PERMEABILITY EVOLUTION OF UNLOADED COAL SAMPLES AT DIFFERENT LOADING RATES

by

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As coal mass is often at unloading status during mining process, it is of great significance to push on the research on permeability evolution of unloaded coal samples at different loading rates. A series of triaxial unloading experiments were conducted for initially intact coal samples using an improved rock mechanics testing system, and the permeability was continuously measured by the constant pressure differential method for methane. Permeability evolution law of unloaded coal samples and the influence mechanism of loading rates on that were studied. The results of triaxial unloading experiments indicate that the permeability of coal samples increases throughout the whole testing process without a descent stage, which is different from the permeability evolution law in conventional triaxial compression tests. The maximum permeability of unloaded coal sample, which is 4 to 18 times to its initial permeability, often appears before reaching the peak stress and increases with the decrease of axial loading rate. Stress state corresponding to the surge point of permeability of the unloaded coal samples is also discussed.

Key words: *permeability evolution, coal, loading rate, triaxial unloading experiment*

Introduction

With the reduction in surface coal resource reserves and the increasing demand of economic development for energy, the mining depths and mining intensity of coal resources are continuously increased accompanying with disasters. The coal bed gas, which mainly consists of methane and remains to be a major hazard affecting safety and efficiency of underground coal mining practice, is being widely utilized as a kind of energy resource in the USA, Australia, China, and many other countries [1, 2]. One of the fundamental factors affecting the recovery of gas in coal bed is the permeability of coal mass, whose evolution law not only has an important influence on the resource utilization of coal bed gas, strength and stability of the coal seams, but also relates the damage process of coal mass and occurrence of calamity accidents [3].

A great deal of researches on the permeability of coal mass, which is one of the critical parameters to characterize the gas flowing capacity of porous materials, and its evolution process have been conducted. The measurements of coal permeability in the laboratory show that permeability of coal to adsorbing gases (*e. g.* CH_4 and CO_2) is lower than that to non-adsorbing or lightly adsorbing gases (*e. g.* nitrogen and argon) due to the coal matrix swelling [4-6]. Under constant temperature, the variation in confining pressure has a significant influence on the permeability of coal [6, 7], which decreases with the increase of pore pressure as a

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result of coal swelling [8-11]. According to the experimental results based on the laboratory or field observation, various stress-dependent coal permeability models have been proposed to analysis or forecast the deformation and permeability evolution of coal on the basis of the idealized coal structure and specific conditions assumed [6, 12-18]. Grounded on these vast number of literatures, it can be concluded that the permeability of coal is stress-related. Consequently, more attention should be paid to the influence of the real mining-induced stress condition on the permeability evolution law of coal mass.

Due to shaft excavation or mining face advancing, stress field near the free surface redistributes as the vertical stress acting upon the concerned coal mass increases, and meanwhile the horizontal one decreases [19]. However, most of the existing researches concerning about the permeability evolution law of coal are conducted by doing conventional triaxial compression tests, which are not based on the real mining-induced stress evolution process, and the testing results of them can only reflect the permeation property of coal as a kind of rock-like material. In this paper, an attempt is made to investigate the real permeability evolution process of coal, so the following researches should be conducted under real field conditions. Since the vertical loading rate, which has a significant impact on mechanical properties and space–time evolution rules of acoustic emission location of unloaded coal samples [19-20], is associated with specific mining conditions, a series of unloading triaxial permeability tests of coal with different loading rates are designed and conducted according to the real mining-induced stress evolution process. The permeability evolution process of coal under unloading conditions is discussed as well as the related influence of vertical loading rate.

Experimental set-up and procedure

Sample preparation

The anthracite block, which was taken from Baijiao mining area in Yibin, Sichuan Province, China, was drilled for coal samples. The coal samples were prepared as cylinders with dimensions of $\varnothing$ 50 mm$\cdot H$ 100 mm according to the standard copyrighted by ASTM. The samples' mineral components are mainly organic compounds containing carbon (70.77%), calcite (5.39%), and kaolinite (5.78%), tested by X-ray diffraction meter (DMAX-3C) and X-ray fluorescence spectrometer (XRF-1800 CCED). The average uniaxial compressive strength of coal samples is 10.1 MPa at an axial strain rate of 10^{-4} and the average triaxial compressive strength is 96.6 MPa using the same loading rate when confining pressure was set to be 25 MPa.

Experimental equipment

An improved MTS815 Flex Test GT rock mechanics testing system with high stiffness, high loading sensing accuracy (1% kN) and high deformation sensing accuracy (0.1% mm), and equipped with self-designed external gas flow system, was employed to carry out the tests. Maximum axial compression load of the testing system is 4600 kN and the test ranges of confining pressure, axial and hoop deformation extensometer are 0-140 MPa, -2.5 ± 5.0 mm and -2.5 ± 8.0 mm, respectively. The external gas flow system is shown as fig. 1. The test range of pore pressure is 0.1-20 MPa and the temperature of gas can be heated from room temperature to 70 °C.

Experimental procedures

Initially coal mass is at in-situ stress state in mining practice. Then vertical stress increases and horizontal stress decreases due to shaft excavation or mining face advancing until the unloaded coal mass is completely damaged. To investigate the mechanical characteristics, permeation property and permeability evolution process of unloaded coal, a stress path of the coal samples was designed as shown in fig. 2 considering the above-mentioned stress evolution process.

The tests were divided into three stages stated as confining pressure loading stage, first unloading stage and second unloading stage. During second unloading stage, three axial loading rates were used in the test.

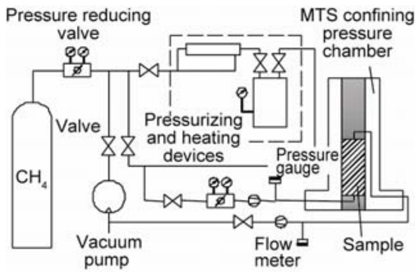


Figure 1. Schematic diagram of the external gas flow system

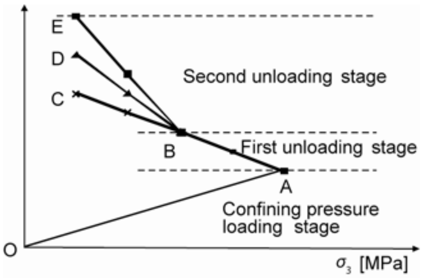


Figure 2. Stress path of coal samples

Confining pressure loading stage

Assuming overburden depth of the samples was 1000 m, the hydrostatic confining pressure was set at 25 MPa (point A in fig. 2, $\sigma_1 = \sigma_2 = \sigma_3 = 25$ MPa) and the stress loading rate was 3 MPa/min which is shown as line segment OA in fig. 2.

First unloading stage

Confining pressure of the coal samples was unloaded from point A to point B ($\sigma_1 = 37.5$ MPa, $\sigma_2 = \sigma_3 = 15$ MPa) at a rate of 1 MPa/min and the axial deviatoric stress loading rate was 2.25 MPa/min in the meantime.

Second unloading stage

All the samples were loaded to failure from point B at a constant unloading rate of 1 MPa/min. Meanwhile, the deviatoric stress loading rates of sample group E, D, and C were 4.75M Pa/min, 3.5 MPa/min, and 2.25 MPa/min, respectively.

To protect the experimental equipment, the confining pressure was stopped decreasing as soon as peak strength of the sample was detected, and the axial strain was kept on increasing until the residual strength was measured.

At the beginning of the test, the sealed sample was fixed in the MTS confining pressure chamber. After the confining pressure was loaded and the entire pipeline was vacuumed, the methane (CH_4) pressure in the closed chamber and pipeline was set to be 2 MPa. The First unloading stage began after the saturation adsorption of coal accomplished. Devices with high permeability and pressure sensing accuracy (0.1%) were employed to record the testing data of the external gas flow system.

Assuming that gas permeation through the sample is an isothermal process, and that the ideal gas law applies, the equation for the horizontal linear steady permeation of compressive gas which can be used for permeation data processing is stated as:

$$K = \frac{2qp_0\mu L}{A(p_1^2 - p_2^2)} \tag{1}$$

where K is the permeability of the sample, q – the flow rate, p_0 – the atmospheric pressure, μ – the viscosity of the fluid, L – the length of the sample, A – the cross sectional area of the sample, and p_1 and p_2 are upstream and downstream pore pressure, respectively.

Results and discussion

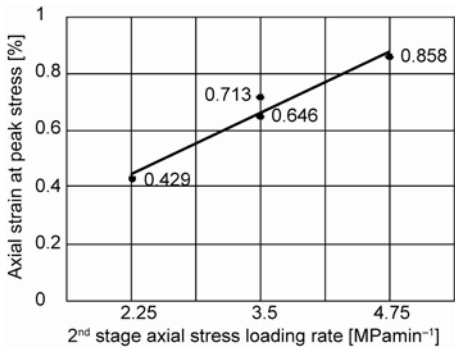
The effect of loading rate on mechanical characteristics and permeability of unloaded coal samples

Basic information, loading conditions and the main results of the tested coal samples are summarized in tab. 1. The gas pressure difference (p_p) and confining pressure unloading rate keep constant during the whole test, which are 2 MPa and 1 MPa/min, respectively, and the first and second deviatoric stress loading rates are set up according to the experimental procedures. Figure 3 shows the changing trend of every sample's mechanical parameters, initial and peak permeability with increasing the second stage deviatoric stress loading rate.

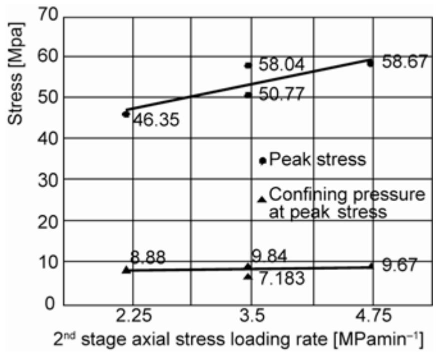
Table 1. Testing conditions and main results

Test no.	Diameter [mm]	Length [mm]	Density [kgm^{-3}]	p_p [MPa]	Confining pressure unloading rate [MPamin^{-1}]	First stage deviatoric stress loading rate [MPamin^{-1}]	Second stage deviatoric stress loading rate [MPamin^{-1}]	Peak stress [MPa]	Confining pressure at peak stress [MPa]	Axial strain at peak stress [%]	Initial permeability [m^2]	Peak permeability [m^2]
E-2-1	50.14	97.23	1435.2	2	1	2.25	4.75	58.67	9.67	0.858	5.89E-17	2.38E-16
D-2-1[a]	50.09	99.42	1498.8	2	1	2.25	3.50	50.77	9.84	0.646	4.49E-17	–
D-2-2	50.16	98.23	1479.6	2	1	2.25	3.50	58.04	7.18	0.713	6.32E-17	4.45E-16
C-2-1	50.17	99.97	1454.1	2	1	2.25	2.25	46.35	8.88	0.429	2.60E-17	4.62E-16

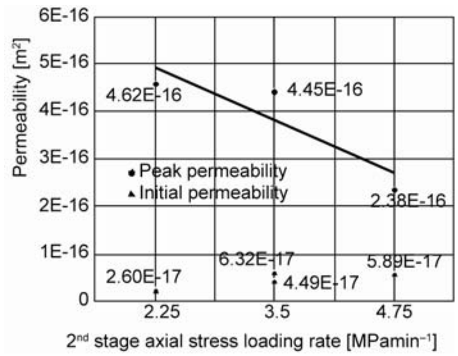
[a] The permeation data of D-2-1 in the test was not recorded duo to equipment failure.



(a) Axial strain at peak stress



(b) Peak stress and corresponding confining stress



(c) Peak permeability and initial permeability

Figure 3. Relationship between deviatoric stress loading rates and mechanical and permeation parameters of coal samples

Firstly, according to tab. 1 and figs. 3(a) and (b), the mechanical properties of unloaded coal samples under different loading rate can be analyzed. According to tab. 1, the peak stress of sample E-2-1 which get the highest second stage deviatoric stress loading rate is 58.67 MPa, and its corresponding axial strain is 0.858%, which, respectively, are 1.27 times and 2.00 times that of sample C-2-1 whose loading rate is the lowest. The corresponding measured data of sample D-2-1 and D-2-2 are just between the above two. According to figs. 3(a) and (b), when the confining pressure unloading rate is constant, peak stress and its corresponding axial strain of the samples grow linearly with the increasing deviatoric stress loading rate. This experimental phenomenon is coincident with the general consequences of rock materials. The axial deformation of samples with a higher deviatoric stress loading rate is larger than the low rate ones due to the higher average stress level during the tests.

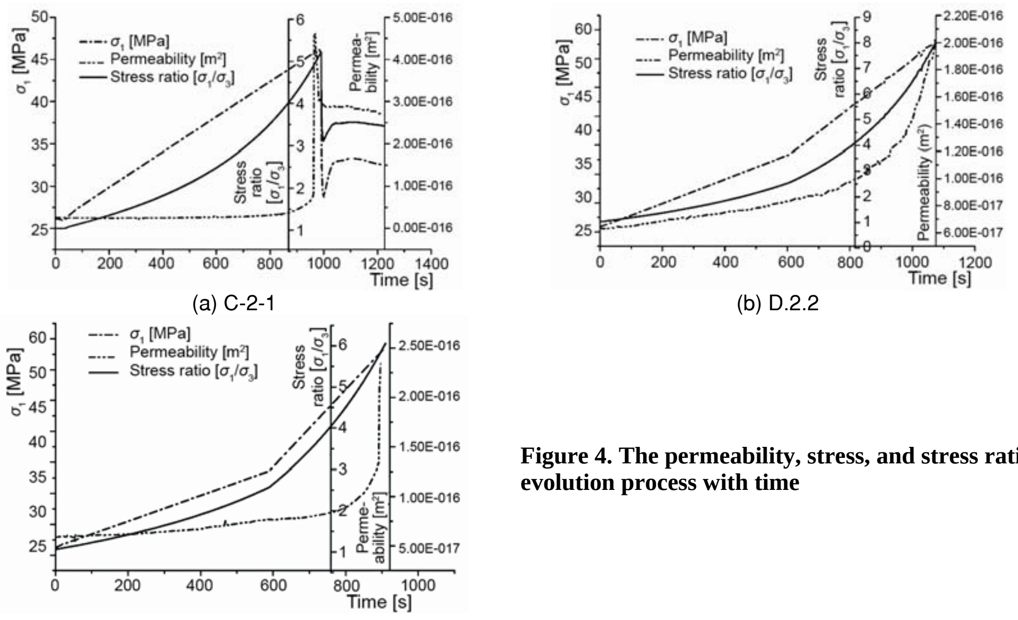
Secondly, according to tab. 1 and fig. 3(c), the permeability properties of unloaded coal samples can be analyzed. Table 1 shows that the average amount of samples' initial permeability is about $4.83 \cdot 10^{-17}$ m^2.The peak permeability of sample E-2-1 whose initial permeability is a little higher than the average amount was $2.38 \cdot 10^{-16}$ m^2, which is the minimum peak permeability of all samples and 4.04 times as much as its initial amount. The peak permeability of sample C-2-1 is $4.62 \cdot 10^{-16}$ m^2, which is the maximum amount of all samples and 17.77 times the amount of its initial permeability. The permeability of sample D-2-2 increases to 7.04 times as much as its initial permeability. According to fig. 3(c), the permeability of unloaded coal samples can increase to 4-18 times the amount of its initial permeability, and both the samples' peak permeability and permeability increment decrease with the increase of the second stage deviatoric stress loading rate. The mechanism of this phenomenon can be explained as follows. Under the same unloading conditions, axial stress of samples at low deviatoric stress loading rate is apparently lower than the amount of high rate samples when the confining pressure unloads to the same level at second unloading stage, and the average stress level of high rate samples is also higher than the others. When an unloaded sample is in a high average stress level condition, pores and cracks in it will be compressed and tend to be closed, but not extend and connect well, so its permeability and permeability increment will be lower than that of low rate samples.

Thirdly, as shown in tab. 1 and fig. 3, confining pressure corresponding to the peak stress of samples do not appear apparent linear growth trend with increasing deviatoric stress loading rate, but keep in the range of 7-10 MPa. As the samples damage at a higher confining pressure, there is a higher probability that the unloaded coal mass during mining process will be damaged more seriously, which is very dangerous for mining safety.

Permeability evolution considering real mining-induced stress evolution process

We define the stress ratio as the ratio of axial stress to the hoop stress at the corresponding moment, so the stress ratio equals to one when it comes to hydrostatic stress condition. Equation (1) is used for permeation data processing. The permeability, stress and stress ratio evolution process with time of coal samples are stated in fig. 4.

As shown in fig. 4, the permeability evolution curves have a similar trend of variation. In the first unloaded stage, the axial and hoop loading rate are constant and the permeability of samples increases slowly and linearly. Then, in the second unloading stage, the amount of permeability is still increasing with a similar linear growth trend as in the first stage when the stress ratio is not more than four. But when the stress ratio is larger than four, the permeability of all tested samples has a higher increasing rate which shows exponential



(a) C-2-1

(b) D.2.2

(c) E-2-1

Figure 4. The permeability, stress, and stress ratio evolution process with time

growth trends. The surge point of permeability always appears before the peak stress point and the peak permeability of samples also appears before reaching the peak stress in the second unloading stage. Around the transition section of the two unloading stage, there is no sudden change in the amount of permeability of samples. After reaching the peak stress, the permeability fluctuates a few seconds, then keeps to be constant due to stability of the confining pressure at that time. There is no significant influence of axial loading rate on the permeability evolution process of the samples, but as mentioned above, axial loading rate does have an effect on the amount and the increment of coal permeability.

The characteristics of the coal samples' permeability evolution process are obviously different from the results of the conventional triaxial compression tests [21]. Permeability of unloaded coal samples are constantly increasing along the test without a descent stage before reaching the peak stress. But the coal samples' permeability which is measured in conventional triaxial compression tests often decreases at the beginning of the tests and then gradually increases back to its initial amount with increasing deviatoric stress. When the deviatoric stress is larger than a specific amount, permeability of coal samples will suddenly increase 3-4 orders-of-magnitude.

Under the same conditions of temperature and stress, permeation capacity of coal cleat system is much better than the coal matrix, so gas permeation in coal mass is primarily determined by the distribution of fractures [21]. At the beginning of conventional triaxial compression tests, the samples are compressed along the axial direction and limited by the constant confining pressure. The pores, cracks, and cleats in the coal samples are tightly compressed and tend to be closure, which lead to a decrease in coal samples' permeability. As the deviatoric stress increases, expansion phenomenon of coal appears which results in the cracks aggregation and connection, so the permeability of coal increases at first and then have a sharply growth when the main flow path is connected.

But if the coal samples are in unloading conditions, apparent radial expansion of the samples will happen. The axial cracks in the coal will open and propagate, which probably increase the axial permeation capacity of coal. As the axial stress is increasing in the test, the sample is compressed along the axial direction, and the oblique and transverse cracks tend to be closure which lead to a decrease in transverse permeation. Even though axial compression of coal may decrease the axial permeation capacity of coal, the confining pressure effect has a more powerful influence on that. So the permeability of the samples does not decrease at the beginning of the unloaded tests, but constantly increases before reaching the peak strength, which shows a different permeability evolution process comparing with the results of conventional triaxial compression tests.

As is shown in fig. 4, a rapid growth of the permeability of coal appears when the ratio of axial stress to hoop stress is more than 4, so the stress ratio corresponding to the permeability rapid growth starting point equals to 4 according to the unloaded testing results. To determine the real permeability rapid growth starting point of specific coal, a series of unloaded triaxial tests should be conducted considering the real mining-induced stress evolution process. Then the stress condition of the starting point can be calculated to predict the permeability surge regions in the coal seams and it is of great help to mining safety.

Conclusions

To investigate the real permeability evolution process of coal and the related influence of axial loading rate on that, a series of unloading triaxial permeability tests have been designed and conducted with different axial loading rates to simulate the real mining-induced stress evolution process.

The results of triaxial unloading experiment indicate that the permeability of coal samples increases throughout the whole testing process without a descent stage, which is quite different from the permeability evolution law in conventional triaxial compression tests. The stress ratio corresponding to the permeability rapid growth starting point equals to 4 and the permeability of coal increases slowly and linearly when the stress ratio is lower than 4.

There is no significant influence of axial loading rate on the permeability evolution process of the samples, but it does have an effect on the amount and the increment of coal permeability. The permeability of tested unloaded coal samples can increase 4-18 times the amount of its initial permeability. The amount and the increment of coal permeability decrease with the increasing deviatoric stress loading rate at the second unloading stage, but the peak strength and the corresponding axial strain of the samples increase with that.

The results of the tests which have considered the real mining-induced stress evolution process are closer to the real permeability evolution process of in-site coal, so the mining-induced stress evolution process should be considered during the future experimental study on permeation property of coal.

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Nomenclature

A – cross-sectional area of the sample, [m^2]
K – permeability of the sample, [m^2]
L – length of the sample, [m]
p_0 – atmospheric pressure, [Pa]
p_1 – upstream pore pressure, [Pa]
p_2 – downstream pore pressure, [Pa]
p_p – gas pressure difference, [MPa]
q – flow rate, [m^3s^{-1}]

Greek symbols

μ – viscosity of the fluid, [Pa·s]
σ_1 – axial stress, [MPa]
σ_2, σ_3 – confining stress, [MPa]

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