Non-Darcy flow and stress coupling mechanism of fault rocks: Effect of gas compression

Kechuan Cai¹, Dan Ma¹2*, Saibo Kong¹

1. School of Resources & Safety Engineering, Central South University, Changsha 410083, Hunan, China
2. State Key Laboratory of Coal Resources & Safe Mining, School of Mines, China University of Mining & Technology, Xuzhou 221116, Jiangsu, China

E-mail address: dan.ma@cumt.edu.cn
ORCID: 0000-0002-7586-4116

Abstract. This study aimed to analyze the evolution of the porosity and permeability of fault rocks under non-Darcy flow-stress coupling. The permeability of broken coal, mudstone, and sandstone with different particle size gradations under different stresses was investigated using an experimental system for the permeability evolution of broken rocks. Experimental results show that broken coal exhibits the best compressibility, followed by broken mudstone, and broken sandstone presents the worst compressibility. The porosity and permeability of the broken rocks decrease rapidly with the increase in confining pressure and then decrease slowly until they stabilize. The crushing of large particles into fine particles under stress is the main reason behind the decreasing porosity and permeability of mixed broken rocks. The smaller the fractal dimension of the particle size gradation during loading, the more serious the particle breakage, the greater the mass loss of large particles, and the greater the decrease in porosity and permeability.

1 Introduction

Coalbed methane, a common associated resource in coal mining, is stored in coal seam voids. Hydraulic fracturing, drilling, and coal mining can change the stress distribution in the coal seam, resulting in the large-scale release of coalbed methane and leading to gas protrusion accidents[1]. However, this phenomenon is obvious for broken coal rock masses, which are likely to cause gas outburst[2]. Therefore, characterizing the gas permeability of broken coal is important for the safe exploitation of coalbed methane.
Chilton et al.[3] summarized the relationship between effective grain size and critical pore pressure from the permeability tests of broken rocks with different grain sizes. The permeability of porous media is determined by the number of pores. Liu et al.[4, 5] and Ma et al.[6] studied the permeability of broken sandstone, coal, and shale by using axial displacement control and analyzed the relationship between porosity and permeability parameters. Pore structure is an important factor affecting the permeability of porous media, and the pore structure of porous media is determined by its particle size and particle arrangement. Yamada[7], Li[8], and Ma[9-11] studied the effect of particle size and particle ratio on the permeability of porous media and concluded that small particles in crushed rocks can fill pores and block seepage channels.

Using water as the permeability medium, the current research characterizes the porosity, particle size, and ratio on the permeability of broken rocks without considering the effect of stress. However, the seepage pattern of gas in the pore space is different from that of liquid. To understand the porosity evolution of fractured rocks, the current research mainly focuses on the evolution of permeability characteristics and does not analyze the fundamental reasons for the variations in porosity and permeability parameters in terms of porous media properties. Therefore, this paper improves the permeability test system of broken rocks to facilitate the permeability test of broken rocks with different lithologies and particle size distributions under the action of axial pressure using gas as the permeability medium. The influence of different stresses on the permeability of broken rocks is analyzed, and the results could serve as a reference for the safe exploitation of coalbed methane.

2 Sample preparation and test system

The coal, mudstone, and sandstone used in the test were obtained from the Xiaojihan Coal Mine in Yulin, Shaanxi, and their natural densities were 1768, 2273, and 2651 kg/m³, respectively. The coal, mudstone, and sandstone were crushed into particles with diameters of 0–2.5, 2.5–5, 5–8, 8–10, 10–12, 12–15, and 15–20 mm to obtain samples with different particle gradations. According to the fractal of continuous grading for mixed crushing specimens, the fractal distribution of particle size is as follows[12]:

\[
P(d_i) = \left(\frac{d_i}{d_{\text{max}}}\right)^{3-D},
\]

where \(P(d_i)\) is the proportion of particles with a diameter of \(d_i\), \(d_{\text{max}}\) is the largest particle diameter in the mixed sample, and \(D\) is the fractal dimension.

According to Formula (1), the fractal dimension \(D\) values are 1.4, 2.0, and 2.6, and the mass of each group of samples is 2 kg. The particle size distribution curve of the sample is shown in Figure 1.
Figure 1 Particle size distribution curve of mixed broken rocks

The test was carried out using the MTS815.02 test system (Figure 2). The test system is composed of three parts: an axial loading tester (a), a permeability test loop (b), and a permeability testing apparatus (c). The permeate medium is nitrogen.

3 Test procedure and calculation principle

3.1 Test procedure

(1) The test system was assembled as follows. G2 felt and G3 porous plates were installed, and mixed samples weighing 1.8 kg with fractal dimension $D=1.4$ were selected and placed into the G1 packing chamber. The G4 indenter was installed, and the preloading force of 0.1 kN was controlled by the testing machine. The height of the sample in the initial state was recorded as $H_0$.

(2) The axial pressure was increased to 1 MPa, and the displacement sensor was used to record the change in sample height.

(3) After the height of the sample stabilized, the outlet of the gas cylinder was opened, and the inlet pressure of the penetrator was set at 1.5 MPa. The pressure and flow at the outlet of the penetrator were recorded.
(4) The axial compression was adjusted to 2, 3, 4, and 5 MPa, and step (3) was repeated. The compressed sample was sieved by a grading sieve to obtain their particle size distribution.

(5) The mixed sample was replaced with fractal dimension $D$ values of 2.0 and 2.6, respectively, and steps (2) to (4) were repeated.

3.2 Calculation principle

As a typical porous media material, crushed rock consists of solid particles and filled voids, and its porosity is calculated as follows:

$$\phi = \frac{V_0 - V_{\text{particle}}}{V_0}$$

(2)

where $V_0$ is the volume of the accumulated state of broken rocks, and $V_{\text{particle}}$ is the volume of solid particles. The porosity of the broken rocks in this test is

$$\phi = \frac{V_0 - V_{\text{particle}}}{V_0} = \frac{\pi r^2 H_0 - m/\rho}{\pi r^2 H_0}$$

(3)

where $H_0$ is the height of the crushed rock in the penetrometer, $r$ is the inner diameter of permeability testing apparatus, and $m$ and $\rho$ are the mass and density of the broken rocks, respectively.

The flow of gas in the pore space follows Forchheimer’s theory:

$$-\frac{\partial p}{\partial h} = \frac{\mu v}{k} + \rho g \beta v^2$$

(4)

where $\frac{\partial p}{\partial h}$ is the seepage pressure gradient, $\mu$ is the hydrodynamic viscosity of nitrogen, $v$ is the fluid velocity, $k$ is the permeability, and $\beta$ is the non-Darcy factor.

If $\frac{\partial p}{\partial h}$ is the constant in the test, then it can be expressed as

$$-\frac{\partial p}{\partial h} = \left( \frac{p_{\text{out}} - p_{\text{in}}}{H_0} \right).$$

(5)

In this test, the seepage velocity is obtained by the following equation:
\[ v = \frac{Q}{\pi r^2}, \]  

where \( Q \) is the gas flow.

In previous studies, the relationship among non-Darcy factors \( \beta \), permeability \( k \), and porosity \( \phi \) can be expressed as

\[ \beta = \frac{1.15 \times 10^{-6}}{k \phi}. \]  

Permeability can be calculated by combining Equations (4), (5), (6) and (7) as follows:

\[ \frac{p_{in} - p_{out}}{H_0} = \frac{\mu Q}{k \pi r^2} + p_e + \frac{1.15 \times 10^{-6}}{k \phi} \frac{Q^2}{\pi^2 r^4}, \]

where \( p_{in} \) is the inlet pressure of the permeameter, and \( p_{out} \) is the outlet pressure of the permeameter.

4 Test results and discussion

4.1 Non-Darcy Seepage properties under different lithologies

On the basis of Equation (2) and the test results, the relationship between the axial pressure and porosity of the broken rocks under different lithologies can be obtained, as shown in Figure 3.

Figure 3 Evolution of the non-Darcy seepage properties of broken rocks under different lithologies. (a) porosity; (b) permeability

In Figure 3, the evolution of seepage properties of the broken rocks with the increase in
axial stress shows two stages. In the first stage, the porosity and permeability decrease rapidly from 0 to 3 MPa; in the second stage, the porosity decreases slowly and tends to be flat from 3 MPa to 5 MPa. As displayed in Figure 3(a), obvious differences exist among the three lithologies of the broken rocks in the stress process. The initial porosities of broken coal, mudstone, and sandstone with the same fractal dimension in the natural accumulation state (when the axial stress is 0) are 0.291, 0.325, and 0.362, respectively. When the axial stress is 5 MPa, the porosities of the three are 0.149, 0.196, and 0.259, respectively, and the changes in the magnitude are 48.6%, 39.7%, and 28.5%, respectively. Broken coal is the most easily compressed, followed by broken mudstone, and broken sandstone is the most difficult to be compressed. This result can be ascribed to the fact that the rock particles are crushed and their positions are rearranged when the crushed rock particles are compressed. Among the three specimens, coal is the softest and has the lowest strength; thus, it is the easiest to be compressed. By the same token, sandstone has the highest strength; thus, it is the most difficult to be compressed. Figure 3(b) shows that the permeability of broken sandstone is the largest and the permeability of broken coal is the smallest during the loading stage. Meanwhile, the rate of broken sandstone tends to stabilize at 2 MPa, and the rate of broken coal tends to stabilize at 3 MPa.

4.2 Non-Darcy Seepage properties under different fractal dimensions

On the basis of Equation (5) and the test results, the pressure and flow data measured by the test can be obtained for the permeability evolution under different fractal dimensions, as shown in Figure 4.

Figure 4 Evolution of non-Darcy seepage properties of broken rocks under different fractal dimensions. (a) porosity; (b) permeability

As shown in Figure 4, the seepage property evolution of the broken rocks with the increase in axial stress is divided into a fast decreasing stage and a stabilizing stage. Figure 4(a) shows that initial porosity of broken coal with different dimensions in the natural accumulation state is less different. However, when the axial stress is 5 MPa, the porosities of the three samples are 0.133, 0.149, and 0.165 with variations of 52.7%, 48.6%, and 44.1%, respectively. The smaller the fractal dimension of particle gradation, the greater the reduction
of porosity. This result can be ascribed to the fact that the smaller the fractal dimension, the more the proportion of large particles in the samples, the more easily the samples are further compressed and broken, and thus the greater the reduction. Figure 4(b) illustrates that for broken coal, the permeability with a small fractal dimension is the largest during the loading process, but the permeability variation is the smallest. After loading, the permeability with fractal dimension \( D=1.4 \) decreases by 55.5\%, and the permeability with fractal dimension \( D=2.6 \) decreases by 64.1\%.

4.3 Evolution of particle size distribution after compression

After sieving the compressed sample, the weight variation evolution of particles in each particle size range under different lithologies and gradation conditions can be obtained, as shown in Figure 4.

![Figure 5](image)

Figure 5 Weight variation of broken rocks after axial compression. (a) lithology; (b) fractal dimension

As displayed in Figure 4, the proportion of large particles (8–20 mm) decreases significantly after compression of crushed rock particles. The larger the particle diameter, the more its proportion decreases, and the proportion of small particles (0–5 mm) increases significantly. The smaller the particle diameter, the more its proportion increases. As illustrated in Figure 5(a), the mass of particles in the size range 0–5 mm increases significantly, and the mass of particles in the size range 8–20 mm decreases significantly. The largest change in particle size distribution is observed for broken coal, with a 93 g decrease for particles with diameters of 15–20 mm and a 105 g increase for particles with diameters of 0–2.5 mm. The smallest change in particle size distribution is observed for broken sandstone, with a 49 g decrease for particles with diameters of 15–20 mm and a 35 g increase for particles with diameters of 0–2.5 mm. In Figure 5(b), the mass of particles in the size range 0–5 mm increases significantly, and the mass of particles in the size range 10–20 mm decreases significantly. The largest change in particle size distribution is observed for the fractal dimension \( D=1.4 \), with a 93 g decrease for particles with diameters of 15–20 mm and an 105 g increase for particles with diameters of 0–2.5 mm. The smallest change in particle size distribution is observed for the fractal dimension \( D=2.6 \), with a 69 g decrease for
particles with diameters of 15–20 mm and a 53 g increase for particles with diameters of 0–2 mm.

4.4 Permeability prediction based on porosity

The permeability evolution of CPB (cemented paste backfill) is a critical parameter. The Kozeny–Carman equation has been widely adopted to predict permeability[13]:

\[ k_i = \frac{d_i^2 \phi_i^3}{180(1 - \phi_i)^4}, \]  

(9)

where \( k_i \) is the predicted value of permeability when the porosity of the sample is \( \phi_i \), and \( d_i \) is the mean particle size. The particle size of each range is assumed to be uniformly distributed, and it can be calculated as follows:

\[
d_e = \begin{cases} 
2.5 \times \frac{50\%}{p_{0.25}}, & p_{0.25} \geq 50\% \\
2.5 + 2.5 \times \frac{50\% - p_{0.25}}{p_{0.5} - p_{0.25}}, & p_{0.25} \leq 50\% \leq p_{0.5} \\
5 + 3 \times \frac{50\% - p_{0.5}}{p_{0.8} - p_{0.5}}, & p_{0.5} \leq 50\% \leq p_{0.8} \\
8 + 2 \times \frac{50\% - p_{0.8}}{p_{1.0} - p_{0.8}}, & p_{0.8} \leq 50\% \leq p_{1.0} \\
10 + 2 \times \frac{50\% - p_{1.0}}{p_{1.2} - p_{1.0}}, & p_{1.0} \leq 50\% \leq p_{1.2} \\
12 + 3 \times \frac{50\% - p_{1.2}}{p_{1.5} - p_{1.2}}, & p_{1.2} \leq 50\% \leq p_{1.5} \\
15 + 5 \times \frac{50\% - p_{1.5}}{p_{2.0} - p_{1.5}}, & p_{1.5} \leq 50\% \leq p_{2.0}
\end{cases}, \]  

(10)

where \( p_{0.25}, p_{0.5}, p_{0.8}, p_{1.0}, p_{1.2}, p_{1.5}, \) and \( p_{2.0} \) are the percentages of mass with particle sizes less than 2.5, 5, 8, 10, 12, 15, and 20, respectively. According to the initial permeability of the broken rock sample, Equation (9) can be expressed as

\[
\frac{k_i}{k_0} = \left( \frac{d_{e_i}}{d_{e_0}} \right)^2 \left( \frac{\phi_i}{\phi_0} \right)^3 \left( \frac{1 - \phi_0}{1 - \phi_i} \right)^2, \]  

(11)

where \( k_0 \) and \( \phi_0 \) are the initial permeability and porosity of the broken sample, respectively. According to Equation (11), the comparison between the prediction results of permeability and the test results is shown in Figure 6.
As illustrated in Figure 6, the permeability prediction results are in good agreement with the experimental results. The predicted permeability according to Equation (11) is generally larger than the experimental results, especially when the porosity is small. The reason for this phenomenon is that when the axial compression effect is intense, the fragmentation of the specimen particles increases, and the increase in the proportion of fine particles (0–1 mm) with a size of 0–2.5 mm occupies the majority, which also causes the average particles to be small. This phenomenon causes the predicted values of permeability to be higher than the test values.

5 Conclusions

(1) For broken coal, mudstone, and sandstone, the porosity and permeability decrease with the increase in axial stress. The porosity and permeability of broken sandstone are always the largest, and the porosity and permeability of broken coal are the smallest. The porosity and permeability of broken coal rocks decrease the most with the increase in axial stress.

(2) The porosity and permeability of the broken samples decrease with the increase in axial stress under all fractal dimensions. The porosity and permeability of the broken samples are smaller when the fractal dimension is larger, and the decrease is more obvious with the increase in axial stress.

(3) After loading, the specific proportion of 0–5 mm particles increases significantly, and the proportion of 8–20 mm particles decreases in different degrees. The larger the particle diameter, the greater the decrease in their proportion. The fragmentation of large particles and the rearrangement of particles cause the changes in porosity and permeability. The broken coal particles are the easiest to be compressed, whereas the broken sandstone particles are the most difficult to be compressed in graded broken rocks.

(4) Comparison of the predicted permeability with the experimental results shows that the predicted value is larger than the experimental value. This result can be explained by the
fact that the increase in fine particles during the compression of the crushed specimens accounts for the majority, resulting in a small mean particle size and increasing the predicted value of permeability.

References

[1] Zhou H, Zhang R, Cheng Y, Dai H, Ge C, Chen J. Methane and coal exploitation strategy of highly outburst-prone coal seam configurations. Journal of Natural Gas Science and Engineering. 2015;23:63-9.

[2] Zhang Z, Zhang R, Xie H, Gao M, Xie J. Mining-Induced Coal Permeability Change Under Different Mining Layouts. Rock Mechanics & Rock Engineering. 2016;49(9):1-16.

[3] Chilton TH, Colburn AP. II—Pressure Drop in Packed Tubes1. Indengchem. 2002;23(8):913-9.

[4] Liu W, Miao X, Yu W, Fang J, Liu M. Experimental determination of gas permeability of broken rocks Experimental Mechanics. 2006;03:399-402.

[5] Liu W, Miao X, Chen Z. Experimental determination of permeability of broken rocks. Experimental Mechanics. 2003;01:56-61.

[6] Ma Z, Lan T, Pan Y, Ma J, Zhu F. Experimental study of pore change law during creep of saturated fractured mudstone. Journal of Rock Mechanics and Engineering. 2009;28(07):1447-54.

[7] Yamada H, Nakamura F, Watanabe Y, Murakami M, Nogami T. Measuring hydraulic permeability in a streambed using the packer test. Hydrological Processes. 2010;19(13):2507-24.

[8] Li S, Miao X, Chen Z, Mao X. Experimental study on the permeability characteristics of non-Darcy seepage in pressurized fractured rocks. Engineering Mechanics. 2008;04:85-92.

[9] Ma D, Kong S, Li Z, Zhang Q, Wang Z, Zhou Z. Effect of wetting-drying cycle on hydraulic and mechanical properties of cemented paste backfill of the recycled solid wastes. Chemosphere. 2021;282:131163.

[10] Ma D, Wang J, Cai X, Ma X, Zhang J, Zhou Z, et al. Effects of height/diameter ratio on failure and damage properties of granite under coupled bending and splitting deformation. Engineering Fracture Mechanics. 2019;220:106640.

[11] Ma D, Zhang J, Duan H, Huang Y, Li M, Sun Q, et al. Reutilization of gangue wastes in underground backfilling mining: Overburden aquifer protection. Chemosphere. 2021;264:128400.

[12] Tyler SW, Wheatcraft SW. Fractal Scaling of Soil Particle-Size Distributions: Analysis and Limitations. Soil Science Society of America Journal. 1992;56(2).

[13] Karacan CÖ. Prediction of Porosity and Permeability of Caved Zone in Longwall Gobs. Transport in Porous Media. 2010;82(2):413-39.