EXPERIMENTAL ANALYSIS AND MODEL STUDY ON EFFECTIVE STRESS SENSITIVITY OF COAL ROCK PERMEABILITY

by

Cai-Qin BI [a], ***Xiao-Lin XIN*** [b*], ***Shuang LIU*** [b], ***Cheng-Zheng CAI*** [c], ***and Zheng-Chao ZHU*** [c]

[a] Oil and Gas Survey, China Geological Survey, Beijing, China
[b] CNPC Greatwall Drilling Engineering Co., Ltd., Beijing, China
[c] State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering, China University of Mining and Technology, Xuzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI2502545B

Using the unsteady pressure drop method, permeability measurements of coal samples were conducted across various bedding directions under different effective stresses. Mercury injection, SEM, and micro-CT techniques were employed to analyze pore/fracture structures. By integrating experimental data, existing stress-sensitive permeability models were validated and refined. The results demonstrated that gas permeability in cores from different directions exponentially correlates with effective stress. During decompression, the permeability exhibited limited recovery and irreversible damage. Stress sensitivity assessments with varying parameters indicated high sensitivity of coal permeability to effective stress, both perpendicular and parallel to bedding planes. The revised permeability model predicts permeability with an error margin of less than 15%.

Key words*: coalbed methane, stress sensitive, bedding direction, permeability model, permeability damage*

Introduction

In CBM production, water production and methane gas desorption reduce coal reservoir pressure, leading to a decrease in effective stress. This, in turn, significantly alters coal permeability [1, 2]. Accurate prediction of coal permeability under varying effective stress is crucial. Numerous empirical relationships have been established to describe the stress-dependent permeability of various rock types [3, 4]. However, the stress-dependent permeability mechanism in coal reservoirs is particularly complex due to CBM unique characteristics, including high compressibility, intricate pore/fracture structures, and low porosity. This paper first examines the stress sensitivity of coal permeability. Subsequently, it analyzes the stress sensitivity mechanism using SEM, mercury injection, and CT techniques. Lastly, based on the Walsh fracture permeability model, the permeability-stress model is refined by incorporating fracture aperture, achieving a precision exceeding 85%.

Stress sensitivity experiment

Coal samples were selected from eastern Yunnan and western Guizhou, China. The ten cores from different seams were drilled in parallel and vertical bedding directions. Based

[*] Corresponding author, e-mail: 1399291214@qq.com

on the unsteady pressure drop method, coal permeability was measured with nitrogen at indoor temperature.

Stress-permeability relationship

Figure 1 shows the relationship between dimensionless permeability and effective stress. On both vertical and parallel bedding directions, coal permeability decreases sharply and then tends to be stable with the increase of the effective stress.

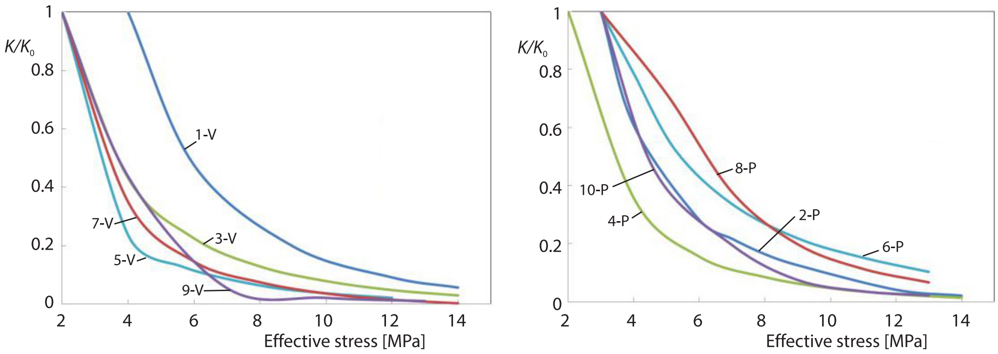

Figure 1. The graph of dimensionless permeability variation with effective stress on vertical and parallel directions

Stress-permeability sensitivity evaluation

The permeability damage rate D_{k1} is calculated:

$$D_{k1} = \frac{K_1 - K_{\min}}{K_1} \times 100\% \tag{1}$$

where D_{k1} is the permeability damage maximum in the process of stress increasing to the highest point, K_1 – the permeability of coal sample for the first stress point, and $K_{\min}$ – the minimum permeability value of coal sample after reaching the critical stress.

The irreversible permeability damage rate D_{k2} can be calculated:

$$D_{k2} = \frac{K_1 - K_{1r}}{K_1} \times 100\% \tag{2}$$

where D_{k2} is the permeability damage rate after the stress restoring to the first stress point and K_{1r} – the coal permeability corresponding to final stress point.

The stress sensitivity coefficient, S_s, is given [3]:

$$S_s = \frac{1 - \left(\dfrac{K}{K_0}\right)}{\lg \dfrac{\sigma}{\sigma_0}} \tag{3}$$

where S_s is the stress sensitive coefficient, K – the permeability under the condition of applied stress, and K_0 – the permeability under the condition of initial pressure σ_0.

Table 1 shows that both vertical and parallel bedding directions of the coal samples have strong stress sensitivity. The permeability damage rate of each coal sample is over 94%. The irreversible damage rate is as high as 70%.

Table 1. Different evaluation parameters for permeability damage

Sample number	k_0	k_{min}	k'_0	D_{k1}	D_{k2}	S_s	Stress sensitivity degree	
	[mD]	[mD]	[mD]	[%]	[%]		D_{k1}	S_s
1-V	0.2417	0.0135	0.0790	94.42	67.31	1.1355	Extremely high	Extremely high
2-P	2.6516	0.0550	0.7679	97.92	71.04	0.8629	Extremely high	High
3-V	0.1915	0.0055	0.0627	97.12	67.23	0.8208	Extremely high	High
4-P	0.5764	0.0078	0.1793	98.65	68.90	0.9017	Extremely high	High
5-V	0.1528	0.0032	0.0347	97.94	77.28	0.9326	Extremely high	High
6-P	2.0823	0.2141	0.7137	89.72	65.73	0.8346	Extremely high	High
7-V	0.5696	0.6321	3.4667	99.83	69.72	1.0412	Extremely high	Extremely high
8-P	0.3849	0.0256	0.1258	93.34	67.32	1.1075	Extremely high	Extremely high
9-V	0.0201	0.0002	0.0065	99.06	67.68	0.9706	Extremely high	High
10-P	0.0652	0.0014	0.0192	97.85	70.53	1.1338	Extremely high	Extremely high

V is the vertical bedding direction and *P* is the parallel bedding direction.

Micro-structure analysis

Figure 2 shows a typical slice of 2-D gray-scale CT scanning for coal sample. Large-scale fractures can be observed clearly in the coal sample, to a certain extent, it can reflect the coal seepage channel morphology intuitively. The CT images usually used the pixels to characterize the size of CT value, the areas with a low CT value shows the dark black, which is mainly pores and fractures in the coal and rock samples. The regions with a high CT value shows the white, which is mainly high density material in the coal sample.

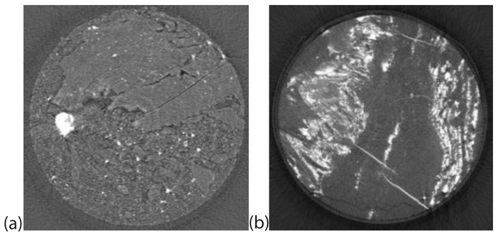

Figure 2. The CT scan images of coal; (a) Sample-1 (25 mm) and (b) Sample-1 (2 mm)

Figure 3 shows the SEM images of various coal samples. We can find that fracture width is mainly at nanometer-micron level. Pore size is in the range of a few nanometers to hundreds of nanometers. The micro-fracture has a good connectivity and plays the dominant role for seepage.

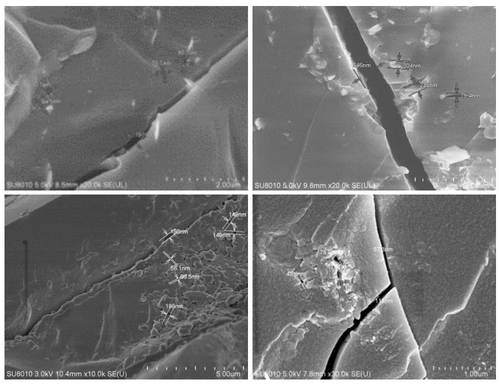

Figure 3. The SEM images of coal

Figure 4 is the diagram of relationship between pore size and mercury saturation gradient. Pore diameter distribution has a big pore peak at about 40 μ, which suggests that there exist a large amount of microfracture in coal samples that control most of the permeability. More than 80% of pore distributes between 10 μm and 70 μm. However, the coal samples may be compressed and generate new fractures under high pressure, which may bring some error. Coal is a typical dual medium with both pore and micro-fracture systems. Microfractures are easy to compress and show a strong stress sensitivity. With the increase of effective stress, the fractures are deformed by compressive stress. It may block the seepage channel and bring a great permeability damage.

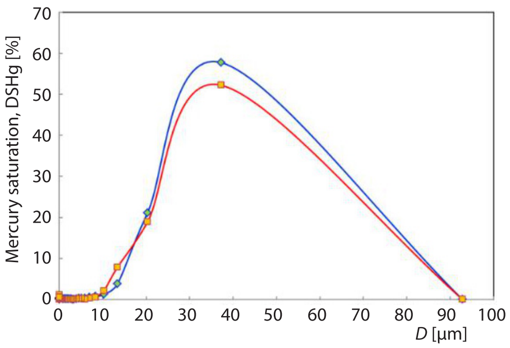

Figure 4. The relationship between pore size and mercury saturation

Fracture permeability model

Walsh model improvement

Based on the Poiseuille flow formula for plate fractures, Walsh [5] derives the permeability stress-sensitive expression of plate-like fracture model. According to the experimental results, Walsh *et al.* [4] revises the simplified equation:

$$\left(\frac{K}{K_0}\right)^{1/3} = 1 - \frac{\sqrt{2}h}{a_0}\ln\frac{\sigma}{\sigma_0} \tag{4}$$

where h is the mean square root of height distribution of fracture and a_0 – the fracture aperture under the reference pressure.

By referencing the establishing process of Walsh model, the influence of effective stress on fracture aperture is introduced into the permeability model. The change of fracture aperture and contact area of fractures with the stress is characterized by introducing the parameter α:

$$\frac{\mathrm{d}\ln K}{\mathrm{d}\sigma} = \frac{3}{a}\left(\frac{\mathrm{d}a}{\mathrm{d}\sigma}\right) - \left(\frac{2}{1-a^2}\right)\left(\frac{\mathrm{d}a}{\mathrm{d}\sigma}\right) \tag{5}$$

where a is the aperture degree.

According to the research of Greenwood *et al.* [6] and Whitehouse *et al.* [7], it can confirm the relationship:

$$\frac{\mathrm{d}a}{\mathrm{d}\sigma} = b = \frac{\sqrt{3}\pi\left(\frac{f}{h}\right)}{E(1-\nu^2)} \tag{6}$$

where E and ν are the elastic modulus of coal and the Poisson's ratio and f – the coefficient associated with the fracture aperture.

After the extrusion, the local fracture is broken or split, and the contact area increases, the compression quantity of fracture surface shows the exponential characteristic, and the exponential function is [8]:

$$x = a_0\left(1 - \mathrm{e}^{-\frac{\sigma_e - \sigma_{e0}}{a_0 k_n}}\right) \tag{7}$$

$$a = a_0 - x =_0 \left(1 - \mathrm{e}^{-\frac{\sigma_e - \sigma_{e0}}{a_0 k_n}}\right) \tag{8}$$

where x is the compression amount of fracture plane, a_0 – the initial aperture of fracture, a – the aperture degree (when the effective stress is σ_e), σ_{e0} – the initial effective stress, and k_n – the normal stiffness of fracture surface.

According to eqs. (6), (8), and (5), after organizing and integrating, the formula can be obtained:

$$\ln\frac{K}{K_0} = \left[\frac{3}{a_0 k_n}(\sigma_e - \sigma_{e0})\right]\left[\frac{1 - b(\sigma_e - \sigma_{e0})}{1 + b(\sigma_e - \sigma_{e0})}\right] \tag{9}$$

where b is the change rate of contact area of fracture with the increase of effective stress, which is related to the fracture roughness and the mechanical properties of rock.

In the low pressure stage, the contact area of the fracture can be regarded as a constant, the fracture aperture decreases with the increase of applied effective stress, thus the constant b is zero approximately. Equation (9) can be written:

$$\ln\frac{K}{K_0}=\frac{3}{a_0 k_n}(\sigma_e-\sigma_{e0}) \tag{10}$$

Model validation

As shown in fig. 5, the experimental results were fitted by the model and the fitting correlation coefficients are greater than 0.94. The logarithm value of coal permeability is linear with effective stress. Therefore, we can get the value of for each coal seam. Figure 6 shows the model predicted errors under different effective stress. It can be found that the relative errors of the model are within 15% basically. The parameters in this model are easy to obtain. The model is simple and suitable for engineering applications. However, the error at initial effective stress is high. It needs further work to make the calculation of more precise.

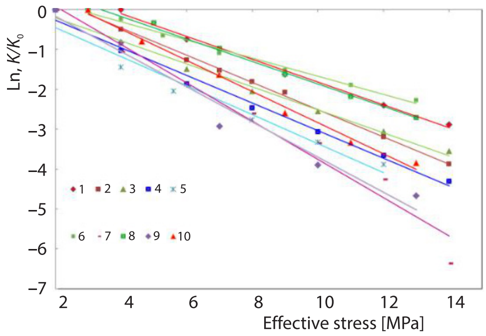

Figure 5. Experimental data and model fitting

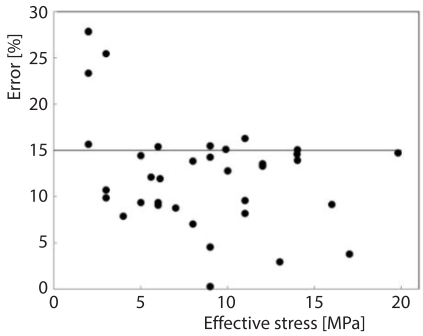

Figure 6. Model errors of coal permeability

Conclusion

With the increase of the effective stress, the permeability decreases sharply and then tends to be stable. The coal samples from eastern Yunnan and western Guizhou have strong stress sensitivity. The damage rate of coal samples is more than 94%. The irreversible damage rate is about 70%. The improved Walsh model can better describe the change law of coal permeability with stress. The permeability prediction error is basically less than 15%.

Acknowledgment

This research was funded by the National Key R&D Program of China (Grant No. 2022YFE0129100), and the project of the China Geological Survey (Grant No. DD20240051).

Nomenclature

a_0 – fracture aperture, [m]
D_k – permeability damage rate, [–]
E – elastic modulus, [MPa]
h – mean square root of fracture height, [m]
K – permeability of coal sample, [10^{-15} m^2]
K_{min} – minimum permeability value, [10^{-15} m^2]
k_n – normal stiffness of fracture surface, [MPacm^{-1}]
S_s – stress sensitivity coefficient

Greek symbols

σ_e – effective stress, [MPa]
ν – Poisson's ratio, [–]

References

[1] Jasinge, D., *et al*., Effects of Effective Stress Changes on Permeability of Latrobe Valley Brown Coal, *Fuel*, *90* (2011), 3, pp. 1285-1291

[2] Connell, L. D., A New Interpretation of the Response of Coal Permeability to Changes in Pore Pressure, Stress and Matrix Shrinkage, *International Journal of Coal Geology*, *162* (2016), 5, pp. 169-182

[3] Jones, F. O., A Laboratory Study of the Effects of Confining Pressure on Fracture Flow and Storage Capacity in Carbonate Rocks, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *27* (1975), 1, pp. 55-55

[4] Walsh, J. B., *et al*., The Effect of Pressure on Porosity and the Transport Properties of Rock, *Journal of Geophysical Research: Solid Earth*, *89* (1984), B11, pp. 9425-9431

[5] Walsh, J. B., Effect of Pore Pressure and Confining Pressure on Fracture Permeability, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, *18* (1981), 5, pp. 429-435

[6] Greenwood, J. A., *et al*., Contact of Nominally Flat Surfaces, *Proceedings of the Royal Society of London*, *295* (1966), 1442, pp. 300-319

[7] Whitehouse, D. J., *et al*., The Properties of Random Surfaces of Significance in Their Contact, *Proceedings of the Royal Society of London*, *316* (1971), 1524, pp. 97-121

[8] Meng, Z. P., *et al*., In-Situ Stress, Pore Pressure, and Stress-Dependent Permeability in the Southern Qinshui Basin, *International Journal of Rock Mechanics and Mining Sciences*, *48* (2011), 1, pp. 122-131

Paper submitted: October 23, 2024
Paper revised: November 26, 2024
Paper accepted: December 5, 2024