Coal Permeability Study for Gas Disaster Control under Stress Paths of Three Mining Layouts

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Abstract

Combined with underground engineering practice of gas disaster control, the permeability evolution of coal under mechanical characteristics of three mining layouts is studied. According to the abutment pressure distribution of three mining layouts (protective coal seam, top-coal caving and non-pillar mining), the seepage experiment of gas-containing coal under stress paths of three mining layouts is implemented with a self-developed triaxial seepage device. The results show that the permeability variation of coal under three mining layouts is different, the relationship is revealed between the stress state and the permeability changes of coal. The research results will provide some basic theories for the technology of coal and gas simultaneous extraction as well as gas disaster control in the exploiting area of underground coal mines.

Key Words: Three Mining Layouts, Mechanical Characteristics, Stress Path, Permeability, Coal Mining

1. Introduction

During the process of underground coal mining, disasters caused by coal and gas outburst often bring about the substantial casualties and damage. When mining coal, the instability and destruction of coal is formed with mining, and the permeability characteristics of coal is also dynamically changed, which is one of the reasons leading to gas-containing coal or rock dynamic disasters [1]. Therefore, in order to better reflect the gas migration during underground mining of coal, the mining-induced stress and the seepage change are studied, the intrinsic characteristics are further revealed, and some basic theories are then provided for the technology of coal and gas simultaneous extraction as well as gas disaster control in the exploiting area of underground coal mines.

Since 1856, Darcy’s law was put forward by Darcy, the permeability of rock has been studied as a hotspot by various engineering fields. Due to the permeability changes of coal are influenced by comprehensive factors [2], which are closely associated with fracture of coal [3], but also with stress, pore pressure, coal matrix shrinkage/expansion and other factors [4–7], many scholars carried out a large number of theoretical and experimental research.

Gray [8] firstly established the permeability model under the influence of stress and deformation of adsorption on coal pore. The relationship among permeability, coal porosity and stress was also studied [9]. Furthermore, permeability change regularity of lignite was obtained by Jasinge D [10] under swelling and stress change of coal, the results showed a negative exponential relationship between effective stress and carbon dioxide permeability.
In China, Shining Zhou academicians of China University of Mining and Technology (Beijing) firstly set up an independent system of coal seam gas flow theory, and established the determination method of permeability coefficient of coal seam and the experiment method of gas pressure in coal seam based on previous theoretical research [11]. Under two-dimensional stress state, permeability test of many small coal samples was carried out [11], and two influencing factors of permeability were obtained: gas pressure and confining pressure.

The effect of temperature and external pressure on permeability of coal has been extensively studied [12–15]. With a true triaxial test system, permeability characteristics of briquette coal under triaxial stress were studied [16] to make up for the deficiencies of quasi triaxial stress in the past. Through coal permeability test and microstructure analysis, a research was carried out to investigate the hard-to-drain problem. The permeability test was conducted by using two different apparatus. The testing methods of coal permeability under different triaxial conditions were discussed [17]. On the basis of Klingberg effect, many studies [18–20] regarding the gas seepage characteristics of coal seam have been performed. Under constant effective stress, methane permeability of five coal samples was measured and the linear relations between methane permeability and the reciprocal of mean gas pressure were observed [21]. The permeability evolution during deformation of raw coal was investigated [22]. The relationship between the anisotropic properties of fractured rock and the coupled effect of seepage and stress was investigated, a seepage-stress cross-coupling anisotropic model was proposed, and the influence of principal orientations of joint sets on anisotropic properties of rock was analyzed [23]. The seepage experiment of typical gas-containing coal was conducted in coal and gas outburst prone coal seam, and the gas permeability in the full stress-strain process was obtained [24]. The permeability variation of gas-containing coal under different stress paths was studied, and the permeability was calculated [25]. Liu et al. [13] studied the deformation and permeability variation of gas-containing coal during the unloading process of confining pressure. The permeability characteristics of layered natural coal were studied under different loading and unloading conditions [26,27], and the evolution characteristics of mining-enhanced permeability were obtained in deeper gas-containing coal seam.

Previous research had focused more on the basic research of coal permeability properties, and ignored the change of mining stress and fracture development induced by mining. This paper is focused on the seepage experimental study of gas-containing coal under stress paths of different mining layouts. The permeability variation of raw and briquette coal is studied under loading and unloading stress paths of three mining layouts (protective coal seam mining, top-coal caving mining and non-pillar mining) to reveal the relationship between stress state and permeability of coal.

2. Experimental Methods

2.1 Experimental Equipment

The quasi triaxial seepage equipment of gas-containing coal is developed by China University of Mining and Technology (Beijing). The instrument is shown in Figure 1 and 2. The instrument mainly consists of loading system, gas supply system, temperature control system, data acquisition system, three-shaft gripper and their auxiliary systems. The main performance parameters include confining pressure 0–20 MPa, accuracy ±0.1 MPa; gas pressure 0–5 MPa, accuracy ±0.1 MPa; axial compression 0–2000 KN, accuracy ±0.02 KN; maximum constant temperature at 60 °C; specimen φ25 mm × 100 mm, φ50 mm × 100 mm, φ75 mm × 100 mm for size.

2.2 Coal Sample Preparation

The tested coal was taken from the 28408 working face of Guandi coal mine in Shanxi Province of China. The preparation process of coal specimens is as follows: firstly, according to the sampling standard, large piece of hard coal samples from stope were immediately encapsulated and transported to the laboratory, then processed into U50 mm × 100 mm raw coal sample by drilling in a clockwise direction. Secondly, according to the sampling standard, the small lumps of coal removed from the fresh coal wall were immediately encapsulated and transported to the laboratory, then processed into U50 mm × 100 mm raw coal sample by drilling in a clockwise direction. Secondly, according to the sampling standard, the small lumps of coal removed from the fresh coal wall were immediately encapsulated, delivered to the laboratory, then ground by a muller. Coal dust between 60 and 80 mesh was got with a sample sieve, and then blended with pure water to make standard cylindrical briquette with a size of U50 mm × 100 mm. Af-
ter drying for at least 24 h in an oven (under constant temperature at 80 °C), the qualified coal samples were made. The processed coal samples are shown in Figure 3 (Guandi 1, Guandi 2, Guandi 3 for the raw coal sample, 1, 2, 3, 4, 5, 6 for the briquette coal).

2.3 Principles of Experiment

With the development of modern mining techniques, high production and high efficiency in coal mining exploration, safety mining and green mining are emphasized. Now synthetically considering coal mining efficiency, mining safety and environment effect, the fluid-solid coupling seepage experiment of gas-containing coal is performed with loading and unloading stress paths of three typical working layouts or methods of coal mining, namely, pressure relief mining of protective coal seam, single working face mining of top-coal caving and stress superposition mining of non-pillar mining [28].
The distribution of supporting stress along with the advancing working face under three mining layouts are as follows: affected by the advancing working face, the supporting stress in front of working face will increase from original rock stress to the peak point, after which the supporting stress begins to decline, and the horizontal stress reduces with the change of supporting stress. The process reflects the true stress conditions during the mining process of coal and rock. The initial stress state of coal and rock is in a Quasi-hydrostatic pressure, which is destroyed by underground mining. Therefore, with the advancing working face, the vertical supporting stress in front of the working face will gradually increase to peak, and a stress concentrated area will be formed, then the coal and rock is damaged and accelerated into unloading state. The supporting pressure will constantly reduce until single pressure residual strength is formed in coal wall, and the horizontal stress will be also reduced.

The loading and unloading stress paths of experiment is based on theory of stress paths under three mining layouts, which was proposed [28]. (that is: the peaks \( \sigma_2 = \sigma_3 = \frac{1}{3\alpha} \sigma_1 \) \((\alpha = 2.0, 2.5, 3.0)\), the curve reversal points of central section of pressurization district \( \sigma_2 = \sigma_3 = \frac{2}{5} \sigma_1 \).)

The hypothesis of steady-state method is that the gas flow through coal is in accordance with Darcy’s law. In the experiment, the inlet gas pressure of three-shaft gripe is constant, the outlet is linked with the atmosphere. The pressure differential of import and export is unchanged. Under this condition, by measuring the velocity of gas within a certain time, the permeability of coal sample is calculated on the basis of Darcy’s law, as given in Eq. (1) [11].

\[
K = \frac{2q\mu L}{A(p_1^2 - p_2^2)}
\]  

where, \( K \) is the permeability, \( \text{md} \); \( q \): seepage discharge, \( \text{cm}^3/\text{s} \); \( p_0 \): measurement point atmospheric pressure, \( \text{MPa} \); \( \mu \): gas viscosity coefficient, \( \text{MPa}\cdot\text{s} \); \( L \): sample length, cm; \( A \): cross-sectional area of specimen, \( \text{cm}^2 \); \( p_1 \): imported gas pressure, \( \text{MPa} \); \( p_2 \): exported gas pressure, \( \text{MPa} \).

2.4 Methods

According to the distribution of supporting and horizontal stress of coal and rock in front of the working face under three mining layouts, the quasi-triaxial loading-unloading seepage experiment is performed with axial pressure instead of supporting stress, and confining pressure instead of horizontal stress. The stress path with the advancing working face is simulated by increasing axial stress in definite ratio, and decreasing the confining pressure, according to the corresponding ratio in a fixed position of supporting and horizontal stress.

On account of different mining conditions of working face, the loading and unloading stress path under non-pillar mining is used in Guandi 1, top-coal mining in Guandi 2, protective coal mining in Guandi 3. The whole process of seepage experiment is divided into three stages: the initial hydrostatic pressure seepage stage, the first loading-unloading seepage stage and the second loading-unloading seepage stage. The scheme of loading-unloading seepage experiment is as follows:

(1) The stage of applying pressure to the initial hydrostatic pressure:

\[
\sigma_1 = \sigma_2 = \sigma_3 = \gamma H
\]  

(2) The bearing load of coal and rock before instability and failure:
\( \sigma_1 = \alpha \gamma H \)  

where, the stress concentration coefficients \( \alpha \) are 2, 2.5, 3 under protective coal mining, top-coal mining, non-pillar mining; \( \gamma \) is the bulk density, kN/m\(^3\); \( H \) is the buried depth, m.

(3) \( \sigma_1 \) is increased from \( \gamma H \) to \( \alpha \gamma H \), \( \sigma_2 = \sigma_3 \) (the horizontal stress), the whole process of seepage experiment is divided into two stages:

1. The first loading-unloading seepage stage: \( \sigma_2 = \frac{2}{5} \sigma_1 \);

2. The second loading-unloading seepage stage: \( \sigma_2 = \sigma_3 = \frac{1}{5\alpha} \sigma_1 \).

The above loading-unloading programme is based on the supporting stress evolution of coal and rock in front of the working face, which is obtained after the analysis of stress change in front of the working face under different mining layouts. It reflects the real change of stress path in front of the working face.

In Eq. (3), \( \alpha \) denotes the difference of supporting peak stress under different mining layouts and the impact of different mining layouts on the mechanical characteristics of coal in front of the working face. However, \( H \) denotes the impact of different mining depth on the mechanical characteristics of coal in front of the working face.

The 28408 working face of Guandi mine is in the depth of 264–425 m. Because the coal sample is taken from the coal seam in the depth of 360 meters, the depth \( H \) is set as 360 m, the hydrostatic pressure in this location is \( \sigma_1 = \sigma_2 = \sigma_3 = \gamma H = 9 \) MPa.

The loading-unloading stress path under non-pillar mining is as follow:

\[
\sigma_{\text{min}} = \begin{cases} 
\{ \text{the first seepage stage:} \\
\sigma_1 = 1.5\gamma H = 13.5 \text{MPa, } \sigma_2 = \sigma_3 = \frac{2}{5} \sigma_1 = 5.4 \text{MPa} \\
\{ \text{the second seepage stage:} \\
\sigma_1 = \alpha \gamma H = 3 \times 9 = 27 \text{MPa, } \sigma_2 = \sigma_3 = \frac{1}{5\alpha} \sigma_1 = 1.8 \text{MPa} 
\end{cases}
\]

The loading-unloading stress path under top-coal mining is as follow:

\[
\sigma_{\text{min}} = \begin{cases} 
\{ \text{the first seepage stage:} \\
\sigma_1 = 1.5\gamma H = 13.5 \text{MPa, } \sigma_2 = \sigma_3 = \frac{2}{5} \sigma_1 = 5.4 \text{MPa} \\
\{ \text{the second seepage stage:} \\
\sigma_1 = \alpha \gamma H = 2 \times 9 = 18 \text{MPa, } \sigma_2 = \sigma_3 = \frac{1}{5\alpha} \sigma_1 = 1.8 \text{MPa} 
\end{cases}
\]

The loading-unloading stress path under protective coal mining is as follow:

\[
\sigma_{\text{min}} = \begin{cases} 
\{ \text{the first seepage stage:} \\
\sigma_1 = 1.5\gamma H = 13.5 \text{MPa, } \sigma_2 = \sigma_3 = \frac{2}{5} \sigma_1 = 5.4 \text{MPa} \\
\{ \text{the second seepage stage:} \\
\sigma_1 = \alpha \gamma H = 2.5 \times 9 = 22.5 \text{MPa, } \sigma_2 = \sigma_3 = \frac{1}{5\alpha} \sigma_1 = 1.8 \text{MPa} 
\end{cases}
\]

The specific experimental processes are shown in Table 1. The experimental processes are implemented by controlling the loading rate. In order to meet the load requirements of the experimental equipment, the axial pressure units is converted to kN. The specific test steps are as follows: (1) The initial hydrostatic pressure seepage stage: Increase the axial pressure to 9 MPa, keep the loading rate at 1.5 MPa/min; at the same time increase the confining pressure to 9 MPa, keep the loading rate at 3 MPa/min; the loading ratio of two loading ways is 1:1. (2) The first loading-unloading seepage stage: The loading-unloading paths under non-pillar mining, top-coal mining and protective coal mining are the same, increase the axial pressure to 13.5 MPa, which is loaded to the hydrostatic pressure of 1.5 times, keep the loading rate at 3 MPa/min; while unload the confining pressure to 5.4 MPa, keep the unloading rate at 1.2 MPa/min. (3) The second loading-unloading seepage stage: in the loading-unloading path under non-pillar mining, increase the axial pressure to 27 MPa, keep the loading rate at 3 MPa/min; meanwhile, the confining pressure is unloaded to 1.2 MPa at the rate of 1 MPa/min; in the loading-unloading path under top-coal mining, increase the axial pressure to 22.5 MPa, keep the loading rate at 3 MPa/min; meanwhile, the confining pressure is unloaded to 1.2 MPa at the rate of 1.2 MPa/min; in the loading-unloading path under protective coal mining, increase the axial pressure to 18 MPa, keep the loading rate at 3 MPa/min; meanwhile, the confining pressure is unloaded to 1.2
MPa at the rate of 3 MPa/min. During the whole experiment, the coal sample is filled with gas, and the constant pressure is 1.2 MPa. The loading scheme is shown in Figure 4 [28].

3. Results and Analysis

3.1 Raw Coal Sample

The permeability test experiment of raw sample from Guandi mine was carried out under constant temperature of 25 °C, and the inlet gas pressure is maintained at 1 Mpa. The experiment data under the loading and unloading process is shown in Table 2.

According to the experiment data, the permeability-axial pressure curve of loading and unloading stress path under three mining layouts is shown in Figures 5–7.

It can be seen from Figure 5 that at the quasi-hydrostatic pressure stage under the stress path of non-pillar mining, the permeability coefficient of coal sample has been reduced at a slower rate, because the increasing effective stress around coal makes the micro-hole of coal closed. In the first loading and unloading process, the permeability of coal sample still declines slowly. In the second loading and unloading process, the initial permeability of coal sample shows a slowly increasing trend with the increase of axial and confining pressure. When the confining pressure is unloaded, the growing rate of permeability become bigger. The unloaded confining pressure plays a leading role in the change of permeability coefficient of coal sample. The axial pressure is loaded to the theoretical value of 27.3 MPa, the coal sample is still not damaged. When the axial pressure is loaded to 28.8 MPa under the loading rate of 3 MPa/min, the specimen is damaged and the permeability of coal sample is growing rapidly. The peak of axial pressure is 28.8 MPa and the quasi-hydrostatic pressure is set as 9

Table 1. Processes of loading and unloading tests under three mining layouts

<table>
<thead>
<tr>
<th>Exploitation mode</th>
<th>Initial hydrostatic pressure seepage stage</th>
<th>First loading-unloading seepage stage</th>
<th>Second loading-unloading seepage stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\sigma_1 = \sigma_2 = \sigma_3)</td>
<td>(\sigma_1)</td>
<td>(\sigma_1)</td>
</tr>
<tr>
<td>Non-pillar mining</td>
<td>9 MPa</td>
<td>13.5 MPa</td>
<td>27 MPa</td>
</tr>
<tr>
<td>Top-coal mining</td>
<td>9 MPa</td>
<td>13.5 MPa</td>
<td>22.5 MPa</td>
</tr>
<tr>
<td>Protective coal mining</td>
<td>9 MPa</td>
<td>13.5 MPa</td>
<td>18 MPa</td>
</tr>
</tbody>
</table>

Table 2. Experiment data under loading and unloading process

<table>
<thead>
<tr>
<th>Exploitation mode</th>
<th>Sampling places</th>
<th>Length (m)</th>
<th>Area (10^{-4} m²)</th>
<th>Axial pressure range (MPa)</th>
<th>Permeability range (10^{-4} md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-pillar mining</td>
<td>Guandi 1</td>
<td>0.102</td>
<td>19.8</td>
<td>0-28.86</td>
<td>2.493-10.51</td>
</tr>
<tr>
<td>Top-coal mining</td>
<td>Guandi 2</td>
<td>0.099</td>
<td>19.8</td>
<td>0-25.53</td>
<td>0.195-6.173</td>
</tr>
<tr>
<td>Protective coal mining</td>
<td>Guandi 3</td>
<td>0.102</td>
<td>19.7</td>
<td>0-23.48</td>
<td>0.129-0.958</td>
</tr>
</tbody>
</table>

Figure 4. Schematic view of loading and unloading stress paths under three mining layouts.
MPa, so the stress concentration coefficient of peak abutment pressure is 3.17.

Figure 6 shows that at the quasi-hydrostatic pressure stage under the stress path of top-coal mining, the initial permeability of coal is relatively high, and the permeability decreases rapidly when the axial pressure and confining pressure increase. In the first loading and unloading process, there is a small fluctuation in a certain scope on the permeability of coal. In the second loading and unloading process, after the axial pressure is loaded to 13.6 MPa, the permeability of coal sample shows a slowly increasing trend. When the axial pressure is loaded to the theoretical value of 23.8 Mpa, the coal sample is still not damaged. When the axial pressure is continued to load to 25.3 MPa, with maintaining the constant confining pressure of 1.2 MPa, the specimen is damaged and the permeability of coal sample is growing rapidly. The peak of axial pressure under stress path of top-coal mining is 25.3 MPa, the quasi-hydrostatic pressure is set as 9 MPa, so the stress concentration coefficient of peak abutment pressure is 2.78.

Figure 7 shows that at the quasi-hydrostatic pressure stage under the stress path of protective coal mining, the internal closure pore fissure leads to a sharp decrease of permeability because of the rapid rise of confining pressure. The permeability of coal does not start to rise in the first and second loading and unloading phase, but begins to slowly rise at the end of the second loading and unloading phase, this may be because the unloading rate of confining pressure is too fast and the internal damage of coal under the initial confining pressure is not reversible, which belongs to the plastic deformation. When the axial pressure is loaded to the theoretical value of 18.3 Mpa, the coal sample is still not damaged. When the axial pressure is continued to load to 23 MPa at the rate of 3 MPa/min with maintaining the constant confining pressure of 1.2 MPa, the specimen is damaged and the permeability is rapidly growing. The peak of axial pressure under the stress path of top-coal mining is 23 MPa, the quasi-hydrostatic pressure is set as 9 MPa, so the stress concentration coefficient of peak abutment pressure is 2.78.

Figure 5. Permeability - axial pressure curve under stress path of non-pillar mining.

Figure 6. Permeability - axial pressure curve under stress path of top-coal mining.
The stress concentration coefficient of peak abutment pressure of three loading scheme is more than the theoretical value, it may be because the load confining pressure equipment is not accurate enough.

### 3.2 Briquette Coal Sample

The permeability test experiment of briquette coal was carried out for 1 and 4th coal sample, 2 and 5th coal sample, 3 and 6th coal sample under the constant temperature of 25 °C, and the inlet gas pressure is maintained at 1 Mpa. The experiment data under the loading and unloading stress paths of three mining layouts is shown in Table 3.

According to the experiment data, the permeability axial pressure change curve of coal sample is shown in Figure 8. It can be seen that the permeability changing trend of coal under different mining paths is basically similar. In the original rock stress phase $\delta_1 = \delta_2 = \delta_3 = 9$ MPa, there is no outside stress disturbance and the permeability is in a stable state. In the first loading and unloading phase, the permeability of coal is not stable, which is higher than in the original rock stress phase.

In the second loading and unloading phase, there is a significant growth of permeability, especially approaching the peak stress where the permeability has a sudden increase. This may be due to the increase of inelastic deformation of coal and the expansion of pore and fissure.

### 4. Discussion

Due to the permeability changes of coal are subject to comprehensive factors [2], previous research had focused on exploring the law between the permeability and influencing factors, many of triaxial or quasi three-axis permeability experiments were carried out on the basis of basic mechanics theory of coal and rock, and the variation regularity of permeability was studied during the failure and damage process of coal and rock. This is only a study on the basis of the intrinsic mechanical behavior of coal and rock. That cannot represent the mechanical behavior of coal and rock during the process of underground mining.

Therefore, in order to better reflect the gas migration and control gas disaster during underground coal mining,
the mining-induced stress and the seepage change caused by mining are studied. It is also the innovation of this paper to study the seepage regularity under the mechanical behavior of three mining layouts. On the basis of the mining-induced mechanical behavior in coal seams under different mining layouts [28], the seepage experiment of gas-containing coal has been implemented by simulating the distribution of supporting and horizontal stress of coal and rock in front of the working face under three mining layouts.

Based on the distribution of abutment pressure in Figure 9, the results of this experiment is shown in Figures 5–8. The distribution of coal permeability can be divided into slow growth stage, growth stage and rapid growth stage in the advancing process of working face. The loading-unloading stress path under non-pillar mining is shown as an example in Figure 9, and there are a similar trend under top-coal mining and protective coal mining. The first loading and unloading phase in Figures 5–8 is the AB phase in Figure 9, the second loading and unloading phase in Figures 5–8 is the BD phase in Figure 9, but the axial

![Figure 8. Permeability - axial pressure curve under stress path of three mining layouts ((a) and (b) under stress path of non-pillar mining, (c) and (d) under stress path of top-coal mining, (e) and (f) under stress path of protective coal mining).](image-url)
pressure peak point C of coal sample and the loading point of each stage is different under stress paths of non-pillar mining, top-coal mining and protective coal mining. In Figure 9, point C is the stress peak point of coal sample failure, P is the quasi-hydrostatic pressure, R’c and D is the residual stress, EF represents a section of coal in front of the working face. When the working face advances to EF, the stress path point loaded on the EF is displayed on the L line, the blue point represents the loading point before the stress peak point and the red point represents the stress path point after the stress peak point.

According to the mining-induced mechanical behavior, the confining pressure is unloaded, and the volumetric strain is less than 0, the deformation of coal is mainly the volume expansion deformation. With the axial stress loading, the permeability under non-pillar mining is the highest and the permeability under protective coal mining is the lowest, because the volume expansion and deformation of coal under non-pillar mining is relatively larger, and under protective coal mining is the smallest.

As to raw coal, during the process of axial and confining pressure loaded to the quasi-hydrostatic pressure at the same rate, the permeability coefficient of coal sample has been reduced at a slower rate, because the increasing effective stress around coal makes the micro-hole of coal closed, and the reduction rate under non-pillar mining is smaller than under protective coal mining and top-coal mining.

In the second loading and unloading phase, because the unloading confining pressure plays a dominant role on the permeability coefficient change of coal sample, the permeability shows a slow upward trend under non-pillar mining and top-coal mining, but the permeability under protective coal mining begins to increase at the end of loading and unloading process. After the stress peak, the coal samples have been damaged, the permeability of three schemes is greatly increasing.

Underground gas drainage is one of the important technologies for controlling dynamic disasters of coal and rock. In this study, the permeability evolution under mechanical characteristics of three mining layouts is shown. On the whole, the effect of gas drainage is more ideal, especially after the peak stress points near the working face. The peak stress of non-pillar mining is the largest, and the mining-induced pressure-relief range is also the widest. Therefore, the permeability evolution study of gas-containing coal under stress paths of three mining layouts is helpful for the accurate prediction of gas emission, conducive to the optimization of gas drainage, also helpful to study the mechanism of coal and gas outburst disaster from the perspective of permeability.

Because the number of experiments is not large enough, the research only reveals the qualitative relationship between the stress state and the permeability changes of coal under mining-induced mechanical characteristics, and it needs more experiments for the quantitative analysis. The quantitative study is also not carried out between the permeability variation of coal and the advancing distance of the working face.

5. Conclusions

(1) The overall trend of permeability curves have similar
variation rules under stress paths of three mining layouts, but the characteristics of permeability are different for different phases of stress paths under three mining layouts.

(2) In the whole process, the permeability is the highest under non-pillar mining whereas the permeability is the lowest under protective coal mining. As to raw coal in the process of quasi-hydrostatic pressure, the permeability under stress paths of three mining layouts decreases with increasing initial axial pressure, the reduction rate is smaller under non-pillar mining than under protective coal and top-coal mining. As to briquette coal, the permeability maintains in a stable value. In the second loading and unloading phase, the permeability shows a slow upward trend during the loading and unloading process of non-pillar mining and top-coal mining, but the permeability under protective coal mining begins to increase at the end of loading and unloading process. After the peak stress, coal samples have been damaged and the permeability of three schemes increases greatly.

(3) The distribution of coal permeability is divided into slow growth stage, growth stage and rapid growth stage in the advancing process of working face. The effect of gas drainage is more ideal, especially after the peak stress points near the working face. The peak stress of non-pillar mining is the largest and the mining-induced pressure-relief range is also the widest. With the advancing of working face, the supporting stress of protective coal mining in front of the working face is the smallest, the mining safety factor is higher and the growth rate of permeability is also very obvious.

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