Experimental Research on Dynamic Variation of Permeability and Porosity of Low-Rank Inert-Rich Coal Under Stresses

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ABSTRACT: The effective stress variation can cause permeability change during coalbed methane (CBM) production. At the same time, macerals have an important influence on the stress sensitivity of coal reservoirs. To investigate the low-rank inert-rich coal permeability dynamic response to effective stress during the production of CBM, eight low-rank coal samples were collected from the Huanglong coalfield, China, and the dynamic changes in helium permeability and porosity were tested under conditions in which the effective stress changed from 0, 15, to 0 MPa. Then, the permeability dynamic change, stress sensitivity control mechanism, and their influence on the development of low-rank CBM are discussed. The results show that with the increase in effective stress, the permeability and porosity of coal samples decrease in the form of negative exponents. During the process of effective stress increase, the permeability variation of low-rank coal includes three stages: rapid loss stage (0−3 MPa), slow loss stage (3−9 MPa), and stable loss stage (>9 MPa). In the process of effective stress reduction, the irreversible damage rate linearly increases. Fracture permeability is easier to recover than pore permeability during pressure relief. Coal macerals have an important influence on the initial permeability and stress sensitivity of low-rank coal. The ratio of vitrinite to inertinite of low-rank coal is positively correlated with initial permeability, but negatively correlated with the permeability loss rate and the fracture compression coefficient ($C_f$). $C_f$ shows a decreasing trend of the negative index with an increase in effective stress and is highly positively correlated with the average permeability loss rate. The porosity−permeability index model and the permeability−effective stress-sensitive model of low-rank coal under effective stress are established. Research shows that inertinite is helpful to improve the stress sensitivity of low-rank coal. Accordingly, to reduce the damage of coal reservoir permeability, the pressure should steadily change either in the process of fracturing or drainage.

1. INTRODUCTION

Coalbed methane (CBM) has become an important clean energy resource.1 Permeability in coal is more complicated than that in conventional gas reservoirs.2 The permeability of coal reservoirs is the key factor that affects the adsorption/desorption, diffusion, and seepage of CBM.3 To a certain extent, this permeability determines the gas production capacity and development efficiency of CBM. The original coal reservoir permeability is affected by a number of factors, such as in situ stress, geological structure, coal burial depth, coal structure, lithofacies characteristics, coal quality, coal rank, pore structure, temperature, water saturation, and natural fracture development degree.5−9 Coal reservoirs are classified as pore-fracture-type reservoirs. Compared with conventional oil and gas reservoirs, these are porous medium reservoirs with low porosity and low permeability, low strength, large deformation, and strong stress sensitivity.2,4,8 The permeability of low-rank coal is anisotropic under varying effective stresses, and a good coupling effect between aperture, porosity, connectivity, and permeability is detected.10

In the CBM development process, the permeability of a coal reservoir dynamically changes under the influence of effective stress, matrix shrinkage, and gas slippage.11−13 The specific...
Figure 1. Structure outline and sampling location map. (a) Location of Ordos Basin on the map of China, (b) general location of the Huanglong coalfield of Ordos Basin on a tectonic division map, and (c) sources of coal samples used in this study.

performance is as follows: in the early stage of drainage and depressurization, the reservoir pressure gradually decreases (leading to an increase in effective stress), the fracture pore closes, and the coal reservoir permeability decreases with an increase in effective stress. In the gas production stage, the coal reservoir permeability increases with an increase in coal matrix shrinkage after gas desorption.\(^{14,15}\)

A considerable number of experimental studies have demonstrated that the permeability and porosity of coal reservoirs considerably vary under different stress states, and the permeability and porosity of coal have an exponentially decreasing relationship with an increase in effective stress.\(^{16−19}\) The permeability test results of medium- and high-rank coals under a confining pressure show that the low confining pressure condition (<10 MPa) is more stress sensitive than the high confining pressure condition (>10 MPa); the higher the moisture content in coal, the worse the development of original fracture, the higher the experimental temperature, and the greater the permeability loss rate.\(^{19,20}\) The stress sensitivity of coal rock is also influenced by its own properties (e.g., coal maturity, mineral, microstructure, mechanical parameters, compression property, and carbon content), and the stress sensitivities of different rank coal reservoirs considerably vary.\(^{21−25}\) Meng and Li demonstrated that the stress sensitivity coefficient decreased with an increase in vitrinite reflectivity.\(^{26}\) Bao et al. indicated that the smaller the elastic modulus and the greater the fracture compressibility coefficient, the greater the stress sensitivity of low-rank coal.\(^{24}\) The stress sensitivity of low-rank coal with fractures is greater than that of coal without fracture, and the stress sensitivity in the Huolinhe area (low-rank coal) relative to gas production is greater than that in the Fanzhuang area (high-rank coal). The stress sensitivity of permeability of low-rank coal increased after a nitrogen injection and sealing, and the decrease in permeability with increasing effective stress was greater than that of untreated samples.\(^{25}\) The in situ X-CT images indicate that the reason for irreversible permeability is that the microcleats cannot recover after the stress loading.\(^{25}\) The experimental study of loading pressure and release pressure shows that the irreversible permeability loss rate is 36.04−82.31% (average, 60.33%) for medium- and high-rank coals; this is equivalent to that of low-permeability argillaceous sandstone (average, 60%), indicating that the elastic and plastic deformations of coal simultaneously occur under stress.\(^{20,27,28}\)

A number of investigations have been conducted on the change mechanism of effective stress on the permeability of medium- and high-rank coals; however, studies related to the permeability variation of low-rank coals are limited, particularly for understanding the change in permeability in the methane production process of low-rank inert-rich coal.\(^{9,20,25,29}\) The condensation of lower-rank coal is considerably lower than that of higher-rank coal, resulting in more macrofractures and fractures in the former.\(^{30}\) The change mechanism of the effective stress in medium- and high-rank coal permeability, however, differs from that of low-rank coal. In recent years, medium- and high-rank CBMs have been exploited in China on a large scale, and industrial gas flows have also been derived from low-rank CBM wells in the southwest and east edge of Ordos Basin.\(^{29,31}\) China has 1.47 billion m\(^3\) of low-rank CBM resources with great development potential.\(^{32}\) Compared with medium- and high-rank coals, however, low-rank coal is characterized by high porosity and low mechanical strength, and reservoir sensitivity is stronger in the drainage process.\(^{24}\) Moreover, fracturing, workover, and other operations in the CBM development process lead to reservoir pressure fluctuation, which causes repeated pressurization and effective stress pressure relief that can eventually damage the permeability of a coal reservoir. With the rapid development of low-rank CBM in China, the low permeability of low-rank coal reservoirs has become a key factor restricting the high production of low-rank CBM well.\(^{25,33}\) The content of inertinite is generally high in the Jurassic low-rank CBM-rich area in Northwest China.\(^{34}\) The differences in the physical properties between inertinite and vitrinite result in different permeabilities and stress sensitivities. Therefore, studying the stress sensitivity of low-rank inert-rich
coal is of great significance for the development of low-rank coalbed methane in Northwest China.

In view of the above-mentioned reasons, based on the actual development of low-rank CBM in the southwest edge of Ordos Basin, eight groups of low-rank coal samples are collected for permeability and porosity effective stress sensitivity experiments on a coal reservoir. The purpose of this study is to demonstrate the dynamic change rule and identify the influencing factors of the permeability of low-rank inert-rich coal reservoirs at varying effective stresses of 0–15 MPa, establish the relationship model of porosity—permeability and the sensitive model of permeability—effective stress, and provide suggestions for the development of low-rank CBM in the southwest edge of Ordos Basin.

2. COAL SAMPLES AND EXPERIMENTAL METHOD

2.1. Coal Samples and Preparation. The Huanglong Jurassic coalfield is located in the southwest margin of Ordos Basin, which is one of the key areas devoted to the development of CBM in China (Figure 1a). The central and western parts of the Huanglong Jurassic coalfield are located in the Weibei uplift on the southern margin of Ordos Basin, and the eastern area is located at the southern end of Shanbei Slope (Figure 1b). In this work, the coal samples are collected from eight coal mines in the Huanglong Jurassic coalfield, Shaanxi Province. From east to west, these are Huangling No. 2 coal mine, Cuijiagou coal mine, Liushicun coal mine, Weniapao coal mine, Dafosi coal mine, Xiaogou coal mine, Hujiahe coal mine, and Guojihe coal mine (Figure 1c). The coal-bearing stratum of the coalfield is the Yan’an formation of Middle Jurassic, with a total of 3–8 coal seams. The maximum thickness of a single coal seam is 43.87 m, and the buried depth is generally 300–1200 m. In this work, the coal samples are taken from Nos. 2 and 4 coal seams (Table 1).

The collected fresh coal samples from coal mines are first cut into coal pillars 25 mm in diameter and 20–50 mm in length using a wire cutting machine; both ends of the pillars are smoothed with fine sandpaper to obtain smooth cylindrical coal blocks. In accord with the Chinese Petroleum Industry Standard SY/T 5358-2002 (2002), the coal pillars are oven-dried at 80 °C for 24 h, cooled, and thereafter stored for future use in a dryer at a constant temperature of 25 °C. The coal samples remaining after the pillars are cut are used for coal petrology analysis and proximate analysis. The coal vitrinite average reflectance and coal composition are according to ISO 7404.3-1994 and ISO 7404.5-1994, respectively. Also, the coal proximate analysis is performed according to the Chinese National Standard GB/T212-2008 (2008).38

2.2. Measurement of Overburden Porosity and Permeability. The permeability and porosity of coal samples under different confining pressures are measured by a CMS-300 automatic helium porosity/permeability analyzer (American Rock Core Company) (Figure 2). The maximum buried depth of the Jurassic coal seam in the Huanglong coalfield does not exceed 1500 m; hence, the effective maximum confining pressure is set to 15 MPa. The average measured temperature of the coal reservoir in the study area is 25 °C, which is used as the experimental temperature. Helium has certain advantages: it has strong diffusion ability, it is nontoxic, and it causes no damage to the sample. In view of these, helium is selected as the test gas in this study.

The non-steady-state pressure-drop method employed in the experiment is in accord with the Chinese Petroleum Industry Standard SY/T 6385-1999 (1999). During the experimentation, the pressure difference between the core gripper ends is set to a constant value (0.7 MPa). This study follows the previous research methods of simulating effective stress by changing the confining pressure (load pressure and relief pressure). The original permeability and porosity of the coal sample are measured without confining pressure. Second, by adjusting the constant flow pump, the confining pressure is gradually increased to obtain the effective stresses of 3, 6, 9, 12, and 15 MPa and then the effective stress is decreased to 12, 9, 6, 3, and 0 MPa to complete the loading-

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Table 1. Sample Information

| sample ID | R<sub>m</sub> (%) | coal seam | initial porosity (%) | initial permeability (mD) | V | I | E | M | M<sub>ad</sub> | A<sub>ad</sub> | V<sub>ad</sub> | F<sub>cad</sub> |
|-----------|-----------------|-----------|----------------------|-----------------------|---|---|---|---|---|---|---|---|
| GJH1      | 0.50            | 2         | 8.92                 | 10.96                 | 69.30 | 28.00 | 0.90 | 1.80 | 7.86 | 6.60 | 42.26 | 49.69 |
| LSC2      | 0.52            | 4<sup>−2</sup> | 5.60                 | 1.230                 | 36.70 | 48.40 | 0.90 | 14.00 | 6.32 | 24.21 | 41.11 | 41.81 |
| CJG3      | 0.55            | 4<sup>−2</sup> | 7.40                 | 1.601                 | 37.70 | 56.80 | 0.60 | 4.90 | 5.12 | 17.33 | 41.15 | 46.17 |
| XG5       | 0.61            | 4         | 6.80                 | 0.083                 | 13.50 | 79.00 | 2.20 | 5.30 | 6.38 | 8.47 | 30.84 | 59.26 |
| WJF6      | 0.66            | 4         | 4.50                 | 0.007                 | 18.30 | 78.10 | 0.50 | 3.10 | 6.34 | 8.68 | 31.11 | 58.92 |
| HJ7H      | 0.68            | 4         | 9.10                 | 0.422                 | 14.50 | 79.30 | 0.90 | 5.30 | 6.00 | 5.07 | 31.45 | 61.17 |
| DFS8      | 0.65            | 4         | 6.00                 | 0.581                 | 15.90 | 71.50 | 1.00 | 11.60 | 5.30 | 17.41 | 35.24 | 50.65 |
| HL9       | 0.75            | 2         | 4.30                 | 0.124                 | 56.80 | 37.90 | 1.10 | 4.20 | 3.78 | 12.01 | 34.76 | 55.24 |
| average   | 0.62            |           | 6.58                 | 1.876                 | 32.84 | 59.88 | 1.01 | 6.28 | 5.89 | 12.47 | 35.99 | 52.86 |

*R<sub>m</sub>*, mean random vitrinite reflectance; V, vitrinite; I, inertinite; E, exinite; M, mineral; M<sub>ad</sub>, moisture content on an air-dried basis; A<sub>ad</sub>, ash yield on an air-dried basis; V<sub>ad</sub>, volatile yield on a dry ash-free basis; and F<sub>cad</sub>, fixed carbon content on an air-dried basis.
and-relief cycle. Finally, the porosity and permeability measurement test results under the corresponding effective stress conditions are obtained. To eliminate the influence of pressurization time, bulk volume change, and gas slippage, each pressure point is balanced for 30 min, and the interval between two pressure points is adjusted to 30 s.9

3. RESULTS AND DISCUSSION

3.1. Composition of Coal. Based on the test results (Table 1), it is observed that the degree of coal metamorphism in the study area is relatively low and gradually increases from west to east, and the average random reflectance of vitrinite is between 0.50 and 0.75%. The average contents of vitrinite, inertinite, and exinite, which are typical inert-rich coals, are 32.84, 59.88, and 1.01%, respectively. The coal-forming environment under a dry oxidation environment is the key factor in the formation of high-inertinite coal in the Huanglong coalfield.34 The coal quality in the study area is characterized by low amounts of ash, sulfur, and phosphorus and the coal species belong to long-flame coal, noncaking coal, and weak-

Figure 3. Relationship of permeability with $R_o$ (a), the ratio of vitrinite to inertinite (b), and porosity (c).

Figure 4. Relationship between porosity and permeability of coal and effective stress.
with that the permeability of low-rank coal is negatively correlated
bars are added to some
that of the other samples due to the development of
permeability.41,42
assumed that the higher the porosity, the higher the
conventional oil and gas reservoir evaluations, it is generally
developed than inertinite, so the permeability is positively
increase of coal metamorphism, resulting in the closure of
vitrinite to inertinite and porosity (Figure 3b,c). This is
covered, which is conducive to the reformation of coal
structure, and coal structure has little e

Because the compaction of low-rank coal increases with the
vitrinite content, the higher the initial permeability. However,

The test results show that the initial porosity and permeability of low-
rank coal samples in the Huanglong coalfield are relatively high (Table 1): the initial porosity and permeability ranged between
4.30 and 9.10% and 0.007 and 10.960 mD, respectively. The

ting curve, respectively. It can be observed from Figure 4 that

tting curve, respectively; the blue dot and blue line represent

4.3. Relationship between Effective Stress and Permeability

In Figure 4, the red dot and red line represent the permeability test value and the permeability vs effective stress fitting curve, respectively; the blue dot and blue line represent the porosity test value and the porosity vs. effective stress fitting curve, respectively. It can be observed from Figure 4 that with an increase in effective stress, the porosity and permeability of eight samples decrease, and the opposite trend is observed when the effective stress decreases. In the

where \( \sigma \) is the effective stress (MPa), \( \alpha \) is the stress sensitivity coefficient that depends on the initial permeability, and \( \beta \) is the stress sensitivity index, which reflects the change range in permeability with effective stress.

Through fitting, it is found that there is also a negative exponential relationship between porosity and effective stress (Figure 4), which can also be expressed by eq 1. The fitting results are summarized in Table 2. Based on the list, the relationship between porosity \((R^2 > 0.8250)\), permeability \((R^2 > 0.8717)\), and stress can be well fitted using eq 1. It is also observed that different coal samples vary in stress sensitivity coefficients and indices. The stress sensitivity coefficient and sensitivity index of porosity and permeability in the pressure

process of effective stress reduction, the permeability and porosity at the same pressure point cannot be completely restored, that is, the values of permeability and porosity in the process of pressure reduction are smaller than those in the process of pressure increase.

Seidle et al. proposed a negative exponential formula for permeability with an increase in effective stress, as follows43

\[
k = \sigma e^{\alpha \sigma}
\]

3.2. Porosity and Permeability Variations

The test results show that the initial porosity and permeability of low-
rank coal samples in the Huanglong coalfield are relatively high (Table 1): the initial porosity and permeability ranged between
4.30 and 9.10% and 0.007 and 10.960 mD, respectively. The
initial permeability of a coal matrix is controlled by many
factors, such as coal rank, porosity, coal structure, and macerals.41 In this work, the coal samples are of primary
structure, and coal structure has little e

However, the permeability of GJH1 is obviously higher than that of the other samples due to the development of microfractures. To show potential data errors, standard error bars are added to some figures. It can be seen from Figure 3 that the permeability of low-rank coal is negatively correlated with \( R_\alpha \) (Figure 3a), but positively correlated with the ratio of vitrinite to inertinite and porosity (Figure 3b,c). This is

because the compaction of low-rank coal increases with the increase of coal metamorphism, resulting in the closure of microfractures. Generally, the fractures of vitrinite are more developed than inertinite, so the permeability is positively correlated with the ratio of vitrinite to inertinite. In conventional oil and gas reservoir evaluations, it is generally assumed that the higher the porosity, the higher the permeability.31,42

In Figure 4, the red dot and red line represent the permeability test value and the permeability vs effective stress fitting curve, respectively; the blue dot and blue line represent the porosity test value and the porosity vs. effective stress fitting curve, respectively. It can be observed from Figure 4 that with an increase in effective stress, the porosity and permeability of eight samples decrease, and the opposite trend is observed when the effective stress decreases. In the

Figure 5. Relationship between \( \alpha \) with \( R_\alpha \) (a), the ratio of vitrinite to inertinite (b), and initial permeability (c).

| Sample ID | \( \bar{R}_\alpha \) (%) | Load Relief | Permeability Relief |
|-----------|---------------------|-------------|---------------------|
| GJH1      | 0.50                | 8.6102      | 0.019               |
| LSC2      | 0.52                | 5.3521      | 0.012               |
| CJG3      | 0.55                | 7.2174      | 0.014               |
| XG4       | 0.61                | 6.5203      | 0.026               |
| WF5       | 0.66                | 4.4838      | 0.040               |
| HJH6      | 0.68                | 8.9757      | 0.016               |
| DFS7      | 0.65                | 5.5817      | 0.034               |
| HL8       | 0.75                | 4.1066      | 0.029               |

Table 2. Relationship between Porosity and Permeability of Coal and Effective Stress
0.7%, the permeability (Figure 3b) and stress sensitivity coefficient (Figure 5b) will decrease rapidly. The stress sensitivity of low-rank coal permeability is highly positively correlated with the initial permeability (Figure 5c), indicating that the higher the initial permeability, the stronger the stress sensitivity. It can be seen from the error bars that the GJH1 sample has high errors of initial permeability (Figure 3) and the permeability stress sensitivity coefficient (Figure 5) due to the existence of microfractures. At the same time, the coal metamorphism degree of the GJH1 sample is low and the vitrinite content is high, which macropores and fractures are developed and is beneficial to the formation of high-permeability coal reservoir, so it has little influence on the overall conclusion of this paper.

4. DISCUSSION

4.1. Stress Sensitivity Analysis of Permeability in Low-Rank Coal. Generally, the permeability loss rate (PLR) and irreversible permeability damage rate are employed to analyze the stress sensitivity of coal reservoirs.\(^8,20\) The PLR reflects the percentage of permeability loss of coal reservoir under the influence of effective stress. The PLR is calculated by eq 2\(^10,20\)

\[
\text{PLR} = \left( 1 - \frac{k_i}{k_o} \right) \times 100\% 
\]

where \(k_o\) is the permeability of the coal sample at the initial stress point (mD); \(k_i\) is the permeability of the coal sample when the pressure increases to \(P_i\) (mD).

Figure 6 indicates that the PLR of low-rank coal increases with an increase in effective stress. When the effective stress increases to 15 MPa, the PLR is 93.62–97.39% (average, 95.52%) (Table 3) and the permeability is basically lost. As a result of the development of low-rank coal pores and fractures, the increase in effective stress leads to the deformation of pores and fractures as well as the closure of effective permeability pores and fracture channels, thereby decreasing permeability. With the increase in effective stress, the microfractures and macropores perform a key function in coal permeability close, and the permeability rapidly decreases. As the effective stress continues to increase, the mesopores and transition pores close, and the decline rate of permeability gradually slows down until it becomes stable. Based on the loss range of permeability during the increase in effective stress, the permeability loss can be divided into three stages (Figure 6a). In the first stage (0–3 MPa), rapid permeability loss occurs. In this stage, the stress sensitivity of the coal sample is extremely strong, and the permeability is rapidly lost in the process of stress increase. The average PLR is 66.71%, and the permeability loss rate gradient is 22.24%/MPa. In the second stage (3–9 MPa), gradual permeability loss occurs. In this stage, the stress sensitivity of coal and rock is medium, and the permeability loss is slow in the process of stress increase. The average PLR is 24.14%, and the PLR gradient is 4.02%/MPa. In the third stage (>9 MPa), the permeability loss is stable. The permeability loss rate slightly changes with the increase in stress. Figure 6b shows that the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage. This is because the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage. This is because the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage. This is because the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage. This is because the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage. This is because the ratio of vitrinite to inertinite is highly negatively correlated with PLR in the rapid permeability loss stage.

The irreversible permeability damage rate reflects the fact that the permeability of the coal reservoir cannot be restored as the effective stress increases from \(P_i\) to the maximum stress value and thereafter decreases to \(P_f\). The irreversible permeability damage rate (IPDR) is calculated by eq 3\(^9,10\)

\[
\text{IPDR} = \left( 1 - \frac{k_i}{k_i'} \right) \times 100\% 
\]

where \(k_i\) is the permeability of the coal sample when the stress is \(P_i\) (mD); \(k_i'\) is the permeability of the sample after the stress returns to \(P_i\) (mD).

Figure 7a shows that the IPDR gradually increases with a decrease in effective stress during the pressure relief process. When the effective stress decreases to 0 MPa, the IPDR is 26.61–84.70%, with an average of 55.36% (Table 3). The IPDRs of samples at the same pressure point are relatively different, and the IPDR curves intersect, indicating that the

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**Table 3. Permeability Stress Sensitivity Parameters of a Low-Rank Coal Reservoir**

| Sample ID | 3 MPa | 9 MPa | 15 MPa | 0 MPa | 3 MPa | 9 MPa |
|-----------|-------|-------|--------|-------|-------|-------|
| GJH1      | 53.21 | 86.50 | 95.82  | 43.74 | 40.12 | 17.38 |
| LSC2      | 68.37 | 92.06 | 97.39  | 58.30 | 42.46 | 30.81 |
| CJG3      | 69.27 | 90.32 | 93.62  | 26.61 | 20.20 | 10.91 |
| XG4       | 74.58 | 93.01 | 95.66  | 83.13 | 58.29 | 22.41 |
| WJP5      | 67.14 | 91.14 | 97.16  | 84.70 | 74.40 | 46.60 |
| HJH6      | 66.83 | 91.75 | 94.82  | 30.59 | 38.06 | 16.25 |
| DFS7      | 73.40 | 90.98 | 94.85  | 39.62 | 29.85 | 20.04 |
| HL8       | 60.89 | 91.05 | 94.84  | 76.21 | 68.04 | 28.83 |
| Average   | 66.71 | 90.85 | 95.52  | 55.36 | 46.43 | 24.15 |

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**Figure 6.** Relationship between permeability loss rate with effective stress (a) and the ratio of vitrinite to inertinite (b).
IPDR is controlled by the effective stress and affected by its own physical properties. With an increase in effective stress, the elastic deformation of coal microfracture and pore is accompanied by plastic deformation. In this process, because of the difference in the mechanical properties between pores and fractures, plastic deformation occurs successively in microcracks, macropores, mesopores, and micropores as the stress increases. It will also be affected, however, by the shape of pores and fractures, and other factors. The plastic deformation of the coal sample causes damage to the pore and microfracture. Eventually, this can lead to the permanent loss of pore and fissure permeability. In the process of pressure return, therefore, the permeability cannot be completely restored.\(^{20}\) Figure 7b shows that the IPDR of low-rank coal has a negative linear correlation with the initial porosity of coal, that is, the higher the original porosity, the better the permeability recovery of coal reservoir in the process of pressure return. Coal porosity includes the initial porosity and fracture porosity (or fracture space); fracture porosity is the main channel for CBM seepage.\(^4\) It can therefore be inferred that the higher the porosity of low-rank coal, the higher the permeability recovery of the coal sample causes damage to the pore and microfracture. The microfractures mainly undergo elastic deformation as the stress increases, and the microfracture connectivity recovers well after the pressure decreases. The low porosity of coal, however, indicates that the porosity is mainly composed of pore porosity, which easily deforms with compression, and the recovery of pore connectivity is weak after the pressure decreases. Finally, the higher the original porosity, the better the permeability recovery.

### 4.2. Effect of Dynamic Variation of Porosity on Permeability

Coal reservoir is a type of dual-pore system medium that includes a matrix pore system and a fracture pore system.\(^4,12\) The more the fracture pores in the coal reservoir, the greater the fracture porosity, resulting in higher permeability of the coal reservoir.\(^9\) The permeability of low-rank coal is not only controlled by macropores and fractures but also depends on the development of mesopores and micropores.\(^4,15\) It can be seen from Figure 8a that porosity is positively correlated with permeability during pressure loading and relief. Through mathematical fitting, it is found that the permeability of low-rank coal decreases exponentially with the porosity in the process of dynamic change of effective stress (Figure 8b). The relationship model between porosity and the permeability index is therefore established as follows

\[
k = a e^{b\phi}
\]

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**Table 4. Relationship between Coal Porosity and Permeability**

| sample ID | load a   | b   | Rsquared |
|-----------|---------|-----|----------|
| GJH1      | 0.0001  | 1.2978 | 0.9606 |
| LSC2      | 8 \times 10^{-9} | 3.4265 | 0.9028 |
| CJG3      | 1 \times 10^{-6} | 1.8778 | 0.9842 |
| XG4       | 8 \times 10^{-6} | 1.3328 | 0.9757 |
| WJP5      | 3 \times 10^{-6} | 1.7090 | 0.9917 |
| HJH6      | 2 \times 10^{-7} | 1.5778 | 0.9819 |
| DFS7      | 0.0006  | 1.1388 | 0.9859 |
| HL8       | 4 \times 10^{-5} | 1.9061 | 0.9239 |

| relief a  | b   | Rsquared |
|-----------|-----|----------|
| 1 \times 10^{-5} | 1.6786 | 0.9262 |
| 4 \times 10^{-12} | 11.0690 | 0.9733 |
| 2 \times 10^{-8} | 4.1037 | 0.9643 |
| 6 \times 10^{-12} | 3.2365 | 0.9708 |
| 2 \times 10^{-9} | 4.3525 | 0.9616 |
| 6 \times 10^{-12} | 3.0161 | 0.9419 |
| 2 \times 10^{-3} | 5.0112 | 0.9964 |
| 0.0001 | 1.4387 | 0.9615 |

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**Figure 7.** Relationship of IPDR with effective stress (a) and initial porosity (b).

**Figure 8.** Relationship between porosity variation (a) and permeability (b).
where $k$ is the permeability under the influence of effective stress (mD), $\varphi$ is the porosity under the influence of effective stress (%), $a$ is the porosity sensitivity coefficient, and $b$ is the porosity sensitivity index.

The relationship model of porosity and permeability is employed to fit the eight test results. The results show that the fitting degree ($R^2$) is greater than 0.90 (Table 4). The porosity sensitivity index ($b$) of pressure load and relief is $1.1388 - 3.4265$ and $1.0525 - 11.0690$, respectively. When the initial porosity is more than 5%, the porosity sensitivity index of the pressure relief process is greater than that of the pressure load process. When the initial porosity is less than 5% (WJP5 and HL8), the porosity sensitivity index of the pressure relief process is less than that of the pressure load process. The results of microfracture observations show that when the porosity is greater than 5%, the microfracture is developed to a greater extent in coal samples, and the microfracture development is poor when the porosity is less than 5%. This shows that the more developed the fracture porosity, the easier it is to recover the permeability of low-rank coal in the process of pressure relief. However, the pore channels of low-porosity coal samples produce plastic deformation during the increase of effective stress, and the permeability recovery is poor.

### Table 5. Compressibility of Coal Cores at Different Effective Stresses

| effective stress (MPa) | GJH1 | LSC2 | CJG3 | XG4 | WJP5 | HJH6 | DFS7 | HL8 |
|------------------------|------|-----|------|-----|------|------|------|-----|
| 3                      | 0.0877 | 0.1313 | 0.1490 | 0.1760 | 0.1355 | 0.1484 | 0.1615 | 0.1301 |
| 6                      | 0.0759 | 0.1022 | 0.0975 | 0.1127 | 0.1009 | 0.0990 | 0.1030 | 0.0918 |
| 9                      | 0.0719 | 0.0912 | 0.0801 | 0.0898 | 0.0897 | 0.0836 | 0.0826 | 0.0796 |
| 12                     | 0.0695 | 0.0858 | 0.0707 | 0.0785 | 0.0837 | 0.0750 | 0.0730 | 0.0733 |
| 15                     | 0.0683 | 0.0826 | 0.0655 | 0.0718 | 0.0802 | 0.0702 | 0.0669 | 0.0696 |
| average value           | 0.0747 | 0.0990 | 0.0926 | 0.1058 | 0.0980 | 0.0952 | 0.0974 | 0.0889 |

### Figure 9. Relationship between $(\sigma - \sigma_0)$ and $C_F$

### Figure 10. Relationship of average $C_F$ with $R_o$ (a), initial porosity (b), ratio of vitrinite to inertinite (c), and average PLR (d).

\[ y = -0.1015x + 0.1024 \quad R^2 = 0.8674 \]

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4.3. Control Mechanism of Low-Rank Coal Permeability. An increase in effective stress leads to the compression of pore fissures, causing a decrease in permeability. Seidle et al.\textsuperscript{43} proposed the fracture compression coefficient, which is widely used in the industry to characterize the dynamic change in permeability with effective stress.\textsuperscript{2,9,15,46} The coefficient can reflect the stress sensitivity of coal reservoir permeability during the development of CBM.\textsuperscript{9} The fracture compression coefficient ($C_f$) is expressed as follows:\textsuperscript{2,19}

$$-\frac{1}{3} \ln \left( \frac{k}{k_0} \right) = C_f (\sigma - \sigma_0)$$

where $C_f$ is the fracture compression coefficient (MPa$^{-1}$), $k_0$ is the initial permeability (mD), $\sigma_0$ is the initial effective stress (MPa), and $k$ is the corresponding permeability when the effect stress is $\sigma$ (mD). The fracture compression coefficient can therefore be determined by fitting the slope of the curve with the abscissa ($\sigma=\sigma_0$) and ordinate ($-1/3 \ln (k/k_0)$) in the coordinate system.\textsuperscript{2,19}

$$C_f = \frac{\ln (k/k_0)}{-3(\sigma - \sigma_0)}$$

The $C_f$ value can be calculated by substituting permeability values at different pressure differences into the linear fitting formula. Based on the list in Table 5, the $C_f$ value of low-rank coal is between 0.0747 and 1.057 MPa$^{-1}$ (average, 0.0939 MPa$^{-1}$). The $C_f$ value of low-rank coal is significantly higher than that of high-rank coal (0.0382–0.0714 MPa$^{-1}$; average: 0.0537 MPa$^{-1}$).\textsuperscript{8} In low-rank coal, pores, fractures, loose structure, and low mechanical strength develop, resulting in easy compaction of primary pores of the coal matrix. However, the $C_f$ value of low-rank coal is found to be higher than that of high-rank coal; hence, low-rank coal is easily compressed than medium- and high-rank coals. Although the initial permeability of each sample is different, the average compression coefficient of each sample is between 0.08 and 0.10 MPa$^{-1}$, and the change in the average $C_f$ is small. Figure 9 shows that the $C_f$ value of low-rank coal exhibits a decreasing trend in the negative index with an increase in the pressure difference, which is consistent with the changing trend in medium- and high-rank coals.\textsuperscript{19,47} With the increase in the effective stress difference, the $C_f$ value of pore and fracture compression gradually decreases, and finally tends to become stable.

The $C_f$ value of coal is affected by various factors, such as the type of gas tested, maceral, porosity gas pressure, initial permeability, and temperature.\textsuperscript{4,16,30,40} From Figure 10a,b, it can be seen that the $C_f$ of low-rank coal has a parabolic relationship with $R_s$ and porosity. The $C_f$ reaches its maximum value near the first coalification jump point ($R_s$ 0.60%). This is because the physical and chemical properties of the coal are significantly different before and after the coalification jump, so the $C_f$ trend reverses. The research in Section 4.2 shows that the fracture compression mechanism is obviously different before and after the initial porosity of 5%, so the trend of compression coefficient changes around 0.5% porosity. Figure 10c shows that the $C_f$ is highly negatively correlated with the ratio of vitrinite to inertinite. The reason is that with an increase of inertinite content, the fracture of coal decreases, which leads to the low initial permeability. In addition, the PLR decreases with an increase of the ratio of vitrinite to inertinite (Figure 6b), indicating that the stress sensitivity of pore is greater than that of fractures. Figure 10d shows that the average $C_f$ of coal samples is highly positively correlated with the average PLR, which shows that $C_f$ of coal has an important control effect on PLR.

4.4. Insight into CBM Development. During CBM development, the permeability of coal reservoirs is affected by the variation of in situ stress and reservoir pressure. If the total stress remains unchanged, the dynamic change in permeability is essentially the increase in effective stress caused by the decrease in reservoir pressure.\textsuperscript{79} Based on the results of the permeability–stress test, the average permeability, average permeability loss rate, and average irreversible permeability loss rate of all coal samples under different effective stress conditions are calculated (Figure 11). It can be observed from Figure 11 that with an increase in effective stress, the permeability (Figure 11a), permeability loss rate (Figure 11b), and irreversible permeability loss rate (Figure 11c) exhibit negative exponential decreasing trend, logarithmic increasing trend, and linear decreasing trend, respectively; all have a high degree of fit. The relationship between the average of permeability parameters and effective stress is consistent with that between the single coal sample and effective stress.

Based on the above three permeability–stress sensitivity parameters, the stress sensitivity model of low-rank coal is established (Figure 12). In the early water pumping stage, the pressure in the coal reservoir decreases, thereby increasing the effective stress and decreasing the permeability. Excluding other permeability factors, it is found that the higher the coal reservoir pressure, the higher the pressure reduction range, the greater the effective stress increase range, and the greater the damage to the coal reservoir permeability. Taking the Binchang block of the Huanglong coalfield as an example, the exploration and development depth of CBM is 473.58–1007.6 m (average, 718.60 m) and the coal reservoir pressure is 0.83–10.04 MPa (average, 4.93 MPa). According to the CBM production experience in the United States, the borehole pressure can decrease to approximately 0.7 MPa at most. The effective stress increase range during the CBM drainage is
An increase in effective stress. Some parts of the pores and fractures, however, are destroyed as the effective stress increases, and the coal reservoir permeability cannot be effectively recovered after the effective stress reduction. The IPLR of low-rank coal increases linearly with a decrease in effective stress (Figure 12). This means that the IPLR is mainly controlled by the effective stress difference. The increase and decrease in repeated coal reservoir stress will lead to the plastic deformation of coal reservoir pores and fractures and will always cause irreversible permeability damage. Moreover, the IPLR of low-rank coal has a positive correlation with permeability sensitivity, indicating that the stronger the permeability stress sensitivity, the stronger the irreversible permeability damage caused by pressure fluctuation. The pump injection pressure should therefore be kept stable in the process of low-rank coal fracturing, especially in areas with high-permeability sensitivity. The operation in DFS-67 well started in the Huanglong coalfield in December 2014; it was repaired thrice between April and December 2015. With the increase in workover times, the daily gas production of the CBM well gradually decreased to 10 m$^3$/day; its operation was forced to shut down for secondary stimulation measures. In the initial drainage stage of CBM, the interruption of drainage will also cause the deposition of fracturing sand and coal powder, block the formation channel, or cause stuck pumps. The low-rank wells (especially low-permeability reservoirs) must therefore maintain continuous production, avoid production interruption, and reduce reservoir pressure fluctuations caused by discontinuous drainage. If workover and other operations are necessary, then the interruption time of production should be shortened as much as possible to reduce the effective stress difference and permeability damage of coal reservoirs.

5. CONCLUSIONS

This study revealed the change law of permeability and porosity of low-rank inert-rich coal in the range of effective stress from 0, 15, to 0 MPa, and discussed the control mechanism of effective stress in the permeability of low-rank coal. The following conclusions were drawn:

1. The initial permeability of low-rank coal has a negative exponential relationship with $R_o$, but has a positive exponential relationship with the ratio of vitrinite to inertinite and initial porosity. Both permeability and porosity show a negative exponential relationship with the increase in effective stress. The sensitivity coefficient and sensitivity index of porosity and permeability in the increased stage of effective stress are higher than those in the decreased stage.

2. On increasing the effective stress of low-rank coal, the permeability loss rate can be divided into three stages: rapid loss stage (0–3 MPa), slow loss stage (3–9 MPa), and stable loss stage (>9 MPa). The influence of coal macerals on the PLR of low-rank coal is obvious, and the ratio of vitrinite to inertinite is negatively correlated with PLR. During the pressure relief process, the irreversible permeability loss rate gradually increases as the effective stress decreases. The higher the initial porosity, the lower the irreversible permeability loss rate of the coal reservoir during the pressure relief process.

3. The porosity–permeability index relationship model of low-rank coal under effective stress is established. The more developed the fracture porosity, the easier it is to...
recover the permeability of low-rank coal in the process of pressure relief. The $C_P$ value of low-rank coal is 0.0747–0.1057 (average: 0.0939), which is significantly higher than that of medium- and high-rank coal. $C_P$ decreases negatively with the effective stress and the ratio of vitrinite to inertinite but has a highly positive correlation with the average PLR.

The permeability—effective stress-sensitive model of low-rank coal is established. The stress sensitivity of low-rank inert-rich coal is high; hence, the pressure should be kept stable in the fracturing process and production process. The irreversible permeability damage rate of low-rank coal is mainly dependent on the effective stress difference and permeability stress sensitivity; hence, the interruption time of CBM production should be reduced.

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**Notes**

The authors declare no competing financial interest.

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