Mechanical behaviour and seepage characteristics of coal under the loading path of roadway excavation and coal mining

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ABSTRACT
The mechanical behaviour and seepage characteristics of coal under the mining engineering disturbance are of great significance to prevent gas disasters. Based on the geological conditions of the No. 12 mine of the China Pingdingshan Mining Group, the mechanical seepage experiments of coal under the stress path of roadway excavation and coal mining were carried out. The experimental result shows that: The coal in fracture zone is most strongly affected by the roadway excavation. The samples showed obvious expansion phenomenon, and their cracks were the most complex. They formed effective permeability before the peak strength, and their permeability was the largest; the coal in disturbance zone is less affected by roadway excavation, and the coal samples formed effective permeability after the peak strength. Their permeability was smaller than the samples in fracture zone; the coal in original rock stress zone is only affected by coal mining, and its crack growth degree is the lowest. The coal samples formed stable permeability in the residual strength stage, and their permeability was the smallest. In practical engineering, special attention should be paid to the sudden gas gushing caused by the sudden increase of coal seam permeability, which will cause gas disaster.

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1. Introduction
With the gradual exhaustion of shallow mineral resources, the depth of resource mining continues to increase, deep resource mining has gradually become a new normal (Xie et al. 2015; Xie 2019; Gao, Liu, et al. 2020). The high ground stress, high temperature, and high osmotic pressure environment of deep engineering makes the structure, mechanical characteristics, seepage characteristics, and engineering response...
of deep rocks different from those of shallow rocks, resulting in more frequent and severe dynamic disasters (Peng et al. 2019; Xie et al. 2019, 2021).

Under deep mining conditions, gas disasters such as coal and gas outburst, gas explosion, and gas suffocation are one of the most frequent and serious disasters (Yuan et al. 2020). In order to prevent gas disasters, many scholars have conducted research on the formation mechanism and prevention methods of gas disasters, the disturbance effect of mining engineering, and the seepage characteristics of coal and rock (Gao, Zhang, Yin, et al. 2018; Gao et al. 2019; Ma et al. 2020). Skoczylas (2012) and Wang et al. (2011) studied the role of gas in the outburst process. Wold et al (2008) studied the influence of parameters such as strength and porosity of coal seam on gas outburst. Pan (2020) and Tu et al. (2019) studied the influence of tectonism on coal and discussed the relationship between tectonic coal and outbursts. Laubach et al. (1998) analyzed the influence of the size, aperture, occurrence, crack spacing, and other physical characteristics of the fracture structure on the permeability of coal. Li et al (2007) found that coal will expand and deform when it absorbs gas, and deformation will also cause volume stress, which will reduce the strength of coal body and increase the risk of gas outburst. Connell (2009) studied the coupling relationship between gas seepage and ground stress. Wang et al. (2010) studied the evolution law of coal permeability under the influence of mining through on-site mining coal permeability tracer test. Pan et al. (2005) pointed out that high gas content and high gas pressure in coal seam essentially affected the stability of coal body. Paterson (1986) considers that gas pressure gradient is the main force leading to coal body breakage during outburst. Ding et al. (1990) believes that the coupling of coal crushing and gas seepage is the internal factor of coal and gas outburst. Some scholars have explained gas outburst from the perspective of energy principle(Yu et al. 2015; Lu et al. 2019; Lei et al. 2021), and Li (1987) believes that the outburst process is the process of sudden release of the elastic strain energy and gas internal energy accumulated in coal. Xie et al. (Xie, Gao, Liu, et al. 2020; Xie, Gao, Zhang, Liu, et al. 2020; Xie, Gao, Zhang, Ren, et al. 2020) studied the influence of fracture complexity of coal on gas seepage characteristics and discussed the evolution process of coal permeability under loading and unloading conditions.

Engineering disturbance such as coal mining, blasting and roadway excavation is an important cause of gas disaster (Gao, Zhang, Xie, et al. 2018; He et al. 2019; Ren et al. 2019; Zhang et al. 2019; Hao 2020). However, most of the existing studies only consider the disturbance of coal mining, rarely consider the disturbance of roadway excavation. Based on the geological conditions of the No. 12 mine of the China Pingdingshan Mining Group, the mechanical seepage experiments of coal under the stress path of roadway excavation and coal mining were carried out. The mechanical behaviour and seepage characteristics of coal under the roadway excavation and coal mining are studied, and the possible disasters are analyzed.

2. Engineering background

This study is based on the geological conditions of the No. 12 mine of the China Pingdingshan Mining Group. And the experimental samples were also taken from the coal seam of this mine. The buried depth of the coal seam is nearly 1000 m, and its
overall occurrence is relatively stable, with an average thickness of about 3.5 m and an average dip angle of 10°. The cohesion $C_m$ of coal is 2.5 MPa and the internal friction angle $\varphi_m$ is 25°. The original gas content of this mine is 17.81 m$^3$/t, and the original gas pressure is 2.2 MPa, which belongs to a typical high gas mine.

3. Mechanical seepage experiment of coal under the loading path of roadway excavation and coal mining

3.1. Sample preparation

The coal samples used in this experiment are from the No. 12 mine of the China Pingdingshan Mining Group. Using standard cylinder raw coal sample with diameter of 50 mm and height of 100 mm. In order to reduce the error caused by sample differences, ultrasonic testing and density measurement were carried out on coal samples. And six samples with similar density and ultrasonic wave velocity were selected and numbered as F1, F2, D1, D2, N1 and N2.

3.2. Experimental equipment

This experiment adopts the fracturing and seepage experimental system for multi-physical field and multiphase coupling of porous media developed by the State Key Laboratory of coal mine disaster dynamics and control of Chongqing University, as shown in Figure 1. This equipment can be used to study the mechanical characteristics and seepage characteristics of coal containing methane under the combined action of temperature, seepage and stress fields.

3.3. Design and scheme for mechanical seepage test

In order to explore the stress path of coal under the superposition disturbance of roadway excavation and coal mining, based on the theory of elastic-plastic mechanics,
the stress distribution of surrounding rock after roadway excavation was calculated. The surrounding rock after roadway excavation is divided into fracture zone, disturbance zone and original rock stress zone, as shown in Figure 2. Among the six samples, B1 and B2 samples correspond to fracture zone, D1 and D2 samples correspond to disturbance zone, N1 and N2 samples correspond to original rock stress zone.

Firstly, it is assumed that the surrounding rock is homogeneous, isotropic and continuous, and is under hydrostatic pressure before roadway excavation. Then, a roadway with radius of $R_0$ is excavated. After excavation, a plastic fracture circle is formed around the free face, with radius of $R_1$. The rock inside the circle obeys Mohr-coulomb criterion, while the rock outside the circle is still in elastic state, as shown in Figure 3 (Liu 2009).

Take a small micro-unit abdc in the surrounding rock, and its stress state is shown in Figure 3. When the micro-unit is in the equilibrium state, according to the principle of force balance, the radial and tangential projections of the resultant force acting on the micro-unit are 0, and the equilibrium equation is obtained as Equation (1) (Liu 2009):

$$\sigma_r r d\theta - (\sigma_r + d\sigma_r)(r + dr)d\theta + 2\sigma_0 dr \sin\left(\frac{d\theta}{2}\right) = 0$$  \hspace{1cm} (1)

When $d\theta$ is very small, $\sin\left(\frac{d\theta}{2}\right) \approx \frac{d\theta}{2}$. By expanding Equation (1) and omitting the high-order infinitesimal, Equation (2) is obtained:

$$\left(\sigma_0 - \sigma_r\right) dr = r dr$$  \hspace{1cm} (2)

The rock in the fracture zone satisfies the criterion conditions of Mohr-coulomb criterion, as shown in Equation (3) ($C_m$ is cohesion and $\varphi_m$ is internal friction angle):
\[
\frac{\sigma_\theta + C_m \cot \varphi_m}{\sigma_r + C_m \cot \varphi_m} = \frac{1 + \sin \varphi_m}{1 - \sin \varphi_m}
\] (3)

Equation (4) is obtained from Equation (2):

\[
\sigma_\theta = \frac{rd\sigma_r}{dr} + \sigma_r
\] (4)

Substituting Equation (4) into Equation (3), Equation (5) is obtained:

\[
\frac{d(\sigma_r + C_m \cot \varphi_m)}{\sigma_r + C_m \cot \varphi_m} = \left( \frac{1 + \sin \varphi_m}{1 - \sin \varphi_m} - 1 \right) \frac{dr}{r} = \frac{2 \sin \varphi_m}{1 - \sin \varphi_m} \frac{dr}{r}
\] (5)

After integrating both sides of Equation (5), Equation (6) is obtained:

\[
\ln (\sigma_r + C_m \cot \varphi_m) = \frac{2 \sin \varphi_m}{1 - \sin \varphi_m} \ln r + A
\] (6)

In Equation (6), A is an integral constant, which can be determined by the boundary conditions: \(r=R_0, \sigma_r=p_i\) (\(p_i\) is the support force on the inner wall of the roadway). Equation (7) is obtained:

\[
A = \ln (p_i + C_m \cot \varphi_m) - \frac{2 \sin \varphi_m}{1 - \sin \varphi_m} \ln R_0
\] (7)

After substituting Equation (7) into Equation (6), the radial stress \(\sigma_r\) is obtained as shown in Equation (8):

\[
\sigma_r = (p_i + C_m \cot \varphi_m) \left( \frac{r}{R_0} \right)^{\frac{2 \sin \varphi_m}{1 - \sin \varphi_m}} - C_m \cot \varphi_m
\] (8)
Similarly, the circumferential stress $\sigma_\theta$ can be obtained, as shown in Equation (9):

$$
\sigma_\theta = (p_i + C_m \cot \varphi_m) \frac{1 + \sin \varphi_m}{1 - \sin \varphi_m} \left( \frac{r}{R_0} \right)^{2 \sin \varphi_m} - C_m \cot \varphi_m
$$

(9)

In summary, the stress distribution of surrounding rock in the fracture zone is obtained, as shown in Equation (10):

$$
\begin{align*}
\sigma_r &= (p_i + C_m \cot \varphi_m) \left( \frac{R_0}{r} \right)^{2 \sin \varphi_m} - C_m \cot \varphi_m \\
\sigma_\theta &= (p_i + C_m \cot \varphi_m) \frac{1 + \sin \varphi_m}{1 - \sin \varphi_m} \left( \frac{r}{R_0} \right)^{2 \sin \varphi_m} - C_m \cot \varphi_m \\
\tau_{r\theta} &= 0
\end{align*}
$$

(10)

It is considered that except for the rocks in the fracture zone, other rocks are still in an elastic state. Under the condition of hydrostatic pressure, the stress distribution in the elastic area is shown in Equation (11):

$$
\begin{align*}
\sigma_r &= \sigma_0 \left( 1 - \frac{R_0^2}{r^2} \right) \\
\sigma_\theta &= \sigma_0 \left( 1 + \frac{R_0^2}{r^2} \right) \\
\tau_{r\theta} &= 0
\end{align*}
$$

(11)

Using the condition that the elastic stress is equal to the plastic stress on the interface between the fracture zone and the elastic zone, the stress distribution on the interface can be obtained, as shown in Equation (12):

$$
\begin{align*}
\sigma_r &= \sigma_0 (1 - \sin \varphi_m) - C_m \cos \varphi_m \\
\sigma_\theta &= \sigma_0 (1 + \sin \varphi_m) + C_m \cos \varphi_m \\
\tau_{r\theta} &= 0
\end{align*}
$$

(12)

After the roadway excavation and before the support, the surrounding rock has experienced unloading failure. In order to simulate the process of unloading effect after roadway excavation, the influence of support force is not considered when calculating the stress environment of coal in the fracture zone.

According to Equations (10), Equations (11) and (12), based on the geological conditions and coal samples of No. 12 mine of the China Pingdingshan Mining Group, we designed the mechanical and seepage characteristics experiments of coal under three stress paths. The experimental scheme of each stress path is as follows:

1) Fracture zone

The unloading of roadway excavation makes the coal in this zone experience a strong unloading effect. The research object of this scheme is the coal on the roadway wall, as shown in Figure 4. According to the Equation (10), the stress state of the roadway wall unit after unloading can be calculated. After the roadway excavation and before the support, the confining pressure in the horizontal direction should be unloaded to 0 MPa. However, in order to prevent the gas osmotic pressure from breaking down
the thermoplastic film on the surface of the coal sample in the seepage experiment, the minimum confining pressure should not be less than the gas osmotic pressure, so the minimum confining pressure unloading is set to 3 MPa. The stress path is shown in Figure 4.

The experimental steps are as follows:
(a) Install and stabilize the sample: Before formal loading, 2 kN axial pressure ($\sigma_1$) was applied to stabilize the sample, and 2 kN confining pressure ($\sigma_2$ and $\sigma_3$) was applied at the same time.
(b) Hydrostatic pressure stage: Loading $\sigma_1$, $\sigma_2$ and $\sigma_3$ to 25 MPa at the rate of 3 MPa/min (the vertical stress gradient was 25 KPa/m and the buried depth was 1000 m). During the process of oil filling and confining pressure application, vacuum the intake pipe for about 30 minutes. After pressurization, under the condition of ensuring that the thermoplastic film is not damaged, CH$_4$ gas is filled into the intake pipe, and the gas pressure is stabilized to make the coal sample fully adsorb for 60 min.
(c) Roadway excavation stage: During the roadway excavation, the confining pressure ($\sigma_2$ and $\sigma_3$) is unloaded to 3 MPa at the rate of 0.1 MPa/s, and the axial pressure $\sigma_1$ is unloaded to 9.5 MPa at the rate of 0.07 MPa/s.
(d) Mining stage: Keep the sample stable for 5 min. Keep the confining pressure ($\sigma_2$ and $\sigma_3$) unchanged, increase the axial stress $\sigma_1$ until the residual strength appears. The loading rate of axial pressure is 0.0625 MPa/s. In order to ensure that the stress-strain curve of the residual strength stage is obtained, the sample is subjected to displacement control after yielding, and the displacement rate is 0.1 mm/min.

(2) Disturbance zone
The distance between the interface of plastic zone and elastic zone and the centre point of roadway after excavation is $R_1$, as shown in Figure 3. Equation (12) can be used to calculate the stress state of the micro-unit on this interface after roadway excavation. And the stress path of micro-unit on this interface is shown in Figure 5.

The experimental steps are as follows:
(a) Install and stabilize the sample: The same as fracture zone.
(b) Hydrostatic pressure stage: The same as fracture zone.

(c) Roadway excavation stage: At the rate of 0.1 MPa/s, the axial pressure $\sigma_1$ was loaded to 37.6 MPa, and the confining pressures $\sigma_2$ and $\sigma_3$ were unloaded to 12.5 MPa.

(d) Mining stage: Keep the sample stable for 5 min. The axial pressure is increased at the rate of 0.0625 MPa/s, and the confining pressure is decreased with the unloading rate of 0.05 MPa/s. The axial displacement control is adopted after the sample yields, and the displacement rate is 0.1 mm/min.

(3) Original rock stress zone
The coal rock in the original rock stress zone is not affected by the roadway excavation, but only by the coal seam mining. The stress path is shown in Figure 6.

The experimental steps are as follows:
(a) Install and stabilize the sample: The same as fracture zone.
(b) Hydrostatic pressure stage: The same as fracture zone.
(c) Mining stage: The axial pressure $\sigma_1$ is increased at the rate of 0.0625 MPa/s, and the confining pressures $\sigma_2$ and $\sigma_3$ are decreased at the rate of 0.05 MPa/s. The axial displacement control is adopted after the sample yields, and the displacement rate is 0.1 mm/min.

Under the above three stress paths, the gas seepage pressure in the whole experiment is kept at 2 MPa, and the minimum value of confining pressure is not less than the gas seepage pressure.

4. Experimental results and analysis

4.1. Mechanical behaviour

The deviatoric stress-strain curves of coal samples in fracture zone are shown in Figure 7. It shows that due to the large initial confining pressure, the confining pressure and axial pressure are unloaded after roadway excavation, resulting in unloading rebound of the samples. The axial strain, circumferential strain and volumetric strain all appear negative value. During coal seam mining, axial pressure continues to increase. The sample has experienced elastic stage and yield stage, and then enters the residual strength stage after reaching the peak strength. Due to the strong disturbance of roadway excavation, the strength of coal in the fracture zone decreases, and its peak strength is only about 25 MPa. The volume strain of the sample is negative, so the sample has been in a state of expansion. This shows that the cracks are produced inside the samples. The reason is that the rapid unloading effect causes the stress in the sample to have no time to re-adjust the distribution, so tensile stress which is greater than the tensile strength of the sample appears, resulting in the internal damage of the sample.

The deviatoric stress-strain curves of coal samples in disturbance zone are shown in Figure 8. It can be seen from Figure 8 that the axial pressure of the coal in the disturbance zone increases after the roadway excavation. Although the confining pressure decreases to 12.5 MPa, it can still limit the circumferential strain of the sample. Therefore, compared with the fracture zone, the disturbance zone does not appear expansion phenomenon after roadway expansion. After the roadway excavation, the coal seam began to be mined. When loaded near the peak strength of the sample, the stress-strain curve fluctuates significantly. The reason is that the unloading disturbance in the early stage causes stress concentration inside the sample, which leads to secondary microcracks appear inside the sample. When the sample is loaded near the peak strength, under the superposition effect of the stress environment, primary cracks and secondary microcracks, the internal structure of the sample is destroyed to form penetrating cracks, which affect the strength of the sample. Therefore, the stress state of the sample is constantly changing and adjusting, the stress-strain curve fluctuates.

The deviatoric stress-strain curves of coal samples in original rock stress zone are shown in Figure 9. Because original rock stress zone is far away from the roadway, the coal in original rock stress zone is basically not affected by the roadway excavation, but only affected by the coal seam mining. The samples experienced elastic stage and yield stage, reached the peak strength and finally entered the residual strength stage. On the whole, there is no strong expansion in the early stage of the samples,
and there is no obvious fluctuation phenomenon in the stress-strain curve near the peak strength. This shows that compared with the fracture zone and the disturbance zone, the stress concentration and crack propagation process in the original rock stress zone are relatively gentle.

By comparing the stress-strain characteristics of the samples in the three zones, it can be found that the larger the distance between the coal and the roadway is, the smaller the influence of the roadway excavation disturbance on the coal is. The coal in the fracture zone is most significantly disturbed by roadway excavation. Under the influence of rapid unloading, large tensile stress concentration occurs in the samples, which leads to the increase of internal cracks. The coal in the fracture zone has a strong expansion phenomenon when the roadway is excavated, and its strength is also the weakest among the three zones. The coal in disturbance zone is less disturbed by roadway excavation than the coal in fracture zone. Under the influence of unloading, a certain amount of

Figure 7. Deviatoric stress-strain curve of samples in fracture zone.
micro damage accumulated in the coal. When the sample is loaded near the peak strength, under the superimposed influence of the stress environment, primary cracks and secondary microcracks, the internal structure cracking morphology and stress state of the sample are constantly changing, so the stress-strain curve fluctuates significantly. There is no obvious expansion phenomenon during the early unloading stage, and the coal samples still maintain a high strength. The original rock stress zone is not affected by roadway excavation basically, and the stress evolution and fracture evolution process of coal samples are relatively stable.

4.2. Macroscopic failure characteristics

The macro failure characteristics of coal considering the influence of roadway excavation and coal mining disturbance are very different from those only considering the

[Figure 8. Deviatoric stress-strain curve of samples in disturbance zone.]
influence of mining. Studying the macroscopic failure characteristics of coal under different stress paths can further explain its mechanical and seepage evolution characteristics. The specific fracture development of coal samples in different zones is shown in Figures 10–12.

Figure 10 shows that the fracture zone samples present the tensile-shear mixed failure characteristics similar to that under uniaxial compression. The reason is that the confining pressure is 3 MPa when the sample is damaged, while the rock failure modes under low confining pressure are mostly tensile failure and shear failure. The sample is relatively broken, and the cracks are mainly composed of one or more tensile shear composite cracks running through the sample in an oblique direction, accompanied by X-type, Y-type small cracks and tensile small cracks. The reason is that after the roadway excavation, the sample is unloaded from high confining pressure to almost zero, and the rapid unloading effect leads to the tensile stress concentration, resulting in the formation of micro secondary cracks. Then affected by the

Figure 9. Deviatoric stress-strain curve of samples in original rock stress zone.
abutment pressure produced by coal mining, strong stress concentration occurs at both ends of the small cracks, which leads to the development and continuous extension of the cracks, and finally forms multiple macroscopic large cracks.

Figure 10. Surface failure characteristics of coal samples in fracture zone.
Figure 11 shows the fracture structure characteristics of the coal samples in the disturbance zone. The cracks are still mainly tension-shear compound cracks that penetrate the samples obliquely. The shear failure occurred at both ends of the samples and the tensile failure occurred at the middle of the samples. Compared with the coal samples in the fracture zone, the cracks in the disturbance zone are less. A small
amount of X-type, Y-type cracks and small tension cracks are also associated on both sides of the main cracks. Especially in sample D2, it can be seen that there is a group of Y-type conjugate cracks in the lower part. The reason is that there are two groups of maximum shear stress planes in the strain ellipsoid. Under a certain stress

Figure 12. Surface failure characteristics of coal samples in original rock stress zone.
combination state, shear cracks on the two groups of shear planes are likely to develop at the same time. But in fact, due to the uneven distribution of primary joints and internal minerals in the rock mass, the two groups of cracks are usually unbalanced.

Figure 12 shows the macro fracture structure characteristics of the coal sample in the original rock stress zone. Because the coal in this zone is almost not affected by roadway excavation, compared with the other two groups of samples, its integrity is the highest and the number of cracks is the least. The crack surface of coal sample is also the smoothest, which indicates that the failure mode of coal sample changes from tensile failure to shear failure. This is because the original rock stress zone sample is not affected by the unloading of roadway excavation, and there is no expansion in the early stage, so the tensile failure characteristics are not obvious.

Fractal dimension is a feature quantity that can effectively reflect the space occupation and complexity of complex shapes. It is often used to quantitatively describe the irregularity and complexity of cracks. In this study, the fractal dimension of cracks is calculated by box covering method. Firstly, the cracks depicted in Figures 10–12 are transformed into bitmaps and binarized, and then the binarized image is divided into several squares with sides of $\delta$. Calculate the number of squares containing at least one pixel on the image, and record the number as $N_\delta$. Change the size of $\delta$ and repeat the above process. Finally, the fractal dimension is obtained from Equation (13) (Gao, Zhang, et al. 2020):

$$D_B = \lim_{\delta \to 0} \frac{\log N_\delta(F)}{-\log \delta}$$ \hspace{1cm} (13)

In Equation (13), F is the bounded set of cracks on the two-dimensional plane; $N_\delta(F)$ is the minimum number of fractures that can be covered by $\delta$ with the largest diameter; $D_B$ is the fractal dimension of the fracture set. The fractal dimension is shown in Figure 13.

Figure 13 shows that the crack fractal dimension of the sample after failure ranges from 1.270 to 1.340. The fractal dimension of coal crack in fracture zone, disturbance
zone and original rock stress zone shows a downward trend. This shows that with the increasing distance from the roadway, the fracture structure of coal gradually changes from complex to simple, and the failure form gradually changes from tensile-shear composite failure to shear failure.

4.3. Seepage characteristics

Coal seam permeability is an indicator of the difficulty of gas flow in the coal seam (Xu et al. 2006). According to the recorded gas instantaneous flow rate and the set constant osmotic pressure difference, the real-time permeability of coal can be calculated. Coal seam permeability is usually calculated using Darcy’s equation as (Kumar et al. 2018):

\[
K = \frac{2Q_0P_0\mu L}{(P_1^2 - P_2^2)A}
\]

In Equation (14), K is the permeability; \(P_0\) is the atmospheric pressure at the measurement location; \(Q_0\) is the instantaneous seepage flow; \(\mu\) is the gas viscosity coefficient; \(L\) is the length of the sample; \(P_1\) is the gas pressure at the inlet; \(P_2\) is the gas pressure at the outlet; \(A\) is the cross-sectional area of the sample.

The stress-strain-seepage curve of coal in fractured zone is shown in Figure 14. It shows that under the initial state of high confining hydrostatic pressure of kilometre level, the sample does not produce a seepage channel. After roadway excavation, unloading effect caused the samples appeared obvious expansion phenomenon. However, since no transfixion cracks were formed, no effective seepage channels were formed at the beginning of the test, and the permeability was 0. Then the coal seam begins to be mined, and the axial pressure begins to increase. Under the influence of gradually increasing axial pressure, primary cracks and secondary microcracks of the samples begin to develop and connect, and finally form seepage channels. The permeability of the samples increases from 0. When the samples are loaded to the strength limit, the bearing structure of the samples is completely broken, and the cracks are connected to form macroscopic cracks throughout the samples. The strength of the samples decrease sharply and the permeability increase rapidly. After entering the residual strength stage, the seepage channel is mature, the permeability growth rate decreases, and the permeability gradually tends to a fixed value.

Figure 15 shows the stress-strain-seepage curve of coal in disturbance zone. It shows that the coal samples in disturbance zone did not form effective seepage channels under the state of kilometre level hydrostatic pressure and during the unloading process of roadway excavation. The permeability of D1 sample increased exponentially in the early stage of strength drop. However, the permeability growth rate of sample D2 fluctuates, and the permeability increases exponentially when loading to the residual strength stage. As shown in Figure 15(b), the post peak stress-strain curve of D2 sample fluctuates, which is speculated to be caused by the dislocation and slip adjustment of the internal structure in the sample. This is also the reason why the increasing rate of permeability fluctuates. After the sample enters the residual
strength stage, its internal structure gradually stabilizes, the seepage channel is mature, and the permeability tends to a fixed value.

Figure 16 shows the stress-strain-seepage curve of coal in original rock stress zone. It shows that there is no effective seepage channel formed in the original rock stress zone samples in the early stage of the experiment. The permeability of N1 increases sharply at the stage of plastic deformation to the peak strength, and decreases sharply to 0 after the peak strength. It is speculated that there are some original pores and cracks which are not connected with each other in the sample. Under loading, they are connected with each other to form a temporary seepage channel. However, after loading to the peak strength of the sample, the internal entity bearing structure is suddenly destroyed, blocking the seepage channel, so the permeability drops sharply. In actual roadway excavation engineering, a sudden permeability-enhancing effect will cause a large amount of

**Figure 14.** Stress-strain-seepage curve of the coal samples in fracture zone.
gas in the coal seam to flow into the roadway, causing gas disasters. Therefore, when excavating coal seam roadways, the gas concentration at the excavation face should be monitored at all times. Until it enters the residual stage, with the increase of the time of the force and the downward movement of the pressure head of the test machine, the secondary penetrating cracks develop and further open, and then the seepage channel is formed again. The final permeability is very small. Due to the limited accuracy of the airflow sensor used in the experiment, it is not sensitive to the weak permeability changes of the surrounding rock in the original rock stress zone. Therefore, the seepage curve of the coal samples in original rock stress zone is jagged.

Figure 15. Stress-strain-seepage curve of the coal samples in disturbance zone (Figure 15(a) shows the stress-strain-seepage curve of the D1 coal sample, Figure 15(b) shows the stress-strain-seepage curve of the D2 coal sample).

There are two main differences in seepage characteristics of coal samples under three stress paths: (1) Permeability. The peak permeability of coal samples in different zones are sorted from the largest to the smallest as the excavation fracture zone,
disturbance zone, and the original rock stress zone. (2) Permeability increasing nodes. The time sequence of effective seepage channel formation of coal samples in different zones is fracture zone, disturbance zone and original rock stress zone.

4.4. Disaster prevention

Combined with the above conclusions, we can give some suggestions on the prevention of coal mine disasters. During roadway excavation and coal mining, pay attention to the increase of surrounding rock cracks and permeability caused by unloading rebound and abutment pressure, which will lead to gas emission overrun. The gas concentration should be monitored at all times. If necessary, adopt gas extraction technology extract coal seam gas in advance. The surrounding rock in the fracture zone, which is disturbed by the superimposition of roadway excavation and coal mining, has the lowest strength and is prone to roof and side fall accidents. The roadway should be inspected regularly, and the surrounding rock with roof falling and rib spalling risk should be reinforced in time. Advance support should be carried out in the roadway in front of the working face.

Figure 16. Stress-strain-seepage curve of the coal samples in original rock stress zone.
5. Conclusions

Gas disaster is the most frequent and serious disaster in coal mine. In order to prevent gas disasters, based on the geological conditions of the No. 12 mine of the China Pingdingshan Mining Group, the mechanical seepage experiments of coal under the loading path of roadway excavation and coal mining were carried out. The experimental result shows that:

The coal in fracture zone is most strongly affected by the roadway excavation. The rapid unloading of confining pressure caused by roadway excavation led to the expansion of coal samples in fracture zone, and the coal sample strength was the lowest. The coal samples formed effective permeability before the peak strength, and the peak permeability was the largest; Affected by roadway excavation, some small damage developed inside the coal samples in disturbance zone, but they were still in elastic state and basically maintained the original strength. The coal samples formed effective permeability after the peak strength; The coal samples in original rock stress zone were not affected by the roadway excavation. They formed effective permeability in the residual strength stage, and the peak permeability was the smallest. With the increasing distance from the roadway, the fractal dimension of coal crack shows a decreasing trend, and the failure mode changes from complex tensile-shear composite failure to shear failure.

Disclosure statement

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Disclaimers

The authors declare that they have no competing interests.

Data availability statement

The data used and generated in this study is available from the corresponding author upon reasonable request.

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