Effects of pore morphology and moisture on CBM-related sorption-induced coal deformation: An experimental investigation

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Abstract
Coalbed methane (CBM) is an important resource of energy. For CBM recovery, sorption-induced coal deformation can cause significant reservoir permeability change. Moisture content and coal pore morphology affect the gas adsorption capacity and can alter the coal deformation of the coal seam. Therefore, it is crucial to establish a coal gas moisture-coupled model for CBM production prediction. However, there are currently insufficient data available for quantitative analyses. In this paper, a series of typical sorption-induced strain experiments were carried out during methane adsorption and desorption on coal samples with different metamorphic degrees and moisture content. The pore morphology and adsorption capacity of coals were measured to analyze the reason for different deformation of coals with various pore structures and moisture. Results show that the adsorption capacity and deformation is corresponding to the specific surface area of micropore, which first decreases and then increases with coal ranks. The deformation and adsorption gas content of dried coals is greater than that of natural moisture coals, which means that moisture can reduce the sorption capacity of coals, resulting in the decrease of gas adsorption-induced coal deformation. There is also residual deformation of coal samples after gas desorption caused by the residual adsorbed gas in coals. This paper quantitatively investigates the effects of pore characteristics and moisture on coal deformation and the internal mechanism. This work will provide essential information for building out a fully cross-coupled model of coal gas-moisture relationships for CBM production prediction.

KEYWORDS
CBM, coal deformation, coal pore morphology, gas adsorption, moisture
1 | INTRODUCTION

CBM, as a concomitant product of coal, is an abundant, low-cost, energy fuel that has important long-term potential for discovery and development.¹² CBM is currently producing and selling as pipeline gas, or utilizing for electrical generation directly on or near sit in the USA, Australia, China, Canada, etc.³

Understanding the gas transport properties in coal is of great significance for the accurate prediction of CBM production. It is generally accepted that permeability defines the level of transportability of methane in the coal seam. The permeability of a coalbed is a function of its cleat system. A complication with coal permeability is that it can vary significantly during gas production in response to decreases in pore pressure and gas sorption-induced coal deformation.⁴ Experimental and theoretical results show that the evolution of permeability is controlled by the competing influences of effective stresses and sorption-induced coal deformation.⁵

The shrinkage and swelling of coal as methane is desorbed or adsorbed is defined as sorption-induced coal deformation. It has been shown that sorption-induced strain may be computed by equating the changes in the coal matrix surface energy to the changes in the elastic strain energy. Sorption-induced coal deformation causes a change in the width of fractures that must be accounted for when modeling permeability evolutions.⁷ Thus, accurate measurement of sorption-induced coal deformation becomes important when modeling the effect of gas sorption on coal permeability.

Harpalani and Schraufnagel⁸ showed that sorption-induced coal strain was not necessarily a linear function of gas pressure, but might be nonlinear with decreasing gas pressure. Levine⁹ summarized a series of measurements of sorption-induced coal deformation and found that the swelling behavior followed the same form as the adsorption isotherm. This phenomenon has also been observed by Chikatamarla et al.¹⁰ Their results also showed that the volumetric strain and pressure can be described using a Langmuir-like equation and the volumetric strain is approximately linearly proportional to the amount of gas adsorbed. Robertson¹¹ developed an optical apparatus to speed up the strain experiments and eliminate the equipment problems associated with strain gauges. His measurements showed that the CO₂ sorption-induced linear strain of the sub-bituminous coal was 2.1% and it was more than twice as much as the bituminous coal at 5.5 MPa. Most observations show that swelling generally follows the form of the adsorption isotherm. It can be spontaneously deduced that the sorption-induced coal deformation is closely related to the sorption capacity.

It is known that the gas sorption capacity of coals is a function of pressure, temperature, coal rank, maceral composition, and water content.¹² Apart from pressure and temperature, the sorption capacity of coals is determined by moisture content and coal rank. The sorption capacity on dry and moist coals is often compared by measuring the CH₄ or CO₂ sorption isotherms on dry and moisture-equilibrated coals,¹³¹⁴ and the moisturized coals exhibited lower sorption capacity in all cases. For instance, B.M Krooss et al ¹⁵ concluded that the sorption capacity of CH₄ on moist coals reduced by 25% compared with the dry ones. The mechanism can be attributed to the pore-blocking effect and the competition sorption behavior.¹⁶ The dependence of CH₄ sorption capacity on coal rank is a bit complicated. With the change of coal rank, the molecular structure, pore structure, and adsorption characteristic of coal alter continuously.¹⁷¹⁸ Many researchers found a clear positive relation between CH₄ sorption capacities of moist coals with rank, but for dry coals, sorption capacity shows a parabolic dependence on rank.¹²¹⁹²⁰

Moisture adsorption and pore morphology affect the gas adsorption capacity and can alter the coal deformation of the coal seam. Most recently, the effect of dynamic loss of moisture on gas sorption-induced coal deformation during CBM production attracted more attention. Building out a fully cross-coupled model of coal gas-moisture relationships for CBM production prediction is crucial. Recognizing this, some recent studies have considered the influences of moisture content and rank on sorption-induced coal deformation.¹¹²² However, there are still insufficient data currently available for making quantitative analyses.

In this research, a series of typical sorption-induced strain experiments are done on coal samples with different coal ranks and moisture content in two phases: adsorption and desorption. The coal deformation during both methane adsorption and desorption, and the residual deformation were measured. The gas adsorption/desorption experiment was carried out to obtain the sorption capacity of these coals, and the pore morphology was measured based on the fluid flow method to analyze the sorption capacity of these coals. Then the relationships between coal deformation and gas pressure, gas content was studied. The effects of coal pore morphology and moisture on coal deformation are quantitatively analyzed, and the internal mechanism is investigated in this paper, which is conducive to build a cross-coupled model of coal gas-moisture relationships for CBM production prediction.

2 | EXPERIMENTAL TECHNIQUE

2.1 | Coal sample preparation

Three different metamorphic degree coal samples were collected from Yuanzigou (YZG) coal mine in Shaanxi Province, Sijiazhuang (SJZ) coal mine in Shanxi Province, and Kongzhuang (KZ) coal mine in Jiangsu Province, as shown in Figure 1. These samples are with different coal ranks, representing long-flame coal (YZG), anthracite coal (SJZ), and coking coal(KZ), respectively.
The large coal blocks were transported into the laboratory immediately after taken from the working face and then were cut into different specifications according to the experimental needs. The $\phi 25 \text{ mm} \times 50 \text{ mm}$ cylindrical coal samples were used in the methane adsorption/desorption experiment, and the cubic coal samples with a side length of 20 mm were used to measure the deformation. The prepared coal samples were divided into two groups: One group was natural moisture coal, which was sealed immediately after drying naturally to reduce the loss of original moisture content; and the other group was dried coal, which was dried in the vacuum environment with a temperature of 45°C until the weight change keeps within ±0.001 g. The remained coal chunk after making standard coal samples was crushed and sieved into proper sizes for other tests. The coal particles were dried in the vacuum environment with a temperature of 45°C for 48 hours.

To obtain the coal basic properties, proximate analyses were carried out using 5E-MAG6600 proximate analyzer, the vitrinite reflectance was measured by ZEISS microscope photometer, and the consistent coefficient was obtained using the FMJ-1 measurement device. The basic parameters of the

| Coal sample | Coal rank       | Proximate analyses | Fixed Carbon | Vitrinite Reflectance | Consistent Coefficient (f) |
|--------------|-----------------|--------------------|--------------|-----------------------|---------------------------|
|              |                 | Moisture $M_{ad}$ (%) | Ash $A_{ad}$ (%) | Volatile $V_{ad}$ (%) | Fixed Carbon $FC_{ad}$ (%) | Vitrinite Reflectance $R_o$ (%) | Consistent Coefficient (f) |
| YZG          | Long-flame coal | 6.01               | 9.92         | 20.76                 | 63.31                     | 0.64                        | 1.20                        |
| KZ           | Coking coal     | 1.95               | 11.93        | 32.36                 | 53.76                     | 0.98                        | 0.98                        |
| SJZ          | Anthracite      | 3.65               | 36.53        | 8.92                  | 50.90                     | 2.87                        | 1.23                        |

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coal samples are listed in Table 1. According to the results of vitrinite reflectance, the SJZ coals have the highest metamorphic grade, which represents the high-rank coal. The vitrinite reflectance of KZ coals and YZG coals are quite smaller, which are both medium rank coals. The moisture content of the YZG coal sample is the largest, followed by the SJZ coal sample, and the KZ coal sample is the smallest. The ash content of SJZ coals is much higher, while the volatile content is much lower than the other coals.

2.2 | Pore morphology measurement

As a complex porous media, the coal pores provide storage and migration space for gas. The pore structure of coal determines the adsorption/desorption performance, which affects the adsorption deformation characteristics of coal. Thus, the study of pore structure has great significance for understanding the adsorption/desorption characteristics and deformation characteristics of coal.

In this paper, the mercury intrusion porosimetry (MIP) using PM33-GT-12 mercury porosimeter was to determine the macropore morphology. And both N₂ (77 K) adsorption in the relative pressure (P/P₀) range of 0.001 ~ 0.995 and CO₂ (273 K) adsorption in the relative pressure range of 3 × 10⁻⁵ ~ 0.0289 were performed by AUTOSORB-IQ2 automatic gas adsorption analyzer.

2.3 | Methane-coal adsorption/desorption experiment

Two methane-coal adsorption and desorption experiments were carried out in this study: The methane adsorption/desorption experiment was to acquire the isothermal adsorption characteristics of coal samples, and the experiment of methane desorption at atmosphere pressure was to obtain the desorption characteristics.

As can be seen in Figure 2, the methane adsorption/desorption experiment was performed by the gas adsorption/desorption experimental setup that includes a reference tank, a sample tank, and a measuring cylinder. The adsorption/desorption experiment includes two stages of gas adsorption and desorption: first, place the φ25 mm × 50 mm sample in the sample tank and connect the sample tank with the reference tank. Before methane adsorption, the dead space of the system V_dead was measured using helium, then vacuumize them in the 60°C water for 0.5 hours and then place them in the 30°C water for isothermal adsorption; second, inject high-pressure methane with a concentration of 99.99% into the reference tank, after pressure steady, record the pressure p₁; and third, open the valve between the reference tank and coal tank, and record the gas pressure in the reference tank and sample tank p₂ after adsorption equilibrium. The volumes of the reference tank V_ref and the dead space V_dead are known, and the adsorption volume can be calculated based on the conservation of matter and the ideal gas law, repeat the operation until the maximum adsorption pressure.

High-pressure gas desorption is the reverse process of adsorption. After methane adsorption phase, connect the sample tank to the measuring cylinder for deflation until the predetermined pressure, record the gas volume in the measuring cylinder and then close the valve. After desorption equilibrium, record the gas pressure in the sample tank, and the adsorbed gas amount under the corresponding pressure can be calculated according to the ideal gas equation. Repeat the operation until the gas pressure in the sample tank decrease to atmospheric pressure. The adsorption volumes of coal

![Diagram of gas adsorption/desorption experimental setup](image)
samples under five equilibrium pressures during methane adsorption and desorption were measured. It takes much longer for a cylindrical sample than coal particles to reach adsorption equilibrium. In this study, the equilibrium criterion was pressure change less than 0.01 MPa (0.01 MPa is the accuracy of pressure gauge) in both the sample tank and the reference tank within 4 hours. The adsorption time of these coal samples at each pressure point was all more than 48 hours.

The experiment of methane desorption at atmosphere pressure was implemented using the sample tank and measuring cylinder; place the ϕ25 mm × 50 mm coal sample in the sample tank and vacuumize them in the 60°C constant temperature water for 0.5 hours; inject methane into the reference tank until the predetermined pressure, and then place the coal sample tank in 30°C water for adsorption equilibrium. After adsorption equilibrium, connect the sample tank to the measuring cylinder, open the valve of the sample tank, and record the gas volume in the measuring cylinder at each moment.

2.4 | Coal sample deformation measurement

The experimental apparatus and process of adsorption/desorption deformation for coals containing gas is shown in Figure 3. The apparatus can measure the coal deformation under a certain temperature and different gas pressure, or under certain gas pressure and different temperature. The surface of the coal samples was polished and cleaned with anhydrous alcohol and then attach strain gauges on three adjacent surfaces perpendicular to each other. According to the size of the coal sample, the BFH120-3AA-D100 resistance strain gauge with a sensitivity coefficient of 2.0 ± 1% was selected. The strain instrument was the TS-3862 digital dynamic strain acquisition instrument, which can collect the strain data of 16 strain gauges at the same time. To avoid the coal deformation caused by temperature, a compensating coal sample was prepared. Attach strain gauge to it, and then connect to strain instrument; put the cubic coal sample and compensation sample with strain gauge into the high-pressure visible kettle, and open the strain acquisition instrument to collect the strain data. After vacuuming for 0.5 hours, the adsorption/desorption test was performed under different gas pressures (0.74, 2, 3, 4, 5 MPa). The temperature control system provides a constant temperature environment, and the system is centrally arranged in the incubator. The temperature range of the constant temperature air bath was −20 ~ 100°C, the temperature fluctuates ≤0.5°C, and the temperature uniformity was ≤±2°C.

3 | THE PORE MORPHOLOGY OF THE COAL SAMPLES

From the point of view of gas occurrence and flow in the coal seam, it is considered that pores with size less than 10 nm are the main space of methane adsorption, pore between 10 and 100 nm is the space of capillary condensation and gas diffusion, and pores with size from 100 to 1000 nm constitute slow laminar gas seepage space, and the pores with the pore diameter of larger than 1000 nm constitute the space of strong gas seepage.23 According to the decimal classification criterion,24 the pore structure was divided into micropore (<10 nm), minipore (10-100 nm), mesopore (100-1000 nm), and macropore (>1000 nm).

3.1 | Results of mercury intrusion porosimetry

Due to the coal pore morphology and connectivity, the mercury withdrawal curve is generally hysteresis. The mercury injection/ejection curves of three coal samples are shown in Figure 4. The mercury curve forms of the three samples are different, which reflects the difference in pore morphology among the coal samples. The curve of YZG sample shows obvious hysteresis loops, which indicates
that there are a large number of pores that inhibit mercury ejection, such as ink-bottle shaped pores and airtight pores closed at one end. The KZ sample has a high closing degree curve and high mercury withdrawal efficiency, which indicates that the coal mainly contains pores that are conducive to mercury withdrawal, such as the through-pore. The hysteresis loop in SJZ sample is between that of YZG and KZ, which indicates that the pore of SJZ coal sample has the pore morphology like both YZG sample and KZ sample.

According to the relationship between the mercury pressure and the amount of mercury injected, the pore volume and specific surface area were obtained, as is shown in Table 2. The relationship of total pore volume between three coal samples is SJZ > YZG > KZ, and the total specific surface area is YZG > SJZ > KZ. Pore volumes of the three samples are mainly contributed by minipores and micropores. The sum of minipore volume and micropore volumes for YZG, KZ, and SJZ accounting for 95.8%, 84.8%, and 84.6% of total pore volume, respectively; and the proportion of the specific surface areas of minipore and micropore for YZG, KZ, and SJZ coals is 99.8%, 98.6%, and 99.2%, respectively. The above results indicate that pore volume and specific surface area are mainly contributed by minipores and micropores, which provides the space for gas storage.

### 3.2 N₂ adsorption/desorption isotherms

The adsorption/desorption isotherms obtained by N₂ adsorption are shown in Figure 5. According to the IUPAC classification standard, the adsorption isotherms of three coal samples can be regarded as the combination of the low relative pressure stage of type IV curve and the high relative pressure stage of type II curve. In low relative pressure, the adsorption isotherm rises rapidly, which was due to the filling of N₂ molecules in micropores. When \( P/P₀ \approx 0.01 \), the first inflection point of the adsorption curve appears, indicating the ending of monolayer adsorption and the beginning of multilayer adsorption. At high relative pressure, due to the capillary condensation in mesoporous, the second inflection point appeared and the adsorption capacity increased rapidly.
When \(P/P_0 \approx 1\), due to the existence of macropores >300 nm in coal, the adsorption isotherm did not stop growing.

The shape of the coal adsorption hysteresis loop is related to the pore shape. According to the IUPAC classification standard,\textsuperscript{,25} the hysteresis loops of these three coal samples belong to type H4, indicating that the samples contain a large number of slit pores. The hysteresis loop of YZG and SJZ is not closed. This phenomenon is common in high-rank coal and low-rank coal with well-developed pore structure,\textsuperscript{,26,27} and may be related to the expansion effect of microporous adsorption gas in coal.\textsuperscript{,28} As can be seen in Figure 5, when the relative pressure is about 0.5, and the desorption curve of YZG dropped dramatically, which indicates that the existence of ink-bottle shaped pore and conical pore in YZG. The adsorption and desorption curves of KZ and SJZ change relatively modestly, which means that the pore shape of the two coal samples is mainly cylindrical.

Based on the data of N\textsubscript{2} adsorption isotherms, the specific surface area and volume of pore were analyzed through the Brunauer–Emmett–Teller (BET) model, the Barrett–Joyner–Halenda (BJH) model, and density functional theory (DFT). The BET method was used to obtain the apparent specific surface area, the DFT method was used to calculate the micropore volume and specific surface area, and the BJH method was used to analyze the volume and specific surface area of mesopores and minipores. As is shown in Table 3, the BET-specific surface area of YZG coal is much larger than other coal samples, which provides more space for gas storage. The volume and specific surface area of all pores first decreases and then increases with the increase of coal ranks.

### 3.3 Pore size distribution (PSD)

The micropore with a diameter less than 10 nm is the main space for methane storage, while the larger pores have little effect on the gas adsorption capacity of coal. Therefore, the PSD of micropores was analyzed. The DFT method based on N\textsubscript{2} (77 K) is mainly used to determine the pore distribution with a pore width less than 300 nm. However, due to the quadrupole and pre-adsorption of nitrogen molecules, when pore size <2 nm, the relationship between pore and pressure would be lost, which cannot accurately reflect the PSD characteristics.\textsuperscript{,29} Generally, CO\textsubscript{2} adsorption using DFT (DFT-CO\textsubscript{2}) represents the PSD of micropores (<2 nm). Therefore, the PSD of coals in this study was analyzed by using DFT-N\textsubscript{2} and DFT-CO\textsubscript{2}. The micropore size distributions are shown in Figure 6.

The results of the PSD of three coals show that micropores with pore size less than 10 nm are most developed, which is related to coal metamorphism. The DFT-CO\textsubscript{2} results show that at pore size below 2 nm, the SIZ sample has
the largest specific surface area among three coal samples, and with the decrease of metamorphism degree, and the specific surface area of coal first decreases and then increases. The DFT-N$_2$ results show that for pore of 2-10 nm, the YZG coal sample has the largest specific surface area among three coal samples, which is much more than that of SJZ sample and KZ sample. The specific surface area of pore under 2 nm is much more than that of pore between 2 and 10 nm. Due to the most CH$_4$ adsorbed in pores under 2 nm in the form of micropore filling, the development degree of micropore below 2 nm will determine the gas adsorption capacity of coal samples.

### TABLE 3  Experimental results of pore volume and specific surface area (N$_2$)

| Coal sample number | BET specific surface area (m$^2$/g) | Pore volume/10$^{-2}$ mL/g | Specific surface area (m$^2$/g) |
|--------------------|-------------------------------------|---------------------------|---------------------------------|
|                    |                                     | Micropore | Micropore | Mesopore | Micropore | Micropore | Mesopore |
| YZG                | 14.036                              | 1.3107    | 0.6474    | 0.6154   | 10.261    | 1.032     | 0.108    |
| KZ                 | 0.784                               | 0.0458    | 0.1473    | 0.2631   | 0.292     | 0.147     | 0.047    |
| SJZ                | 1.562                               | 0.1397    | 0.2068    | 0.2814   | 1.091     | 0.221     | 0.056    |

### FIGURE 5  Results of the N$_2$ adsorption/desorption isotherms

4 | THE COAL DEFORMATION CHARACTERISTICS INDUCED BY METHANE ADSORPTION/DESORPTION

4.1 | The adsorption/desorption characteristics of coal samples

The sorption-induced coal deformation characteristic is controlled by the adsorption capacity of coal. The swelling deformation occurs when the coal adsorbs methane, and shrinkage deformation occurs when the gas is desorbed. The
FIGURE 6  The micropore size distribution of different coals

FIGURE 7  Methane adsorption and desorption isotherms
adsorption/desorption performance of coal is affected by many factors such as the metamorphic degree of coal, moisture content and temperature. The presence of water will occupy the adsorption position in the coal matrix pore surface and the channel of gas transport, and it has a great influence on the adsorption/desorption characteristics of coal. In this paper, isothermal adsorption/desorption and methane desorption at atmospheric pressure were carried out on natural moisture coal samples and dried coal samples.

4.1.1 | Isothermal adsorption/desorption characteristics of coal samples

The gas adsorption/desorption process of natural moisture coal samples and dried coal samples at 30°C were recorded. Studies suggest that the methane-coal sorption obey Langmuir’s law, and thus, the Langmuir equation can be used to calculate the amount of methane adsorbed by coal:

\[ Q = \frac{abP}{1 + bP} \]  

where \( P \) is the gas pressure, MPa; \( Q \) is the gas amount per mass of coal sample, m³/t; \( a \) is the Langmuir volume, which represents the maximum gas adsorption capacity of coal, m³/t; \( b \) represents the reciprocal of the Langmuir pressure, MPa⁻¹.

Many researchers have found hysteresis between the process of coal adsorption and desorption in their work, and the methane desorption had the residual adsorption amount. Among these three coal samples, the maximum gas adsorption capacity of the SJZ coal sample is the largest, while the KZ coal sample has the minimum adsorption capacity. This is because the pore volume and specific surface area of KZ coal sample are relatively smaller (seeing in Section 3.2), which provides less space for methane adsorption. The adsorption capacity of SJZ coal is stronger than that of YZG coal (both the natural moisture samples and the dried samples). Based on the pore morphology of the coal samples, the authors believe that this is a result of the PSD of micropores less than 2 nm, which provides the main space for methane storage. As is seen in Section 3.3, for the specific surface area of pores below 2 nm, the relationship between the coal samples is the SJZ sample > YZG sample > KZ sample.

Table 4 lists the value of the Langmuir volume \( a \), the reciprocal of the Langmuir pressure \( b \), and the residual gas amount \( c \) in the process of methane adsorption and desorption. Among these three coal samples, the maximum gas adsorption capacity of the SJZ coal sample is the largest, while the KZ coal sample has the minimum adsorption capacity. This is because the pore volume and specific surface area of KZ coal sample are relatively smaller (seeing in Section 3.2), which provides less space for methane adsorption. The adsorption capacity of SJZ coal is stronger than that of YZG coal (both the natural moisture samples and the dried samples). Based on the pore morphology of the coal samples, the authors believe that this is a result of the PSD of micropores less than 2 nm, which provides the main space for methane storage. As is seen in Section 3.3, for the specific surface area of pores below 2 nm, the relationship between the coal samples is the SJZ sample > YZG sample > KZ sample.

It can be seen from Figure 7 and Table 4 that the gas amounts of dried coal samples are higher than that of the natural moisture coal samples at the same pressure. This means the adsorption capacity of natural moisture coal samples is weaker than that of dried coal samples, and the moisture inhibits the methane adsorption capacity of the coal sample. It is commonly believed that the sorption is closely related to the hydrophilic sites or polar sites, which have high energy. Water molecules existing around the polar sites on the pore surface will occupy these higher energy sites, and thus inhibits the CH₄ sorption capacity. Furthermore, the adsorption constant \( b \) of dried coals is also larger than the natural moisture coals. The results reflect that the dried coal sample

| Coal sample | Adsorption process | Desorption process |
|-------------|-------------------|--------------------|
|             | \( a \) (m³/t)    | \( a' \) (m³/t)    |
|             | \( b \) (MPa⁻¹)   | \( b' \) (MPa⁻¹)   |
|             | \( R^2 \)         | \( c' \) (m³/t)    |
| YZG(wr)     | 28.696            | 26.181             |
|             | 0.307             | 0.346              |
|             | 0.9972            | 0.9832             |
| YZG(dr)     | 32.765            | 28.371             |
|             | 1.107             | 1.218              |
|             | 0.9936            | 3.512              |
| KZ(wr)      | 8.431             | 7.855              |
|             | 1.987             | 2.116              |
|             | 0.9946            | 0.502              |
| KZ(dr)      | 9.445             | 7.094              |
|             | 2.369             | 1.929              |
|             | 0.9989            | 2.325              |
| SJZ(wr)     | 39.190            | 32.589             |
|             | 0.879             | 0.954              |
|             | 0.9985            | 5.047              |
| SJZ(dr)     | 44.615            | 36.098             |
|             | 1.394             | 1.704              |
|             | 0.9988            | 7.139              |

\( \text{Note: wr represents the natural moisture coal sample, and dr represents the dried coal sample.} \)
reaches the adsorption equilibrium more easily than the natural moisture coal sample.

4.1.2 Methane desorption at atmospheric pressure

The experiment of methane desorption at atmospheric pressure by the natural moisture coal samples was implemented at equilibrium pressures of 0.74, 2, 3, 4, and 5 MPa, and the desorption curves are shown in Figure 8. The cumulative gas desorption volume shows a monotonically increasing parabola with time, and at the same time, the higher the original equilibrium pressure, the larger the desorption amount. Under the same original equilibrium pressure, the cumulative desorption gas volume of YZG and SJZ coal samples is quite larger than that of KZ coal samples, which is consistent with the result of the isothermal adsorption/desorption experiment.

In order to analyze the influence of moisture on the desorption characteristics of coals, the desorption curves of natural moisture coal samples and dried coal samples at initial equilibrium pressures of 2 and 4 MPa were drawn in Figure 9. The natural moisture coal sample and dried coal samples have a similar desorption law, which increases parabolically with time. However, the desorption rate of dried coal samples is faster than that of natural moisture coal samples in the initial stage, and the desorption curve of dried coal samples is always above the desorption curve of natural moisture coal samples under the same original gas pressure. The basic reason is that the existence of water inhibits the adsorption capacity coals, leading to the decrease of adsorption gas amount, and as a result, the desorption volume is smaller.

4.2 Coal deformation during methane adsorption/desorption

4.2.1 Coal deformation during methane adsorption

Figure 10 shows the strain of natural moisture coal sample during gas adsorption, in which the positive value represents
shrinkage strain and the negative value represents swelling strain. \( \varepsilon_x \), \( \varepsilon_y \), and \( \varepsilon_z \) represent the strain in three mutually perpendicular directions of the cubic coal sample, respectively. The coal strains in three directions rose when being vacuumized, and first jumped and then fell dramatically in a very short time during gas charging. After gas filled in, the curves decrease gradually with time, which means the coal samples began to adsorb methane and expand. The curve falling speed is fast in the initial stage and then decreases with time, and finally, the deformation curves tend to be stable. With the increase of equilibrium gas pressure, the strain of coal samples increase. Comparing the deformation of three coal samples, the strain of KZ sample is much smaller than the other two samples. The deformation of SJZ coal sample is larger than that of YZG coal sample at 0.74 MPa, while the difference between them decreases as the equilibrium gas pressure grows and even reverses at 5 MPa.

Since the strain in the three directions of the coal samples has the same trend during the adsorption process, the volumetric strain \( \varepsilon_v \) can be used to characterize the deformation features of the coal:

\[
\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z
\]

It can be known from the data, the gas filled in the tank will produce two opposite effects on coal deformation: The free gas in the tank will produce confining pressure on the coal body and promote the coal compression; and after adsorbing gas, the coal surface energy decreases, resulting in the thickness of the surface layer increase and the coal sample swelling. Therefore, the deformation monitored by the strain gauge is the result of the superposition of the two effects. In order to eliminate the deformation caused by the confining pressure of free gas in the tank, the deformation of the coal samples under the same pressure was measured with nonadsorption helium, and the results are shown in Figure 11. The strain of coal samples increases linearly with equilibrium pressure.

The volumetric strain of the coal samples induced by methane adsorption can be calculated using the measured
Taking the beginning of adsorption as the time point 0 and the strain at that time as 0, the gas sorption-induced volume strain of coal samples is shown in Figure 12. It can be seen that the swelling strain increases with time, while the increase rate is decreasing. The strain changing with time shows a parabolic relationship. For the same sample, the swelling of coals increases with the increase of adsorption equilibrium pressure. For YZG coal sample, the volumetric swelling is about $500 \, \mu\text{e}$ at 0.74 MPa and jumps to $3700 \, \mu\text{e}$ at 5 MPa. In addition, the strains of YZG and SJZ are much larger than the strain of KZ coal sample, which corresponds to the adsorption capacity of these coal samples.

FIGURE 10 Coal sample strain during gas adsorption
4.2.2 Coal deformation during methane desorption

Figure 13 shows the strain in three mutually perpendicular directions of natural moisture coal samples in the methane desorption process. The desorption occurred under atmospheric pressure and started from opening the valve to release the gas in the tank. The test of desorption deformation was carried out continuously after methane sorption in this experiment. Thus, part of the data during the adsorption was retained in the diagram. The strain first decreased and then increased rapidly at the moment of pressure relief. After that, the strain grew gradually and became stabilized eventually. The coal strain curve of gas desorption can be divided into three stages: (a) The free gas in the tank release, causing the rapid decrease of confining pressure and elastic expansion of coal blocks. The diffusion process of most adsorbed gas in minipore and micropore is relatively slow, and as a result, the initial desorption shrinkage is not obvious. (b) With the pore pressure decreasing fast, the elastic deformation of the coal body recovers rapidly. (c) The desorption of adsorbed gas increases the coal surface energy, causing the surface to shrink. Besides, with the free gas in the coal pore diffusing out, the gas pressure in the pore decrease, and this results in the closure of the pores and the contraction of the coal block.

Taking the beginning of desorption as time point 0, and the strain at that time as 0, the volume strains of coal samples are plotted in Figure 14. The volumetric strain increases fast at the initial time, and then slows down, and finally tends to be stable, which has a parabolic relationship with time. The strain of YZG coal sample and SJZ coal sample is much larger than the strain of KZ coal sample. For the same coal sample, the deformation during desorption increases with adsorption equilibrium pressure.
5 | DISCUSSION

5.1 | Factors influencing adsorption deformation

5.1.1 | Relationship between coal swelling and gas pressure

The ultimate swelling strain of three coal samples under different equilibrium pressure is listed in Table 5 and plotted in Figure 15. Under the same gas pressure, the SJZ coal sample has the largest adsorption strain, followed by the YZG coal sample, and the KZ coal sample has the smallest strain. This is consistent with the results of adsorption capacity. Because these samples with different coal ranks have the approximate value of $f$ (Table 1), the influence of hardness on the deformation results can be ruled out. Therefore, it is considered that the main controlling factor for the difference of adsorption swelling between three coal samples is the pore morphology. As for the pores with the width less than 2 nm, the SJZ sample has the largest specific surface area among the three coals, inducing the largest adsorption capacity, and thus, leading to the largest deformation.

With the increase of equilibrium pressure, the adsorption swelling strain of three coal samples increases gradually, but the growth rate slows down, and finally, the strain tends to be stable. This changing trend conforms to the general law of Langmuir equation, so Langmuir equation was used to fit the volume strain and gas pressure. The fitted results are shown in Table 5, and the fitting goodness $R^2$ are more than 0.96.

5.1.2 | Relationship between coal swelling strain and gas adsorption capacity

The coal deformation was measured under special pressure, while the gas amount was obtained under uncertain pressure. To analyze the relationship of coal swelling and gas adsorption capacity, the adsorption gas amount under special gas pressure was calculated by methane adsorption isotherm. The adsorption gas amount under five specific equilibrium pressures in the adsorption deformation experiment was calculated, and the relation between adsorption gas volume and adsorption swelling volume strain is shown in Figure 16. The volumetric swelling strain of coal
samples increases linearly with the increase of adsorption capacity, which is consistent with the experimental results of Liu, et al.35 The data of adsorption swelling strain and gas contents were fitted by a linear function, and the fitting accuracy is above 0.95. Therefore, the relationship between adsorption strain of coal and adsorbed gas capacity can be expressed as follows:

\[ |\epsilon_v| = kQ \quad (4) \]

where \(|\epsilon_v|\) represents the absolute value of coal sample strain; \(k\) is the fitted coefficient; \(Q\) is the adsorbed gas amount, m³/t.

5.1.3 | Effects of moisture on sorption-induced coal deformation

To investigate the influence of moisture on the sorption-induced coal swelling characteristics, the deformation during
methane adsorption of three dried coal samples with different metamorphic degrees was also measured. As shown in Figure 17, the strain changes of dried coals with equilibrium pressure are the same as that of natural moisture coal samples, which conforms to the Langmuir equation. The adsorption swelling strain of dried coal samples is much larger than that of natural moisture coal samples, which is similar to the relation of the adsorption capacity between natural moisture coals and dried coals. It can be known from Section 5.1.2 that the adsorption swelling strain increases linearly with the absorbed gas contents. However, the moisture inhibits the methane adsorption capacity of the coal sample and, as a result, leads to the decrease of adsorption swelling deformation of natural moisture coal samples.

Taking equilibrium pressure of 5 MPa as an example, the volumetric strain of dried coals and natural moisture coals was compared. At the equilibrium pressure of 5 MPa, the volume strain of YZG dried coal sample was $4.21 \times 10^{-4}$, and that of the natural moisture coal sample was $2.5 \times 10^{-4}$, which decreased by $1.71 \times 10^{-4}$, accounting for 41.05% of the strain of dried coals. The volume strain of KZ dried coal sample and natural moisture coal sample was $1.74 \times 10^{-4}$, and $1.39 \times 10^{-4}$, respectively. The volumetric strain decreasing by $3.13 \times 10^{-4}$, which is 18.35% of the strain of dried coals. The volume strain of SJZ dried coal sample was $3.96 \times 10^{-4}$, and that of natural moisture coal sample was $3.25 \times 10^{-4}$, which decreased by $8 \times 10^{-4}$ (17.99%) compared to the former. The volumetric strain of three coal samples

**TABLE 5** Volumetric strain under different pressure during methane adsorption

| Coal sample | Volumetric strain $|e_v| \times 10^{-4}$ | Fitting results |
|-------------|------------------|-----------------|
| YZG         | 5.49             | $e_v = 11.922P/(1 + 0.267P)$ | 0.9658 |
| KZ          | 3.00             | $e_v = 5.468P/(1 + 0.187P)$ | 0.9908 |
| SJZ         | 12.64            | $e_v = 20.287P/(1 + 0.433P)$ | 0.9822 |
with natural moisture decrease by 42.41%, 18.35%, and 17.99%, respectively. This shows that moisture has a greater influence on the adsorption deformation of low metamorphic coals than high metamorphic coals. The low-rank coals have a large amount of oxygen-containing functional groups which are of high energy. Therefore, low-rank coals show stronger hydrophilicity and this makes the sorption property more sensitive to moisture.

5.2 Relationship between coal shrinkage strain and gas pressure

The shrinkage strain during methane desorption of three coal samples under different equilibrium gas pressure is listed in Table 6 and plotted in Figure 18. With the increase of gas...
pressure, the desorption shrinkage strain of three coal samples increases gradually. The volumetric strain in the process of gas desorption has a power function with the original equilibrium pressure, seeing Equation (5). The fitted results are shown in Table 6, with fitting goodness $R^2$ being more than 0.96. Under the same equilibrium gas pressure, the relationship of shrinkage deformation between three coal samples is $SJZ > YZG > KZ$.

\[ \varepsilon_v = gP^h \]  \hspace{1cm} (5)

where $g$ and $h$ are fitting coefficients.

### 5.3 Residual deformation

During the experiments, it was found that the shrinkage strain of the coal sample after methane desorption was less than its swelling strain, which means the coal sample was still keeping in the swelling state after gas desorption; that is, there was a certain residual deformation. Table 7 lists the adsorption swelling strain, desorption shrinkage strain, and residual strain of the three coal samples under various gas pressure. The residual strain under different gas pressure is shown in Figure 19. There is an abnormal point of the residual strain of YZG coal sample at a gas pressure of 2 MPa. The overall

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**FIGURE 17** Comparison of volumetric strain between natural moisture coals and dried coals

**TABLE 6** Volumetric strain under different pressure during methane desorption

| Coal sample | Volumetric strain $|\varepsilon_v| (10^{-4})$ | Fitting results |
|-------------|------------------------------------------|-----------------|
|             | 0.74 MPa | 2 MPa | 3 MPa | 4 MPa | 5 MPa | Fitted formula | $R^2$ |
| YZG         | 3.78     | 8.51  | 13.74 | 14.89 | 17.09 | $\varepsilon_v = 5.453 P^{0.730}$ | 0.9602 |
| KZ          | 1.84     | 4.21  | 4.72  | 5.68  | 6.79  | $\varepsilon_v = 2.471 P^{0.620}$ | 0.9735 |
| SJZ         | 8.24     | 12.65 | 15.04 | 17.99 | 20.54 | $\varepsilon_v = 9.067 P^{0.496}$ | 0.9895 |
trend of residual deformation with gas pressure is evident, so the point does not affect the rule of residual deformation. Except for the normal data, the residual deformation of three coal samples increases with the increase of adsorption equilibrium pressure and then tends to approach a constant value.

As the adsorption/desorption experiment in Section 4.1.1, the curves in the desorption process lags behind the curves in the adsorption process; that is, the adsorbed gas amount in the depressurization desorption process is more than that in the pressurization adsorption process. After gas pressure relief, the gas adsorbed in coal cannot be desorbed completely, and there is residual adsorption gas amount. Based on the results mentioned above, the causes of residual deformation of coal samples are analyzed as follows: When the pressure decreases, the methane that was combined with carbon molecules by strong attraction still remained in the coal pore, and the gas wedged into the micropore by high pressure cannot be released from coal matrix. On the other hand, due to the contraction of the coal matrix after pressure relief, the gas migration channel was narrowed and the gas was confined in the coal. The gas retained in the pore made the coal still keep a swelling state, which leads to the residual coal deformation. The residual deformation between three coals is SJZ > YZJ > KZ, which is consistent with pore morphology. This is a result of the micropore growth degree, which is inconducive for gas desorption.

6 | CONCLUSION

To investigate the effects of coal pore morphology and moisture on coal-methane sorption deformation, a series of coal sample deformation experiments during gas sorption and desorption were carried out. The natural moisture coal samples and dried coal samples of three different metamorphic degree coals were used in the experiment. The pore morphology and gas adsorption capacity of three coal samples was measured to analyze the difference of coal deformation induced by adsorption. The conclusions can be summarized as follows:

1. The results of gas adsorption/desorption experiments show that the adsorption capacity of three coal samples is SJZ > YZG > KZ, while the metamorphic grade between them is SJZ > KZ > YZG. According to pore characteristics, this is a result of the development degree of micropores below 2 nm, which provides the main space for methane storage. The SJZ coal has the largest specific surface area for pores less than 2 nm. The adsorbed gas amount of dried coal samples is greater than that of natural moisture coal samples, and the reason is that the water in coal pore inhibits the adsorption capacity of coal samples, resulting in the decrease of adsorption capacity of natural moisture coal samples.

2. The coal deformation during gas adsorption can be divided into three stages: coal shrinkage during vacuum, compression deformation and recovery during gas charging, and coal swelling during methane adsorption. The swelling strain of SJZ coal sample is the largest, followed by YZG coal sample, and that of KZ coal sample is the smallest. It is considered that the main controlling factor

![Correlations between volumetric strain and gas pressure during methane desorption](image)

**FIGURE 18** Correlations between volumetric strain and gas pressure during methane desorption

| Coal Sample | Strain (10⁻⁴) | 0.74 MPa | 2 MPa | 3 MPa | 4 MPa | 5 MPa |
|-------------|--------------|----------|-------|-------|-------|-------|
| YZG         | Swelling strain | 5.49     | 16.52 | 20.96 | 22.68 | 25.00 |
|             | Shrinkage strain | 3.78     | 8.51  | 13.74 | 14.89 | 17.09 |
|             | Residual deformation | 1.71     | 8.01  | 7.22  | 7.79  | 7.91  |
| KZ          | Swelling strain | 3.00     | 8.10  | 10.89 | 12.49 | 13.93 |
|             | Shrinkage strain | 1.84     | 4.21  | 4.72  | 5.68  | 6.79  |
|             | Residual deformation | 1.16     | 3.89  | 6.17  | 6.81  | 7.14  |
| SJZ         | Swelling strain | 12.64    | 20.69 | 25.89 | 29.98 | 32.50 |
|             | Shrinkage strain | 8.24     | 12.65 | 15.04 | 17.99 | 20.54 |
|             | Residual deformation | 4.40     | 8.04  | 10.85 | 11.99 | 11.96 |
FIGURE 19 Residual strain of coal samples

for the difference of adsorption swelling is the pore morphology, especially micropores less than 2 nm. In the process of methane desorption, the strain of coal sample includes elastic swelling stage after pressure relief, elastic deformation recovery, and shrinkage deformation induced by gas desorption. Moreover, the methane adsorption-induced volumetric strain of coal and time follows a parabolic relationship.

3. The adsorption swelling volume strain of coal sample increasing with equilibrium gas pressure conforms to the Langmuir equation, and the strain increases linearly with the increase of adsorbed gas content. The volume strain of dried coal is greater than that of natural moisture coal, indicating that moisture can decrease the gas adsorption-induced coal deformation, which is because the water in the coal pore reduces the adsorption capacity of coal samples. Due to residual adsorbed gas, there is residual deformation of coal samples after gas desorption. The residual deformation of three coal samples increases with the increase of adsorption equilibrium pressure and is consistent with pore morphology.

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