

Article

Lithology-Dependent Evolution of Porosity and Permeability in Fault Fracture Zones: Implications for Sustainable Mine Water Hazard Mitigation and Groundwater Resource Protection

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Abstract

Ensuring the sustainability of deep coal mining requires a comprehensive understanding of hydrogeological risks, particularly fault-induced water inrush, which threatens human safety, depletes freshwater resources, and causes irreversible ecological damage. This study addresses the sustainability gap in managing heterogeneous fault fracture zones by conducting coupled loading–seepage experiments on representative limestone, sandstone, coal, and coal–rock mixtures from the Zhaogu No. 2 Mine. Results demonstrate that seepage behavior follows the Forchheimer non-linear regime ($E = 0.2–0.95$), deviating significantly from Darcy’s law. We quantified that effective stress induces particle crushing and rearrangement, leading to a drastic porosity reduction (up to 97.52% in coal). Crucially, lithology dictates permeability evolution: coal and mixtures exhibit exponential decay, whereas sandstone and limestone follow quadratic functions. The fractal dimension of particles correlates negatively with permeability ($R^2 > 0.95$). These findings provide a quantitative framework for predicting water inrush channels, enabling proactive strategies to prevent catastrophic groundwater loss and ensure the long-term viability of mining operations. This research supports SDG 6 (Clean Water) and SDG 12 (Responsible Consumption and Production) by offering scientific guidance for balancing resource extraction with hydrogeological integrity.

Keywords: fault water inrush; mine sustainability; hydrogeological hazard mitigation; multi-lithology seepage; groundwater protection; particle crushing; non-Darcy flow



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1. Introduction

As global energy demands drive coal mining into deeper strata, the industry faces escalating challenges in reconciling resource extraction with environmental stewardship and social responsibility—core tenets of sustainable development. Deep mining operations frequently encounter complex geological structures, such as fault fracture zones, which serve as high-risk interfaces between mining activities and confined aquifers [1–3]. The instability of these zones often triggers water inrush disasters, leading to massive groundwater depletion, surface subsidence, and severe threats to miner safety [4–7], as shown in Figure 1. Such incidents undermine the “triple bottom line” of sustainability: economically

through operational shutdowns, socially through loss of life and community displacement, and environmentally through aquifer contamination. While previous studies have explored the mechanical properties of single-lithology rock masses, the heterogeneous nature of fault fillings—comprising diverse lithologies—necessitates a more nuanced investigation. This study aims to fill this gap by elucidating the hydrogeological controls of lithological variability on seepage evolution, thereby providing a scientific basis for developing resilient and sustainable water hazard prevention strategies in deep mining environments. It also has substantial significance for engineering applications, such as underground reservoir construction [8] and the utilization of abandoned mine goaf [9].

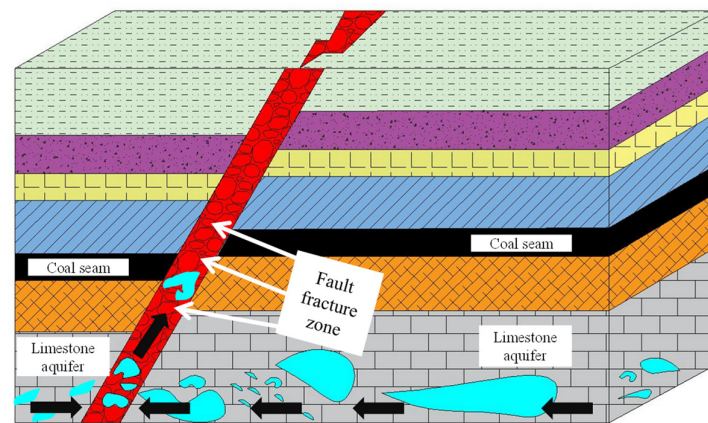


Figure 1. Schematic diagram of fault fracture zone.

Darcy's linear flow law has been widely adopted to describe fluid flow behaviors in porous media [10–12]. However, the internal channels of broken coal and rock masses are not composed of a single micropore. The channels consist of pores, fractures and voids [13,14]. The cross-section of flow channels in the fault fracture zones fluctuates sharply, and the throats of those are tortuous. When a fluid flows through these channels, its velocity and pressure gradient deviate from Darcy's linear law, showing obvious non-linear and non-Darcy seepage characteristics [15–17]. To accurately quantify this non-linear characteristic, Forchheimer [18], Ergun [19], Barree–Conway [20] and other non-linear equations have been proposed. These equations are also applied to the characterization of porous media seepage.

Researchers have carried out a wealth of theoretical studies and laboratory tests focusing on the loading compaction and seepage evolution of broken coal and rock masses. In terms of experimental methods, Miao et al. developed uniaxial confined seepage tests with different lithologies and discussed the influence mechanisms of void compaction on seepage [21]. Wang et al. performed seepage instability experiments on broken porous rock masses, utilizing a self-developed particle migration visualization testing system [22]. Li et al. carried out seepage tests under loading–unloading conditions using a self-developed triaxial seepage testing system and analyzed the effects of particle size, the coal–rock mixing ratio, and loading–unloading cycles on permeability [23]. Regarding seepage models and structural characteristics, Yang et al. constructed a hybrid flow field model integrating Darcy, Forchheimer, and Navier–Stokes equations that accounts for variable mass seepage [24]. Cao et al. established a prediction model for the hydraulic conductivity of broken rock masses, incorporating the Kozeny–Carman model and a liquid limit index characterizing the effective particle size [25]. Xu et al. developed a prediction model for Forchheimer seepage parameters based on internal pore structures, a piecewise-treated non-Darcy equivalent hydraulic conductivity, and a corresponding equivalent seepage model [26]. In terms of particle crushing and fractal characterization, Wu et al. quantified

the fractal evolution laws of broken gangue based on gradation theory and the Talbot index [27]. Feng et al. obtained the energy dissipation characteristics of broken rock masses under loading by acoustic emission and developed a correlation model with the degree of crushing [28]. Xue et al. achieved a three-dimensional visual characterization of the pore structure of broken rock masses under varying axial pressures using real-time CT scanning and elucidated the influence mechanism of microstructural evolution on macro-permeability [29]. In terms of numerical modeling, Li et al. conducted a sensitivity analysis of the risk of water inrush caused by faults using FLAC3D fluid–structure coupling numerical simulation [30]. Xue et al. simulated the flow state transition from linear seepage in an aquifer to non-Darcy high-speed seepage in a collapse column during water inrush [31]. Xian et al. used PFC3D-CFD coupling simulation to reveal the evolution of porosity, permeability, and mass loss caused by fine particle migration and loss under water pressure and the mechanism of unstable seepage in broken rock masses caused by faults [32]. These studies indicate that the reliable prediction of mine water hazards requires experimentally calibrated hydraulic parameters, including porosity, permeability, non-Darcy coefficients, and their stress-dependent evolution.

Although numerous studies have investigated the seepage characteristics of single-lithology broken media, the filling materials in fault fracture zones in coal mines typically comprise mixtures of various rocks and coal. They exhibit stark contrasts in hardness, strength, and brittleness. Consequently, relying solely on the seepage behaviors derived from single-lithology media fails to accurately capture the evolution of water inrush channels in actual fracture zones at the engineering scale. Furthermore, experimental investigations into the loading–seepage characteristics of broken media with different lithologies remain relatively scarce.

To this end, this study investigates broken limestone, sandstone, coal, and coal–rock mixtures from the fault fracture zone of the Zhaogu No. 2 Mine. Utilizing a self-designed coupled loading–seepage testing system, we conducted seepage experiments on these different broken coal and rock masses under different axial loading conditions. The seepage characteristics of samples were obtained during fluid flow. We analyzed how effective stress, porosity, and fractal dimension affect the seepage behaviors. This study provides a data reference for the prevention and control of water hazards on-site caused by broken coal and rock masses in fault fracture zones, which has practical significance for coal mine production.

2. Experimental Plans

2.1. Experimental Materials

Broken coal and rock samples were taken from the western main roadway of the Zhaogu No. 2 Mine in Henan Province. This section is located in the hanging wall strata of the F_{17-1} fault, where the underlying Taiyuan Formation limestone directly connects with the footwall, the karst fissure aquifer of Ordovician limestone. Affected by the F_{17-1} fault, the surrounding areas have developed secondary faults and structurally damaged rock layers. The areas are characterized by developed fractures, broken strata, and significantly reduced compressive strength. In addition, the fractures connect the aquifers, resulting in a certain hydraulic connection between the aquifers and the fractures.

In this study, the selected broken coal and rock samples are highly representative, reflecting the occurrence of weak coal bodies (coal), medium-hard rocks (sandstone), and hard rocks (limestone) in the fault zones. In addition, coal–rock mixtures were prepared, composed of limestone, sandstone and coal particles. Before the seepage experiment, we carried out uniaxial compression tests to obtain the strengths of the coal and rock. The basic physical and mechanical parameters of these materials are shown in Table 1. Subsequently,

the materials underwent secondary crushing and were sieved using standard sieves into seven particle size intervals, as shown in Figure 2: less than 5 mm, 5–10 mm, 10–15 mm, 15–20 mm, 20–25 mm, 25–30 mm, and greater than 30 mm. To simulate the disordered distribution characteristics of fault filling materials under natural conditions, the initial particle size distribution was prepared at a mass ratio of 1:1:1:1:1:1:1. Four different types of broken samples were obtained: sandstone, limestone, coal, and coal–rock mixtures.

Table 1. Basic physical and mechanical parameters of coal and rock materials.

Material Type	Density ρ (kg/m ³)	Uniaxial Compressive Strength σ_c (MPa)	Elastic Modulus E_c (GPa)	Lithological Feature Description
Limestone	2955	121.1	45.3	It has a dense structure and high brittleness and produces particles with extremely sharp angularities after crushing.
Sandstone	2980	85.4	32.8	It has moderate particle cementation and produces a substantial volume of medium-sized particles after crushing.
Coal	1300	21.6	2.5	It has extremely low strength and high stress sensitivity and is highly susceptible to crushing.
Coal–rock mixtures	-	42.5 (estimate)	-	It exhibits strong heterogeneity, with alternating soft and hard phases, and has complex stress transmission channels. The estimated UCS is calculated using the geometric mean model.

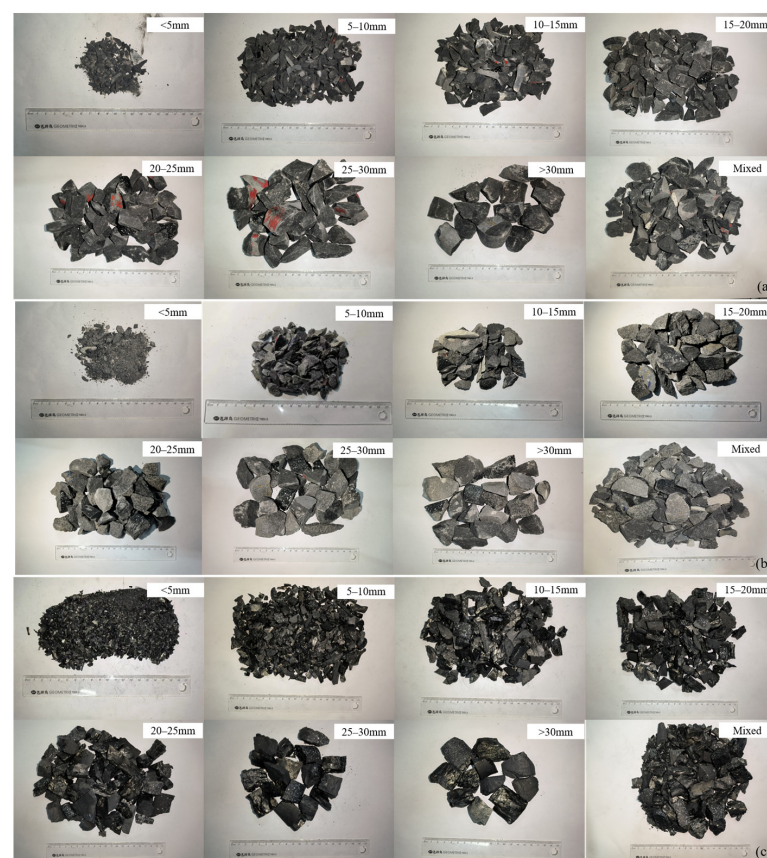


Figure 2. Broken coal and rock samples: (a) limestone, (b) sandstone, and (c) coal.

2.2. Experimental Equipment

The coupled loading–seepage testing system for broken coal and rock masses used in this study was developed by modifying an MTS universal servo testing machine, as shown in Figure 3. Its core components include:

- (1) High-strength seepage chamber: The dimensions comprise a radius of 5 cm and a height of 15 cm. It is made of special alloy steel, which can withstand axial loads of up to 50 MPa and remains without radial deformation.
- (2) Sealing and filtration assembly: The bottom of the chamber and the piston are provided with waterproof sealing rings to prevent fluid flow from overflowing from the side walls. Felts are also installed at both ends to prevent the loss of fine particles during the seepage experiment.
- (3) Water injection pump: It injects water into the chamber, providing a water injection pressure ranging from 0 to 10 MPa.
- (4) Data acquisition terminal: The axial load, displacement and strain data were continuously monitored and recorded using the control and data acquisition software of the MTS universal servo testing machine. The flow data were monitored using a measuring cylinder and a real-time recording balance. During each seepage stage, the raw data were continuously recorded, and the steady-state values were extracted for later analysis.

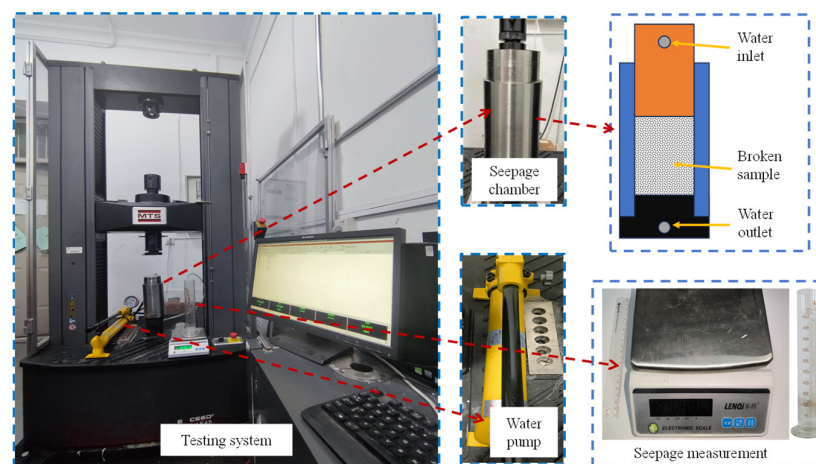


Figure 3. Coupled loading–seepage testing system for broken coal and rock masses.

2.3. Experimental Procedure

Based on experimental materials and systems, loading–seepage experiments were conducted on the broken coal and rock masses. The process is illustrated in Figure 4.

- (1) Preloading stage: A preload of 0.1 MPa was applied to the broken sample in the chamber to ensure sufficient particle contact. Subsequently, the initial height was measured.
- (2) Incremental loading stage: The axial stress σ_z was set incrementally to 1, 3, 5, 7, and 10 MPa. Each level of axial pressure was run for 10 min until the displacement rate dropped below 0.01 mm/min, ensuring stabilization. The deformed height of the chamber was then recorded to calculate the instantaneous porosity of the sample.
- (3) Steady-state seepage stage: Under each axial stress level, water was injected in a top-down manner. The injection pressure was applied in five increments ranging from 0.5 to 2.5 MPa, and the steady-state volumetric flow rate was recorded. The steady-state seepage measurement was designed by referring to the constant-head permeability

testing principle for granular materials, such as that in ASTM D2434. At room temperature, the water density and dynamic viscosity are taken as $1.0 \times 10^3 \text{ kg/m}^3$ and $1.01 \times 10^{-3} \text{ Pa}\cdot\text{s}$.

- (4) Post-test recovery stage: After completing unloading, the sample was retrieved, oven-dried, and re-sieved to quantify the evolution of the fractal dimension before and after loading.

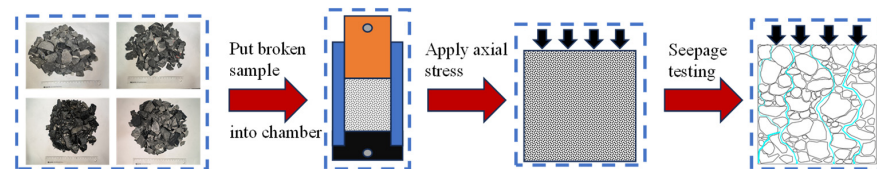


Figure 4. Loading–seepage experiment process.

2.4. Experimental Principle

During the experiments, the seepage velocity was calculated using Equation (1):

$$v = \frac{Q}{A} \quad (1)$$

where v is the seepage velocity (m/s), Q is the volumetric flow rate (m^3/s), and A is the cross-sectional area of the broken sample perpendicular to the flow direction (m^2).

The porosity φ was calculated based on the measured height variations in the broken sample in the chamber, as expressed in Equation (2):

$$\varphi = \frac{V - V_0}{V} \quad (2)$$

where φ is the porosity of the broken sample, V is the bulk volume (m^3) calculated from the instantaneous packing height of the broken sample in the chamber and its inner diameter, and V_0 is the volume of the standard sample prior to crushing (m^3).

In porous media with large pores and high interconnectivity, such as broken coal and rock masses, fluid flow is not merely impeded by fluid viscous forces. It also suffers significant inertial force losses. These losses arise primarily because fluid particles frequently accelerate and change directions in tortuous channels [33]. Numerous studies have demonstrated a non-linear relationship between seepage velocity and the pore pressure gradient during fluid flow through broken coal and rock masses [34–36]. The Forchheimer equation is widely recognized as the optimal model for describing this non-linear characteristic, and its general expression is given as:

$$-\frac{\partial P}{\partial x} = \frac{\mu}{k}v + \rho\beta v^2 \quad (3)$$

$$\frac{\partial P}{\partial x} = \frac{P_2 - P_1}{H} \quad (4)$$

where $\partial P/\partial x$ is the pore pressure gradient; μ is the dynamic viscosity of the fluid ($\text{Pa}\cdot\text{s}$); k is the permeability of the broken sample (m^2); ρ is the fluid density (kg/m^3); β is the non-linear seepage factor (m^{-1}), which is generally considered to be positively correlated with the complexity and roughness of the pore structure; and P_1 and P_2 are the pore pressures at the inlet and outlet of the broken sample, respectively (MPa).

From the perspective of physical mechanisms, the linear term $\frac{\mu}{k}v$ represents the viscous drag generated when the fluid slides over solid surfaces. Conversely, the binomial non-linear term $\rho\beta v^2$ accounts for the pressure loss resulting from kinetic energy conversion.

Experimental evidence indicates that in large-scale pore structures like broken coal and rock masses, the proportion of the non-linear term increases rapidly with an increasing Reynolds number, ultimately causing the seepage curve to deviate significantly from the Darcy linear relationship.

Because the seepage outlet is directly vented to the atmosphere, the outlet pressure P_2 equals 0 ($P_2 = 0$). H is the packing height (m) of the broken sample in the chamber. Combining Equations (3) and (4) yields:

$$\Delta P = \frac{\partial P}{\partial x} = -\frac{P_1}{H} = \frac{\mu}{k}v + \rho\beta v^2 = av + bv^2 \quad (5)$$

where a is the linear term coefficient and b is the non-linear term coefficient. The coefficients a and b can be determined by applying a quadratic fit to the experimental data of the pore pressure gradient and seepage velocity.

The geometric evolution of broken coal and rock masses is inherently a dynamic process characterized by the continuous alteration of their particle size distributions [37,38]. Due to the self-similar nature of rock crushing, fractal theory has been widely adopted to characterize the intensity of particle crushing. According to the mass–size fractal model established by Tyler and Wheatcraft [39], the cumulative mass fraction of particles with a radius smaller than R can be expressed as follows:

$$P(r) = \frac{M(r < R)}{M_t} = \left(\frac{R}{R_{\max}} \right)^{3-D} \quad (6)$$

where $M(r < R)$ is the cumulative mass of the broken particles with a radius smaller than R (g), M_t is the total mass of the sample (g), R is the particle radius currently under evaluation (mm), $R_{\max}$ is the maximum particle radius in the sample (mm), and D is the fractal dimension. By applying logarithmic transformation and subsequent fitting to the experimental sieving data, D can be quantified. Generally, the value of D ranges between 2.0 and 3.0. A larger D value indicates a higher mass proportion of fine particles, implying that the structure of the medium tends toward a denser packing state. Under loading conditions, the growth in D is driven by the coupled mechanisms of particle compaction and secondary crushing, thereby reflecting the extent to which the internal void spaces are filled by fine particles.

3. Experimental Results and Analysis

3.1. Experimental Result Parameters

By establishing a multi-type coupled loading–seepage testing system for broken coal and rock masses, we conducted experiments to evaluate the evolution of the seepage characteristics of broken samples under different uniaxial compressive loads. Following the experiments, the masses of the oven-dried samples across distinct particle size intervals were determined. Ultimately, the porosity, permeability, and fractal dimensions of the broken samples under varying axial pressures were calculated, as summarized in Table 2.

Table 2. Parameters of loading–seepage experiment results for broken coal and rock samples.

Sample	Axial Pressure/MPa	Porosity φ	Permeability k/m^2	Fractal Dimension D
Sandstone	1	0.4828	9.91×10^{-12}	2.08
	3	0.3701	5.83×10^{-12}	2.18
	5	0.3049	3.21×10^{-12}	2.27
	7	0.2774	1.35×10^{-12}	2.35
	10	0.2555	1.21×10^{-12}	2.40

Table 2. Cont.

Sample	Axial Pressure/MPa	Porosity φ	Permeability k/m^2	Fractal Dimension D
Limestone	1	0.4806	8.94×10^{-12}	2.04
	3	0.4095	5.94×10^{-12}	2.13
	5	0.3566	3.86×10^{-12}	2.21
	7	0.3264	1.88×10^{-12}	2.28
	10	0.3047	1.24×10^{-12}	2.33
Coal	1	0.1736	8.79×10^{-13}	2.15
	3	0.0854	6.81×10^{-13}	2.27
	5	0.0473	4.82×10^{-13}	2.37
	7	0.0059	1.85×10^{-13}	2.45
	10	0.0043	9.75×10^{-14}	2.52
Coal-rock mixtures	1	0.3421	1.58×10^{-12}	2.11
	3	0.2232	1.18×10^{-12}	2.21
	5	0.1895	8.94×10^{-13}	2.32
	7	0.1526	8.52×10^{-13}	2.40
	10	0.1262	6.64×10^{-13}	2.45

3.2. Seepage Characteristics of Broken Coal and Rock Masses

During the experiments, scatter plots of the seepage velocity v and the pore pressure gradient ΔP under varying axial pressures were plotted and fitted using quadratic polynomials. Taking the broken sandstone as an example, the relationship between its seepage velocity and pore pressure is shown in Figure 5. It was found that its seepage characteristics conform to a non-linear seepage relationship. The Forchheimer equation can accurately characterize seepage characteristics under different axial pressure conditions. Through further analysis of the other broken samples, it was shown that the equation has universality. The coefficients of determination of the Forchheimer equation were significantly higher than the critical value of 0.95 for all tested broken samples.

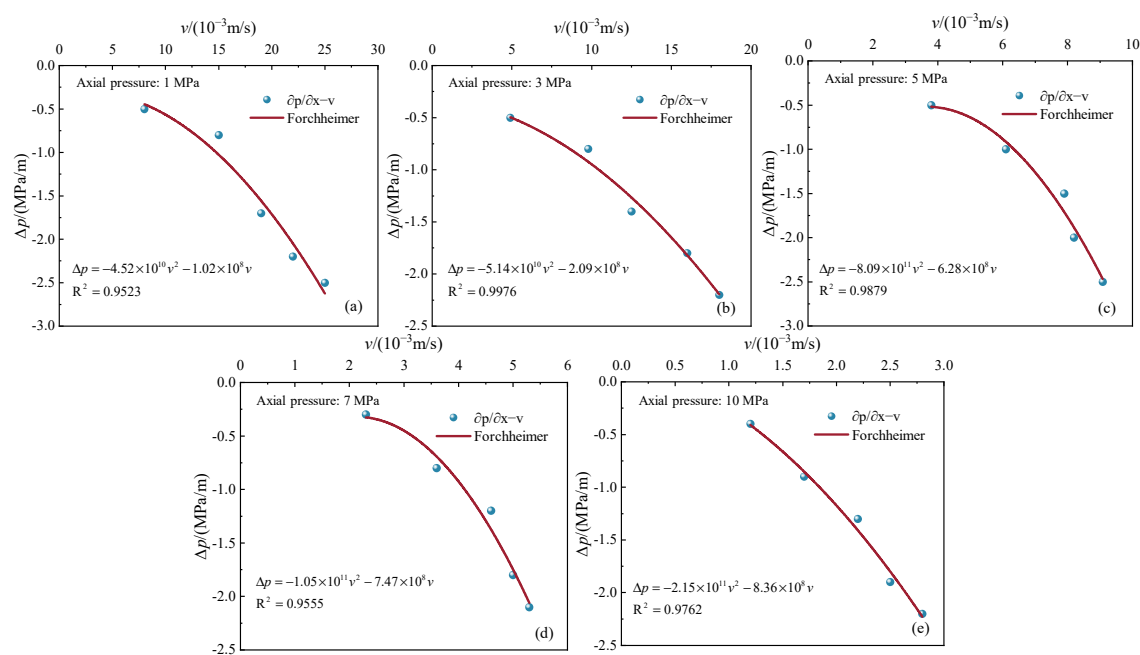


Figure 5. Relationship between pore pressure gradient and seepage velocity: (a) 1 MPa, (b) 3 MPa, (c) 5 MPa, (d) 7 MPa, and (e) 10 MPa.

Identifying the fluid flow regime is an essential prerequisite for applying the Forchheimer law. In this study, the non-linear effect factor E , proposed by Zeng and Grigg [40], was adopted to determine the flow regime and quantitatively describe the non-linear characteristics during the seepage testing of the broken media. Its mathematical expression is given in Equation (7). Generally, it is well accepted that when the value of E is less than 0.1, the seepage process in the broken samples adheres to Darcy's linear flow law. Conversely, when E exceeds 0.1, the seepage behavior complies with the Forchheimer non-linear flow law. Therefore, the critical value of 0.1 serves as the boundary demarcating linear from non-linear seepage regimes.

$$E = \frac{bQ^2}{aQ + bQ^2} \quad (7)$$

Figure 6 illustrates the relationship between the non-linear effect factor E and the hydraulic pressure under varying axial pressures during the seepage process of the broken samples. As observed in the figure, E increases monotonically with increasing hydraulic pressure during the seepage process, with its asymptotic value gradually approaching 1. Under the same axial loading conditions, the higher the hydraulic pressure in the broken coal and rock mass, the greater the seepage velocity. Therefore, the relationship between the two is relatively similar to that between the non-linear effect factor E and hydraulic pressure. In addition, under the axial pressures of 1, 3, 5, 7, and 10 MPa, E is significantly greater than 0.1. This indicates that Darcy's linear flow law is no longer applicable to describing the seepage characteristics of broken coal and rock masses. Compared to intact rock samples, the porosity of broken coal and rock samples is higher. Under higher pore pressure gradients, the pressure loss caused by non-linear terms cannot be ignored. The broken coal and rock masses conform to the Forchheimer non-linear seepage characteristics during the seepage process.

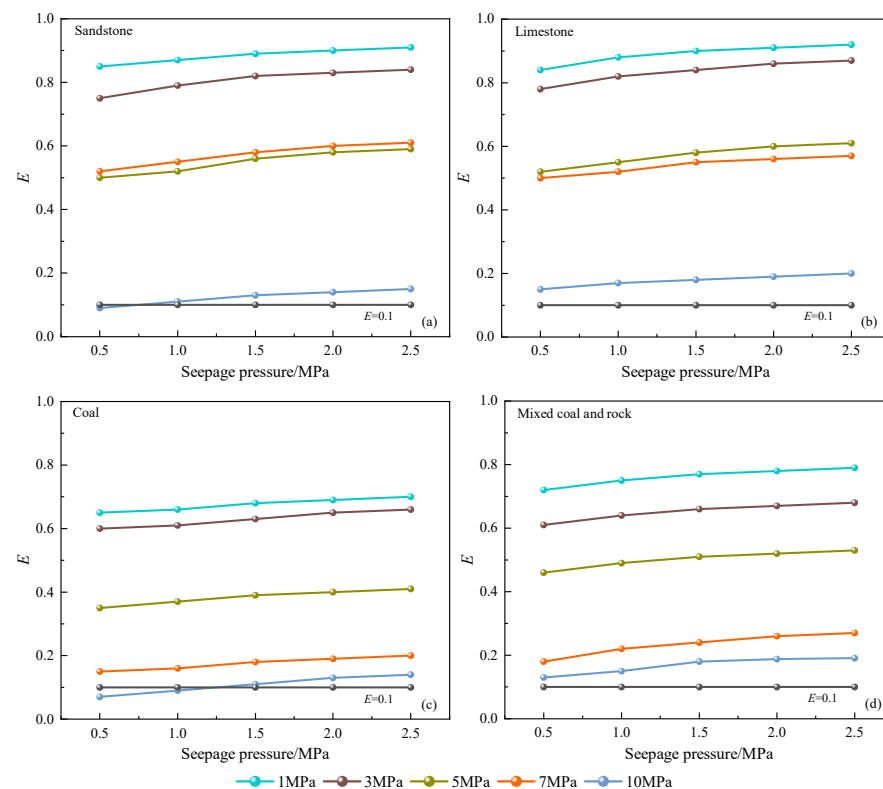


Figure 6. Relationship between non-linear effect factor and hydraulic pressure: (a) sandstone, (b) limestone, (c) coal, and (d) coal–rock mixtures.

3.3. Effective Stress and Seepage Velocity

Effective stress was employed to analyze the mechanical response characteristics of the broken coal and rock masses in the chamber during the seepage experiments. Because the seepage parameters of the broken media undergo dynamic alterations with varying axial pressures, effective stress provides a more accurate characterization of the stress evolution laws during the seepage process. Given that the experiments were conducted under uniaxial compression conditions, the confining pressure exerted on the broken coal and rock masses during the experiments could not be directly measured. Consequently, the calculation formula for the effective stress of porous media derived from Li and Zhu [41] was adopted, as expressed in Equation (8):

$$\sigma = \frac{\sigma_o - \varphi P}{1 - \varphi} \quad (8)$$

where σ is the effective stress (MPa), σ_o is the axial stress (MPa), and P is the pore pressure (MPa).

Figure 7 illustrates the relationship between effective stress and seepage velocity for the broken samples during the seepage process. The seepage velocities of all four broken sample types exhibit a monotonic, non-linear decline with increasing effective stress. Furthermore, as the axial pressure increases, the magnitude of the seepage velocity reduction progressively diminishes, causing the curves to flatten. Under a low axial pressure of 1 MPa, an increase in effective stress causes the seepage velocities of the broken sandstone, limestone, coal, and coal-rock mixtures to attenuate sharply from their peak values of 25.0×10^{-3} m/s, 21.2×10^{-3} m/s, 18.0×10^{-3} m/s, and 20.2×10^{-3} m/s to 9.0×10^{-3} m/s, 10.6×10^{-3} m/s, 9.4×10^{-3} m/s, and 12.0×10^{-3} m/s, respectively.

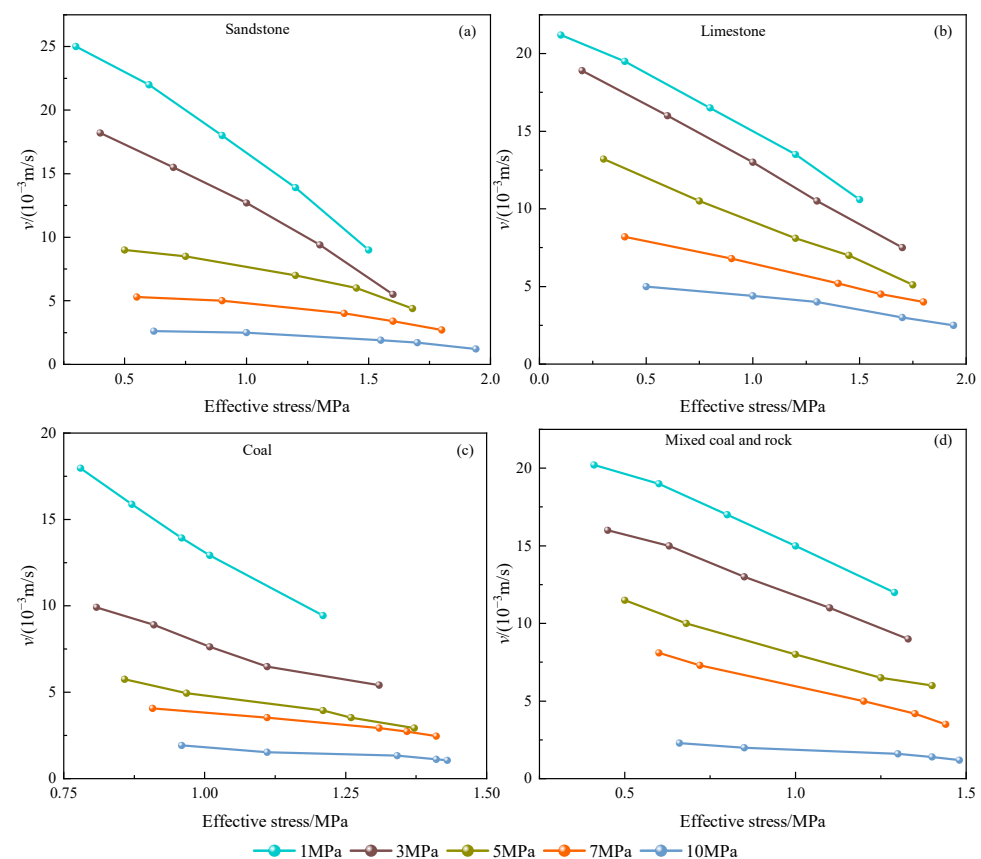


Figure 7. Relationship between effective stress and seepage velocity: (a) sandstone, (b) limestone, (c) coal, and (d) coal-rock mixtures.

When the axial pressure escalates to 10 MPa, the flow channels in all samples undergo stress-induced closure, reducing the seepage velocities to extremely low levels. Among them, due to its strong compressive strength, the broken limestone still maintains the highest residual flow velocity. The flow velocity of broken coal is extremely low, ranging from 1.1×10^{-3} m/s to 1.9×10^{-3} m/s. This is because the effective stress range of broken coal is extremely narrow and prone to re-crushing. The broken coal and rock sample has many voids before loading. These voids are gradually compacted with the increase in effective stress. The decrease in porosity causes blockages in the seepage channels of water inside the broken coal and rock masses. Ultimately, this leads to a decrease in seepage velocity. In addition, as the axial pressure increases during the seepage process, the magnitude of the decrease in the seepage velocity gradually decreases. This is mainly due to the gradual decrease in void compressibility between particles as the axial pressure increases. The internal pores of the broken coal and rock masses are smaller than the voids between particles. The fluid basically does not flow through the internal pores. In underground mines, seepage velocity is further affected by the three-dimensional in situ stress state, mining-induced stress redistribution, repeated loading and unloading, fracture connectivity, hydraulic gradient fluctuation, anisotropic seepage channels, and the scale effect of fault fracture zones [2,42].

3.4. Porosity and Permeability

The porosity of the broken coal and rock masses was calculated using Equation (2). The samples were sequentially subjected to axial pressure to obtain the corresponding porosities. The variation in porosity is shown in Figure 8. As shown in the figure, with the increase in axial pressure, the porosity of the broken coal and rock samples with different lithologies shows a roughly similar downward trend. Under the action of axial stress, the void spaces of the broken samples are compacted, the fractures are closed, and the particles undergo rearrangement and compaction effects [43]. This leads to a decrease in overall void volume. By fitting the data with an exponential function, it is found that the porosity of the broken coal and rock masses decreases exponentially with axial pressure during the loading process, which is formulated in Equation (9).

$$\varphi = A_0 + A_1 e^{-\frac{\sigma_x}{f}} \quad (9)$$

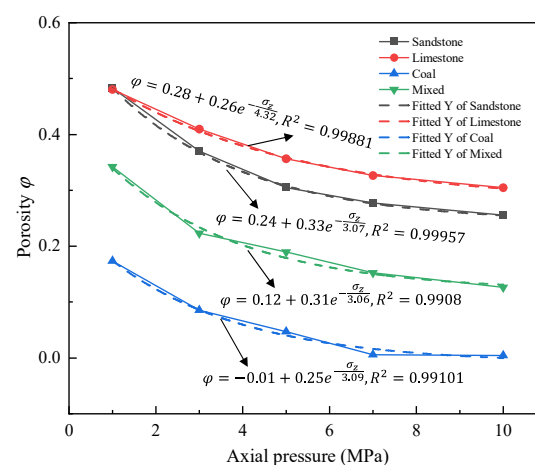


Figure 8. Porosity change of broken coal and rock masses.

Under the same axial compression conditions, the porosity order is limestone > sandstone > coal–rock mixtures > coal. This is mainly due to the low elastic modulus of coal

particles and their susceptibility to crushing deformation. When the axial pressure increases from 1 MPa to 10 MPa, the porosity of the limestone, sandstone, coal–rock mixtures, and coal decreases by 29.11%, 48.08%, 63.11%, and 97.52%, respectively. In contrast, limestone has the lowest compression rate. This indicates that the reduction in its voids is mainly due to the displacement rearrangement between particles rather than the crushing of the particles themselves.

During the loading process, as the axial pressure changes, the porosity of the broken coal and rock samples changes, causing a change in permeability. The relationship between porosity and permeability is shown in Figure 9. An increase in axial pressure leads to a decrease in the porosity and permeability of the broken coal and rock samples. This is because the increase in axial pressure causes the broken coal and rock masses to be compressed more densely, resulting in a further decrease in porosity. Furthermore, it leads to a decrease in permeability. According to the fitting results of porosity and permeability, it is found that the broken coal and coal–rock mixtures follow an exponential function relationship (as shown in Equation (10)) and the broken sandstone and limestone exhibit a quadratic function relationship (as shown in Equation (11)). Factors including lateral confining pressure, fracture aperture and roughness, fault gouge content, clay mineral filling, particle migration, and pore clogging may modify the porosity–permeability relationship in underground mines [2,6]. Therefore, the relationships obtained in this study provide laboratory-based parameters for water hazard assessment, but field prediction should be combined with geological exploration, in situ hydraulic testing, and real-time mine water monitoring.

$$k = a\varphi^b \quad (10)$$

$$k = B_2\varphi^2 + B_1\varphi \quad (11)$$

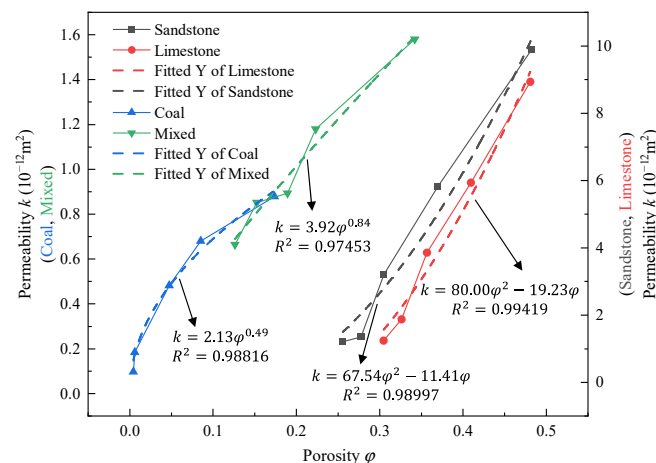


Figure 9. Relationship between porosity and permeability.

3.5. Fractal Dimension and Permeability

The fractal dimension efficiently reflects the evolution of particle size distributions in broken media during the loading process, with existing studies indicating a positive correlation between the fractal dimension and the crushing rate of broken media [44]. Figure 10 illustrates the mass proportions of various particle size intervals and their corresponding fractal dimensions under different axial pressures. As observed in the figure, the fractal dimensions of all tested broken sample types exhibit a monotonic increase with increasing axial pressure. Under elevated axial loads, large-sized particles undergo secondary crushing, causing the particle size distribution to progressively evolve from an initially uniform state to a fine-enriched fractal structure. The medium-sized particles (10–20 mm)

are the transition zone between broken coal and rock mass crushing, and their variation is relatively gentle.

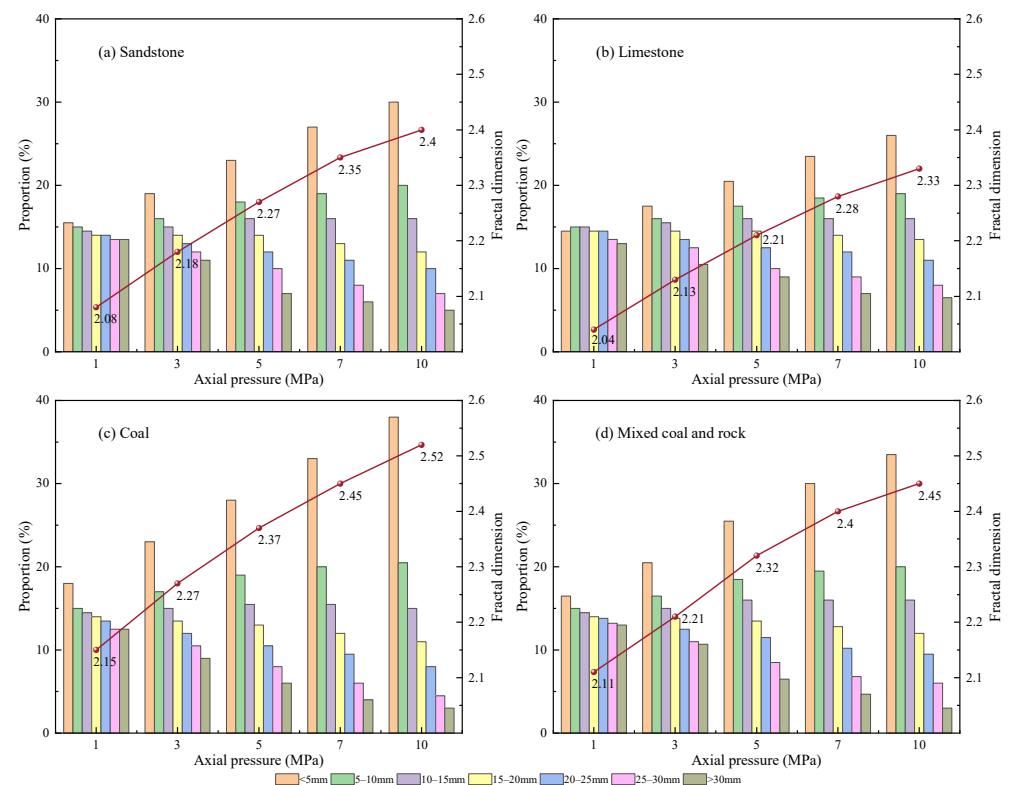


Figure 10. Mass proportion and fractal dimension of each particle size under different axial pressures.

Axial pressure is divided into low-pressure, medium-pressure, and high-pressure stages, corresponding to 1–3 MPa, 3–7 MPa, and 7–10 MPa. In the low-pressure stage, the fractal dimension is relatively small, and the mass distribution of each particle size is still close to the initial uniform state; this stage is mainly due to particle rearrangement and void compaction. In the medium-pressure stage, the fractal dimension increases rapidly, particles with a size less than 5 mm increase significantly, and particles with a size larger than 30 mm reduce significantly; this stage is dominated by particle crushing. In the high-pressure stage, the increase in the fractal dimension decreases, and the change in particle size distribution slows down.

Under the same axial pressure conditions, the order of the fractal dimension is coal > coal–rock mixtures > sandstone > limestone. This is due to differences in strength. The broken coal is more prone to particle crushing during loading, and its fractal dimension is the highest. The broken sandstone and limestone have high strength. They are limited in crushing under 0–10 MPa axial pressure loading, and their fractal dimension is relatively low. The broken coal–rock mixtures are subjected to the coupling effect of different lithological strengths, and their fractal characteristics are between those of the broken coal and rock.

The increase in the fractal dimension of the broken coal and rock masses directly reflects the intensification of particle crushing. Figure 11 illustrates the relationship between the fractal dimension and permeability. As observed in the figure, the permeability of the broken samples decreases progressively with the increasing fractal dimension, exhibiting a broadly linear declining trend. This phenomenon occurs because, as the axial pressure escalates, large particles undergo secondary crushing and refinement. Consequently, the increasing proportion of small particles progressively fills the internal void spaces, reducing

the pore interconnectivity and ultimately leading to a continuous reduction in permeability, as shown in Figure 12.

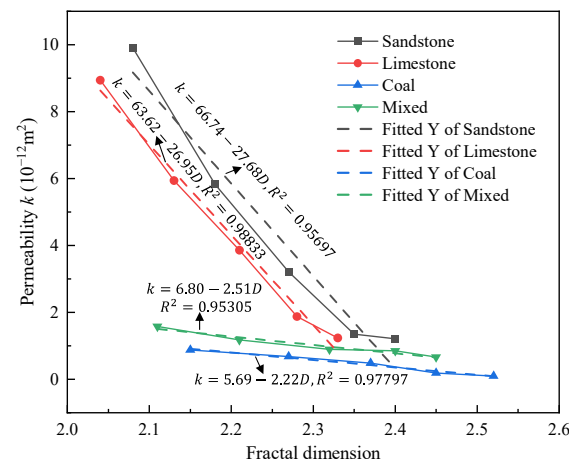


Figure 11. Relationship between fractal dimension and permeability.

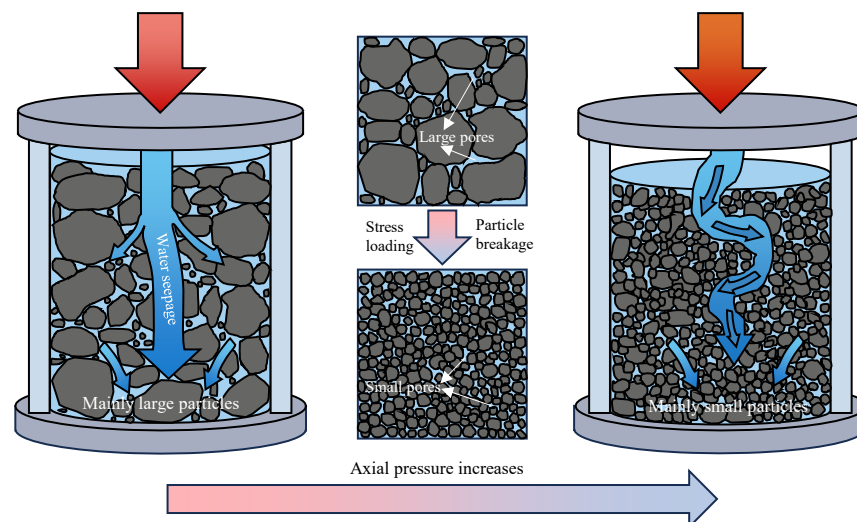


Figure 12. Schematic diagram of particle changes during the loading process of broken coal and rock masses.

The fitted slope of the k - D relationship varies significantly across different lithologies, following a descending order of sandstone, limestone, coal–rock mixtures, and coal. Specifically, the high-strength broken sandstone and limestone exhibit high sensitivity to alterations in the fractal structure. Conversely, the low-strength broken coal and coal–rock mixtures display lower sensitivity, making them more prone to reaching a steady state of permeability evolution as porosity decreases. Although the fractal dimensions of the broken sandstone and limestone also increase with increasing axial pressure, their crushing intensity remains lower than that of the broken coal, thereby retaining a larger proportion of large particles. As the fractal dimension gradually increases, the permeabilities of the distinct broken sample types progressively converge toward a consistent value. This indicates that under continuous axial loading, differing types of broken coal and rock masses gradually exhibit behavioral convergence during the seepage process.

4. Conclusions

- (1) The seepage characteristics of broken coal and rock masses comply with the Forchheimer law. Through a non-linear regression analysis of the experimental data using the Forchheimer equation, it was found that the equation accurately characterizes seepage behaviors under different axial stress states. The non-linear effect factor E remains between 0.2 and 0.95 during the coupled loading–seepage process, which is higher than the critical threshold of 0.1 for the Darcy-to-non-Darcy flow transition.
- (2) The voids between broken coal and rock masses gradually become denser with the increase in effective stress, resulting in a decrease in porosity; the seepage velocity shows a monotonically non-linear decrease. As the compressibility of voids between broken coal and rock masses gradually decreases, the internal pores of the particles are poorly permeable, resulting in a gradual decrease in the reduction magnitude of seepage velocity and a flattening of the curve.
- (3) The porosity of broken coal and rock masses has an exponential negative correlation with axial pressure during the loading process. The porosity reduction rate is influenced by the strength of the rock lithology. This manifests as coal (97.52%) > coal–rock mixtures (63.11%) > sandstone (48.08%) > limestone (29.11%). The relationship between permeability and porosity shows lithological differences. Broken coal and coal–rock mixtures follow an exponential function variation relationship. Broken sandstone and limestone exhibit a quadratic relationship.
- (4) The fractal dimension D of broken coal and rock masses increases monotonically with the increase in axial pressure. It shows the characteristics of three stages: low axial pressure is stable, medium axial pressure increases sharply, and high axial pressure slows down. The permeability of broken coal and rock masses gradually decreases as the fractal dimension increases, and their relationship basically conforms to a linear negative correlation of a linear function.
- (5) The obtained lithology-dependent relationships among porosity, permeability, non-Darcy seepage behavior, and the fractal dimension provide useful indicators for mine water hazard prevention and control. In mines, areas with high hydraulic pressure, high fracture connectivity, and significant particle crushing should be regarded as potential water inrush risk zones. Methods including advanced geological probing, borehole water pressure monitoring, grouting reinforcement, and optimization of water-resistant pillars are recommended to reduce hydraulic connectivity and secure mine production.

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