Research Article

Permeability Characteristics of Water-Sand Seepage in Fracture by Experiment

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Studies on the seepage characteristics of water-sand cracks are of great significance to reveal the mechanisms of water and sand inrush. Using a self-made water-sand fracture seepage test instrument, a water-sand seepage test was carried out, and the permeability of water and sand in the fracture was determined. The hysteresis characteristics of water-sand flow in the fracture were obtained after the required permeability was attained. The results show that the hysteresis curve changes from type I to type IV with the increase in sand particle size and concentration. The hysteresis parameters are described by the maximum hysteresis Gp^* and the hysteresis area S , both of which show an increasing trend with the increase in sand particle size and concentration; however, this increase is not synchronous. The average velocity and turbulent kinetic energy distribution of the water-sand fluid on the fracture cross section are greatly affected by the particle size and concentration of the volume of sand. This study can provide a reference for further study of water inrush from a shallow coal seam. Through simulation, it is found that the particle size has a great influence on the seepage velocity, and the influence near the side wall surface is greater than that in the middle position.

1. Introduction

Water and sand inrush is a serious menace to mine safety and needs to be understood well. The sand-bearing water layer that is always located above the coal seam is shown in Figure 1. Experimental and theoretical research was done to obtain the mechanism of water and sand inrush [1–4]. Analysis shows that the mechanism of interaction of water and sand is complicated, and the influencing factors include the channel of fracture, starting pressure gradient of water and sand particles, and concentration of sand and water.

Material flow in a smooth fracture may be described by a cubic relationship, but natural fractures are rough and the flow is difficult to measure, leading to much research [5–8]. During studies on the seepage in the fracture, many scholars found the permeability in the fracture to be non-linear [9–12]. Till recently, Forchheimer's law was used widely for modeling; in addition, the Reynolds number of the fracture flow was also discussed [13–15]. The Izbash law was further revised to account for roughness [16, 17] and the seepage in

fracture related to surface roughness and fracture aperture [18–20]; this is difficult to determine given the lack of accurate characterization and measurement techniques because fracture geometries are heterogeneous and invisible. To measure the roughness of the fracture, many parameters were established to express it [21–24].

Du et al. [25] obtained the law of water and sand flow in the broken rock, and Liu et al. [26] obtained the permeability of water and sand in the fracture under different conditions. Sui et al. [27] obtained the law of dry sand migration and discussed the initial conditions of water and sand. Ma et al. [28] and Liu and Liu [29] obtained the water-sand flow from seepage to tube flow, and Hu et al. [30] further proved it.

On studying the water and sand flow, some new characteristics of the water and the flow in the fracture are discussed. Liu et al. [31] identified the phenomenon of hysteresis in the flow of water and sand, but the detailed characteristics were not discussed. Hysteresis was also found for the magnetic force and stress-strain fields, and similar laws were also found for gas permeability [31, 32]. Fan and

FIGURE 1: Water and sand inrush. (a) Schematic diagram. (b) Accident site [1].

Liu [33] obtained the permeability hysteresis during the cyclic loading-unloading. Hu et al. [34] and Duan et al. [35] obtained the permeability hysteresis and stress sensitivity coefficients on the loading path, which were higher than those on the unloading path.

Through analysis, the mechanism of water and sand transport has been recognized and elucidated. As the main transport channel, the fracture is the main channel for water and sand migration, but its migration rule is yet to be determined, resulting in the need for further analysis when water and sand flow through the fracture.

The purpose of this work is to identify the water infiltration characteristics of sand as the research object, use indoor testing to determine the hysteresis change characteristics of the fracture seepage of water and sand, and use numerical simulation to study the influence factors of the water and sand seepage field. This is of great significance to grasp the mechanism of water inrush and movement of sand.

2. Test Principle and Method

2.1. Test Materials. In this paper, the rock sample is sandstone from below -265 m at the Luan mine in Shanxi, China, and the length of fracture is $L = 125$ mm, the height is $h = 75$ mm, and $b = 0.25$ mm, 0.5 mm, 0.75 mm, and 1.0 mm, as shown in Figure 2. The sand was taken from Lingshou County, Hebei Province, with four particle sizes: $0.092\text{--}0.138$ mm, $0.138\text{--}0.184$ mm, $0.184\text{--}0.230$ mm, and $0.230\text{--}0.276$ mm. Permeation tests were carried out at 20 kg/m^3 , 40 kg/m^3 , 60 kg/m^3 , and 80 kg/m^3 , respectively.

2.2. Experimental Equipment and Steps. A set of experimental systems was designed and manufactured as shown in Figure 3, which consists of a mixing system of water and sand (1), water and sand loading system (2), data acquisition system (3), computer (4), and seepage apparatus (5).

The test steps were as follows:

- (1) The test system was assembled according to Figure 3, and the sample was loaded. The leakage of the experiment system was tested.
- (2) The sand particle with a diameter of $0.038\text{--}0.044$ mm was placed into the mixing pool, and the sand concentration was 20 kg/m^3 at 1 cubic meter of water.
To control the motor speed, the flow and pressure under different rotational speeds were recorded while the fracture aperture was 0.75 mm; the motor speed was varied as 200 r/min , 400 r/min , 600 r/min , 800 r/min , and 1000 r/min . Different pressures and seepage velocities of the fracture were obtained using a paperless recorder. The sand concentration ρ_s in water was 40 kg/m^3 , 60 kg/m^3 , and 80 kg/m^3 , respectively.
- (3) The flow and pressure under different particle diameters ($0.038\text{--}0.044$ mm, $0.061\text{--}0.080$ mm, $0.090\text{--}0.109$ mm, and $0.120\text{--}0.180$ mm) were recorded during the different rotational speeds. For ease of calculation, we consider the arithmetic mean of each range of the particle diameter, 0.041 mm, 0.071 mm, 0.100 mm, and 0.150 mm.
- (4) According to equation (1), the permeability parameters can be obtained by least square fitting [36].

$$\frac{\mu_e}{k_e} \frac{Q}{bh} + m\beta \left(\frac{Q}{Q} \right)^2 = -\frac{dp}{dl}, \quad (1)$$

where μ_e is the effective viscosity, k_e is the effective permeability, β is the non-Darcy factor, Q is the flow, and p is the pressure.

3. Results and Discussion

3.1. Influence of Fracture Aperture on the Permeability. Let $I_e = k_e/\mu_e$, and the permeability parameters of water and sand in the fracture are obtained as shown in Figure 4.

The mass concentration of sand is 20 kg/m^3 and 40 kg/m^3 . The fracture openings are divided into five grades: 0.5 mm, 0.75 mm, 1.00 mm, 1.25 mm, and 1.50 mm. The data from the pressure transmitter and flow sensor are collected after the pressure and flow of the seepage system are

FIGURE 2: Fracture specimen.

FIGURE 3: Water injection system to measure hydraulic extrusion: 1, mixing system; 2, sewage pump; 3, acquisition card; 4, computer; 5, seepage instrument.

stabilized. The seepage test results for sand particle size $0.038 \sim 0.044$ mm, sand mass concentration 20 kg/m^3 and 40 kg/m^3 , and joint roughness coefficient (JRC) 2–4, respectively.

From Figure 4, the effective fluidity of water and sand in the fracture increases with the width of fracture, and the non-Darcy factor decreases with the width of the fracture.

Fracture aperture has considerable influence on the permeability [37]; many scholars studied it with reference to water and gas [38, 39] and modified the cubic law or the Izbash law. In this study, we discussed the effective fluidity, which depends on the shape of the fracture and the characteristics of the fluid and thus differs for water and gaseous substances. The obtained results could be fitted using the cubic law.

3.2. Influence of Fracture Roughness on Permeability. Table 1 shows the changes in the effective fluidity and non-Darcy flow factor β of water-sand mixture seepage with the roughness. Permeability of water and sand in the fracture is obtained by changing fracture roughness and mass concentration. The relationship between I_e , β , and JRC is an exponential function.

Along with the increase in the aperture and JRC of fracture, the effective fluidity increases, and non-Darcy

factor decreases. In the range of the fracture aperture $0.5 \text{ mm} \sim 1.5 \text{ mm}$ and JRC 2–8, the field of effective fluidity is $10^{-8} \sim 10^{-5} \text{ m}^{n+2} \cdot \text{s}^{2-n} / \text{kg}$, and the non-Darcy factor β is $10^5 \sim 10^8 \text{ m}^{-1}$.

Hu et al. [40] concluded that the roughness will influence the distribution of the concentration and decrease the effective dispersion coefficient. Peng et al. [41] discovered that an increase in fracture roughness and concentrations will cause a decrease in the Darcy permeability coefficient. Yu and Li [42] discussed the roughness and the relationship between the solute transport curve and the maturity of the dominant channel. Here, we discussed water and sand flow through the fracture, and effective fluidity $I_e = K_e / \mu_e$ was introduced, where K_e is the permeability of water and sand in fracture and μ_e is the viscosity of water and sand. It is a new method to determine the common influence characteristics of water and sand in the fracture.

3.3. Variation of Hysteresis Characteristics. The fracture aperture is 0.75 mm , and the ratio of the fracture aperture to average particle size was $2.7 : 1$. Seepage tests are carried out step by step. In Figure 5, there is no one-to-one correspondence between the pressure gradient and seepage velocity in the two stages of the rise and fall of the pressure gradient.

FIGURE 4: Curves of permeability parameters changing with the aperture at $d_s = 0.038 \sim 0.044$ mm and $p_s = 20$ kg/m³. (a) Curve of I_e - b at JRC = 2~4. (b) Curve of β - b at JRC = 2~4.

TABLE 1: Fitted equations of permeability parameters changing with JRC at $d_s = 0.061 \sim 0.080$ mm.

Number	ρ_s (kg/m ³)	Parameter of permeability	Fitting equations	Coefficients
1	20	I_e	$I_e = 6.40 \times 10^{-5} e^{-0.38\text{JRC}}$	0.9979
		β	$\beta = 8.10 \times 10^4 e^{0.45\text{JRC}}$	0.9943
2	40	I_e	$I_e = 8.08 \times 10^{-6} e^{-0.35\text{JRC}}$	0.9246
		β	$\beta = 2.41 \times 10^6 e^{0.32\text{JRC}}$	0.9946
3	60	I_e	$I_e = 3.75 \times 10^{-6} e^{-0.38\text{JRC}}$	0.9004
		β	$\beta = 1.55 \times 10^6 e^{0.47\text{JRC}}$	0.9763
4	80	I_e	$I_e = 5.36 \times 10^{-6} e^{-0.44\text{JRC}}$	0.9871
		β	$\beta = 2.15 \times 10^6 e^{0.43\text{JRC}}$	0.9827

With the increase and decrease of the pressure gradient, the pressure gradient and seepage velocity form a closed curve in plane coordinates. During the increase and decrease of the pressure gradient, four hysteresis curves are obtained. The complete hysteresis curve is divided into two parts: lift section OAB and return section BA and O. The lift curve and return curve of the type I curve intersect, the type II curve is similar to the hysteresis curve, the lift curve and return curve of type III curve coincide partly, and the lift curve and return curve of type IV curve have no coincidence point in the entire process.

With the increase in sand particle size and concentration, the hysteresis curve composed of the pressure gradient and seepage velocity gradually changes from type I to type IV, as shown in Tables 2 and 3.

The hysteresis curves of type I, II, III, and IV can be transformed from the former to the latter with the increase in sand particle size and concentration in Tables 2 and 3. The reason is that there are many movement patterns of water-sand flow in fractures, such as single-phase flow (there is no relative velocity between sand and water), two-phase flow (there is relative velocity between sand and water), and slug flow (there is one or more interface between sand and water). The hysteresis curve changes with the change in particle size and concentration of sand.

3.4. Influence of Sand Particle Size on Hysteresis Characteristics. To analyze the influence of sand particle size on the hysteresis parameters of the type IV hysteresis curve, the maximum hysteresis of seepage velocity-pressure gradient hysteresis curve and hysteresis area S of four groups of samples are summarized in Figure 6.

Figure 6 shows that the maximum hysteresis of the velocity-pressure gradient hysteresis curve of type IV water-sand flow tends to increase with the increase in sand particle size. The maximum hysteresis of the hysteresis curve increases slowly when the sand particle size is 0.115 mm~0.161 mm and 0.207 mm~0.253 mm. As the hysteresis curve is 0.161 mm~0.207 mm, the maximum hysteresis increases rapidly and approximates a linear growth.

3.5. Influence of Sand Concentration on Hysteresis Characteristics. The fracture aperture $b = 0.5$ mm, sand particle size $d_s = 0.230$ mm~0.276 mm, and sand mass concentration p_s were selected as variables. The hysteresis curves of fracture seepage were studied by setting four different water-sand mixtures of 20 kg/m³, 40 kg/m³, 60 kg/m³, and 80 kg/m³. Compared with the effect of particle size on seepage, the effect of concentration on permeability is

FIGURE 5: Four types of hysteresis curves. (a) I curve. (b) II curve. (c) III₁ curve. (d) III₂ curve. (e) IV curve.TABLE 2: Typical shapes and conditions of hysteresis curve at $b = 0.75$ mm.

(kg/m ³)	d_s (mm) ρ_s			
	0.092~0.138	0.138~0.184	0.184~0.230	0.230~0.276
20	I	II	III	III
40	I	II	III	III
60	II	II	III	III
80	III	III	III	IV

more intuitive. Compared with the concentration, the particle size varies between 0.138~0.184 mm and 0.184~0.230 mm, but the effect of concentration on hysteresis basically maintains a similar linear relationship.

The hysteresis curves under different particle sizes are shown in Figure 7. The maximum hysteresis of the velocity-pressure gradient hysteresis curve of type IV water-sand

seepage increases with the increase in sand concentration. When the sand concentration ranges from 20 kg/m³ to 40 kg/m³ and 60 kg/m³ to 80 kg/m³, the hysteresis area of the hysteresis curve increases linearly, but the maximum hysteresis increases slowly.

Loading and unloading cycles have a significant impact on the permeability hysteresis of the samples [35, 43], and

TABLE 3: Typical shapes and conditions of hysteresis curve at $b = 1.25$ mm.

(kg/m ³)	$d_s(\text{mm}) \quad \rho_s$			
	0.092~0.138	0.138~0.184	0.184~0.230	0.230~0.276
20	I	I	I	II
40	I	II	II	II
60	I	II	III	III
80	II	III	IV	IV

FIGURE 6: Hysteresis indicators of type IV hysteresis curves under different sand particle sizes at $b = 0.5$ mm and $\rho = 80$ kg/m³. (a) Maximum hysteresis. (b) Hysteresis area.

the hysteresis effect is more significant under triaxial stress conditions than that under true-triaxial stress [44]. The size effect is an important factor to be analyzed, and in general, larger sizes have greater hysteresis [45].

In this study, two new parameters are introduced: the first is the maximum hysteresis and the second is the hysteresis area, which is more clearly stated. The water and sand in the fracture exhibit a similar trend: with the increase of particle size and concentration, the hysteresis shows an increasing trend, but the process is very non-linear.

4. Simulation of the Water and Sand Flow in Fracture

4.1. Velocity of Water and Flow in the Fracture. Figure 8 shows the velocity cloud map when the crack inlet velocity is 0.869 m/s and $t = 0.27$ s. As can be seen from Figure 8(a), the velocity distribution changes dramatically when the fluid enters the fracture passage through the fracture inlet. The flow in the fracture can be roughly divided into two parts. The roughness of the fracture may lead to turbulence, resulting in the decrease in the velocity of water-sand flow, and the velocity in the middle of the water-sand flow is obviously greater than that near the fracture wall. One part is the main flow between $X_2 = 1$ mm and $X_2 = 1.8$ mm. The velocity ranges from 2.21 m/s to 3.16 m/s, and there are many

discontinuous high-speed areas. The main flow curve is generated at the sharp angle of the fracture, and the curve is distributed unevenly along the flow direction. The other part is the vortex area at the concave angle of the fracture, and the fluid velocity in the vortex center and the wall boundary layer area is low. As X increases, the velocity of water and sand decrease.

As can be seen from Figure 8(b), the absolute pressure gradient-seepage velocity curve of two-phase fracture water-sand flow obtained by numerical simulation is consistent with the curve obtained by the test, and there is a non-linear relationship between the absolute pressure gradient and seepage velocity. The numerical simulation results are smaller than the experimental results, and the relative error is between 18.5% and 46.7%. It should be noted that the absolute errors in the numerical simulation results and experimental results are close at different flow rates, while the relative errors decrease with the increase in flow rates.

4.2. Variation of Sand Particle Size. The influence of sand particle size on the fracture flow field is discussed under the conditions of sand particle density of 2650 kg/m³ and sand particle volume concentration of 4.06%. Figure 9 shows the absolute value of pressure gradient-sand particle size curve. Water and sand flow in rough fractures.

FIGURE 7: Hysteresis parameters of different concentrations. (a) Maximum hysteresis. (b) Hysteresis area.

FIGURE 8: Nephogram of velocity. (a) 0–20 mm and 20–40 mm start of fracture. (b) Comparison of curves of G_p -V.

FIGURE 9: Uniform velocity distribution of continuous phase fluid on cross section of rough fracture.

The absolute value of the pressure gradient is the largest when the sand particle size is 0, and the absolute value of the pressure gradient is the smallest when the sand particle size is 0.12 mm; the absolute value of the pressure gradient appears to be minimum when the sand particle size is 0.01 mm. At 0.04 mm, the absolute value of the pressure gradient decreases monotonously with the increase in sand particle size. This shows that water and sand flow in the rough fracture. When the sand particle size is small, pressure loss increases with the increase in sand particle size; when the sand particle size is large, pressure loss decreases with the increase in sand particle size.

In Figure 9, water and sand flow in the rough fractures, and the uniform velocity distribution of the continuous fluid phase on the fracture cross section is greatly affected by the volume concentration of sand particles. On the cross section $X_1 = 50.5$ mm, the time-averaged velocity distribution is no longer symmetric, but the peak value is in the vicinity of the central line $X_2 = 1.4$ mm, with multiple extremum points. The mean velocity changed dramatically with the volume fraction of sand particles near the wall surface. In other locations, the time-averaged velocity also varies with the velocity, but it is not significant near the wall surface. This indicates that the influence of sand particle volume fraction on the water-sand two-phase flow in the section $X_1 = 50.5$ mm mainly occurs near the wall surface.

5. Conclusion

- (1) Permeability of water and sand flow in fracture is tested by the homemade experimental apparatus, effective fluidity distribution is in $10^{-8} \sim 10^{-5} \text{ m}^{n+2} \cdot \text{s}^{2-n} / \text{k}$, and non-Darcy factor β distribution is $10^5 \sim 10^8 \text{ m}^{-1}$.
- (2) With the increase in sand particle size and sand mass concentration, the maximum hysteresis of the velocity gradient hysteresis curve increases linearly.
- (3) The structure of the rough fracture surface results in a certain randomness in the water-sand seepage field. The reason is that water and sand are deposited in the rough fracture surface, resulting in a complex relationship among the rough fracture surface, water, and sand and a non-unique relationship between the pressure gradient and water-sand seepage velocity.
- (4) When the sand particle size is small, the pressure loss increases with the increase in the sand particle size. When the sand particle size is large, the pressure loss decreases with the increase in the sand particle size. The distribution of the mean velocity and turbulent kinetic energy of the fluid on the fracture cross section is greatly affected by the size of the sand particle, which is indicated by the deviation of the position of the extreme point.
- (5) Through the simulation, the absolute errors in the numerical simulation results and experimental results are close at different flow rates, while the relative errors decrease with the increase in flow rates.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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