal samples were obtained according to GB/T 23561-2009, and placed in a 65℃ constant temperature drying box. Every 30 minutes, the samples were taken out, weighed, and once the water content approached the preset value, they were removed and placed in a constant temperature and humidity chamber for storage. Prior to testing, a final water content measurement was carried out to obtain the accurate water content value.

Table 1. Basic physicochemical parameters of the coal samples

Coal Seam	Coal Type	Platts Index f	Industrial Analysis			
			Water M_{ad}/%	Ash A_{ad}/%	Volatile Matter V_{ad}/%	Fixed Carbon Fcd/%
Tectonic coal	Anthracite	0.16	1.12	10.8	16.9	71.18
Primary Structural Coal	Anthracite	3.63	1.92	15.1	7.8	75.18

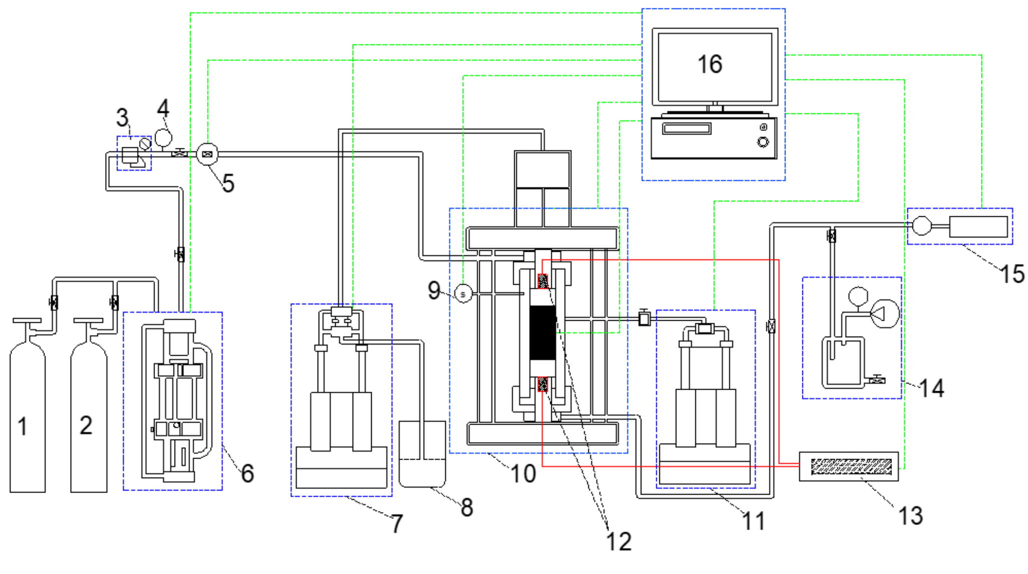

Figure 1. Gas-bearing coal triaxial stress creep seepage experimental system

Note: 1. High-concentration N2; 2. High-concentration CH4; 3. Pressure relief valve; 4. Pressure gauge; 5. Gas flow meter; 6. Gas booster pump; 7. Axial pressure pump CH4; 8. Pump oil; 9. Temperature control external power supply; 10. Clamping device; 11. Confining pressure pump; 12. Acoustic emission probe; 13. Acoustic emission oscilloscope; 14. Vacuum pump; 15. Gas mass flow meter; 16. Data acquisition and analysis system

2.2 Experimental apparatus

The experimental apparatus used was the gas-bearing coal triaxial stress creep seepage experimental system independently developed by the Henan University of Engineering [15]. The system was improved and upgraded based on the original system. The specific experimental system is shown in Figure 1.

2.3 Experimental scheme

To avoid data dispersion in the experiments, coal samples with similar P-wave velocities were selected. Methane gas with a concentration of 99% was used, and the room temperature was maintained at 26°C. During the experiment, the gas pressure must be less than the confining pressure.

The main factors considered in the experiment were the coal sample's water content, gas pressure, and the changes in axial and confining pressures on permeability. Based on the experimental requirements, the gas pressure of the tectonic coal was designed to be 0.3MPa, 0.6MPa, 0.9MPa, 1.2MPa, and 1.5MPa. The water content of the tectonic coal was measured at 0%, 1.52%, 2.97%, 4.37%, and 5.2%. The primary structural coal had water contents of 0%, 1.03%, 2.10%, 3.21%, and 4.06%. The loading conditions for axial and confining pressures during the experimental process were referenced from literature [16]. Permeability was calculated using Darcy's law.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 The influence of effective stress on permeability

During the experiment, the gas pressure was kept constant while the changes in axial pressure and confining pressure were considered, which caused variations in the effective stress. The effect of effective stress on permeability was examined. According to rock mechanics and mining pressure theory, the effective stress is defined as the difference between the total stress acting on the coal body and the fluid pressure within the pores or fractures of the coal body, i.e.:

$$\sigma = \frac{\sigma_1 + 2\sigma_2}{3} - \frac{p_1 + p_2}{2}$$

where, σ is the effective stress in MPa; σ_1 and σ_3 are respectively the axial and confining pressures in MPa; p_1 and p_2 are respectively the gas pressures at the inlet and outlet in MPa.

During the experiment, the gas pressure was maintained at 1.2MPa, and axial and confining pressures were varied to calculate the changes in effective stress. The axial and confining pressures were set at 0MPa, 3MPa, 6MPa, 9MPa, and 12MPa. Steady-state methods were used to measure the permeability, and the changes in gas permeability with effective stress were obtained, as shown in Figures 2 and 3.

From the figures, it can be observed that both the tectonic coal and the primary structural coal have decreasing permeability with increasing effective stress. The effect of effective stress on permeability changes from a relatively steep decline initially to a gradual flattening, following a degradation power law.

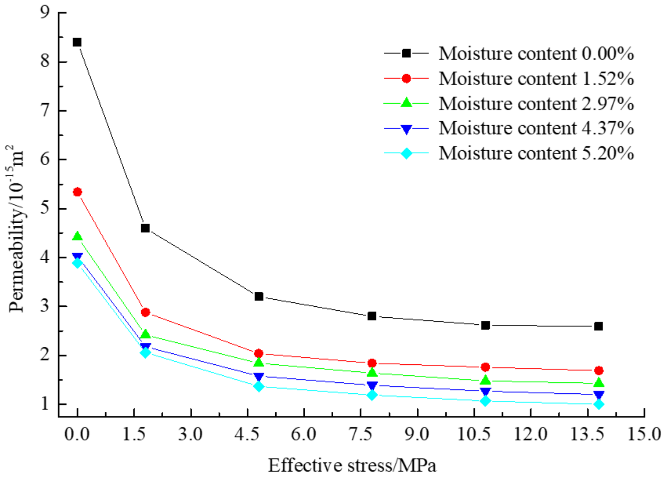

Figure 2. Gas permeability of tectonic coal as a function of effective stress

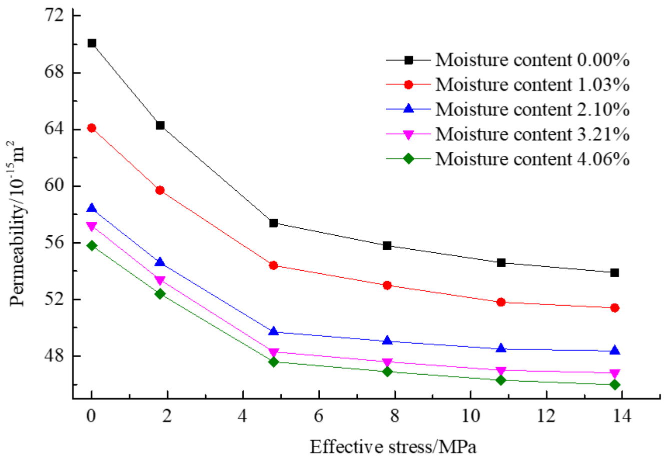

Figure 3. Gas permeability of primary structural coal as a function of effective stress

To examine the sensitivity of permeability to effective stress for the two types of coal, permeability was normalized, and the permeability loss rate was defined as:

$$\kappa_l = \frac{\kappa_0 - \kappa_n}{\kappa_0} \times 100\%$$

where, κ_l is the permeability loss rate; κ_0 is the initial permeability of the coal sample; and κ_n is the permeability corresponding to a certain test time.

Figure 4 shows the comparison of permeability loss rates in dry and water-saturated states for the two coal samples. From the figure, it can be observed that the two coal samples respond quite differently to effective stress. In the 0-14MPa range of effective stress, the tectonic coal exhibits a loss rate of over 60%, while the permeability loss rate for the primary structural coal is less than 20%.

The variation in permeability with effective stress for both coal samples follows the distribution characteristics of a degradation function, and the permeability loss rate with effective stress can be fitted using a Hill function. The slope of the curve in Figure 4 can be calculated, and it is observed that the rate of change of permeability loss rate tends to approach zero as effective stress increases.

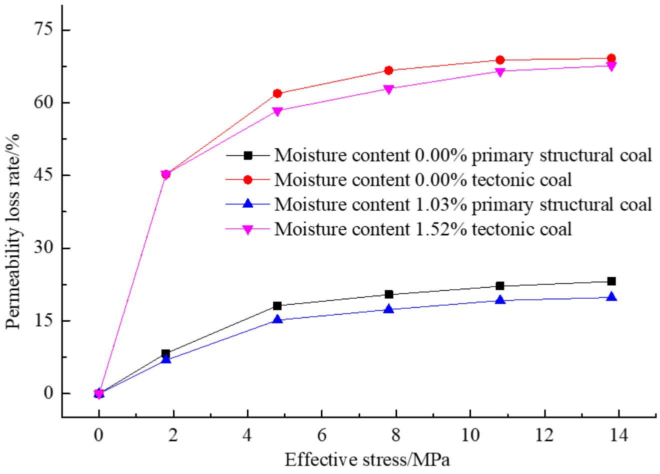

Figure 4. Relationship between permeability loss rate and effective stress

3.2 The influence of gas pore pressure on permeability

During the experiment, the axial and confining pressures were kept constant while the gas pressure applied on the upper surface was varied. After reaching equilibrium, the permeability was measured using the steady-state method. Figure 5 shows the variation of the permeability of tectonic coal with pore pressure when the axial and confining pressures are both 9 MPa. Figure 6 shows the variation of the permeability of primary structural coal with pore pressure.

From the figures, it can be observed that the permeability of the tectonic coal initially decreases sharply with increasing pore pressure and then gradually levels off, while the permeability of primary structural coal decreases in a relatively gentle manner as the pore pressure increases. At the same time, with the increase in water content, the permeability of both coal samples decreases. The permeability of both coal types as a function of pore pressure can be fitted using a degradation function.

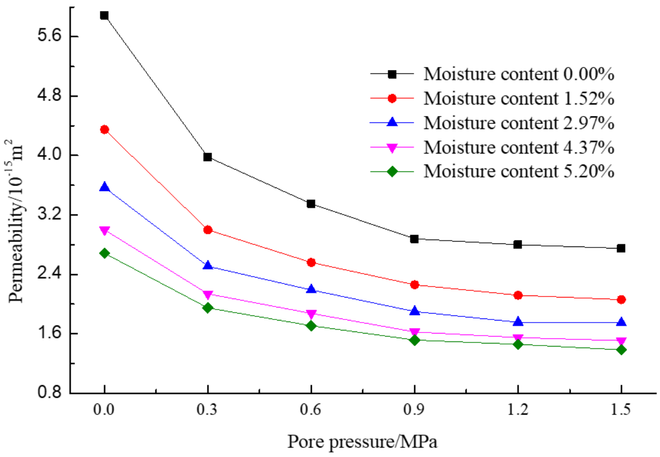

Figure 5. Permeability of tectonic coal as a function of pore pressure

To compare the response rates of the permeability of the two coal samples to pore pressure, the loss rate and effective stress relationship from earlier can be used to obtain Figure 7, which shows the permeability loss rate of tectonic and primary structural coal samples as a function of gas pore pressure. From the figure, it can be seen that the permeability loss rate of tectonic coal increases rapidly with pore pressure, eventually leveling off, while the permeability loss rate of primary structural coal changes more gently with pore pressure. Furthermore, the permeability loss rate of tectonic coal is much higher than that of primary structural coal.

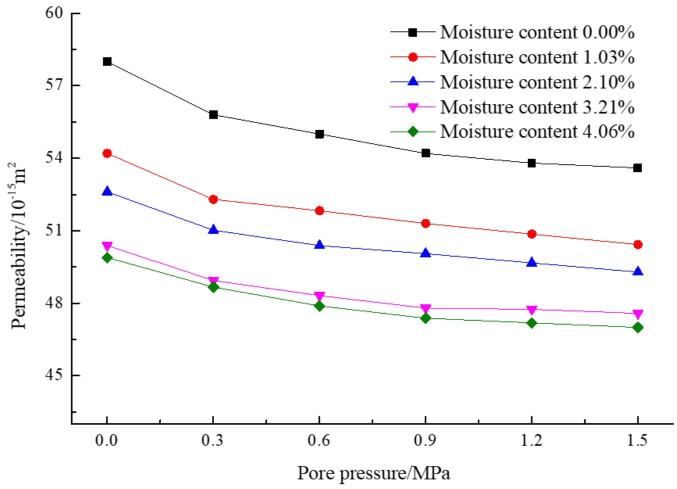

Figure 6. Permeability of primary structural coal as a function of pore pressure

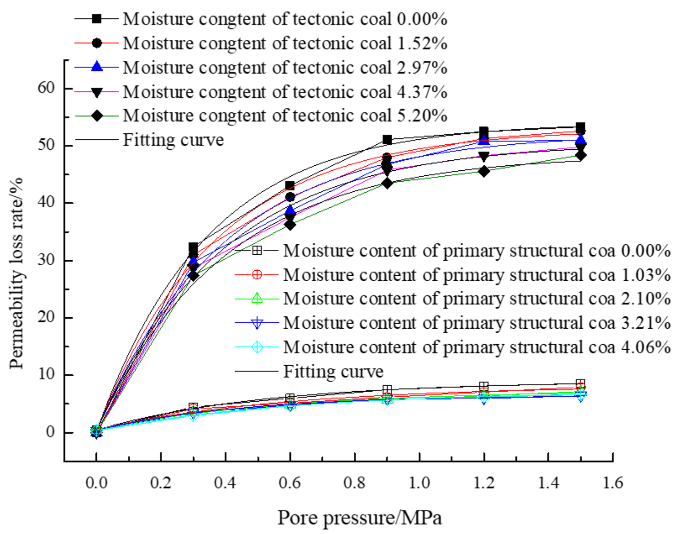

Figure 7. Relationship between permeability loss rate and pore pressure for the two coal samples

The internal mechanisms of the effect of gas pressure on permeability can be explained by the following two aspects: as pore pressure increases, the effective stress on the coal matrix decreases. With the decrease in effective stress, the closure of pore and fracture channels may partially recover, leading to an increase in permeability. At the same time, the increase in pore pressure leads to an increase in gas adsorption. The coal matrix undergoes expansion due to adsorption, and with smaller pore and fracture channels, permeability decreases [17]. Additionally, the enhanced gas adsorption effect strengthens the fluid's Kingberg effect, reducing flow velocity and flow rate. Based on the experimental results, it can be inferred that the gas permeability of tectonic coal in the tested pore pressure range is mainly due to the expansion caused by gas adsorption in the coal matrix, which results in smaller flow channels, leading to a permeability loss rate of more than 50%. Although pore pressure increases and effective stress decreases, for tectonic coal, the low strength makes it difficult for pore channels to recover once closed, leading to reduced permeability.

The relationship between gas pressure and permeability loss rate can be fitted using an exponential function, with a fitting similarity exceeding 96%. The formula is as follows:

$$\delta = A_0 \times e^{-\rho/t} + y_0$$

where, δ is the permeability loss rate; ρ is the gas pore pressure; A_0, t, y_0 are fitting parameters.

3.3 The influence of water content on the gas permeability of two coal samples

During the experiment, the gas pressure was kept constant at 1.2 MPa, and the axial and confining pressures were both 9 MPa. The change in gas permeability of coal samples with different water contents was measured. Figure 8 shows the variation between water content and gas permeability. Since the initial permeability of tectonic coal and primary structural coal differs by an order of magnitude, the comparison between the two mainly considers the permeability loss rate. Figure 9 shows the relationship between permeability loss rate and water content for the two coal samples.

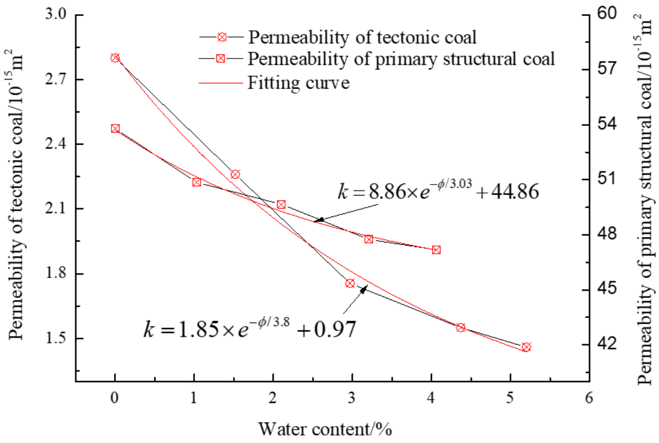

Figure 8. Permeability of two coal samples as a function of water content

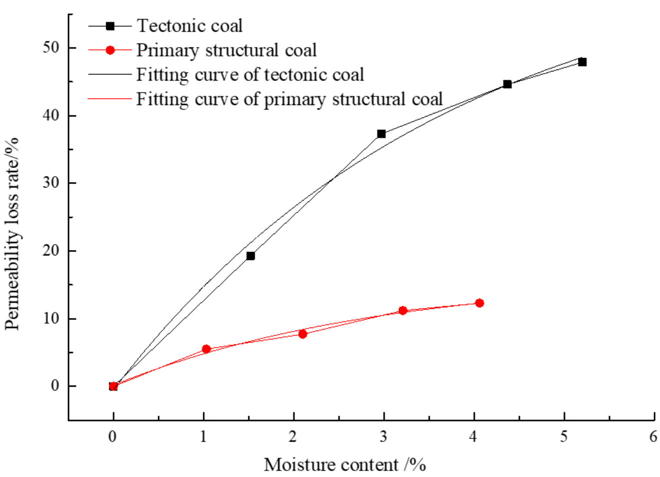

Figure 9. Relationship between permeability loss rate and water content for the two coal samples

Combining the experimental data, it can be found that with increasing water content, the permeability of both coal samples decreases. The permeability of the two coal samples and water content, under a specific stress field environment, follows the distribution characteristics of a degradation exponential function, with fitting variances greater than 0.98. The fitting relationship can be expressed by the following formula:

$$k = A_0 \times e^{-\varphi/t} + y_0$$

where, k is the permeability loss rate; φ is the water content; A_0, t, y_0 are fitting parameters.

Figure 8 does not reflect the sensitivity characteristics of permeability in response to water content. Based on this, the relationship between permeability loss rate and water content can be used to express the sensitivity characteristics of the two coal samples to water content. From Figure 9, it can be observed that the permeability of tectonic coal is more sensitive to water content than that of primary structural coal. In the tested water content range, the permeability loss rate of tectonic coal reaches up to 50%, while the permeability loss rate of primary structural coal remains below 13%. The permeability loss rate and water content follow a negative exponential function distribution, with fitting variances reaching 0.99. The function expression is as follows:

$$\delta = A_0 \times e^{-\varphi/t} + y_0$$

where, δ is the permeability loss rate; φ is the water content; A_0, t, y_0 are fitting parameters.

The main reason for the decrease in coal sample permeability with increasing water content is that both coal matrix and water are polar molecules, while gas is a non-polar molecule, making coal highly hydrophilic. During the seepage process, water molecules are adsorbed on the surface of the coal matrix, occupying a large number of gas adsorption sites. As water content increases, water molecules enter the larger pores of the coal matrix, obstructing the gas seepage channels, thus causing a decrease in gas permeability. Water has a lubricating effect, and after the coal matrix adsorbs water, a layer of water film forms on its surface. On one hand, the water film prevents gas molecules from entering the coal matrix; on the other hand, the water film also creates viscous resistance to gas seepage. This ultimately leads to a reduction in gas permeability as the water content increases.

4. ANALYSIS OF PERMEABILITY DIFFERENCES BETWEEN THE TWO COAL SAMPLES

From the above experiments and data analysis, it can be seen that both primary structural coal and tectonic coal exhibit similar patterns in permeability with respect to effective stress, pore pressure, and water content. However, after investigating the permeability loss rate, significant differences in variation between the two coal samples are observed. Why does such a change occur? The author believes that the main reason lies in the analysis of coal body strength and structural form.

The tectonic coal sample comes from the Jiaoxue No. 3 coal mine and is a type of soft coal formed under the uplifting and sinking action of the Dengfeng Songshan geological movement. It is a fragmented coal, which is brittle and easily crushed. After processing and forming into coal samples, the uniaxial compressive strength of tectonic coal was measured to be 3.23 MPa, which is much lower than that of primary structural coal, which has a uniaxial compressive strength of 61.8 MPa. This also explains why, with increasing effective stress, the permeability of tectonic coal increases rapidly due to deformation, which exhibits typical plastic flow characteristics. The pore and fracture channels are restructured, and rather than increasing the seepage channels, the flow between particles causes obstruction, reducing permeability. On the other hand, primary structural coal has higher strength, and under the stress conditions tested, it remains in the elastic deformation range. Although permeability decreases, the reduction is much less than that of tectonic coal [18]. This also explains the evolutionary changes in permeability under the influence of effective stress for both tectonic and primary structural coal. The reconfiguration of pore fractures under stress in tectonic coal diminishes the effectiveness of pressure relief and permeability enhancement in engineering applications. Although there is a certain permeability enhancement effect in the early stages, later, with mining stress and other engineering stresses, the permeability returns to its original state, or even lower.

Tectonic coal has well-developed pore features and good connectivity, especially in processed coal. Primary structural coal is denser, with good integrity and undeveloped pore fractures. The adsorption capacity of the two coal types was tested in the laboratory. The Langmuir adsorption constant for tectonic coal was found to be a=58.476 m^3/t, b=0.593 MPa^{-1}, and for primary structural coal, a=55.326 m^3/t, b=0.557 MPa^{-1}. The gas adsorption capacity of tectonic coal is slightly higher than that of primary structural coal, but the difference is not significant. The ultimate gas adsorption capacity is primarily determined by the micropore structure [19], which provides the specific surface area that dictates the amount of adsorption. In the experimental samples, tectonic coal has a developed pore structure, and the processed coal exhibits the same feature. In the experiments, the saturated water content of tectonic coal reached 18.6%, while the saturated water content of primary structural coal was below 5%. Thus, the internal pore structure of tectonic coal is a major factor contributing to its inconsistent response to permeability changes under different conditions.

After water is added to the coal sample, the strength further weakens, and the pore structure is occupied by water molecules, reducing the sensitivity of permeability to changes in effective stress and pore pressure. In engineering, hydraulic measures to enhance permeability are increasingly used, with better results in hard coal environments. However, in tectonic coal regions, techniques like hydraulic fracturing and hydraulic slotting often fail to meet engineering needs. The reason is that in the initial stages of water saturation in tectonic coal, water acts as a sealing agent, reducing permeability instead of enhancing it. As water dissipates, the coal particles become more tightly packed due to the molecular attraction of the lost water, and, with the reconfiguration of the pore structure under mining stress, permeability continues to decrease. The later-stage permeability enhancement effect is even less ideal. Therefore, when it comes to gas extraction, some have proposed fracturing the top and bottom layers to create more stable, large fracture channels that do not close. However, this method is also not ideal. The application of high-pressure abrasive jetting in engineering aims to use abrasive particles to support the fractures, forming an ideal network structure. However, tectonic coal particles themselves consist of abrasive particles that form a reconfiguration of multiple spheres, and the increased permeability still does not meet engineering requirements. Gas management in tectonic coal remains a significant challenge in engineering.

5. CONCLUSION

The permeability of tectonic coal and primary structural coal was tested, and based on the experimental results, the following conclusions can be drawn:

(1) The permeability of both coal samples decreases with increasing effective stress. As effective stress continues to increase, the rate of decrease in permeability gradually weakens. The relationship between permeability and effective stress follows a negative exponential function. The permeability of tectonic coal is more sensitive to changes in effective stress, while primary structural coal exhibits a more moderate change under the tested stress conditions.

(2) Both coal samples respond similarly to gas pressure, decreasing permeability with increasing gas pressure. However, the permeability loss rate of tectonic coal increases much more significantly with gas pressure than that of primary structural coal, and both coal types show a reduced sensitivity to gas pressure as water content increases.

(3) Increasing water content leads to the occupation of the coal's pore and fracture channels, which is the primary reason for the decrease in permeability. The permeability of tectonic coal decreases more significantly with increasing water content, and the change in permeability due to water content is much greater than that of primary structural coal. The reconfigurability of the particles in tectonic coal is a critical factor in the recovery or decrease of permeability to its original value. Under water saturation, this reconfigurability is further enhanced.

ACKNOWLEDGEMENT

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