Research Article

Research on Seepage Properties and Pore Structure of the Roof and Floor Strata in Confined Water-Rich Coal Seams: Taking the Xiaojihan Coal Mine as an Example

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During the construction and exploitation process in the Xiaojihan coal mine, which is located in Yulin of northern Shaanxi, we find a special hydrogeological phenomenon that coal seam is acted as a confined fractured aquifer. The water-rich coal seam has natural fissures which are confined with water storage. However, the water comes from the static and original reserves in coal seams, which have a weak link to other aquifers in the roof and floor strata. It indicates that the roof and floor strata provide a natural waterproof barrier for the fissure water in the coal seam, resulting in a relatively closed storage space of confined water. In order to further investigate the critical function that mechanical properties of permeability play in the confined fractured aquifer, the rock complete stress-strain permeability test and pore development structure test are carried out with rock samples of the roof and floor strata in this field. Results are as follows: (1) coal seams of Xiaojihan coal mine are confined fractured aquifers, the fissure confined water in coal seams has a strong relationship with total stress-strain permeability and development characteristics of the pore structure of the roof and floor strata. (2) The permeability of the roof and floor strata is extremely low, when the strata is less than 30 meters away from the coal seam with the magnitude order remaining less than 10^{-12} m/s. If they are closer to the coal seam, the watertightness and plasticity of the strata will be stronger, and the antidestructive capability of the strata during the distortion process will be also increased, resulting in the larger strain for the formation of macroscopic water-conducting fissures. The roof and floor strata effectively cut off the hydraulic connection between the fissure water in the coal seam and other aquifers, which ensure the coal seam acts as water storage space of confined fractured aquifers. (3) For undeveloped fissures, the effective porosity is less than 2% of the roof and floor strata which are less than 30 meters away from the coal seam, and particularly, this index is less than 1% of the strata within 20 meters away from the coal seam, indicating that the strata have good water resistance. When the distance between the roof strata and the coal seam is greater than 40 meters, the effective porosity has a large fluctuation, and the effective porosity of the partial strata is greater than 10%, reflecting that the rock strata fissure has been well developed. It should be attached great importance to prevent water-conducting fissures from getting hydraulic connection with the fractured water-rich coal seams and other aquifers of the roof and floor, so as to reduce the risk of mining water hazards.

1. Introduction

Mining water hazard is one of the serious potential risks that restrict the safe production of China's coal mine industry. With the gradual depletion of coal resources in the eastern China, the main focus of coal mining has shifted to northern Shaanxi, Inner Mongolia, and other western regions [1–4]. However, natural geographical features in the western regions are extremely unique. During the exploitation of the

Xiaojihan coal mine, we find a special hydrogeological phenomenon that the coal seam is acted as a pore-fissure confined aquifer [5–7] and a main water-filling layer. In the mine construction process, such as mine shaft construction, open-off cut, and roadway driving, if they are close to the coal seam, certain serious water inrushes would occur in all coal seams, which may seriously affect coal mine safety and normal mining. According to the on-site investigation and the water quality analysis, water-rich coal seam is found to

have natural fissures for confined water storage, but the water comes from the static and original reserves in the coal seams, which have a weak link to other aquifers in the roof and floor strata. The cause for the coal seam being confined with water storage and acting as the main confined aquifer in the Xiaojihan coal mine still needs to be further investigated. To this end, this paper analyzes the total stress-strain permeability and pore structure of the roof and floor strata. Many scholars have researched from different aspects to study the permeability and pore structure characteristics of the roof and floor strata in coal seams. Based on the nonlinear theory and stochastic differential equation, Miao et al. [8–14] have studied permeability characteristics of cracked rock mass. The qualitative and quantitative relationship between the rock stress-strain and permeability has been established by studying the deformation and failure process of coal by Meng et al. [15, 16]. Wang and Miao [17] established a cusp catastrophe model for the relationship between rock permeability and stress-strain by applying the catastrophe theory. A study about the permeability evolution law in the fissure process of rock strata is presented by Yang et al. [18–21], according to the coupling equation of seepage and stress in the process of rock damage evolution. Some scholars [22–33] used similar simulation, numerical simulation, indoor test, and other methods to study the different areas, such as permeability characteristics and development characteristics of the pore structure of the roof and floor strata. In the rare hydrogeological condition where the coal seam is a pore-fissure confined aquifer, there are relatively few research on the connection between the permeability and development characteristics of the pore structure of the roof, floor strata, and confined water-rich coal seams. This paper uses field samples of the roof and floor rock strata for the rock total stress-strain permeability test and mercury injection test on pore development characteristic and mainly analyzes the critical function of the total stress-strain permeability and pore development characteristics in the roof and floor strata for confined fractured aquifers.

2. Hydrogeological Condition of Water-Rich Coal Seams in Xiaojihan Coal Mine

Xiaojihan coal mine is located in the northern Shaanxi Province and about 20 km on the northwest of Yulin City. The No. 2 coal seam in the Group Yan'an is the principal working section of mining, ranging from 0.68 m to 8.64 m of normal thickness and 3.41 m on average. The position of the coal seam is stable with a low change trend of coal quality. In addition, most parts of the coal seam are exploitable. From the hydrogeological profile (Figure 1), it can be obtained that the fissure aquifer of No. 2 coal seam can get a slow bedding supply from the eastern coal seam outcrop.

In the mine construction process, such as mine shaft construction, open-off cut, and roadway driving, when they are close to the coal seam, serious water intrusions will occur in the coal seam (Figure 2). According to the on-site investigation, the water intrusion is found to come from fractures of the coal seam. When the shaft bottom is disclosed, the water pressure increases to 2.5 MPa, the fissure water

FIGURE 1: The hydrogeological profile of the Xiaojihan coal mine.

FIGURE 2: Water outlet of fracture aquifer in the coal seam.

straightly sprays to the opposite side of the roadway, and the largest inflow is greater than $500 \text{ m}^3/\text{h}$. If the air intake shaft gets close to the coal seam, the amount of water inrush will be greater than $82 \text{ m}^3/\text{h}$, and the water pressure will increase up to 2.3 MPa, submerging the shaft. When the return air roadway discloses the coal seam, the amount of water inflow of the mining face is greater than $320 \text{ m}^3/\text{h}$, reaching the highest at the speed of $540 \text{ m}^3/\text{h}$, and the water pressure is 2.6 MPa. Water exit fractures are all jointing fractures, cutting through the entire or part of the coal seam. While only a few fractures cut through the entire coal seam, most of them locally cut the coal seam. The local cutting position is in the middle part of the coal seam with the cutting height of 40–70 cm.

According to statistics, the fissure direction of water inrush in the coal seams is centered at 290° , obeying the normal distribution (Figure 3). The water outlet fissure occurs in a group on the plane and separates in the syncline axis. From the view of the profile, water inrush points are situated in the middle of the coal seam, and there are generally little water fractures at the upper and lower part of the coal seam. Effluent points of bolt holes are generally presented at the same level. Height of jointing normally ranges from 50 cm to 80 cm, and only a few jointings cut through the entire seam. Fracture angles near the effluent are mostly 90° , while others are in the range of 65° – 90° . Width of fissures and the space between fissures are, respectively, in the range of 0.5 to 7 cm and 50 to 80 cm, indicating that the structural fracture is the main storage space and channel of the confined aquifer.

FIGURE 3: The trend of water gushing fissure.

It is found that the source of the water intrushes comes from the No. 2 coal seam. The position of the underground water probing holes (Table 1) indicates that it starts to gush at the distance of 0.68–6.7 m from the roof. When getting closer to the roof of the coal seam, it has the greater water inflow. When the roof is at the position of about 0.2–1.65 m inside the coal seam, the amount of water inflow increases sharply to the maximum, water pressure also reaches the maximum, and water inflow which reveals the total coal seam no longer increases. Therefore, it is known that the coal seam is a cracked aquifer, which is considered as a main water-filled aquifer if the water inflow is larger than the other water-rich coal seams.

The coal seam has a natural fissure confined water storage, but the water comes from the static and original reserves in the coal seams, which have a weak link to other aquifers in the roof and floor strata. It indicates that the roof and floor strata provide a natural waterproof barrier for the fissure water in the coal seam, resulting in a relatively closed storage space of confined water. Test samples are taken from the roof and floor rock strata of the Xiaojihan coal mine for analyzing the stress-strain permeability and pore structure. These factors directly determine whether the fracture in the coal seams has the condition of being confined with water. It also indirectly explains why the water pressure and water-rich property in the cracked water-rich coal seams are completely independent with other aquifers in the roof and floor, providing theoretical supports for the formation of the special hydrogeological phenomenon of the water-rich coal seam.

3. Analysis on Floor Strata by Indoor Test

Samples used in the following tests were taken from the No. 2 water-rich roof and floor strata in the Xiaojihan coal mine. The electrohydraulic servocontrolled test system MTS815.02 was used to determine the rock total stress-strain permeability, and the Micromeritics Instrument Corp's production of the AutoPore IV 9510 automatic mercury pressure tester

was applied to test development characteristics of the pore structure.

3.1. Complete Stress-Strain Permeability Test

3.1.1. Testing Principle. Permeability characteristics of rock were tested by an instantaneous permeating method. Based on Darcy's law, the instantaneous permeating method uses the time-series difference of pore pressure to calculate the rock permeability. The structure of the testing system is shown in Figure 4.

Testing principle of the instantaneous permeating testing system is illustrated in Figure 5. Two pressure regulators are applied to the pore pressure system, and both of their volume are B . The pressure is, respectively, p_1 and p_2 , the height and cross section area of rock samples are, respectively, H and A . Due to the different rock pressure at the initial moment ($p_{10} > p_{20}$), a pressure gradient $\xi_0 = (p_{20} - p_{10})/H$ exists, so the water in tank 1 flow into tank 2 through the rock samples. Thus, the water pressure of tank 1 continuously decreases, and the water pressure of tank 2 continuously increases until the two tank pressure are equal. If the pore water of the samples is saturated, the water mass flow in tank 1 that flow into rock samples should be equal to the water mass flow in rock samples which flow into tank 2, and both of mass flow are set as q . The seepage velocity in rock samples is $V = (q/\rho A)$. According to the compressibility of fluid,

$$\frac{1}{c_f} = \rho \frac{dp_1}{dp}. \quad (1)$$

Considering the relationship between $d\rho = (-qdt)/B$ and $q = \rho AV$,

$$\frac{dp_1}{dt} = -\frac{AV}{c_f B}. \quad (2)$$

According to the same principle,

$$\frac{dp_2}{dt} = \frac{AV}{c_f B}. \quad (3)$$

The following equation can be obtained by subtracting (2) from (3):

$$\frac{d(p_2 - p_1)}{dt} = 2 \frac{AV}{c_f B}, \quad (4)$$

or

$$V = \frac{c_f B H}{2A} \frac{d\xi}{dt}, \quad (5)$$

where ξ is the pressure gradient of samples and $\xi = (p_2 - p_1)/H$.

The seepage velocity and pressure gradient obey Darcy's law, so

$$\xi = -\frac{\mu}{k_D} V, \quad (6)$$

where μ is the dynamic viscosity of the seepage flow and k_D is the permeability of the Darcy flow.

TABLE 1: Comparison of the water probing holes construction.

Drill	#1	#2	#3	#4	#5	#6	#7	Remarks
Orifice height (m)	914.148	914.637	913.270	901.937	897.344	907.657	907.486	—
Initial water elevation (m)	—	896.847	897.501	893.437	891.801	899.657	896.286	—
Water quantity increase position (m)	894.928	895.997	894.341	892.327	891.436	894.537	895.786	—
Roof of the coal seam (m)	891.048	892.437	891.941	891.107	891.119	892.261	894.966	—
Sudden increase in the water volume (m)	890.248	891.937	891.641	890.387	890.961	890.607	894.766	Enter the coal seam for 0.2~1.65 m
Floor of the coal seam (m)	Not tested	891.537	Not tested	889.457	Not tested	889.877	894.486	—
Final hole height (m)	889.748	888.537	890.941	889.297	890.618	889.797	894.086	—
Water inflow (m ³ /h)	>40	20	>93	29.4	>60	45	Flooded	Measured after drilling
Hydraulic pressure (MPa)	2.6	2.5	2.6	2.4	—	—	—	Measured after drilling

FIGURE 4: Testing system of permeability of rocks under variable grains diameter and axial displacement. Note: A: pressure sensor; B: load controller; C: relief valve; D: regulator; E: pressure difference sensor; F: drainage; S1~S15: switch.

FIGURE 5: Mechanical model of instantaneous permeating testing system.

V from (5) is substituted in (6) to get the following equation:

$$\frac{d\xi}{dt} = -2 \frac{Ak_D}{c_f BH\mu} \xi. \quad (7)$$

The time interval of taking the sample is τ , the total sampling times is n , the pore pressure gradient is ξ_f at the end sampling time of $t_f = n\tau$, and (7) is integrated as follows:

$$\ln \frac{\xi_0}{\xi_f} = 2 \frac{Ak_D t_f}{c_f BH\mu}, \quad (8)$$

where the pressure gradients ξ and ξ_0 are both negative, so ξ_0/ξ is positive and $\ln(\xi_0/\xi)$ is meaningful. Rock

permeability and permeability coefficient can be calculated by (8) as follows:

$$k_D = \frac{c_f BH\mu}{2t_f A} \ln \frac{\xi_0}{\xi} = \frac{c_f BH\mu}{2t_f A} \ln \frac{p_{10} - p_{20}}{p_{1f} - p_{2f}}, \quad (9)$$

$$K = \frac{k_D \gamma}{\mu}, \quad (10)$$

where γ is the liquid proportion.

Equations (9) and (10) are applied in the MTS815.02 rock mechanics testing system to figure out the permeability k_D and permeability coefficient K in the stress-strain instantaneous permeating experiment.

3.1.2. Testing Scheme Design. Samples collected from the roof and floor strata have different distances from the water-rich coal seams in the Xiaojihan coal mine. Distances between the sampling position and the coal seam are listed in Table 2. These samples are machined in standard size. The height and section diameter of samples are, respectively, 100 mm and 50 mm. The test confining pressure p_c is set as

4 MPa. Deionized water is used as the seepage liquid, whose mass density and dynamic viscosity are, respectively, 1000 kg/m^3 and $1.01 \times 10^{-3} \text{ Pa}\cdot\text{s}$. Compression coefficient is $c_f = 0.475 \times 10^{-9} \text{ Pa}^{-1}$, and the regulator volume is $B = 0.332 \times 10^{-3}$. By collecting the time-series difference of pore pressure, the permeability coefficient K of the Darcy flow is calculated on the basis of (10). In the rock stress-strain test, 14 strain values, namely, $\varepsilon_0, \varepsilon_1, \dots, \varepsilon_N$ ($0 < \varepsilon_0 < \varepsilon_1 < \varepsilon_2 \dots < \varepsilon_{N-1} < \varepsilon_N$), are loaded on samples under the axial strain. When the axial strain reaches a preset strain value, the axial loading system maintains axial displacement of rock unchanged and figures out the variation of permeability.

3.1.3. Analysis of Test Results. According to results of the tested samples from the roof and floor strata that have different distances from the coal seam aquifer, the test data are listed in Table 3:

Test for the total stress-strain permeability: 1–8 test data in Table 3 present the variation of the permeability coefficient K with the axial displacement Δ , in which the permeability is influenced by the distance between the roof, floor strata, and the water-rich coal seam. Corresponding curves of rock permeability are shown in Figures 6 and 7. From the test results, it can be obtained that (1) at the initial stage of the test, axial strains of samples increase, which are in the elastic stage. Permeability increases slowly or is substantially unchanged. When the axial strain increases to a certain level, the permeability coefficient K increases sharply and reaches the peak. At that time, the increase level of the permeability coefficient K is dozens of times more than that at the elastic deformation stage. Meanwhile, the fissure of samples propagates and mixes together, having formed a clear macrodamage structure already. Then, the axial strain continues to increase, while the permeability coefficient K begins to decrease. When the decline rate is close to 50%, the permeability coefficient K tends to be stable. Some large cracks and failure surfaces are filled with small particles at this stage. Confining pressure plays a limited role in the crack expansion, resulting in the decrease of samples' permeability at the same time. (2) With the increasing distance to the coal seam, the permeability of the roof samples test has experienced the change process of $10^{-13} \sim 10^{-12} \sim 10^{-13} \sim 10^{-11}$. The magnitude order of the permeability keeps under 10^{-12} , if samples are comparably closer to the coal seam. When the roof strata get closer to the coal seam, it has a lower change speed of permeability and better waterproof character. Besides, resistance ability against the destruction caused by the axial strain is larger as well as the axial strain for forming the macroscopic fissure surface. (3) With the increasing distance to the water-rich coal seam, the magnitude order of permeability has experienced the change process of $10^{-13} \sim 10^{-12} \sim 10^{-13} \sim 10^{-11}$. When the floor strata get closer to the coal seam, it has a lower permeability and better waterproof character. Besides, resistance ability against the destruction by the axial strain is larger, as well as the axial strain for forming the macroscopic fissure surface.

TABLE 2: Sampling position of the roof and floor strata.

Sampling position	Distance from the coal seam (m)	Numbered
Roof rock	36.3	1
	21.5	2
	11.9	3
	1.5	4
Floor rock	0.8	5
	10.5	6
	19.7	7
	28.8	8

3.2. Pore Structure Analysis

3.2.1. Test Equipment and Conditions. AutoPore IV 9510 automatic mercury pressure tester (Figure 8) of the Micromeritics Instrument Corporation was used in the pore structure analysis. The maximum operating pressure is 60 thousand pounds (414 MPa). The sample is $\Phi 25 \times 20\text{--}25 \text{ mm}$ (the diameter is 25 mm, and the length ranges from 20 mm to 25 mm.), and the test aperture is $0.003\text{--}1000 \mu\text{m}$.

3.2.2. Test Method. As the basic principle of the pressure mercury test, the nonwetting phase mercury should be injected into the core pore. Firstly, samples have been dried in an oven at a temperature of $70\text{--}80^\circ\text{C}$ for 10 hours; secondly, samples are put into the dilatometer and evacuated. When the vacuum degree reaches $50 \mu\text{m}$ mercury column, mercury is injected into the dilatometer immediately. Mercury flows into the interspace of rocks to resist the capillary force driven by pressure. The pore equals to (maximum mercury volume/test rock volume) $\times 100\%$, which is calculated by effective penetration of mercury into pores. Therefore, the porosity is actually effective, and the isolated or non-connected pores cannot be measured with this instrument.

3.2.3. Test Result Analysis. Samples are collected from the roof and floor strata at different distances to the water-rich coal seam, and the porosity of their natural state is obtained. Test data are listed in Table 4, and the variation curve is shown in Figure 9.

The results (Table 4 and Figure 9) show that (1) the effective porosity is less than 2% of the roof and floor strata which are within 30 meters from the coal seam. In particular, the effective porosity is less than 1% of the rock strata within 20 meters from the coal seam. Since the test results are effective porosity, the isolated or nonconnected pores cannot be measured, so the actual porosity of samples should be increased correspondingly. (2) The effective porosity is less than 2% of the roof and floor strata which are within 30 meters from the coal seam, where the rock strata can be excellent water-resisting layers due to undeveloped fractures. In this way, the effective water storage space of the confined water-rich coal seams is formed. (3) When the distance between the roof strata and the coal seam is greater than 40 m, the effective porosity has a larger fluctuation, and the effective porosity of partial rock strata is larger than 10%,

TABLE 3: Total stress-strain permeability test data.

Δ (mm)	1 of K ($\times 10^{-11} \text{ m}\cdot\text{s}^{-1}$)	2 of K ($\times 10^{-13} \text{ m}\cdot\text{s}^{-1}$)	3 of K ($\times 10^{-12} \text{ m}\cdot\text{s}^{-1}$)	4 of K ($\times 10^{-13} \text{ m}\cdot\text{s}^{-1}$)	5 of K ($\times 10^{-13} \text{ m}\cdot\text{s}^{-1}$)	6 of K ($\times 10^{-13} \text{ m}\cdot\text{s}^{-1}$)	7 of K ($\times 10^{-12} \text{ m}\cdot\text{s}^{-1}$)	8 of K ($\times 10^{-11} \text{ m}\cdot\text{s}^{-1}$)
0.2	0.29	0.39	1.18	0.18	0.13	0.23	2.81	1.23
0.35	0.37	0.52	3.44	0.41	0.34	0.96	5.72	11.44
0.45	2.13	0.39	6.32	0.33	0.37	0.37	7.16	27.45
0.5	7.13	0.92	8.76	0.51	0.49	0.64	11.65	29.75
0.55	4.86	1.17	11.27	1.12	1.13	1.22	12.97	34.62
0.6	9.22	1.13	14.11	1.17	1.57	1.53	14.28	40.53
0.65	22.75	1.45	16.15	1.36	1.66	2.11	15.21	67.42
0.7	55.52	2.11	20.3	1.43	2.13	3.37	14.35	259.48
0.75	142.16	8.36	73.97	11.97	1.97	3.74	61.33	143.25
0.85	95.88	15.99	18.85	13.85	15.35	20.15	24.25	135.51
1	72.36	75.86	17.34	18.67	55.33	64.47	20.33	133.28
1.2	68.56	36.68	17.45	65.54	32.66	31.73	18.85	132.35
1.4	62.44	32.36	16.89	37.89	27.73	26.82	17.25	132.15
1.5	60.18	32.11	16.68	34.82	25.26	26.34	17.17	130.59

Δ : axial displacement; K : permeability coefficient.

FIGURE 6: Curves of 1–4 roof rock permeability changing with axial displacement.

indicating that fractures in the strata are well developed. It should be attached great importance to prevent the water-conducting fissures from getting hydraulic connection with the fractured water-rich coal seams and other aquifers of the roof and floor, so as to reduce the risk of mining water hazards.

4. Conclusions

- (1) Coal seams of the Xiaojihan coal mine are fractured confined aquifers and water-filling layers. The water-rich coal seam has natural fissures which are confined with water storage, but the water comes from the static and original reserves in the coal seams, which have a weak link to other aquifers in the roof and floor strata. It indicates that the roof and floor

FIGURE 7: Curves of 5–8 roof rock permeability changing with axial displacement.

strata provide a natural waterproof barrier for the fissure water in the coal seam due to the special permeability and pore structures, resulting in a relatively closed storage space of confined water.

- (2) The roof and floor strata which are within 30 meters from the coal seam have a low permeability extremely with magnitude orders remaining under 10^{-12} m/s . When getting closer to the coal seam, it has a stronger water-resisting property and plasticity of the rock strata. Besides, the resistance ability against destruction in the course of the formation of the strata is stronger, and the strain needed for the formation of the macroscopic water-conducting fissure is larger. As a result, the roof and floor strata effectively cut off the hydraulic connection between the fissure water in coal seams and other aquifers,

FIGURE 8: The pressure mercury testing system.

TABLE 4: Porosity of the roof and floor rock strata.

Sampling position	Distance from the coal seam (m)	Porosity (%)
Roof rock	70.9	8.7194
	64.8	1.889
	52.1	10.4468
	49.1	0.3389
	37.1	1.7468
	26.9	0.3562
	12.9	0.2146
	2.5	0.3588
Floor rock	-1.6	0.1985
	-9.3	0.2589
	-19.5	0.3033
	-27.6	1.8036
	-35.8	0.9951

FIGURE 9: Changing regularity of porosity.

ensuring the water-rich coal seam as the water storage space of the pore-fissure confined aquifer.

- (3) Test results of the pressure mercury show that the effective porosity is mostly less than 2% of the roof and floor strata which are within 30 meters from the coal seam. In particular, the effective porosity is less than 1% of the strata within 20 m away from the coal seam, and the fissure is undeveloped, so that the

strata have a good water-resisting property and effectively cut off the connection between the fissure water of the coal seams and other aquifers. Meanwhile, it provides water storage space for the water in the pore-fissure confined aquifers. When the distance between the roof strata and the coal seam is greater than 40 m, the effective porosity has a larger fluctuation, and certain strata would be larger than 10%, indicating that fractures in the strata are well developed. It should be attached great importance to prevent the water-conducting fissures from getting hydraulic connection with the fractured water-rich coal seams and other aquifers in the roof and floor, so as to reduce the risk of mining water hazards.

Data Availability

There are four tables providing the data used to support this study. All these data are obtained from field experiments and indoor tests of rock samples, and any details about them are indicated in this paper. The experimental and original data used to support the findings of this study are included within this article. No additional data are available.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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