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Study on Permeability Characteristics of Gas Bearing Coal under Cyclic Load

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Abstract: With the depletion of shallow coal mine resources, the mining depth of coal mines is deepening year by year, therefore, gas explosion and other disasters occur from time to time. Gas drainage is the main measure to prevent gas disasters, and the permeability of coal is one of the main factors affecting gas drainage. In order to explore the seepage characteristics of coal under different confining pressure loading and unloading conditions and different gas pressure, the seepage test of raw coal samples was carried out by using the coal rock triaxial loading seepage test device. The results show that the permeability of coal samples decreases with the increase of confining pressure in the loading stage, and increases with the unloading of confining pressure in the unloading stage; Through calculation, it is found that the permeability loss of coal body in the loading stage decreases with the increase of loading times, and during unloading, this value also decreases with the increase of unloading times, and reaches the maximum value at the first loading and unloading. With the increase of loading and unloading cycles, the permeability loss of coal samples decreases, and the first loading and unloading is the main stage of permeability loss of coal samples. At the same time, it is found that when the confining pressure increases, the permeability loss of coal samples decreases, and the initial permeability of coal samples maintains a good linear growth relationship with the increase of gas pressure.

Keywords: gas; permeability; confining pressure; cyclic loading and unloading; gas pressure

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1. Introduction

With the exploitation and utilization of coal resources, shallow resources are basically exhausted, and it is an inevitable trend for mining to extend from deep to deeper [1–5]. However, with the deepening of mining depth, the occurrence conditions of coal seams become more and more complex. High ground stress, high gas pressure and low permeability make gas drainage more difficult [4–8]. At the same time, during the advance of the coal mining face, the disturbance stress makes the coal body in the state of cyclic load. Under the action of cyclic load, the micro-structures such as pores and cracks in the coal body change, causing the permeability of the coal body to change, which has the effect of increasing permeability [9]. Therefore, it is of great practical significance to study the permeability characteristics of coal under cyclic loading.

Scholars have carried out a lot of work on the research of coal permeability and achieved excellent research results. Some scholars studied the permeability model of the coal body [10–15], and obtained the permeability evolution model of the coal body under different conditions, which laid a good foundation for subsequent scientific research work. Some scholars took samples on site, and after a series of processing, they carried out indoor laboratory research, studied the permeability evolution characteristics of coal body under external interference [16–20], and solved a series of on-site gas extraction problems. Some scholars used briquettes to replace raw coal to carry out coal-permeability tests [21–23], and some scholars compared the permeability difference between raw coal and briquettes through testing. Through analysis, they believed that briquette samples could replace structural coal to carry out relevant test research to a certain extent [24]. This scheme avoided the workload of on-site sampling, and the briquette production was convenient and simple, greatly reducing the test cost. Since there is often a certain stress in the surrounding coal and rock mass before and after the on-site coal mining, and in the deep mining, the form of the coal seam group is more common. Before the mining of the coal body, it is often affected by the mined coal seams, forcing the penetration of the coal seam to change. Given that, this paper applies a certain horizontal stress and axial stress to the coal mass before the official start of the experiment. On this basis, the coal mass confining pressure cyclic loading and unloading testing under different gas pressure is carried out to study the permeability characteristics of the coal mass. This test can provide some reference for studying the change characteristics of the permeability of the coal body in the non-mined coal seam after the influence of the mining layer under the occurrence form of the coal seam group.

2. Test Plan

2.1. Sample Preparation

The coal samples used in this test come from a mine in Henan Province. In order to eliminate the impact of mining, the roadway 500 m away from the mining coal seam working face is selected for sampling. After the sampling is successful, plastic wrap was used to wrap the coal, put in a wooden box, and the wooden box was filled in with woodchips to prevent the coal sample from being damaged during transportation [25]. According to the coring principle, reasonably plan the coring scheme, process the coal blocks into several cylindrical samples with a diameter of 50 mm and a height of 100 mm, preliminarily screen the coal samples, remove the samples with obvious defects, and number the remaining coal samples before further screening.

In order to further reduce the test error, the samples obtained from the preliminary screening are weighed, and the coal samples with large mass differences are removed. The quality test results of the coal samples are shown in Figure 1. Through comparison, the C-3 sample, C-10 sample, and C-14 sample are finally eliminated. After screening the coal samples, the mass ranges between 258.19 and 271.22 g, the height is between 99.12 and 100.57 mm, and the diameter is between 49.38 and 50.22 mm.

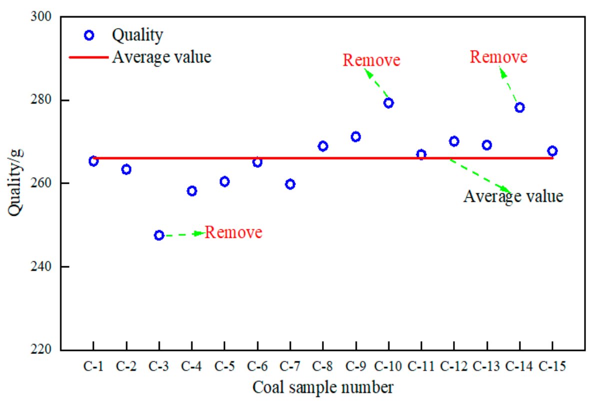

Figure 1. The quality of test coal samples.

2.2. Test Steps

The triaxial stress seepage experiment system was used to carry out the experiment. The system is composed of a device holder, confining pressure and axial pressure control system, negative pressure control system, data acquisition and processing system, and etc. It can test the permeability of coal samples under different stress paths, stress levels, air pressure, and temperature.

This test mainly studies the permeability change law of coal samples during the loading and unloading process of confining pressure cycle under four different gas pressure conditions. First, pre-stress the coal sample, stabilize the confining pressure at 3 MPa and the axial pressure at 8 MPa, then inject a high concentration of methane gas after maintaining this state for 24 h, and then adjust the pressure at the inlet end to the test set pressure (as shown in Table 1) so that the coal sample can absorb gas for 24 h.

Table 1. Test plan.

Group	Coal Sample Number	Gas Pressure/MPa	Group	Coal Sample Number	Gas Pressure/MPa
1	C-1 C-2 C-4	0.5	2	C-5 C-6 C-7	1.0
3	C-8 C-9 C-11	1.5	4	C-12 C-13 C-15	2.0

Confining pressure loading stage: keep the axial pressure at 8 MPa, keep the gas pressure at the set pressure, and load the confining pressure to 10 MPa at the loading rate of 0.05 MPa/min, so as to complete one-time loading; confining pressure unloading stage: during this process, keep the axial pressure and gas pressure unchanged, unload the confining pressure to 3 MPa at the rate of 0.05 MPa/min, so as to complete one unloading. Complete three loading and unloading cycles for each coal sample with the above steps. During the test, record the data every time the confining pressure increases (decreases) 1 MPa. The stress paths of confining pressure and axial pressure are shown in Figure 2.

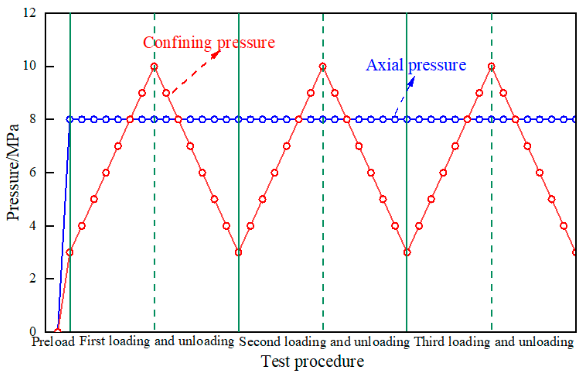

Figure 2. Stress path.

3. Test Results and Analysis

3.1. Variation Law of Coal Sample Permeability with Confining Pressure Loading and Unloading

According to the test plan, the corresponding test data are obtained after completing the loading test of four groups of coal samples. Assuming that the flow of gas in the specimen conforms to Darcy's law, the calculation method of coal sample permeability is shown in Equation (1)

$$k = \frac{2\mu Q p_0 L}{A\left(p_1^2 - p_0^2\right)} \tag{1}$$

where k refers to permeability; μ is the dynamic viscosity coefficient of gas; Q represents the gas flow under standard conditions; p_0 refers to the gas pressure at the gas outlet; p_1 represents the gas pressure at the inlet end; L represents the length of the test piece; and A represents the cross-sectional area of the coal sample.

Calculate the permeability of coal samples under the action of four kinds of gas pressure according to Equation (1), average the permeability of each group of samples, draw the change trend of permeability of each group of coal samples, and fit the change relationship between the average permeability and confining pressure, as shown in Figures 3–6.

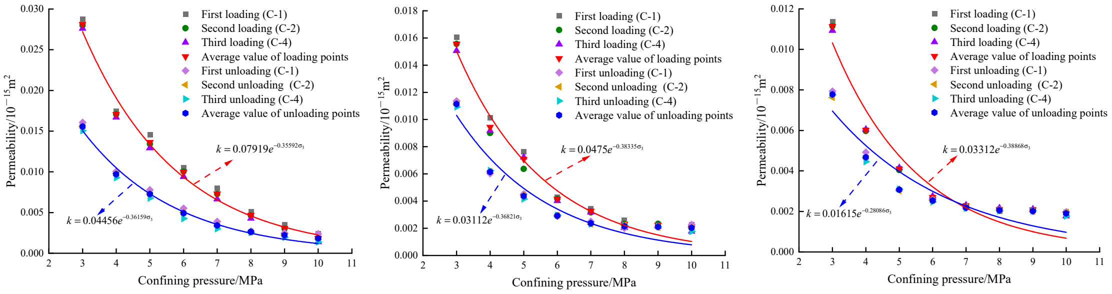

Figure 3. Permeability of coal sample when gas pressure is 0.5 MPa.

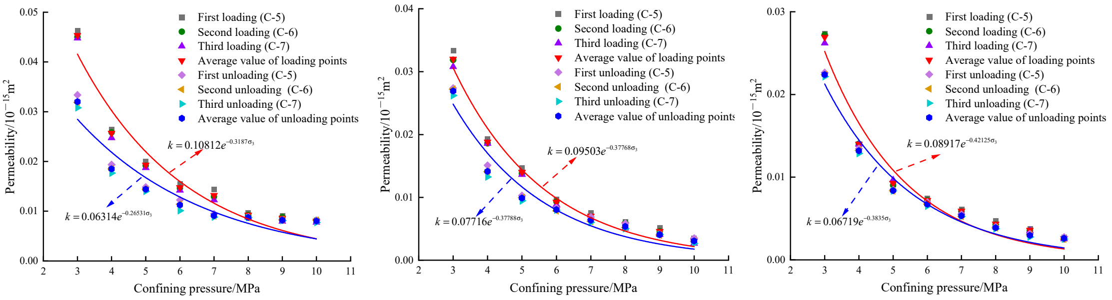

Figure 4. Permeability of coal sample when gas pressure is 1 MPa.

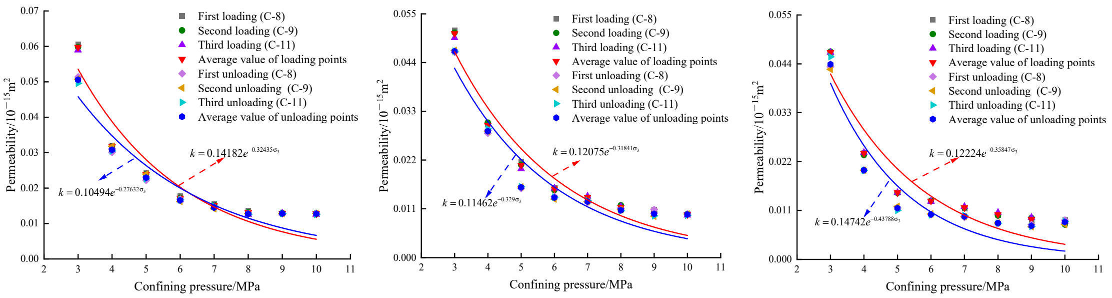

Figure 5. Permeability of coal sample when gas pressure is 1.5 MPa.

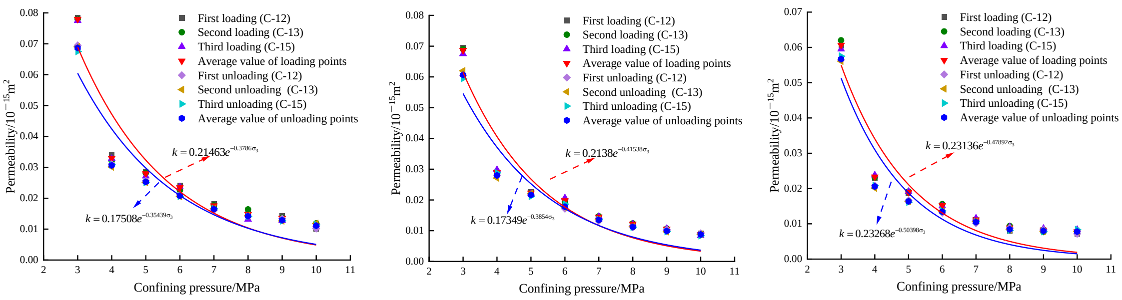

Figure 6. Permeability of coal sample when gas pressure is 2 MPa.

By analyzing Figures 3–6, it can be found that when the confining pressure is low, the permeability of the coal sample changes greatly with the confining pressure, and with the further the increase of the confining pressure, the permeability changes less. This is because when the confining pressure is in a low range, the pores and fractures of the coal sample change greatly which changes the gas seepage velocity, so the permeability floating range is large; when entering the high-confining pressure range, the seepage channel of the coal sample basically remains compressed, making the gas seepage velocity change little, therefore, the floating value of permeability is small.

In the loading stage, the permeability of coal samples decreases with the increase of confining pressure, while in the unloading stage, the permeability of coal samples increases with the unloading of confining pressure, but does not return to the initial permeability. In the loading stage, due to the increase of confining pressure, the micro cracks, pores, and their original defects in the coal sample are squeezed and contracted, and the seepage channel of gas is reduced or even blocked, thus effectively inhibiting the gas flow speed. Therefore, the phenomenon of permeability reduction will occur in the loading stage; in the unloading stage, due to the gradual reduction of confining pressure, the binding force of the original pores and fractures is released, so the deformation of the original pores and fractures begins to recover gradually making the gas flow channel gradually open. Therefore, the permeability increases in the unloading stage, but it is because the compacted fractures have not all recovered to the initial state, which leads to the recovery of permeability, but not the return to the initial permeability [26].

Since the approximate change trend of coal sample permeability in the loading stage and unloading stage is relatively similar, the change trend of average permeability and confining pressure of each group of coal samples is fitted. The fitting results are shown in Figures 3–6. Comprehensive analysis shows that the relationship between permeability and confining pressure shows a negative exponential change, and the general fitting formula is shown in Equation (2).

$$k = ae^{-b\sigma_3} \tag{2}$$

where k refers to permeability; σ_3 indicates confining pressure; and a and b are fitting parameters.

The changes of fitting parameters and fitting degree of four groups of coal samples are shown in Table 2.

Table 2. Fitting parameters and fitting degree.

Group	Stage	Load and Unload Times	*a*	*b*	R^2
1	Load	1	0.07919	0.35592	0.98869
		2	0.04750	0.38335	0.98200
		3	0.03312	0.38868	0.92474
	Unload	1	0.04456	0.36159	0.98985
		2	0.03112	0.36821	0.92882
		3	0.01615	0.28086	0.87786
2	Load	1	0.10812	0.31870	0.94081
		2	0.09503	0.37768	0.98299
		3	0.08917	0.42125	0.95733
	Unload	1	0.06314	0.26531	0.88954
		2	0.07716	0.37788	0.94571
		3	0.06719	0.38350	0.97327
3	Load	1	0.14182	0.32435	0.89129
		2	0.12075	0.31841	0.93293
		3	0.12224	0.35847	0.8813
	Unload	1	0.10494	0.27632	0.90440
		2	0.11462	0.32900	0.89943
		3	0.14742	0.43788	0.85049
4	Load	1	0.21463	0.37860	0.87595
		2	0.21380	0.41538	0.88844
		3	0.23136	0.47892	0.88862
	Unload	1	0.12508	0.35439	0.87369
		2	0.17349	0.3854	0.90545
		3	0.23268	0.50398	0.86712

In the general formula of permeability changing with confining pressure, the value of a is related to the initial permeability, that is, in different loading and unloading stages, it is related to the permeability when the confining pressure is 3 MPa. The relationship between the fitting coefficient *a* and the initial permeability is shown in Figure 7. That is, the fitting coefficient increases linearly with the increase of initial permeability.

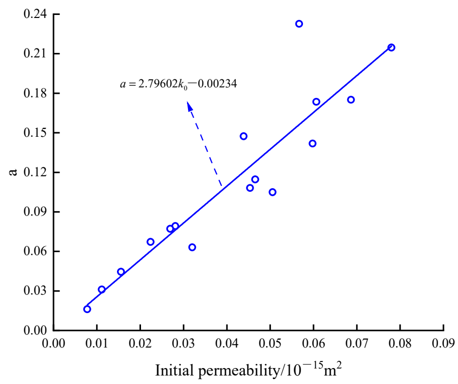

Figure 7. Relationship between fitting coefficient a and initial permeability.

At the same time, it is found that when the initial permeability is small, the distribution range of the fitting coefficient a value is mainly concentrated near the curve and relatively concentrated, whilst when the initial permeability is large, the distribution of the fitting coefficient a value is relatively scattered.

3.2. Variation Law of Permeability Loss of Coal Samples under Different Confining Pressures

According to the above analysis, the permeability of the coal sample in the unloading stage cannot be restored to the initial permeability, that is, there is a difference in permeability in the loading and unloading stage. The reason for this is that the coal sample has not only elastic deformation, but also plastic deformation. In the unloading stage, only the elastic deformation of the coal sample has been restored, and the plastic deformation is irreversible, so there is also irreversible deformation in the gas seepage channel, as a result, the permeability cannot be restored to the initial value [27].

In order to clarify the loss and recovery degree of permeability of coal samples during loading and unloading, the calculation equation of permeability difference in each stage is as follows:

$$k_l = k_0 - k_{01} \tag{3}$$

$$k_r = k_1 - k_{01} \tag{4}$$

$$k_a = k_0 - k_1 \tag{5}$$

where k_l refers to the permeability difference in the loading stage; k_r indicates the permeability difference in unloading stage; k_a represents the total loss of permeability in the same loading and unloading stage; k_0 indicates the initial permeability in the loading stage; k_1 indicates the permeability at the minimum confining pressure during unloading; and k_{01} indicates the permeability at the maximum confining pressure in the loading (unloading) stage.

The permeability difference in the loading stage can reflect the closure degree of the pores and fractures of the coal sample, and the permeability difference in the unloading stage can reflect the recovery degree of the pores and fractures of the coal sample, and the state of the pores and fractures directly affects the permeability of the coal sample. In order to clarify the change law of the permeability difference of the coal sample, the experimental group of coal samples with a gas pressure of 0.5 MPa is analyzed, as shown in Figure 8.

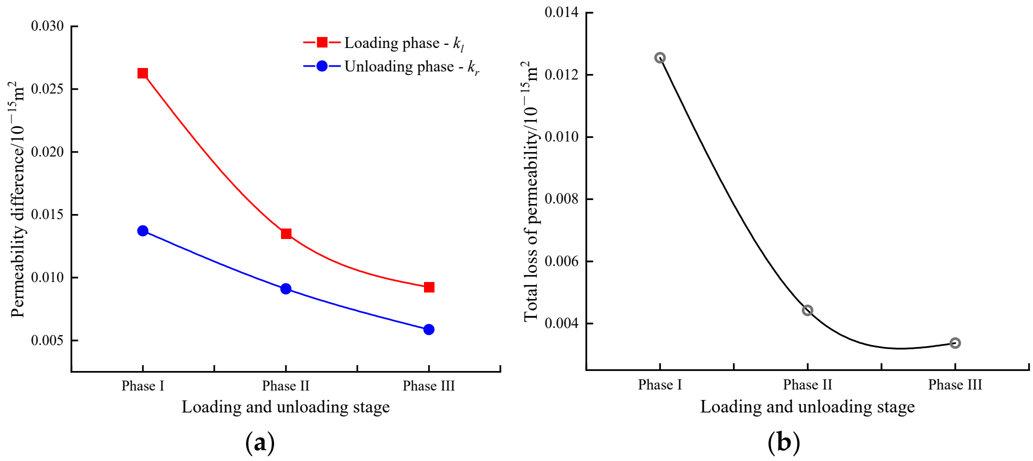

Figure 8. Permeability difference: (**a**) Permeability difference at each loading (unloading) stage; (**b**) Permeability difference at the minimum confining pressure in the same stage.

It can be seen from Figure 8a: the permeability loss in the loading stage decreases with the increase of loading times, and the permeability recovery during unloading also decreases with the increase of unloading times. At the first loading, the permeability difference of the coal sample is the largest, indicating that the number of closed pores and fractures in the coal sample is the largest at the first loading. With the increase of loading times, the permeability difference gradually decreases, that is, with the increase of loading times, the number of closed pores and fractures in the coal sample also decreases; at the first unloading, the permeability difference of coal sample is also the largest, indicating that the recoverable deformation of coal sample is the most during the first unloading. With the increase of unloading times, the permeability recovery difference decreases, that is, with the increase of unloading times, the recoverable deformation of coal sample becomes less and less.

After each cycle of loading and unloading, coal samples will produce different degrees of irreversible deformation, that is, different degrees of permeability loss. It can be seen from Figure 8b: as the number of cycles increases, the loss of permeability of the coal sample decreases, that is, when the number of cycles increases, the irreversible plastic deformation inside the coal sample gradually decreases. That is, the first loading and unloading is the main stage of permeability loss of coal samples, and it is also the stage of plastic deformation of coal samples.

During loading and unloading at the same stage, there is a certain difference in permeability at the same confining pressure, which can characterize the variation law of plastic deformation of coal samples with confining pressure. The calculation formula of permeability loss of coal samples at the same confining pressure is as follows, and the permeability loss corresponding to different confining pressures is as shown in Figure 9

$$k_{ai} = k_{0i} - k_{1i} \tag{6}$$

where k_{ai} refers to the permeability loss when the confining pressure is i in the same loading and unloading stage; k_{0i} indicates the permeability when the confining pressure in the loading stage is i; and k_{1i} refers to the permeability when the confining pressure at unloading stage is i.

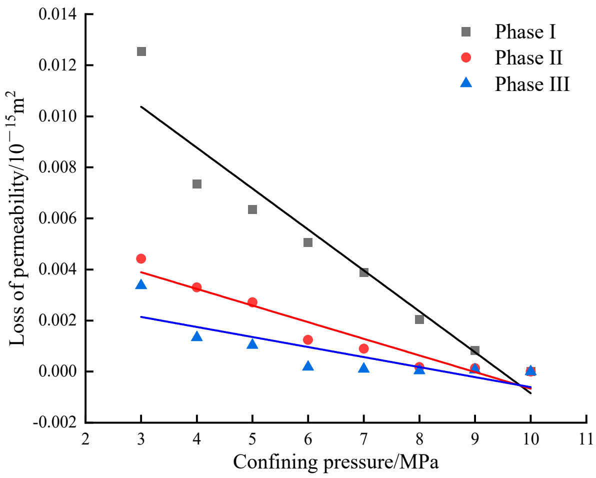

Figure 9. Permeability loss of coal samples at different confining pressures.

It can be seen from Figure 9 that with the increase of confining pressure, the permeability loss of coal samples gradually decreases. Due to different confining pressures, the loading and unloading time of coal samples are different, which leads to different degrees of closure and recovery of cracks in the samples. The amount of permeability loss is also different. When the confining pressure is loaded from 3 MPa to 10 MPa and then unloaded to 3 MPa, the coal sample is loaded for the longest time and the permeability loss is the most, while when the confining pressure is 10 MPa, the coal sample is loaded for the shortest time and the permeability loss is the least.

By fitting the change trend of permeability loss of coal samples at different loading and unloading stages with confining pressure in the figure, it is found that the absolute value of the slope of the fitting curve is the largest at the first loading and unloading stage, and the absolute value of the slope of the fitting curve is smaller with the increase of the number of loading and unloading cycles. It also shows that the change range of permeability loss of coal samples gradually decreases with the increase of the number of cycles, that is, within the experimental range, when the number of cycles increases, the permeability of coal samples decreases.

3.3. Variation Law of Coal Sample Permeability with Gas Pressure

Gas pressure has an important influence on the permeability of coal samples, especially on the initial permeability of coal samples. Figure 10 shows the change trend of the initial permeability of coal samples under different gas pressure.

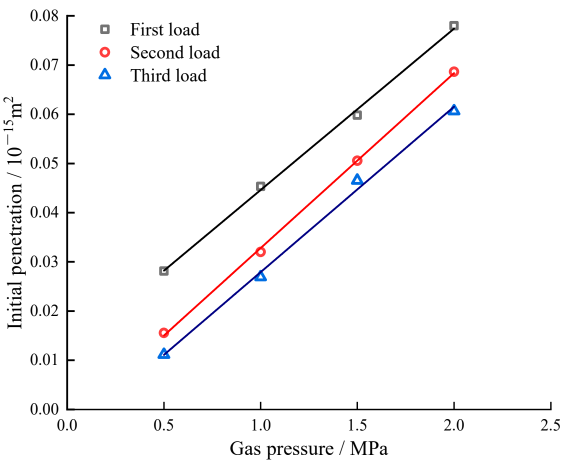

Figure 10. Variation trend of initial permeability of coal samples under different gas pressures.

It can be seen from Figure 10 that the initial permeability of coal samples maintains a good linear growth relationship with the increase of gas pressure at different confining pressure loading and unloading stages. The variation trend of coal sample permeability with gas pressure in three stages is fitted, and the fitting formula and fitting degree are shown in Table 3.

Table 3. Fitting relationship between initial permeability and gas pressure.

Loading-Unloading Phase	Fitting General Formula	*a*	*b*	R^2
1		0.03281	0.0118	0.99823
2	$k_0 = ap + b$	0.03556	−0.00276	0.99936
3		0.03363	−0.00572	0.99641

4. Conclusions

In the loading stage, the permeability of coal samples decreases with the increase of confining pressure, while in the unloading stage, the permeability of coal samples continues to recover with the unloading of confining pressure, but does not return to the initial permeability.

The permeability loss in the loading stage decreases with the increase of loading times, and the permeability recovery during unloading also decreases with the increase of unloading times. The permeability difference of coal samples is the largest at the first loading and unloading.

With the increase of the number of loading and unloading cycles, the loss of permeability of coal samples decreases, that is, when the number of cycles increases, the irreversible plastic deformation inside the coal samples gradually decreases. Furthermore, the first loading and unloading is the main stage of permeability loss of coal samples, and it is also the stage of plastic deformation of coal samples.

When the confining pressure increases, the permeability loss of coal samples gradually decreases; at different confining pressure loading and unloading stages, the initial permeability of coal samples maintained a good linear growth relationship with the increase of gas pressure.

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