Characteristics of Coal Porosity Changes before and after Triaxial Compression Shear Deformation under Different Confining Pressures

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ABSTRACT: It is important to explore the changes in coal pores in response to triaxial compression and shear deformation for coal mine gas drainage and efficient coalbed methane mining. To study the variation in coal pores depending on stress, first, a mechanical analysis was carried out, and then the characteristics of coal samples before and after triaxial compression were quantitatively analyzed combined with low-temperature nitrogen adsorption experiments. The compressive strength of the coal samples with a high elastic modulus is significantly greater than that of coal samples with a low elastic modulus. Sihe coal samples with a larger elastic modulus experienced higher peak stress and strain during compression than those from the Chengzhuang Mine with a smaller elastic modulus. With the exception of the coal sample from the Chengzhuang Mine with a confining pressure of 15 MPa, the peak strength and axial strain of the coal samples gradually increased with an increase in confining pressure. The larger the elastic modulus, the greater the axial strain. After triaxial compression, pores with diameters ranging from 2 to 5 nm exhibited a significant change. After the compression of coal with a high elastic modulus, the pore volume and pore specific surface area decreased with the increase in confining pressure, by 60.7 and 59.7%, respectively (compared with raw coal). The complex pore structure consisting of mesopores and macropores (>11 nm) became simpler. The volume and specific surface area of the pores of the coal samples with a low elastic modulus first increased, then decreased, and then increased again with the increase in confining pressure, and after compression, the roughness and complexity of macropores of coal samples are greater than those of micropores. The changes induced in the coal samples of the two mining areas in response to compression differ, which are related to the mechanical properties of the coal bodies.

1. INTRODUCTION
Coalbed methane (CBM) is an unconventional natural gas associated with coal and strong greenhouse gas. Its greenhouse effect is 21 times stronger than that of carbon dioxide.1 The development and utilization of CBM in coal goafs eliminates the hidden safety hazards caused by gas accumulation in the goafs of abandoned mines, increases the energy supply, and reduces the greenhouse gas emissions.2 In the “three zones” (spanning, fissure, and slow sinking zones) of the goaf, the rock mass is generally subjected to three-dimensional stress. Mining destroys the stress state of the overlying rock and causes redistribution of the internal stress field of the coal body. This stress redistribution creates fractures and may lead to the collapse and caving of the overlying strata, therefore, threatening the safe production of coal mines.3,4 During gas drainage, the geological structure, pore distribution characteristics of the overlying strata, and drainage technology and equipment significantly influence the drainage effect.5 The pore distribution of the overlying rock in the goaf is an important factor affecting the CBM reservoir and migration. Triaxial compression tests can be used to simulate the three-dimensional stress distribution in the upper part of the goaf to determine the change in the mechanical properties of the coal body.
overlying stratum and reconstruction characteristics of the pores. The test results provide a theoretical basis for the pressure relief of gas drainage of the overlying rock in the deep goal.

The mechanical properties of coal are affected by the coal itself as well as the external conditions. A coal reservoir is a type of double-porous rock formation with low strength. The bedding, joints, pores, and fractures of the coal are complex and variable; the components are very different. The size, shape, and connectivity of pores and fractures affect the mechanical properties of the coal. In addition to these internal factors, in situ stress affects the mechanical properties of the coal. The in situ stress increases with the increase of the mining depth; under the environment of high in situ stress and high gas pressure, its nonlinear deformation characteristics are more obvious, resulting in the rheological effect. Deep mining causes the initiation and expansion of coal fractures, resulting in coal instability and fracture. The propagation of cracks in coal leads to gas desorption and flow and accelerates the progressive failure process. Many scholars have carried out numerous studies with respect to the changes due to stress evolution. Medhurst and Brown conducted conventional triaxial compression experiments on coal samples and reported that the peak strength of coal is proportional to the confining pressure. With the increase in confining pressure, the mechanism underlying coal deformation significantly changes from axial splitting to shearing. White carried out triaxial compression experiments using a testing machine and found that the deformation of coal transitions from brittle to ductile with the increase in confining pressure. Ren et al. conducted mechanical tests on white sandstone under different confining pressures and showed that the peak strength of the specimens is linearly related to the confining pressure. They observed that the higher the confining pressure, the higher the peak strength of the white sandstone sample. The peak strength of the specimen has a cubic polynomial relationship with the ratio of the initial axial compression load and porosity. To simulate the stability of the horizontal wellbore in the coal seam, Deisman explored the correlation between the confining pressure and coal permeability using a triaxial compression test and observed that the average effective confining pressure increases and the permeability decreases due to the closure of cleats. Zeng et al. studied the correlation between stress and permeability of coal under triaxial compression and concluded that the permeability of fractured coal samples is higher than that of intact coal samples under lower stress conditions. Jang et al. used computed tomography (CT) scanning and real-time acoustic emission (AE) to visualize the evolution of pore and fissure structures in coal and shale under different stress conditions. Their experiment verified that the pores and fractures of coal and shale increase with the increase in stress. Wang et al. used triaxial compression experiments and CT scanners to quantify the dynamic changes in two- and three-dimensional fractures in coal samples under uniaxial and triaxial conditions. Liu et al. studied the failure mechanism and mechanical parameters of coal and found that with the increase in confining pressure, the coal sample is mainly sheared, and the elastic modulus and peak strength increase linearly. Li et al. used triaxial compression and CT scanning experiments to obtain the three-dimensional fracture distribution of coal samples. They observed that the internal damage of coal as well as the connectivity and surface density of the damaged surface increase with the increase in confining pressure. The results of the abovementioned research provided important references for the macroscopic understanding of the mechanical properties of coal under triaxial compression conditions and also for understanding the microscopic changes.

Coal seam gas mainly exists on the pore surface of coal in an adsorbed state, and nanoscale pores in coal are the main space for gas adsorption. The evolution of the stress field of the overlying strata in the goaf is the basis of the development of pores, fractures, and deformation in the stratum. The change in the coal pore structure directly affects the migration and exploitation of CBM. To improve the quantitative characterization of the pore structure in coal, many researchers have used fractal theory to study the pore structure characteristics of porous media and fractal dimensions. The specific surface area, pore volume, pore size distribution, and other characteristics were numerically analyzed. In this paper, anthracite coal is selected as the experimental sample, and the structural characteristics of coal are obtained using the advantages of the low-temperature liquid nitrogen adsorption method for micropore testing. Xu et al. studied the structure and fractal characteristics of nanopores in coal and found that the number of diffusion pores with fractal dimension D1 (<65 nm) increased with the increase of Brunauer–Emmett–Teller (BET) specific surface area, vitrinite content, and R3.40 While it decreases with increasing permeability and has a weaker correlation with total pore volume. Pan et al. found that the larger the pore fractal dimension of coal, the larger the pore size, the more complex the pore shape, and the tectonic movement promoted the irregularity and fracture of the original pores. Wang et al. observed that the impact load improves the internal structure of pores and reduces the complexity, irregularity, and surface roughness of pores; for the seepage pores, the shock load increases the gas migration velocity of the seepage pores, and for the adsorption pores, the shock load reduces the adsorption capacity of the adsorption pores and promotes the desorption of the gas. Lu et al. pointed out that with the increase of structural deformation, the fractal dimension of adsorption pores increases, while the fractal dimension of seepage pores decreases.

In accordance with the abovementioned research, in this study, triaxial compression experiments were conducted under different confining pressures. Based on the combination of triaxial compression and low-temperature liquid nitrogen experiments with fractal theory, the mechanical properties of the coal and changes of the pores in the coal before and after compression were explored at the microscopic level. The correlations between the mechanical properties of coal and different confining pressures are discussed in depth to quantitatively describe the characteristics of the reservoir pore structure. Our study is of great significance with respect to the exploration, development, and effective utilization of CBM. The results provide references with respect to the migration and rational and efficient exploitation of CBM.

2. EXPERIMENTAL SECTION

2.1. Sample Collection and Preparation. Anthracite samples were obtained from the Chengzhuang and Sihe Mines in the Jincheng Mining Area in the Shanxi Province. The random vitrinite reflectance (R0) and microscopic composition of the coal were tested using an OPTON-II MPV-3 microscope (Zeiss microscope, Germany). Vitrinite is the main component of each coal sample, accounting for more than
Table 1. Basic Parameters of Coal Samples

| mine     | sample no. | R_{vap} (%) | vitrinite (%) | inertinite (%) | exinite (%) | clay (%) | carbonate (%) |
|----------|------------|-------------|---------------|----------------|-------------|----------|---------------|
| Chengzhuang | CZ-1       | 2.44        | 89.00         | 1.67           |             |          | 6.00          | 3.33          |
|           | CZ-2       | 2.37        | 81.28         | 0.91           |             |          | 10.05         | 7.76          |
| Sihe     | SH-1       | 2.53        | 84.67         | 0.36           |             |          | 14.97         |               |
|           | SH-2       | 2.24        | 92.33         | 0.19           |             |          | 7.49          |               |

80%. The R_{vap} distribution ranges from 2.24 to 2.53% and the basic parameters of the experimental samples are shown in Table 1.

2.2. Triaxial Compression Experiment. The triaxial compressive strength of a coal midbody can be determined with a triaxial compression test. The triaxial compression test is used to determine the strength, deformation, and failure characteristics of coal under axial compression and confining pressure. The triaxial compression test under confining pressure better simulates the real underground conditions and the compressive strength obtained under triaxial compression is more realistic than that under uniaxial compression. The experiment was carried out at the School of Energy, Henan University of Technology, using an RMT-150B rock mechanics testing instrument.

Twelve cylindrical samples with a diameter of 50 mm × 100 mm were obtained by drilling of the original lump coal sample (Figure 1). The height, diameter, and flatness of the processed coal samples met the requirements of rock experiments. The “Determination of Physical and Mechanical Properties of Rocks” (GB/T 23561) method was used. A prepared coal sample is shown in Figure 1.

2.3. Low-Temperature Liquid Nitrogen Adsorption Experiment. The determination of the specific surface area and pore size distribution using cryogenic adsorption is based on the adsorption of gas on a solid surface. The volume, size distribution, and specific surface area of the pores were calculated using the Barrett–Joyner–Halenda (BJH) method. The BJH method is used for the pore size characterization based on the cylindrical pore model and modified Kelvin method (MK) and has become a classic pore distribution analysis method. The BJH method is used to correct the radius of the pore core and the area of the liquid film when the thickness of the liquid film changes based on the general rules for the calculation of cylindrical holes. Therefore, the calculation results are closer to reality. The equation is as follows

\[ \Delta V_{pi} = R_i \left[ \Delta V_{ci} - \Delta t_i \sum_{j=1}^{i-1} C_i S_{pj} \right] \]

where \( R_i = \left( \frac{r_i}{r_{ji}} \right) + \Delta t_i \), \( \Delta t_i = t_i - t_{i-1} \), \( C_i = \frac{r_i - r_{ji}}{r_i} \), \( \Delta V_{pi} \) is the pore volume of the capillary pores in group \( i \) and \( \Delta V_{ci} \) is the measured desorption amount of the capillary pores in group \( i \).

In this study, 12 representative samples were obtained before and after compression shearing in two mining areas and used for specific surface area and pore size distribution experiments. The samples were representative for the deformation characteristics of coal. The low-temperature liquid nitrogen adsorption experiment was conducted according to the national standard GB/T19587-2004. A Quadrawin SI automatic specific surface area and pore size analyzer produced by Quanta Instrument Company and the static nitrogen adsorption capacity method were used. The test process was as follows: the sample was first weighed (3.000 g), heated at 90 °C for 1 h, then heated at 300 °C for 5 h, and finally degassed under vacuum. The degassed sample tube was weighed and installed on the analysis end. The net weight of the sample after degassing was used as an input and a vacuum adsorption experiment was carried out at an absolute temperature (in liquid nitrogen). The entire adsorption and desorption process was controlled by a computer. The specific surface area and pore size distribution of the sample were obtained. The experimental process is shown in Figure 2.

3. RESULTS AND DISCUSSION

3.1. Mechanical Parameters of Coal Samples under Triaxial Compression. The triaxial compressive strength of coal linearly increases with increasing confining pressure

\[ \sigma_1 = \sigma_0 + k \sigma_3 \]

where \( \sigma_0 \) is the ordinate intercept of the correlation between \( \sigma_1 \) and \( \sigma_3 \) MPa and \( k \) is the slope.

There is a big difference in the compressive strength of the coal samples from the two mining areas. Figure 3 shows the relationship between the compressive strength and the lateral stress \( \sigma_3 \) in the triaxial compression experiment. For the convenience of comparison, the triaxial compressive strength corresponding to \( \sigma_3 = 0 \) is taken, among which the compressive strength corresponding to the Sihe coal sample is 60.617 MPa (Figure 3), and the corresponding compressive
strength of the Chengzhuang coal sample is 38.517 MPa (Figure 3); that is, the compressive strength of the Sihe coal sample is significantly greater than that of the Chengzhuang coal sample.

The cohesion and internal friction angle, which are indicators of the shear strength of coal, can also be determined by triaxial compression tests. Based on the Coulomb strength criterion, the maximum rock shear stress \( \tau_s \) (shear strength) can be quantitatively expressed based on cohesion and internal friction

\[
\tau_s = c + \mu \sigma
\]

where \( c \) is the cohesion force, MPa; \( \mu \) is the internal friction factor, which can be quantitatively expressed by the internal friction angle \( \varphi \); and \( \sigma \) is the normal stress, MPa.

Multiple pairs of \( \sigma_1 \) and \( \sigma_3 \) can be obtained through multiple sets of triaxial compression tests. The experimental results are shown in Table 2. Linear regression can be used to describe the correlation between \( \sigma_0 \) and \( \varphi \) and the angle of internal friction \( \varphi \) and cohesion \( c \)

\[
c = \frac{\sigma_0 (1 - \sin \varphi)}{2 \cos \varphi}
\]

\[
\varphi = \arcsin \left( \frac{k - 1}{k + 1} \right)
\]

Table 2 shows that, under the same external force, coal samples with a large elastic modulus more easily deform and rupture and their ability to resist pressure and deformation is worse than the coal samples with a small elastic modulus.

### 3.2. Mechanical Properties of Raw Coal under Loading Conditions

To determine the mechanism through which confining pressure affects the deformation characteristics of the coal body, a triaxial compression experiment was conducted.
conducted and stress–strain curves of the coal body under different confining pressures were plotted (Figure 4). The numbers in Figure 4 represent the values of confining pressure $\sigma_3$ and the unit is MPa.

Figure 4 shows that the stress–strain curves of the triaxial compression of two coal samples have different mechanical properties. The axial pressure was kept constant and the confining pressure was continuously increased until the samples failed. The peak strength of the Sihe coal sample with a larger elastic modulus gradually increased with the increase in confining pressure; its axial strain was also larger. The larger the confining pressure, the steeper the prepeak curve. The larger the elastic modulus, the greater the axial strain. The figure shows that the increase in confining pressure improved the resistance of the coal body to axial stress and its strength. After the peak, the curve dropped steeply, indicating that the brittle failure after the peak is relatively significant. The changes in other curves of Chengzhuang Mine coal samples with a smaller elastic modulus were similar to those of the Sihe Mine samples (the exception being the changes observed in response to a confining pressure of 15 MPa). During triaxial compression, the peak stress of the Sihe coal sample varied from 60 to 130 MPa and the maximum strain value ranged from 0.02 to 0.03. The corresponding peak stress of the Chengzhuang coal sample varied from 40 to 80 MPa. The strain value ranged from 0.018 to 0.024. The stress and strain peaks of the coal samples with different confining pressures differed. The stress and strain peaks of the Sihe coal sample with a larger elastic modulus due to compression were larger than those of the samples from the Chengzhuang Mine with a smaller elastic modulus.

During the initial stage of loading, the coal sample entered the stage of compaction and closure with the increase in the axial stress, indicating that the pores and cracks have compacted and the gas flow channel has become narrower. As the loading progressed, the axial stress–strain curve became almost a straight line. During this stage, the elastic deformation of coal, seepage cracks generally undergo only elastic deformation. No damage occurred inside the coal sample and the deformation could be recovered after the unloading of stress. With the continuous increase in the load, fractures and cracks developed in the coal sample, and the damage area increased. The stress–strain curve of the coal body rapidly increased in a nonlinear manner with an increase in the strain in the yield stage. The increase range gradually increased with the increase in confining pressure. The slope of $\sigma$ also increased, indicating that the internal structure of the coal body and the development of microcracks changed. The coal body entered the yield stage of loading. After the axial stress increased to the peak value, the internal cracks of the coal body penetrated each other and then rapidly broke down. A macroscopic fracture surface developed, indicating that the maximum bearing capacity is reached. The coal sample was unstable and damaged, the axial stress decreased rapidly, and the coal body exhibited pronounced brittle characteristics.

Figure 4. Stress–strain curves of coal samples.

### Table 3. Pore Volume of Each Size Category of Coal Samples

| sample no. | total volume ($10^{-4}$ cm$^3$/g) | $2−5$ nm | $5−10$ nm | $10−50$ nm | $50−100$ nm | $2−5$ nm | $5−10$ nm | $10−50$ nm | $50−100$ nm |
|------------|-----------------------------------|----------|-----------|------------|-------------|----------|-----------|------------|-------------|
| SH-1       | 53.29                             | 18.14    | 10.32     | 18.20      | 6.63        | 34.1     | 19.4      | 34.2       | 12.4        |
| SH-2       | 30.92                             | 7.35     | 3.43      | 14.53      | 5.61        | 23.8     | 11.1      | 47.0       | 18.2        |
| SHJ-1      | 37.53                             | 16.67    | 1.38      | 7.69       | 11.80       | 44.4     | 3.7       | 20.5       | 31.4        |
| SHJ-2      | 13.81                             | 3.30     | 1.06      | 6.03       | 3.44        | 23.9     | 7.6       | 43.6       | 24.9        |
| SHJ-3      | 7.61                              | 1.96     | 0.18      | 3.23       | 2.24        | 25.8     | 2.4       | 42.4       | 29.4        |
| SHJ-4      | 7.35                              | 0.63     | 0.08      | 4.14       | 2.50        | 8.6      | 1.0       | 56.3       | 34.0        |
| CZ-1       | 3.77                              | 0.01     | 0.14      | 2.79       | 0.83        | 4.2      | 2.6       | 63.1       | 30.2        |
| CZ-2       | 7.98                              | 0.33     | 0.21      | 5.04       | 2.41        | 32.1     | 15.4      | 52.6       | 27.4        |
| CZJ-1      | 9.90                              | 3.18     | 1.52      | 5.20       | 18.7        | 15.0     | 38.9      | 27.4       | 27.4        |
| CZJ-2      | 22.10                             | 4.13     | 3.32      | 8.60       | 6.05        | 4.2      | 55.7      | 40.2       | 27.4        |
| CZJ-3      | 8.51                              | 0.35     | 4.74      | 3.42        | 4.2        | 10.8     | 5.9       | 55.7       | 27.7        |
| CZJ-4      | 21.32                             | 2.30     | 1.25      | 11.87      | 5.91        | 10.8     | 5.9       | 55.7       | 27.7        |
before and after triaxial compression was roughly the same. Chengzhuang Mine with a slightly lower elastic modulus overall pore size distribution of the coal samples from the Triaxial Compression under Di
Nanoscale Pore Structure in Coal before and after categories, i.e., 2

experimental data, the pore size measured with the liquid accurately determine the changes in the coal samples after compression experiment di

samples from the Sihe Mine with a higher elastic modulus and 50 to 100 nm was relatively small, indicating that these volume of pores with pore diameters ranging from 5 to 10

volume of the coal samples with pore diameters ranging from 2

the probability of pores in these two ranges is relatively large. The main peak occurred between 2 and 4 nm, indicating that

to 5 and 10 to 50 nm had a peak distribution, indicating that

However, the pore size distribution differed under different confining pressures. When the pore diameter ranged between 2 and 5 nm, the peak value of the coal sample appeared and the pore diameter category corresponding to the coal sample at different confining pressure peaks was basically the same. After compression, the pore volume gradually decreased with the increase in confining pressure. As the confining pressure increased, the pores of the coal body were compressed and large pores gradually transformed into small pores. The greater the confining pressure, the greater the pore compression effect. This shows that under confining pressure, coal samples with large pore diameters gradually transition to small pore diameters, the samples are compacted, and the pores are compacted or even close.

In contrast, the pore volume of the samples from the Chengzhuang Mine with a lower elastic modulus slightly increased after triaxial compression. The coal sample pore volume between 2–5 and 10–50 nm was larger and peaked. The main peak occurred between 2 and 4 nm, indicating that the pores between these two categories are affected the most by triaxial compression. During the compression of the coal sample, the pore volume first increased, then decreased, and then greatly increased with the increase in confining pressure. This trend is also related to the mechanical properties of the coal sample. The compressive shear strength of the coal samples from the Chengzhuang Mine was small, and shear failure is more likely to occur. This shows that the coal body first produces microfractures during compression. However, when the confining pressure increases to a certain extent, the internal fractures of the coal sample expand and penetrate, and the pore volume tends to increase in each stage. The largest

Figure 5. Distributions of the pore size and pore volume of coal samples before and after triaxial compression shearing.

Table 4. Specific Surface Area of Each Pore Size Category of the Coal Sample

| sample no. | total specific area (m²/g) | specific surface area for each pore size category (m²/g) | ratio of pore specific surface area (%) |
|------------|---------------------------|------------------------------------------------------|----------------------------------------|
|            | 2–5 nm  | 5–10 nm  | 10–50 nm  | 50–100 nm  | 2–5 nm  | 5–10 nm  | 10–50 nm  | 50–100 nm  |
| SH-1       | 3.59    | 2.47     | 0.66     | 0.42       | 0.04    | 68.8     | 18.4     | 11.6     | 1.2       |
| SH-2       | 1.46    | 0.96     | 0.21     | 0.26       | 0.04    | 65.5     | 14.1     | 18.0     | 2.4       |
| SHJ-1      | 2.89    | 2.61     | 0.08     | 0.14       | 0.06    | 90.2     | 2.8      | 4.8      | 2.2       |
| SHJ-2      | 0.64    | 0.45     | 0.06     | 0.10       | 0.02    | 70.8     | 9.6      | 16.2     | 3.3       |
| SHJ-3      | 0.38    | 0.30     | 0.01     | 0.06       | 0.01    | 79.2     | 2.5      | 14.6     | 3.7       |
| SHJ-4      | 0.17    | 0.09     | 0.07     | 0.02       | 0.02    | 49.6     | 2.0      | 39.3     | 9.1       |
| CZ-1       | 0.06    | 0.05     | 0.01     | 0.09       | 0.02    | 29.8     | 6.2      | 54.9     | 9.2       |
| CZ-2       | 0.17    | 0.05     | 0.01     | 0.09       | 0.02    | 29.8     | 6.2      | 54.9     | 9.2       |
| CZJ-1      | 0.60    | 0.44     | 0.09     | 0.07       | 0.07    | 73.8     | 14.3     | 11.9     |           |
| CZJ-2      | 0.89    | 0.52     | 0.18     | 0.15       | 0.04    | 58.5     | 20.3     | 16.9     | 4.4       |
| CZJ-3      | 0.15    | 0.05     | 0.08     | 0.02       | 0.02    | 32.5     | 53.0     | 14.5     |           |
| CZJ-4      | 0.60    | 0.29     | 0.08     | 0.21       | 0.04    | 47.3     | 12.7     | 34.0     | 6.0       |
The relative pressures (P/P₀) continuously decrease with the increase in confinement pressure. This shows that the gas stored in coal has a tendency to seep during compression. The permeability of the coal samples becomes weaker. The pores with sizes ranging between 2 and 5 nm contributed the most to the specific surface area of the pores and the average proportion after compression (72.4%) increased compared with that before compression (67.2%). The larger peak of the coal samples after triaxial compression increased compared with that before compression (67.2%).

The correlation between the pore size and the pore specific surface area decreases. The correlation coefficient was greater than 0.9, indicating that the Sihe coal samples have good fractal characteristics. Based on the abovementioned data, fractal calculation is used to represent the irregularity of the pore network in the coal seam and therefore represents more complex pore features. Based on the abovementioned data obtained via low-temperature liquid nitrogen adsorption experiments, ln [ln (P/P₀)] and ln V values of each coal sample after triaxial compression can be calculated. The fractal dimension values of different pore size categories of the coal body can be obtained based on the slope. Statistical data are shown in Table 5.

Table 5 shows that the correlation coefficients R² of D fitting of the coal samples from the Sihe Mine are greater than 0.9, indicating that the Sihe coal samples have good fractal characteristics. The fractal dimension is a constant; and D is the fractal dimension. If the pore structure of the coal has fractal characteristics, ln V and ln (P/P₀) will show a linear correlation, K is the slope of the straight line, and D is the fractal dimension. If the pore structure of the coal has fractal characteristics, ln V and ln (P/P₀) will show a linear correlation, K is the slope of the straight line, and D is the fractal dimension.

\[
\ln \frac{V}{V_0} = K \ln \left( \ln \left( \frac{P_0}{P} \right) \right) + C
\]

\[
D = K + 3
\]

where V is the volume of the adsorbed gas under different relative pressures (P/P₀); V₀ is the volume of nitrogen-adsorbed monolayer molecules; P₀ is the gas-saturated vapor pressure; K is the slope of the straight line; C is a constant; and D is the fractal dimension.

Table 5. Fractal Results of the Coal FHH Model

| mine | aperture range (nm) | K   | D   | correlation coefficient R² |
|------|---------------------|-----|-----|-----------------------------|
| SH-1 | 2 ≤ d < 7           | −0.26 | 2.74 | 1.00                        |
|      | 7 ≤ d ≤ 55          | −0.13 | 2.87 | 0.99                        |
| SH-2 | 2 ≤ d < 11          | −0.23 | 2.77 | 0.96                        |
|      | 11 ≤ d ≤ 50         | −0.24 | 2.76 | 1.00                        |
| SHJ-1| 2 ≤ d < 11          | −0.23 | 2.78 | 1.00                        |
|      | 11 ≤ d ≤ 40         | −0.14 | 2.86 | 0.98                        |
| SHJ-2| 2 ≤ d < 5           | −0.50 | 2.50 | 0.99                        |
|      | 5 ≤ d ≤ 51          | −0.25 | 2.75 | 0.98                        |
| SHJ-3| 2 ≤ d < 6           | −0.48 | 2.52 | 0.93                        |
|      | 6 ≤ d ≤ 50          | −0.24 | 2.76 | 0.95                        |
| SHJ-4| 2 ≤ d < 7           | −0.27 | 2.73 | 0.92                        |
|      | 7 ≤ d ≤ 50          | 0.43  | 3.43 | 0.95                        |
| CZ-1 | 2 ≤ d < 8           | −0.02 | 2.98 | 0.80                        |
|      | 8 ≤ d ≤ 54          | −0.61 | 2.39 | 0.99                        |
| CZ-2 | 2 ≤ d < 8           | −0.15 | 2.85 | 0.04                        |
|      | 8 ≤ d ≤ 51          | −0.59 | 2.41 | 1.00                        |
| CZJ-1| 2 ≤ d < 4.5         | −0.86 | 2.14 | 0.98                        |
|      | 4.5 ≤ d < 41        | −0.25 | 2.75 | 0.99                        |
| CZJ-2| 2 ≤ d < 53          | −0.20 | 2.80 | 1.00                        |
| CZJ-3| 2 ≤ d < 11          | −0.05 | 2.95 | 0.39                        |
|      | 11 ≤ d ≤ 50         | −0.63 | 2.37 | 1.00                        |
| CZJ-4| 2 ≤ d < 11          | −0.15 | 2.85 | 0.97                        |
|      | 11 ≤ d ≤ 51         | −0.31 | 2.69 | 1.00                        |
characteristics. It can be seen from Figure 7 that due to the influence of different confining pressures, $P/P_0$ has different fractal dimensions at different demarcation points. In the low-pressure section, nitrogen was mainly adsorbed on the surface...
of coal pores through monomolecular adsorption. When the relative pressure was high, monomolecular adsorption changed to multilayer molecular adsorption and the nitrogen molecules exhibited capillary condensation. When the relative pressure was lower than the boundary point, the fractal dimensions of the pores of the two original coal samples from the Sihe Mine...
before triaxial compression were 2.74 and 2.78, respectively, with an average of 2.75, and the diameter of coal was less than 11 nm. The average fractal dimension of coal sample pores is 2.63, which is slightly smaller than that before compression, indicating that the surface morphology of coal micropores after compression is simple. The fractal dimension of each coal in this size category was generally large, indicating that the heterogeneity of the meso- and macropores is strong. The average fractal dimension before and after compression was 2.82 and 2.95, respectively, representing a slight increase. This indicates that the pore structure in mesoporous and macroporous coal becomes complex due to compression. Large pores were compacted, and then they transformed into small pores or micropores. The macropore structure became complex and reduced the gas seepage capacity. In the same coal sample, the structure of mesopores and macropores was more complex than that of micropores, which indicates that the pore structure of the coal is more complex and more heterogeneous than the pore surface (Figure 8).

According to the pore characteristics of Chengzhuang coal samples, the corresponding \( \ln \left[ \frac{P_0}{P} \right] \) and \( V \) values under different pressures are segmented. It can be seen that the segments are not uniform, indicating that the sample has a strong heterogeneity. Excluding the influence of sample heterogeneity, the correlation coefficient \( R^2 \) of the fitting is greater than 0.75, indicating that coal samples generally have fractal characteristics. In the low-pressure section, the fractal dimension of the coal pores tended to decrease due to compression. In the high-pressure section, the fractal dimension changed insignificantly, indicating that triaxial compression reduces the proportion of pores with small diameters and overall coal sample pore size. The complexity of the structure changed insignificantly, pore segmentation features were not pronounced, and the boundary pore sizes were not uniform, which is mainly related to the heterogeneity of the samples and different confining pressures. Independent of compression, the roughness and complexity of the pore structure of the large pore surface were greater than the roughness and complexity of the pore structure of the small pore surface.

4. CONCLUSIONS

Industrial analysis, mechanical property analysis, and liquid nitrogen adsorption experiments were conducted to study the effect of the coal sample structure on the occurrence and migration of CBM before and after triaxial compression. The main conclusions are as follows

(1) The triaxial compressive strength of coal linearly increases with increased confining pressure. Based on the Coulomb strength criterion, the compressive and shear strengths of the coal samples from the Sihe Mine are significantly greater than those of the coal samples from the Chengzhuang Mine. Based on the stress-strain curves of the samples from the two mines, it can be concluded that the Sihe coal sample with a larger elastic modulus exhibits greater stress and strain peaks during the compression process than the sample from the Chengzhuang Mine with a smaller elastic modulus. With the exception of the coal sample from the Chengzhuang Mine under a confining pressure of 15 MPa, the peak strength and axial strain of the coal samples from the other mines gradually increased with the increase in confining pressure. The larger the elastic modulus, the greater the axial strain. In general, the mechanical properties of the coal samples from the Sihe Mine are better than those of the samples from the Chengzhuang Mine.

(2) The pore size ratios of the coal samples from the two mines changed to varying degrees after compression. The pore size between 2 and 5 nm changed most prominently. The pore specific surface area decreased with increased confining pressure. The average value was 60.7 and 59.7% lower than that of raw coal. The surface morphology of the micropores (2–11 nm) in the coal was simpler after compression and that of mesopores and macropores (>11 nm) was relatively simple. The structure was more complex after compression. The adsorption performance of coal samples is getting worse and worse, and the seepage capacity is relatively weak. The pore volume and pore specific surface area of the sample from the Chengzhuang Mine with a low elastic modulus first increased, then decreased, and then increased again with increased confining pressure. The proportion of the specific surface area of micropores increases compared to before, indicating that the coal sample has a stronger adsorption capacity after compression than before. Triaxial compression reduced the proportion of pores with small diameters, but the segmentation characteristics were not pronounced and the aperture demarcation point was not uniform, which is mainly related to the heterogeneity of the samples and different confining pressures. Before and after compression, the roughness and complexity of the macropores of the coal samples from the Chengzhuang Mine were larger than those of the micropores.

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Notes
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