Permeability experiments with overburden pressure of coal measure reservoirs and numerical analysis of its stress sensitivity: A case study of Qinshui Basin, China

Dan Zhou¹, Kunjie Li², Haichao Wang³, Yi Jin⁴, Zhongliang Ru⁵, Xiaokai Xu⁶, Caifang Wu¹ and Kuo Jian²,⁶

Abstract
The commingled exploitation of coal measure reservoirs has become the main trend in the development of coalbed methane (CBM) in the central and southern Qinshui Basin. In fact, the porosity and permeability (P&P) of coal measure reservoirs and the evolution of their stress sensitivity are a focus of the basic theory of commingling exploitation. In this study, the coal measure reservoirs in this area are taken as the research object, and the P&P characteristics and stress sensitivity of coal measure reservoirs under different overburden pressure conditions were investigated by P&P experiments on coal, sandstone, and mudstone. The results show that the P&P decreases as a negative exponential function with the increase in effective stress, and the initial porosity and initial permeability of coal are both significantly higher than those of mudstone and sandstone. Besides, the permeability stress sensitivity coefficients of coal, mudstone, and sandstone all decline with a wavy trend with the increase in effective stress. Coal is more sensitive to stress than mudstone and sandstone in the medium and low pressure stages (P<5 MPa), while...
their stress sensitivities tend to become equal in the medium and high pressure stages ($P_c > 5 \text{ MPa}$). Since the type of coal rich in organic matter is soft rock, it is more susceptible to damage and deformation in the medium and low pressure state ($P_c < 5 \text{ MPa}$). In contrast, sandstone and mudstone contain more brittle minerals such as cuttings, quartz, and clay minerals, which are, in general, more resistant to deformation, and are less sensitive than coal at the medium and low pressure stages. Finally, a stress sensitivity model based on the Langmuir equation was proposed in this study. With the aid of the model, the stress sensitivities of porosity and permeability of coal, sandstone, and mudstone were analyzed accurately.

**Keywords**
Qinshui Basin, coal measure reservoir, porosity, permeability, stress sensitivity

### Introduction

Coal measures in China are rich in unconventional energy resources, with the amount of coalbed methane (CBM), shale gas, and tight sandstone gas being as high as $60–70 \times 10^{12} \text{ m}^3$ (Cao et al., 2014). Among these resources, tight sandstone gas, which forms in coal measure strata, features close sources and reservoirs as well as short-distance migration and accumulation, while also boasting of abundant gas sources and effective source–reservoir allocation (Guo et al., 2017; Kang et al., 2019; Li et al., 2012). An in-depth study of the coexistence, accumulation, superimposition, and joint exploitation of the three kinds of unconventional coal measure gases is conducive to reducing the cost of exploration and development, increasing the amount of resources that can be recovered by CBM technology, and effectively improving the single-well utilization rate (Liang et al., 2016). This is not only of strategic significance for alleviating the current shortage of natural gas resources and changing the energy structure in the world but is also important for innovations in oil and gas geology and exploration and development (Dai et al., 2014; Qin et al., 2016; Wang et al., 2014; Zou et al., 2019).

Co-exploitation of CBM and tight sandstone gas has been successfully achieved in the Surat Basin in Australia and the Piceance Basin in the United States (Oison et al., 2002). High-yield gas flow has been preliminarily obtained in the Zhengzhuang and Qinyuan blocks of the Qinshui Basin in China (Liang et al., 2014; Qin et al., 2014; Yang et al., 2013). Currently, Qinshui Basin has the largest CBM output and the highest level of CBM exploration and research in China. In 2018, the CBM output reached approximately 3.3 billion m$^3$, accounting for 61% of the total CBM output in China. However, the overall single-well CBM output of the Qinshui Basin is relatively low. In the basin, the coal measure shale generally has a high organic carbon content and large gas generation potential typical of type III kerogen, and the thermal evolution degrees of organic matter are majorly at the peak of gas generation. Moreover, silty interlayers possess superior reservoir performance, a high content of brittle minerals, and good reservoir-forming ability. Gas logging anomalies in sandstone are found in many wells in the basin. In the current situation of limited single-layer CBM exploitation, the joint exploitation of CBM, shale gas, and tight sandstone gas in coal measures is an important measure to promote the single-well output. Shanxi Formation in central and southern Qinshui Basin bears abundant CBM resources that, however, are
difficult to utilize. In recent years, commingling drainage through relevant test wells has been carried out in the Shanxi and Taiyuan Formations, but they failed to achieve a satisfactory effect. The fundamental reason is a lack of deep understanding of the occurrence, distribution, and accumulation laws and patterns of coal measure gases, especially the porosity and permeability (P&P) laws and stress-sensitive characteristics of coal measure reservoirs, which are critical parameters in the commingling drainage of coal measure gases.

In order to realize the efficient co-exploitation of coal measure gases, two basic geological problems must be solved: First, the flow mechanism in multi-layer low-permeability superimposed coal measure reservoirs should be clarified for establishing a multi-layer co-exploitation seepage model. Second, given the different mechanical properties of coal, shale, and tight sandstone, it is necessary to reveal the mechanism of mechanical permeability enhancement of coal measure reservoirs and the evolution of stress sensitivity during the application of commingling fracturing or separate-layer fracturing (Qin et al., 2016). Most scholars believe that low-permeability reservoirs are strongly sensitive to stress (Jiao et al., 2011; Jin et al., 2017; Luo et al., 2009; Wang et al., 2009). Compared with conventional reservoirs, coal reservoirs are characterized by low permeability, low gas saturation, low reservoir pressure, and high water saturation (Jin et al., 2017; Ren et al., 2014), which further complicates the stress sensitivity variations of coal measure reservoirs. Studies by Mckee et al. (1998) revealed that as the burial depth and effective stress of a coal seam increases, the cleat width of the coal seam is reduced, and the permeability of the coal seam also decreases exponentially. Extensive studies have shown that the P&P are closely correlated to stress in coal measure reservoirs. Nevertheless, previous studies focused primarily on the effect of coal matrix shrinkage on permeability enhancement during CBM exploitation, but the permeability characteristics and comprehensive stress sensitivity of multi-layer superimposed coal measure reservoirs are rarely reported. In this study, with coal measure reservoirs in central and southern Qinshui Basin considered to be the research object, the P&P characteristics and stress sensitivity of coal measure reservoirs under different overburden pressure conditions were investigated by means of P&P experiments on coal, tight sandstone, and mudstone. This study provides the novel finding that coal is more sensitive to stress than mudstone and sandstone in the medium- and low-pressure stages ($P_c < 5$ MPa). In addition, the porosity stress sensitivity and permeability stress sensitivity of coal, sandstone, and mudstone are analyzed in depth by building a new stress sensitivity model based on the Langmuir equation. The study is aimed at providing a useful scientific basis for the co-exploitation of coal measure gases.

**Samples and experiments**

The study area lies in central and southern Qinshui Basin. In this area, large faults are developed along the eastern boundary, which play an important role in controlling the evolution of the coal seams in the region. The central fault zone is characterized as a closed fault, which is conducive to CBM accumulation. The area is dominated by a series of wide and gentle secondary folds whose inclination angles generally range $5^\circ$–$15^\circ$, with basically two symmetrical wings. Secondary folds along an axial direction close to SN are mainly developed in the east, while folds with an axial direction of NNE are mainly developed in the west (Figure 1). The coal measure strata in the area under study include the Benxi Formation, Taiyuan Formation, and Shanxi Formation (Figure 2). Among them,
the latter two are the main coal measure strata with an average thickness of approximately 150 m.

Taiyuan Formation ((C₂-P₁) t), which is generally more than 100 m thick, is comprised of gray medium-fine sandstone, gray-black siltstone, mudstone, limestone, and coal seams. In this formation, a total of 8–10 coal seams are developed, among which the No. 15 coal seam in the lower main coal seam is the thickest and most stable one. It is a single seam with a complex structure and is located in the Xiangfen-Qinshui-Jincheng-Changzhi line. In other regions, there are three coal seams separated by sandstone and mudstone, i.e. the No. 9, No. 10, and No. 11 coal seams. Most limestone strata develop from bottom to top. These limestone strata, usually regarded as the immediate roof of the coal seams, are important for the comparative division of coal seams in this formation. Detrital rocks mainly include medium-fine quartz sandstone, detrital quartz sandstone, and siltstone. Besides, 7–28 mudstone strata are uniformly distributed in this formation, with a total thickness of 12–80 m; for a single mudstone stratum, the thickness lies in the range of 0.2–11.5 m and averages 0.7–3.5 m.

Shanxi Formation (P₁s), which is approximately 45 m thick on average, belongs to the coastal delta facies sediment. It is mainly composed of sandstone, sandy mudstone, mudstone, and coal seams. The upper part mainly consists of mudstone, siltstone, and dark grey sandstone, while the lower part primarily consists of dark grey-grayish black mudstone and sandy mudstone. This formation bears 1–4 coal seams, among which the main coal seams are the No. 2 coal seam in the Huoxi Coal Field and the No. 3 coal seam in the Qinshui Coal Field. They are the most important gas-bearing coal seams in this region, and it is found through a comparison that the two seams were formed in the same period. So, they are collectively referred to as the upper main coal seam. In addition, a total of 3–22 mudstone strata are non-uniformly distributed (thicker in the south and east, thinner in the north and

Figure 1. Distribution of sampling sites (modified with reference to Wang et al., 2018).
west) in this formation, with a total thickness of 10–60 m; for a single mudstone stratum, the thickness lies in the range of 0.2–13.5 m and averages 0.7–6.0 m. Moreover, the thick sandstone belt is widely distributed, exhibiting typical river-controlled delta characteristics. The small sandstone body in the south of the basin is generally 10–20 m thick, while the body of sandstone in the Qinyuan-Shizhuang line is over 40 m thick.

The experimental samples come from two blocks of the study area. Among the samples, CP-3\# coal, CP-3\# roof sandstone, and GL-3\# coal and GL-3\# roof mudstone are the coal (anthracite), roof sandstone, and mudstone from the No. 3 main mining coal seam of the Changping Coal Mine (CP) and Gaoliang Coal Mine (GL) in the Shizhuangnan block. LG-9\# coal*, LG-10\# floor mudstone*, AX-2\# floor mudstone*, and AX-2\# roof sandstone* (*represents reference data) are the coal (anthracite), roof and floor sandstone, and mudstone from the No. 2 main mining coal seam and No. 9 and No. 10 coal seams of the Liugou Coal Mine (LG) and Anxin Coal Mine (AX) in the Guxian block.

Figure 2. Synthetical stratum histogram of coal measures strata in Central-South Qinshui Basin (Adapted with permission from the work of Wang et al. (2018).
The degree of development, composition and connectivity of pores and fractures in a reservoir are the key factors that affect the permeability of the reservoir. As can be observed from the SEM images, coal rock in the area contains remarkably developed gas pores, as well as a certain number of moldic pores, intercrystalline pores, dissolution pores, and matrix shrinkage pores (Figure 3(a) to (c)). Besides, micro-fractures are relatively developed, mostly belonging to exogenous fractures. Among them, tensile fractures and shear fractures are the most common, and shear fractures have a smooth surface and extend relatively farther. Usually, two sets of conjugated fractures are developed, indicating that the coal seam has undergone multi-stage structural activity transformation and has a certain connectivity. Sandstone in the area contains various types of pores with extremely irregular shapes, varying sizes, and non-uniformly distributed diameters. They primarily include intragranular dissolution pores, intergranular dissolution pores, clay mineral intercrystalline

Figure 3. SEM images of sample pore and fracture structure. (a) CP-3⁷ coal, gas pore; (b) GL-3⁷ coal, gas pore; (c) LG-9⁷ coal, matrix shrinkage pore; (d) CP-3⁷ roof sandstone, intragranular dissolution pore; (e) CP-3⁷ roof sandstone, clay mineral intercrystalline pore; (f) AX-2⁷ roof sandstone, micro-fracture; (g) GL-3⁷ roof mudstone, organic matter pore; (h) LG-10⁷ floor mudstone, intragranular dissolution pore; (i) AX-2⁷ floor mudstone, micro-fracture.
pores, as well as local micro-fractures, among which poorly connecting intergranular dissolution pores and micro-fractures are dominant (Figure 3(d) to (f)). Shale in the study area contains many intragranular dissolution pores. These pores with micrometer-range diameters and irregular shapes are mostly clay mineral filling dissolution pores developed inside the granules. In addition, there are also a small number of dispersely distributed organic matter pores whose diameters are generally smaller than 1 µm and shapes are relatively smooth. Most of them are round or elliptical (Figure 3(g) to (i)).

In this experiment, according to *The porosity and permeability measurement of core in net confining stress* (SY/T6385-1999), the physical conditions of the P&P of samples under overburden pressure were simulated at room temperature with the aid of the 3H-2000PAGP multifunctional overburden pressure ultra-low-permeability analyzer in Jincheng Campus of the Taiyuan University of Science and Technology. The cylindrical samples were 25 mm in diameter and 50 mm in height, as small cylindrical samples are more sensitive to stress under confining pressure. The overburden pressure of the sample was simulated by applying a confining pressure to the sample; the pore pressure was simulated by the gas pressure in the core of the cylindrical sample; and the effective stress was simulated by the difference between the confining pressure and air pressure. A total of nine confining pressure values, namely 4 MPa, 5.5 MPa, 6 MPa, 7.5 MPa, 8 MPa, 9.5 MPa, 10 MPa, 13 MPa, and 15 MPa, were used in the simulation experiment. To avoid the influence of slippage on sample permeability during the experiment, the pore pressure was designed to remain constant at 440 psi (about 3 MPa). The test gas was helium, and the equilibrium time of each confining pressure value was controlled above 30 min.

**Results and discussion**

**P&P characteristics of coal measure reservoirs**

The P&P of coal measure reservoirs are a key factor that restricts the development of “three gas” resources in coal measures. The results show that the P&P of coal samples, mudstone samples, and sandstone samples all decrease according to a negative exponential function with the increase in effective stress (Figure 4). The relationship can be expressed as follows:

\[
\Phi_i = \Phi_0 \cdot e^{-C_p \cdot p} \\
K_i = K_0 \cdot e^{-\alpha \cdot p}
\]

where \(\Phi_i\) and \(K_i\) are the porosity (%) and permeability (mD) under a given stress, respectively; \(\Phi_0\) and \(K_0\) are the porosity (%) and permeability (mD) under zero initial stress, respectively; \(C_p\) and \(\alpha\) are the reservoir compression coefficient (MPa\(^{-1}\)) and permeability attenuation coefficient (MPa\(^{-1}\)) of the reservoir, respectively; \(p\) is the loaded confining pressure (MPa). The values of parameters \(\Phi_0\), \(K_0\), \(C_p\), and \(\alpha\) can be obtained from the regression analysis equations of P&P and effective stress given in Figure 4.

As shown in Table 1, both porosity and permeability vary exponentially with the effective stress, with the correlation coefficient \(R^2\) being above 0.9 for most samples. The results of the fitting show that the average initial porosity \(\Phi_0\) of the coal samples is 5.25%, while those of mudstone samples and sandstone samples are 1.74% and 1.92%, respectively. The
The average compression coefficient $C_p$ of coal samples is $0.021 \, \text{MPa}^{-1}$, while those of mudstone samples and sandstone samples are $0.025 \, \text{MPa}^{-1}$ and $0.018 \, \text{MPa}^{-1}$, respectively. The average initial permeability $K_0$ of coal samples is $0.20 \, \text{mD}$, while those of mudstone samples and sandstone samples are $0.049 \, \text{mD}$ and $0.014 \, \text{mD}$, respectively. The average

Figure 4. Relationship between porosity ($\phi$), permeability ($K$) and effective stress ($P_c$) (Note: *-data in the figure are quoted from Cheng et al., 2018).
permeability attenuation coefficient $\alpha$ of coal samples is 0.21 MPa$^{-1}$, while those of mudstone samples and sandstone samples are 0.19 MPa$^{-1}$ and 0.22 MPa$^{-1}$, respectively. It can be concluded that in the coal measures of the Qinshui Basin, the initial porosity and initial permeability of coal are significantly higher than those of mudstone and sandstone, whereas the compression coefficient and permeability attenuation coefficient of coal are similar to those of mudstone and sandstone. This is probably because small cylindrical samples are highly sensitive to stress, which makes it difficult to distinguish the stress sensitivities of coal, sandstone, and mudstone. Hence, it is necessary to process the existing data by using the permeability stress sensitivity coefficient or constructing a new stress sensitivity model, to distinguish the stress sensitivities of the three.

### Table 1. Results of exponential fitting between porosity ($\Phi$), permeability ($K$) and effective stress ($P_c$).

| Sample no.         | $C_p$ (MPa$^{-1}$) | $\Phi_0$ (%) | $R^2$ | $\alpha$ (MPa$^{-1}$) | $K_0$ (mD) | $R^2$ |
|--------------------|-------------------|--------------|-------|-----------------------|------------|-------|
| CP-3$^a$ coal      | 0.023             | 4.9475       | 0.9735| 0.240                 | 0.1568     | 0.9701|
| CP-3$^a$ roof sandstone | 0.015         | 1.1758       | 0.9030| 0.268                 | 0.0165     | 0.9380|
| GL-3$^a$ coal      | 0.019             | 5.250        | 0.9829| 0.146                 | 0.166      | 0.9073|
| GL-3$^a$ roof mudstone | 0.013         | 1.8437       | 0.9688| 0.193                 | 0.0458     | 0.9744|
| LG-9$^a$ coal*     | 0.020             | 5.5602       | 0.9362| 0.247                 | 0.2711     | 0.9765|
| LG-10$^a$ floor mudstone* | 0.037      | 1.4727       | 0.8043| 0.169                 | 0.052      | 0.9867|
| AX-2$^a$ floor mudstone* | 0.024     | 1.9168       | 0.9112| 0.214                 | 0.0503     | 0.9669|
| AX-2$^a$ roof sandstone* | 0.021      | 2.6553       | 0.9698| 0.163                 | 0.0119     | 0.9226|

Note: $R^2$: correlation coefficient.

#### Permeability stress sensitivity coefficient

Most scholars held that low-permeability and ultra-low-permeability reservoirs are highly stress sensitive for two reasons. First, rock in low-permeability reservoirs contains high contents of mud and cement and a small pore throat scale (generally smaller than 1 $\mu$m in diameter). After being compressed, the rock undergoes plastic deformation. As a result, the skeleton particles are compacted and become smaller, which leads to the diameter reduction and even closure of pore throat. That is, the rock exhibits high stress sensitivity. Second, from the perspective of seepage theory, when a fluid flows in a low-permeability porous medium, factors such as different pore sizes and different solid-fluid interface interactions result in the existence of different starting pressure gradients in the seepage. The smaller the capillary radius, the larger the starting pressure gradient. When compacted by stress, the low-permeability reservoir experiences a significant reduction in the seepage pore size, resulting in a rapid increase in the starting pressure gradient. Therefore, its permeability shows high stress sensitivity. In fact, in terms of mechanical properties, compared with mudstone and sandstone, coal possesses relatively developed pores and fractures, a smaller elastic modulus, and a greater Poisson’s ratio and gets broken and compressed more easily. This suggests that the stress sensitivity of coal should be quite obvious.
Based on the above analysis, the stress sensitivity coefficient is adopted to analyze the stress sensitivity characteristics of coal, mudstone, and sandstone. The permeability stress sensitivity coefficient $c$ is defined as:

$$c = \frac{K_0}{C_0^1} \frac{\partial K}{\partial p}$$  

where $c$ is the permeability stress sensitivity coefficient (MPa$^{-1}$); $K_0$ is the permeability under zero initial stress (mD); $K$ is the permeability under a given stress (mD); $p$ is the loaded confining pressure (MPa).

As shown in Figure 5, the permeability stress sensitivity coefficients $c$ of coal, mudstone, and sandstone all decrease in a wavy trend with the increase in effective stress $P_c$. The $c$ values of the three reduce notably when $P_c$ is lower than 5 MPa, whereas they only decline slightly when $P_c$ is higher than 5 MPa. Besides, in the medium and low pressure range ($P_c < 5$ MPa), the $c$ values of coal reduce faster than those of roof sandstone and roof mudstone for Changping Coal Mine and Gaoliang Coal Mine, respectively, and the $c$ value of coal also reduces faster than that of floor mudstone for Liugou Coal Mine. In contrast, in the medium and high pressure stages ($P_c > 5$ MPa), this variation law no longer holds, as the $c$ values of all three fluctuate within a very small range. This result indicates that coal is more sensitive to stress than mudstone and sandstone in the medium and low pressure stages ($P_c < 5$ MPa), while their stress sensitivities tend to become equal in the medium and high pressure stages ($P_c > 5$ MPa).

As can be observed from the box diagram of stress sensitivity coefficient $\gamma$ (Figure 6), coal is more sensitive to stress than mudstone and sandstone. In addition, judging from the 50% percentage of the box diagram, sandstone is more sensitive to stress than mudstone overall, as its stress sensitivity coefficient $\gamma$ is more widely distributed than that of mudstone. The box diagram cannot accurately reflect the stress sensitivity characteristics of coal measure reservoirs, and so, further analysis is needed.
Construction and analysis of stress sensitivity model based on the Langmuir equation

To accurately analyze the stress sensitivities of coal, sandstone, and mudstone, a stress sensitivity model based on the Langmuir equation is constructed by taking the relationship between P&P stress damage rates and effective stress into consideration.

The porosity stress damage rate ($D_U$) refers to the percentage of reservoir porosity damage under effective stress, and the permeability stress damage rate ($D_K$) refers to the percentage of reservoir permeability damage under effective stress. The expressions for the two are as follows:

\[
D_U = \frac{U_1 - U}{U_1} \times 100\% \\
D_K = \frac{K_1 - K}{K_1} \times 100\% 
\]

where $U_1$ is the porosity corresponding to the first effective stress point, %; $U$ is the porosity under a certain effective stress, %; $K_1$ is the permeability corresponding to the first effective stress point, mD; $K$ is the permeability under a certain effective stress, mD. As presented in Figure 7, the porosity stress damage rate ($D_\Phi$) and the permeability stress damage rate ($D_K$) both gradually increase with the increase in effective stress and exhibit distinct variation characteristics in two stages. When $P_c < 5$ MPa, both show rapid linear increase. When $P_c > 5$ MPa, both rise at a lower rate and almost level off at the end. Moreover, it can be seen from Figure 7 that the relationship between P&P stress damage rates and effective stress conforms to the Langmuir equation. Thus, the Langmuir equation is adopted to elaborate on the stress sensitivity characteristics of coal measure reservoirs. The expressions are as follows:

\[
D_\Phi = \frac{D_{\Phi,m} \cdot b_\Phi \cdot (P_c - a)}{1 + b_\Phi \cdot (P_c - a)} 
\]
\[ D_K = \frac{D_{K,m} \cdot b_K \cdot (P_c - a)}{1 + b_K \cdot (P_c - a)} \]  \hfill (7)

where \( P_c \) is the effective stress, MPa; \( D_{\Phi} \) is the porosity stress damage rate, \%; \( D_K \) is the permeability stress damage rate, \%; \( D_{\Phi,m} \) and \( D_{K,m} \) are the maximum values of \( D_{\Phi} \) and \( D_K \), respectively, \%; \( a \) is the dimensionless constant \((a \leq P_c)\), namely the effective stress value corresponding to the first pressure point; \( b_{\Phi} \) and \( b_K \) are the dimensionless constants that reflect the sensitivities of porosity and permeability to stress damage, respectively. Equations (8) and (9) can be obtained by transforming equations (6) and (7):

\[ P_c - a = D_{\Phi,m} \cdot \frac{P_c - a}{D_{\Phi}} - \frac{1}{b_{\Phi}} \]  \hfill (8)

\[ P_c - a = D_{K,m} \cdot \frac{P_c - a}{D_K} - \frac{1}{b_K} \]  \hfill (9)

As can be found from Figure 8, both \((P_c-a)/D_{\Phi}\) and \((P_c-a)/D_K\) share a good linear relationship with \(P_c-a\). The fitting results are given in Table 2. The correlation coefficients \( R^2 \) of most fitting results exceed 0.9, demonstrating that it is reasonable to use the Langmuir equation to describe the porosity stress damage rate \( (D_{\Phi}) \) and the permeability stress damage rate \( (D_K) \).

As shown in Table 2 and Figure 9, from the perspective of porosity stress damage rate \( (D_{\Phi}) \), the maximum porosity stress damage rate \( D_{\Phi,m} \) value of coal is smaller than that of floor mudstone for Liugou Coal Mine, and the \( D_{\Phi,m} \) values of coal are greater than those of roof sandstone and roof mudstone for both Changping and Gaoliang Coal Mines. From the perspective of the porosity stress sensitivity constant \( (b_{\Phi}) \), the \( b_{\Phi} \) value of coal is larger than that of roof mudstone for Gaoliang Coal Mine, while the \( b_{\Phi} \) values of coal are smaller than that of roof sandstone for Changping Coal Mine and floor mudstone for Liugou Coal Mine. Meanwhile, the \( b_{\Phi} \) value of coal is also smaller than that of floor mudstone in Anxin Coal Mine. This result
Figure 8. Relationship between \((P_c-a)/D_p\) and \((P_c-a)/D_K\) and \(P_c-a\).

Table 2. Linear fitting results between \((P_c-a)/D_p\) and \((P_c-a)/D_K\) and \(P_c-a\).

| Sample no.          | \(D_{b,m}\) (%) | \(l/b_{b\Phi}\) | \(R^2\) | \(D_{K,m}\) (%) | \(l/b_K\) | \(R^2\) |
|---------------------|------------------|-----------------|---------|-----------------|-----------|---------|
| CP-3\# coal         | 60.505           | 19.271          | 0.9632  | 114.79          | 2.4686    | 0.9953  |
| CP-3\# roof sandstone | 18.102          | 5.3445          | 0.4176  | 120.73          | 2.9541    | 0.9097  |
| GL-3\# coal         | 36.877           | 11.07           | 0.8359  | 99.749          | 2.3607    | 0.9890  |
| GL-3\# roof mudstone | 31.566           | 16.172          | 0.7216  | 115.33          | 3.2571    | 0.9854  |
| LG-9\# coal*        | 34.761           | 7.6965          | 0.9496  | 118.98          | 2.7826    | 0.9944  |
| LG-10\# floor mudstone* | 44.65         | 2.3055          | 0.9975  | 121.45          | 4.6577    | 0.9953  |
| AX-2\# floor mudstone* | 38.678         | 7.6049          | 0.9186  | 113.07          | 2.5361    | 0.9977  |
| AX-2\# roof sandstone* | 46.518         | 13.536          | 0.8855  | 103.49          | 2.3298    | 0.9959  |

Note: \(R^2\): correlation coefficient.

Figure 9. Relationships among coal measure reservoir constants \(b_{\Phi}\), \(b_K\), \(D_{b,m}\), and \(D_{K,m}\).
demonstrates that the porosity stress damage rate of coal is higher than those of sandstone and mudstone, but its porosity stress sensitivity is lower than those of sandstone and mudstone. It can be inferred that after being compressed, sandstone and mudstone mostly undergo plastic deformation. In this process, the skeleton particles are compacted, and pores rapidly become smaller and do not rebound after decompression. In contrast, after being compressed, coal experiences both plastic deformation and elastic deformation. The pores will rebound after decompression. It can thus, be concluded that the pore structures of sandstone and mudstone are more sensitive to stress than that of coal. However, coal has a greater maximum porosity stress damage rate than sandstone and mudstone because its pore and fracture structure is relatively developed and can be broken and compressed easily.

Compositions of the three kinds of rocks are analyzed as follows. Coal is mainly composed of organic matter; sandstone from the Shanxi Formation (P1s) belongs to detrital sandstone containing over 40% debris and many brittle minerals; mudstones from Shanxi Formation (P1s) and Taiyuan Formation ((C2-P1)t) both belong to silty mudstones that contain many clay minerals and some sand. Coal is typical soft rock. According to the above analysis, it can be known that the average initial porosity (Φ0) of coal is 5.25% which are notably greater than those (1.74% and 1.92%) of mudstone and sandstone. Pores in coal, mainly gas pores formed during gas generation, accumulation, and migration, are usually stored in organic matters and can be damaged and deformed easily when exposed to external forces. In contrast, pores in sandstone and mudstone, mainly debris intragranular pores and clay mineral intercrystalline pores, own stronger anti-deformation ability. This explains why the porosity stress damage rate (DΦ) of coal is generally higher than those of sandstone and mudstone, and the porosity stress sensitive constant (bΦ) of coal is smaller than those of sandstone and mudstone. Moreover, debris intragranular pores in sandstone and mudstone do not have the elastic-plastic characteristics of coal which contains abundant organic matters, so they break easily under the action of external forces. As a result, the permeability stress damage rates (DK) of sandstone and mudstone are often higher than that of coal.

From the perspective of permeability stress damage rate (DK), the maximum stress damage rate DK,m values of coal are all smaller than those of roof sandstone and floor mudstone for Changping Coal Mine, Gaoliang Coal Mine, and Liugou Coal Mine. Besides, the constants (bK) that reflect the permeability stress sensitivity of coal are all greater than those of roof sandstone and floor mudstone in the three coal mines (Table 2 and Figure 9). Compared to sandstone and mudstone, coal is a typical soft rock mass which deforms more obviously than sandstone and mudstone after being compressed. Therefore, the permeability of coal is more sensitive to stress damage than those of sandstone and mudstone. Nevertheless, for sandstone and mudstone, the pore and fracture structures are less developed than that of coal, and their seepage pores become significantly smaller after compression so that their starting pressure gradients surge rapidly. As a result, their maximum permeability stress damage rate (DK,m) values are greater than that of coal.

Conclusions

1. The P&P of coal, mudstone, and sandstone in the Qinshui Basin all decrease as a negative exponential function with the increase in effective stress. Besides, the initial porosity and initial permeability of coal are both significantly higher than those of mudstone and sandstone, whereas the compression coefficient and permeability attenuation coefficient
of coal are similar to those of mudstone and sandstone. This is probably because small cylindrical samples are highly sensitive to stress.

2. The permeability stress sensitivity coefficients of coal, mudstone, and sandstone all decrease in a wavy trend with the increase in effective stress. Coal is more sensitive to stress than mudstone and sandstone in the medium- and low-pressure stages ($P_c<5$ MPa), while their stress sensitivities tend to become equal in the medium- and high-pressure stages ($P_c>5$ MPa).

3. The study, which was conducted with the aid of a stress sensitivity model based on the Langmuir equation, reveals that the porosity stress damage rate of coal is higher than those of sandstone and mudstone on the whole, but its porosity stress sensitivity is lower than those of sandstone and mudstone. Moreover, the permeability stress sensitivity of coal is greater than those of sandstone and mudstone, but the maximum permeability stress damage rate of coal is lower than those of sandstone and mudstone.

**Highlights**

1. The initial porosity and initial permeability of coal are both significantly higher than those of mudstone and sandstone.
2. Coal is more sensitive to stress than mudstone and sandstone in the medium and low pressure stage ($P_c<5$ MPa).
3. The porosity stress damage rate of coal is higher than those of sandstone and mudstone on the whole, but its porosity stress sensitivity is weaker than them.

**Acknowledgements**

This research was funded by the Youth Program of the National Natural Science Foundation of China (41972175, 41904118), the General Youth Program of Shanxi Provincial (201901D211284), Coal Seam Gas Joint Foundation of Shanxi (2016012013), the Open Project Funding Project of Key Laboratory of Coal and Coal-Measure Gas Geology of Shanxi Province (MDZ201701), and the Startup Fund for Doctoral Research in Taiyuan University of Science and Technology (20162033). These supports are gratefully acknowledged. The authors are grateful to the two anonymous reviewers for their discerning comments on this paper.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

**ORCID iD**

Kuo Jian https://orcid.org/0000-0001-6055-4097

**References**

Cao DY, Wang CJ, Li J, et al. (2014) Basic characteristics and accumulation rules of shale gas in coal measures. *Coal Geology & Exploration* 42(4): 25–30.
Cheng M, Fu XH, Zhang M, et al. (2018) Comparative study on porosity and permeability in net confining stress of three natural gases in coal series reservoirs in Guxian County, Qinshui Basin. *Natural Gas Geoscience* 29: 1163–1171.

Dai JX, Gong DY, Ni YY, et al. (2014) Stable carbon isotopes of coal-derived gases sourced from the Mesozoic coal measures in China. *Organic Geochemistry* 74: 123–142.

Guo C, Qin Y, Xia YC, et al. (2017) Geochemical characteristics of water produced from CBM wells and implications for commingling CBM production: A case study of the Bide-Santang Basin, Western Guizhou, China. *Journal of Petroleum Science and Engineering* 159: 666–678.

Jiao CY, He SL, Xie Q, et al. (2011) An experimental study on stress-dependent sensitivity of ultra-low permeability sandstone reservoirs. *Acta Petrolei Sinica* 32: 489–494.

Jin Y, Dong JD, Zhang XY, et al. (2017) Scale and size effects on fluid flow through self-affine rough fractures. *International Journal of Heat and Mass Transfer* 105: 443–451.

Jin Y, Li X, Zhao M, et al. (2017) A mathematical model of fluid flow in tight porous media based on fractal assumptions. *International Journal of Heat and Mass Transfer* 108(Part A): 1078–1088.

Kang J, Fu X, Jian K, et al. (2019) Characteristics of physical parameters and the evolution law of anthracite around the coalification jump: A case of the Jincheng and Guxu mining area. *Energy Exploration & Exploitation* 37(4): 1205–1226.

Li JZ, Guo BC, Zheng M, et al. (2012) Main types, geological features and resource potential of tight sandstone gas in China. *Natural Gas Geoscience* 23(4): 607–615.

Liang B, Shi YS, Sun WJ, et al. (2016) Reservoir forming characteristics of “the three gases” in coal measure and the possibility of commingling in China. *Journal of China Coal Society* 41(1): 167–173.

Liang JS, Wang CW, Liu YH, et al. (2014) Study on the tight gas accumulation conditions and exploration potential in the Qinshui Basin. *Natural Gas Geoscience* 25(10): 1509–1519.

Luo RL, Cheng LS, Li XZ, et al. (2009) The deformation characteristics of low permeability reservoir rocks under confining pressure. *Natural Gas Industry* 29(9): 46–49.

McKee CR, Bumb AC and Koenig A (1998) Stress dependent permeability and porosity of coal. *Rocky Mountain Association of Geologist* 21: 143–153.

Oison T, Hobbs B and Brooks R (2002) Paying off for tom brown in white river Dom field’s tight sandstone, deep coals. *The American Oil and Gas Reports* 21: 67–75.

Qin Y, Shen J and Shen YL (2016) Joint mining compatibility of superposed gas-bearing systems: A general geological problem for extraction of three natural gases and deep CBM in coal series. *Journal of China Coal Society* 41(1): 14–23.

Qin Y, Zhang Z, Bai JP, et al. (2014) Source apportionment of produced-water and feasibility discrimination of commingling CBM production from wells in Southern Qinshui Basin. *Journal of China Coal Society* 39(9): 1892–1898.

Ren F, Li XZ and Zhang SA (2014) Study on coal rock stress sensitivity of different cleat directions in ordos basin. *Coal Science and Technology* 42(11): 21–25.

Wang HC, Fu XH, Zhang XY, et al. (2018) Source, age, and evolution of coal measures water in Central-South Qinshui Basin, China. *Energy & Fuels* 32(7): 7358–7373.

Wang LQ, Liu HQ, Zhen SG, et al. (2009) Quantitative research on stress sensitivity of low-permeability reservoir. *Acta Petrolei Sinica* 30(1): 96–99.

Wang T, Wang QW and Fu XH (2014) The significance and the systematic research of the unconventional gas in coal measures. *Coal Geology & Exploration* 42(1): 24–27.

Yang KB, Qian Z, Liu H, et al. (2013) Reservoir-forming conditions of free gas in coal measure strata of Qinshui Basin. *Journal of Oil and Gas Technology* 35: 24–28.

Zou CN, Yang Z, Huang SP, et al. (2019) Resource types, formation, distribution and prospects of coal-measure gas. *Petroleum Exploration and Development* 46(3): 451–442.