INTRODUCTION

Coal and gas outburst is one of the most serious disasters in coal mine production. It will not only cause serious damage to personnel and equipment, but also has a serious impact on society. During the process of working face advancement, the stress field of coal and rock mass undergoes changes complexly, undergoing complex loading and unloading process, the stress redistribution. The coal mass in front of the working face can be divided into a stress reduction zone, a stress increase zone, and an original stress zone. The coal mass is in a stress reduction zone near the goaf, the gas in the coal mass is effectively released and the gas pressure is reduced. Therefore, it is instructive to study the mechanics and permeability of raw coal containing gas under loading and unloading to prevent coal and gas outburst.
According to the “comprehensive action hypothesis” of coal and gas outburst, many factors affecting coal and gas outburst were related to the geo-stress field, gas pressure, physical, and mechanical properties of raw coal.\textsuperscript{1} At present, domestic and foreign scholars have abundant researches on the mechanics, deformation, and permeability characteristics of coal, and in-situ stress plays a decisive role in the permeability of coal seams.\textsuperscript{2,4} The permeability of coal seam has an important influence on gas enrichment, emission and distribution law of gas pressure, while the permeability and mechanical properties of coal body are greatly affected by the gas pressure.\textsuperscript{5-9} The research on the loading and unloading process of gas containing raw coal mainly focuses on the loading axial stress and unloading confining pressure test. Pan et al\textsuperscript{10} studied the permeability characteristics of raw coal samples containing bedding during loading and unloading. Xie et al\textsuperscript{11} discussed the difference of characteristics of the actual mining stress field, fracture field and seepage field of coal rock under different mining modes. Zhao et al\textsuperscript{12} carried out the uniaxial multi-stage cyclic addition and unloading experiments of raw coal, and discussed the internal damage evolution characteristics and precursors of damage during the process of raw coal failure. Zhu et al\textsuperscript{13} studied the mechanical properties of coal-rock composite specimens during uniaxial staged cyclic loading and unloading. Cheng et al\textsuperscript{14} conducted the 3D dynamic evolution analysis of coal-rock damaged field and gas seepage field during the gas extraction process. Zakharov et al\textsuperscript{15} put forward an analytical relation between coal permeability, stresses, and adsorbed gas to define parameters of gas leakage zone parameters and laws of mass transfer. Wei et al\textsuperscript{16} introduced an intrinsic permeability model under variable stress conditions and the impact of the adsorbed layer thickness into a typical apparent permeability model. Zuo et al\textsuperscript{17} determined the effective stress coefficient of coal during gas penetration and investigated the impact of effective stress and gas slippage on coal permeability under cyclic loading conditions. Wang et al\textsuperscript{18} investigated the deformation and gas flow characteristics of coal-like materials under triaxial stress conditions. Geng et al\textsuperscript{19} used reconstituted coal as a research material to study porosity and permeability characteristics of compacted coal fines in coal reservoir fractures. Duan et al\textsuperscript{20} carried out the classified loading and unloading test of raw coal containing gas, analyzed and discussed the deformation, permeability, and energy consumption characteristics of coal and rock, and established damage variable equation combined with energy consumption characteristics. Vishal et al\textsuperscript{21} investigated the bituminous coals from Jharia coalfield in India for changes in the strength of samples due to saturation with moisture and CO\textsubscript{2}. Vogler et al\textsuperscript{22} investigated transmissivity evolution for fluid flow through natural fractures in granodiorite at the laboratory scale. Wang et al\textsuperscript{23} carried out experimental study on permeability of coal samples at different heights under cyclic loading and unloading. Chen et al\textsuperscript{24} performed adsorption and desorption tests and full stress-strain-seepage tests on samples in layers with different dip angles. Yu et al\textsuperscript{25} studied the effects of confining pressure, axial pressure and temperature on the permeability of shaped coal samples. Zhuo et al\textsuperscript{17} investigated the impact of effective stress and gas slippage on coal permeability under cyclic loading conditions, and studied the evolution law of coal anisotropic permeability with effective stress. Zhang et al\textsuperscript{27} used the unsteady-state method determined that the gas water relative permeability. Zhang et al\textsuperscript{27} investigated the mechanical behavior and permeability of coal rock under different degrees of unloading confining pressure-reloading axial stress. For the effect of temperature on the permeability of coal and rock, Li et al\textsuperscript{28} studied the relationship between permeability and temperature and stress using adsorbed gas methane and nonadsorbed gas helium. Yang et al\textsuperscript{29} used the pressure pulse attenuation method to test the permeability of coal and rock before and after low temperature treatment, and discussed in detail the principle of low temperature causing coal rock damage and increasing coal seam permeability. Wei et al\textsuperscript{30} studied the variation law of coal permeability and the mechanism of antireflection under temperature shock conditions, and discussed the distribution law of acoustic emission signals during temperature shock.

Although the above scholars have carried out a lot of mechanical and permeability tests on coal and rock mass under loading and unloading conditions, the study of mechanical and permeability characteristics of coal mass is still insufficient. In this paper, the “Triaxial stress thermal-hydrological-mechanical coal gas permeameter” was used to test the mechanical and permeability characteristics of 2 + 3# coal seam in Shan mushu coal mine of Sichuan Coal Group under different confining pressure and gas pressure conditions. The test scheme conforms to the stress state of coal and rock mass in the field mining process, which can accurately describe the deformation and permeability characteristics of coal mass in the mining process. The research results can provide reference values for disaster control such as coal and gas outburst.

2 | TEST APPARATUS AND SCHEME DESIGN

2.1 | Test apparatus

The test equipment adopts the “Triaxial stress thermal-hydrological-mechanical coal gas permeameter” developed by Chongqing University,\textsuperscript{31} as shown in Figure 1. The equipment can conduct coal-rock gas permeability test under different stress and gas pressure. The maximum axial pressure is 200 kN, the confining pressure is 10 MPa, the maximum
axial deformation displacement is 60 mm, and the maximum radial deformation is 6 mm. The temperature ranges from room temperature to 100°C. The stress measurement system has an accuracy of ±1%, a deformation accuracy of ±1%, and a temperature control accuracy of ±1%.

2.2 | Sample preparation

The test samples were taken from the 2 + 3# coal seam of Shan mushu coal mine, Sichuan Coal Group, the coal seam belongs to the coal and gas outburst coal seam. The lump coal larger than 200 mm was sealed with plastic wrap and transported back to the laboratory for processing into a standard cylinder sample with a diameter of 50 mm and a height of 100 mm. The diameter and height of the sample was measured by a vernier caliper, and the mass of the sample was measured by electronic scale, the density of the raw coal sample was calculated to be 1506.43 kg/m³. The smoothness of both ends of the sample is controlled within 0.05 mm, the processing accuracy meets requirements, the equipment and raw coal samples are shown in Figure 2.

2.3 | Test scheme

During the coal seam mining process, the stress changes complexly in front of the working face, and appear the stress concentration zone, the stress reduction zone and the original stress zone. With the continuous development of the working face, the coal body undergoes a complex loading and unloading process. Therefore, it is of great significance to study the mechanical and permeability characteristics of raw coal samples during the loading and unloading process to prevent and control coal and gas outburst. The design test scheme is as follows:

(a) gradually apply axial stress and confining pressure to hydrostatic pressure state (σ₂ = σ₃ = 8.0 MPa); (b) adjust gas pressure p₁ = 1.0 MPa, the gas was fully adsorbed for 2 hours, open gas outlet valve and wait for steady flow; (c) constant axial stress and gas pressure, unloading confining pressure from 8.0 MPa to 4.0 MPa; (d) constant confining pressure and gas pressure, load axial stress still the coal sample failure at displacement control loading rate of 0.1 mm/min; (e) at the end of the test, replace the coal sample, change the gas pressure to 1.0 MPa, 2.0 MPa, and 3.0 MPa, and unload the confining pressure to 4.0 MPa, 6.0 MPa, and 8.0 MPa,
respectively. In this test, the loading and unloading axial stress at stress loading rate of 0.05 kN/s, the unloading confining pressure at stress control unloading rate of 0.02 MPa/s.

3 | ANALYSIS OF TRIAXIAL SEEPAGE TEST RESULTS OF GAS CONTAINING RAW COAL

Assuming that the sample is homogeneous isotropic material, without considering negative pressure, in the triaxial compression seepage test, the outlet pressure of the sample is equal to atmospheric pressure, and the seepage of gas in coal sample conforms to Darcy’s law. When the gas pressure at the inlet end of the sample is constant, the formula for calculating the permeability of the sample is as follows:

$$k = \frac{2\mu q_0 L}{A(p_0^2 - p_{out}^2)}$$ (1)

Where, $k$ is the permeability (mD); $\mu$ refers to the gas kinematic viscosity (Pa·s); $L$ is the sample length (mm), $p_0$ is 1.0 atmosphere, $A$ is the cross-section area of the sample (mm²); $p_{in}$ is gas pressure at the sample inlet (MPa); $p_{out}$ is gas pressure at the sample outlet (MPa), which is the atmospheric pressure (0.1 MPa); $q_0$ is the seepage flow of $p_0$ at standard atmospheric pressure (cm³/s).

3.1 | Analysis of deformation and permeability of raw coal samples under different gas pressures

Figure 3 presents the complete stress-axial strain-permeability curve of triaxial compression under different gas pressure conditions when the confining pressure was unloaded to 4.0 MPa. It can be seen that from Figure 3, the axial direction is compression deformation of the specimen during constant axial stress of 8.0 MPa and confining pressure was unloaded from 8.0 MPa to 4.0 MPa, the axial strain was increased to $0.026 \times 10^{-2}$, $0.015 \times 10^{-2}$, and $0.027 \times 10^{-2}$ under gas pressure of 1.0 MPa, 2.0 MPa, and 3.0 MPa, respectively. The permeability of the sample increases nonlinearly with the unloading of the confining pressure, the permeability increases from 3.225 mD to 4.203 mD with gas pressure of 1.0 MPa, which is increased by 29.12%. When the gas pressure is 2.0 MPa, the permeability of the sample increases from 3.668 mD to 5.319 mD, which is increased by 45.03%. When the gas pressure is 3.0 MPa, permeability increases from 4.219 mD to 7.301 mD, which is increased by 73.03%. According to the above analysis, during the initial test, the confining pressure was unloaded from 8.0 MPa to 4.0 MPa, the micropores and cracks in the sample are gradually open, the capacity enhancement of gas passing through the sample, the permeability increases gradually. As the gas pressure increases, the permeability increase rate of the sample increases gradually. The possible reason is that as the gas pressure increases, the gas content adsorbed inside the sample increases, and the expansion deformation of the coal sample increases, and at the same time, under the external pressure of the coal sample, the expansion stress of the sample increases, which leads to the increase of gas flow through the sample. Under the conditions of constant confining pressure and gas pressure, the axial direction changes to the displacement control during the loading of the axial stress, the axial strain gradually increases, the permeability and axial strain are inclined in a “V” shape. The permeability of the sample decreases first and then increases with the increases of the axial strain, and decreases until the yield point of the sample.

However, the permeability of the specimen decreases slightly at the initial stage of loading axial stress under gas pressure of 2.0 MPa, and decreases greatly until the loading of the axial stress to 22.57 MPa, which may be that the initial micro-pores and cracks in the sample are not closed due to the low stress conditions in the initial stage of loading axial pressure, resulting in a small reduction in the permeability of samples. However, as the axial stress continued to load, the sample will be damaged when it reached the ultimate bearing capacity, the ultimate strength of the specimen is 41.04 MPa under gas pressure of 1.0 MPa, the corresponding axial strain of the specimen is $1.489 \times 10^{-2}$, the permeability is 0.940 mD; the ultimate strength of the specimen is 39.80 MPa under gas pressure of 2.0 MPa, the corresponding axial strain is $1.514 \times 10^{-2}$, the permeability is 2.555 mD; the ultimate strength of the specimen is 38.52 MPa under gas pressure of 3.0 MPa, the corresponding axial strain is $1.542 \times 10^{-2}$ and the permeability is 2.049 mD. It can be seen that with the increase of gas pressure, the initial permeability of the raw coal sample increases gradually, the ultimate bearing capacity of the
sample gradually decreases, and the axial strain increases gradually when the sample reaches the ultimate strength, compared with the ultimate strength of the sample at gas pressure of 1.0 MPa, the ultimate strength of the sample at gas pressure of 2.0 MPa and 3.0 MPa decreases by 3.02% and 6.14%, respectively.

Figure 4 presents the complete stress-axial strain-permeability curve of triaxial compression under different gas pressure conditions when the confining pressure was unloaded to 6.0 MPa.

It can be seen that from Figure 4, the axial direction compression deformation of specimens during constant axial stress of 8.0 MPa and confining pressure was unloaded from 8.0 MPa to 6.0 MPa, the axial strain was increased to 0.014 × 10⁻², 0.004 × 10⁻² and 0.012 × 10⁻² under gas pressure of 1.0 MPa, 2.0 MPa and 3.0 MPa, respectively. The permeability of the sample increases nonlinearly with the unloading of the confining pressure, the permeability increases from 0.486 mD to 0.494 mD with gas pressure of 1.0 MPa, which is increased by 1.65%. When the gas pressure is 2.0 MPa, the permeability of the sample increases from 0.884 mD to 0.918 mD, which is increased by 3.91%. When the gas pressure is 3.0 MPa, permeability increases from 1.168 mD to 1.264 mD, which is increased by 8.2%. According to the above analysis, in the initial test of unloading confining pressure process, the increment of permeability increases gradually with the increase of the gas pressure. But, under the same gas pressure, the increment of permeability of the sample when the confining pressure was unloaded to 6.0 MPa is much smaller than the increment of permeability of the sample when the confining pressure was unloaded to 4.0 MPa. Perhaps the micropores and cracks in the sample open slowly during the process of unloading confining pressure, and the larger the unloading confining pressure is, the greater the opening degree of the micropores in the sample will be; the stronger of capacity the gas passing through the sample is, the greater the increment of the permeability of the sample will be.

In the process of loading axial stress at displacement control, the permeability decreases nonlinearly with the increase of axial strain. When the axial stress reaches the bearing strength of the specimen, the damage occurs. At this time, the permeability increases rapidly, the permeability increase rate of the postpeak is greater than the permeability decrease rate of the prepeak. Under gas pressure of 1.0 MPa, 2.0 MPa and 3.0 MPa, the peak strength of the specimens were 50.95 MPa, 48.18 MPa and 44.78 MPa, respectively, the corresponding axial strains were 2.006 × 10⁻², 1.57 × 10⁻² and 1.763 × 10⁻², and the permeability is 0.358 mD, 1.025 mD and 0.163 mD, respectively. It can be seen that with the gas pressure increases, the initial permeability of raw coal sample increases gradually, and the ultimate bearing strength of the sample gradually decreases. Compared with the ultimate strength of specimens under gas pressure of 1.0 MPa, the ultimate bearing strength of specimens under gas pressure of 2.0 MPa and 3.0 MPa decreased by 5.42% and 12.11%, respectively.

Figure 5 presents the complete stress-axial strain-permeability curve of triaxial compression under different gas pressure conditions when the confining pressure was 8.0 MPa.

As can be seen from Figure 5, the deviatoric stress-axial strain curves of the sample undergoes roughly four stages, and the permeability-axial strain curves of the coal samples also exhibits a phased change. (a) In the compaction stage, the micropores and cracks in the specimen are slowly compacted and closed, the axial direction is nonlinear deformation, and the stress-strain curve bends upward; (b) In the elastic stage, the stress-strain curve is approximately straight line. The deformation of the unloading specimen
can be recovered at this stage, the internal structure has not been damaged, there are no new cracks, and the permeability of the specimen is always reduced; (c) In the yield stage, the stress-strain curve is bent downward, and the sample is inelastic deformation, the material with lower internal strength first yields and destroys gradually, and the increase rate of axial stress decreases gradually; (d) In the failure stage, the axial pressure reaches the bearing capacity of the specimen, and the strain-strain curve is negative, the specimen forms a through-crack in the direction parallel to the axial pressure, and the permeability of the specimen increases rapidly. Under gas pressure of 1.0 MPa, 2.0 MPa, and 3.0 MPa, the peak strength of the specimen was 62.63 MPa, 61.02 MPa, and 58.75 MPa, respectively, and the corresponding axial strain was $1.805 \times 10^{-2}$, $1.952 \times 10^{-2}$, and $1.808 \times 10^{-2}$, and the permeability was 0.011 mD, 0.013 mD, and 0.002 mD, respectively. It can be seen as the gas pressure increases, the ultimate strength of the specimen gradually decreases. Compared with the gas pressure of 1.0 MPa, the ultimate strength of the sample under gas pressure of 2.0 MPa and 3.0 MPa decreases by 2.57% and 6.2%, respectively.

3.2 | Analysis of deformation and permeability characteristics of raw coal samples under different confining pressures

Figure 6 presents the complete stress-axial strain-permeability curves with gas pressure of 1.0 MPa, 2.0 MPa, and 3.0 MPa under different confining pressure.

It can be seen from Figure 6 that under the condition of gas pressure of 1.0 MPa, the initial permeability of the sample was 3.255 mD, 0.486 mD, and 0.021 mD at the confining pressure of 4.0 MPa, 6.0 MPa, and 8.0 MPa, respectively, and the permeability was 50.95 MPa, and 62.63 MPa, respectively. The corresponding axial strains was $1.489 \times 10^{-2}$, $2.006 \times 10^{-2}$, and $1.808 \times 10^{-2}$, respectively, compared with the confining

![Figure 6](image-url)
pressure of 4.0 MPa, the initial permeability decreases by 85.07% and 99.36% at confining pressure of 6.0 MPa and 8.0 MPa, the peak strength increases by 24.15% and 52.61%, the axial strain increases by 34.72% and 21.22%, respectively. Under gas pressure of 2.0 MPa, the initial permeability of the specimen was 3.668 mD, 0.884 mD, and 0.083 mD, respectively. The ultimate strength of the sample was 39.8 MPa, 48.19 MPa, and 61.02 MPa. At this time, the corresponding axial strain was 1.514 × 10⁻², 2.015 × 10⁻², and 1.952 × 10⁻², respectively. Compared with the confining pressure of 4.0 MPa, the initial permeability decreases by 75.9% and 97.74% at confining pressure of 6.0 MPa and 8.0 MPa, the peak strength increases by 21.08% and 53.52%, the axial strain increases by 33.09% and 28.93%, respectively. Under gas pressure of 3.0 MPa, the initial permeability of the specimen was 4.219 mD, 1.168 mD, and 0.004 mD, respectively. The ultimate strength of the sample was 38.52 MPa, 44.78 MPa, and 58.75 MPa. At this time, the corresponding axial strain was 1.542 × 10⁻², 1.763 × 10⁻², and 1.808 × 10⁻², respectively. Compared with the confining pressure of 4.0 MPa, the initial permeability decreases by 72.32% and 99.9% at confining pressure of 6.0 MPa and 8.0 MPa, the peak strength increases by 16.25% and 52.52%, the axial strain increases by 14.33% and 17.25%, respectively. From the above analysis, it can be seen that under the same gas pressure and different confining pressure, the peak intensity of the sample increases with the increase of confining pressure, and the initial permeability of the sample gradually decreases. It may be that the higher the confining pressure is, the stronger the degree of internal micropores and fracture compaction will be, the greater the restriction on the expansion of micropores and crack is, the smaller the gas flow rate. Therefore, confining pressure has a compression closure effect on the micropores and crack inside the sample.

3.3 | Analysis of strength and deformation modulus of samples

The variation curves of peak strength with gas pressure and confining pressure are drawn as shown in Figure 7.

With the increase of gas pressure, the peak strength of the sample decreases gradually, and the fitted gas pressure is in linear with the peak strength of the sample, the fitting curve is shown in Figure 7A. With the increase of confining pressure, the peak intensity of specimen increases gradually, and fitted confining pressure is in exponential relationship with the peak intensity of the sample, the fitting curve is shown in Figure 7B.

The curves of elastic modulus with gas pressure and confining pressure were drawn as shown in Figure 8.

It can be seen from Figure 8 that under the condition of gas pressure of 1.0 MPa, the elastic modulus of each specimen is 2.65 GPa, 3.08 GPa, and 3.62 GPa at confining pressure of 4.0 MPa, 6.0 MPa, and 8.0 MPa, respectively. Under the condition of gas pressure of 2.0 MPa, the elastic modulus of each specimen is 2.55 GPa, 3.14 GPa, respectively. From the above analysis, it can be seen that under the same gas pressure and different confining pressure, the peak intensity of the sample increases with the increase of confining pressure, and the initial permeability of the sample gradually decreases. It may be that the higher the confining pressure is, the stronger the degree of internal micropores and fracture compaction will be, the greater the restriction on the expansion of micropores and crack is, the smaller the gas flow rate. Therefore, confining pressure has a compression closure effect on the micropores and crack inside the sample.

FIGURE 7 Variation curves of peak strength of samples with gas pressure and confining pressure. (A) peak strength-gas pressure, (B) peak strength-confining pressure

FIGURE 8 Variation curves of elastic modulus of samples with gas pressure and confining pressure. (A) Elastic modulus-gas pressure, (B) Elastic modulus-confining pressure
and 3.66 GPa at confining pressure of 4.0 MPa, 6.0 MPa, and 8.0 MPa, respectively. Under the condition of gas pressure of 2.0 MPa, the elastic modulus of each specimen is 2.89 GPa, 2.74 GPa, and 3.77 GPa at confining pressure of 4.0 MPa, 6.0 MPa, and 8.0 MPa, respectively. It can be seen that the elastic modulus of specimens increases trend with the increase of confining pressure under different gas pressure conditions. The elastic modulus decreases trend with the increase of gas pressure when the confining pressure is 6.0 MPa.

3.4 | Mohr-Coulomb stress circle

Coulomb strength considers that the shear strength τs of coal and rock is determined by cohesion c and internal friction angle φ, and its strength envelope is a straight line.

\[ τ_s = c + \sigma \tan φ \]  

(2)

Where, σ is the normal stress, c is the cohesive force, φ is the internal friction angle, and σ tan φ is the frictional resistance acting on the failure surface when the coal-rock is destroyed.

When the criterion is expressed by the maximum principal stress \( \sigma_1 \) and the minimum principal stress \( \sigma_3 \), it can be written as:

\[ \sigma_1 = i + j\sigma_3 \]  

(3)

\( i \) and \( j \) are strength criterion parameters of coal and rock, \( i \) is the strength parameter corresponding to the complete shear failure of coal and rock under uniaxial compression, and \( j \) is the influence coefficient of confining pressure on the axial bearing capacity, the relationship between \( i \) and \( j \) and internal friction angle φ and cohesion c is as follows:

\[ i = \tan^2(45° + \phi/2) \]  

(4)

\[ j = 2c\cos\phi/(1 - \sin\phi) \]  

(5)
According to the Equation 3, the peak strength of the sample under different gas pressures is regressed with the confining pressure, and the Mohr stress circle and envelope of the sample under different gas pressures are drawn as shown in Figure 9.

According to the Equations 4 and 5, the internal friction angle of the sample is 43.46° and cohesion is 4.1 MPa when the gas pressure is 1.0 MPa; the internal friction angle of the sample is 43.31° and cohesion is 3.8 MPa when the gas pressure is 2.0 MPa; the internal friction angle of the sample is 42.89° and cohesion is 3.4 MPa when the gas pressure is 3.0 MPa. It is known that with the increase of the gas pressure, the internal friction angle and cohesion of the raw coal sample decrease gradually, and the relationship between the internal friction angle and gas pressure, cohesion and gas pressure is in line with a linear function, as shown in Figure 10. The average internal friction angle of the raw coal sample was calculated to be 43.22°, and the average value of cohesion was calculated to be 3.77 MPa.

### 3.5 Relationship curves between deviatoric stress and permeability of sample

The relationship curves between the permeability and the deviatoric stress of the sample under different gas pressures are shown in Figures 11, 12, and 13. It can be seen that the permeability of the raw coal sample increases nonlinearly when constant axial stress and confining pressure are unloaded from 8.0 MPa to 4.0 MPa or 6.0 MPa. Maintain 8 MPa axial stress constant, unloaded confining pressure to a constant state of 4.0 MPa, the permeability of specimen shows a constant pressure boosting flow zone under the gas pressure of 1.0 MPa and...
3.0 MPa, as shown in Figure 11A, C. Maintain 8.0 MPa axial stress constant, unload confining pressure to a constant state of 6.0 MPa, the permeability of specimen shows a constant pressure boosting flow zone under the gas pressure of 2.0 MPa and 3.0 MPa, as shown in Figure 12B, C. The above analysis shows that in the constant pressure zone where the constant axial pressure is 8.0 MPa and confining pressure is unloaded to 4.0 MPa or 6.0 MPa, although the time is short, the raw coal sample is in a three-dimensional creep state during this period, that is, the specimen undergoes axial compression and radial expansion deformation, the micropores and cracks in the sample gradually open, and the ability of the gas passing through the sample is enhanced, resulting in the gas permeability increases nonlinearly. Due to the anisotropy of the sample, not all samples have this phenomenon. During the coal seam mining process, the coal body in front of the working face experiences the original stress zone, the stress increase zone and the stress reduction zone, during which the gas in the coal body continuously gushes out. When the working face is excavated to a certain distance, the stress redistributes to a new equilibrium state in front of the working face, and the stress is in a relatively balanced state, but the permeability of the coal seam is closely related to the stress, the change of the stress state makes the pore and fracture structure change in the coal seam, thus changing the permeability of the coal seam, leading to the change of the change of the gas flow rate in the coal seam. In the coal seam pressure relief area, the pores and fissures develop and penetrate, the gas permeability increases, and the gas flow increases. In the stress increase zone of the coal seam, the cracks in the coal seam shrink and close, the gas permeability is reduced, and the gas flow rate is reduced. In the original stress zone of the coal seam, the permeability does not change much, and the gas flow tends to be stable. Since the raw coal sample required for the test is taken from the S3012 working face, the test results can provide theoretical support for the site.

FIGURE 12 Relationship curves between permeability and deviatoric stress of sample when unloaded confining pressure to 6.0 MPa. (A) $p = 1.0$ MPa, (B) $p = 2.0$ MPa, (C) $p = 3.0$ MPa

$k = -0.2283 \exp (\sigma/108.3684) + 0.7126
R^2 = 0.996$

$k = -0.04331 \exp (\sigma/12.5909) + 0.5372
R^2 = 0.9817$

$k = 2.4973 \times 10^{-4} \exp (\sigma/0.1317) + 1.1676
R^2 = 0.9403$

$k = 1.8964 \exp (\sigma/11.0844) + 0.06532
R^2 = 0.9906$
The permeability decreases nonlinearly with the increase of the axial pressure during displacement controlled loading axial pressure. When the axial pressure reaches the ultimate bearing capacity of the specimen, instability failure occurs, stress drops, and the permeability of the specimen increases rapidly. The relationship curves between permeability and deviatoric stress during the process of unloading confining pressure and prepeak loading axial stress were fitted to satisfy \( \text{ExpDec1} \) function, as shown in Equation 6

\[
k = a \exp\left(-\frac{\sigma'}{b}\right) + c
\]

where, \( k \) is the permeability, mD; \( a, b, c \) are the fitting coefficients, \( \sigma' \) is the deviatoric stress, MPa.

**FIGURE 13** Relationship curves between permeability and deviatoric stress of sample when confining pressure was 8.0 MPa. (A) \( p = 1.0 \) MPa, (B) \( p = 2.0 \) MPa, (C) \( p = 3.0 \) MPa

4 | CONCLUSIONS

In this paper, the “Triaxial stress thermal-hydrological-mechanical coal gas permeameter” was adopted to implement the mechanical and seepage test of the raw coal sample during loading and unloading process. The conclusions are as follows:

1. The permeability of the sample increases nonlinearly during the process of unloading confining pressure. The larger the gas pressure is, the greater the increase range of the permeability will be. The larger the confining pressure unloading amplitude is, the greater the increase range of the permeability will be.
2. As the increase of gas pressure, the peak strength of the specimen decreases gradually, fitted gas pressure and peak strength conform to a linear relationship. As the confining pressure increases, the peak strength of the sample gradually increases, fitted confining pressure is in exponential relationship to the peak strength.

3. The strength characteristics of the sample were analyzed by Mohr-Coulomb strength criterion, and the internal friction angle of the coal sample was 43.22°, and the cohesion was 3.77 MPa. The relationship between the fitted gas pressure and internal friction angle, gas pressure and cohesion is in line with linear functions.

4. Maintain an axial stress constant, unloaded confining pressure to a constant state of target value, the permeability of specimen shows a constant pressure boosting flow zone, the relationship between permeability and deviatoric stress is accordance with the ExpDec1 function during the process of unloading confining pressure and prepeak loading axial stress.

CONFLICT OF INTEREST

The authors declare that they have no competing interests, and the original research has not been published previously. All authors gave final approval for publication.

AUTHOR CONTRIBUTIONS

Dong-ming Zhang and Yu-shun Yang conceived and designed the experiments; Yushun Yang performed the experiments; Yu-shun Yang, Shu-jian Li, Ya-pei Chu and Han Yang analyzed the data; and Yu-shun Yang wrote the paper.

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REFERENCES

1. Yu QX. Methane prevention in coal mine[M]. Xuzhou: China University of Mining and Technology Press; 1993.

2. Yin GZ, Li XQ, Zhao HB, et al. Experimental research on effect of geostress on outburst coal’s gas seepage. Chin J Rock Mech Eng. 2008;27(12):2557-2557.

3. Huang QX, Yin GZ, Jiang YD. Experimental study of mechanical characteristics of coal specimen in process of unloading confining pressure in geostress field and analysis of gas seepage characteristics. Chin J Rock Mech Eng. 2010;29(8):1639-1648.

4. Yin GZ, Huang QX, Zhang DM, et al. Test study of gas seepage characteristics of gas-bearing coal specimen during process of deformation and failure in geostress field. Chin J Rock Mech Eng. 2010;29(2):336-343.

5. Zhang ZP, Gao MZ, Zhang ZT, et al. Research on permeability characteristics of raw coal in complete stress-strain process under different gas pressure. J China Coal Soc. 2015;40(4):836-842.

6. Wang G, Cheng WM, Guo H, Long QM. Study on permeability characteristics of coal body with gas pressure variation. Journal of Mining & Safety Engineering. 2012;29(5):735-745.

7. Zhao HG, Zhang DM, Li WP, et al. Experimental study on influence of gas pressure on mechanical properties of sandstone. Chin J Rock Mech Eng. 2017;36:3239-3246.

8. Yuan M, Xu J, Li BB, et al. Experimental study of permeability and deformation of anthracite during process of gaseous loading-unloading. Chin J Rock Mech Eng. 2014;33(10):2138-2146.

9. Li JW, Liu JF, Zhang ZT, et al. Investigation on mechanical properties and permeability of coal under gas pressure. J China Univ Min & Technol. 2013;42(6):954-960.

10. Pan RK, Cheng YP, Dong J, et al. Research on permeability characteristics of layered natural coal under different loading and unloading. J China Coal Soc. 2014;39(3):473-477(5).

11. Xie HP, Zhang ZT, Gao F, et al. Stress-fracture-seepage field behavior of coal under different mining layouts. J China Coal Soc. 2016;41(10):2405-2417.

12. Zhao YX, Gong S, Teng T, et al. Characteristics of the load/unload response ratio of raw coal under uniaxial multi-level cyclic loading. Chin J Rock Mech Eng. 2018;37(5):1096-1105.

13. Zhu ZH, Feng T, Gong FQ, et al. Experimental research of mechanical properties on grading cycle loading-unloading behavior of coal-rock combination bodies at different stress levels. J Cent South Univ (Science and Technology). 2016;47(7):2069-2075.

14. Cheng HM, Zhang N, Yang YG, et al. 3-D dynamic evolution analysis of coal-rock damaged field and gas seepage field during the gas extraction process. J Nat Gas Sci Eng. 2018;56:444-454.

15. Zakharov VN, Malinnikova ON, Trofimov VA, et al. Effect of gas content and actual stresses on coalbed permeability. J Min Sci. 2016;52(2):218-225.

16. Wei MY, Liu JS, Feng XT, et al. Evolution of shale apparent permeability from stress-controlled to displacement-controlled conditions. J Nat Gas Sci Eng. 2016;34:1453-1460.

17. Zou JP, Chen WZ, Yang DS, et al. The impact of effective stress and gas slippage on coal permeability under cyclic loading. J Nat Gas Sci Eng. 2016;31:236-248.

18. Wang G, Li WX, Wang PF, et al. Deformation and gas flow characteristics of coal-like materials under triaxial stress conditions. Int J Rock Mech Min Sci. 2017;91:72-80.

19. Geng YG, Tang DZ, Xu H, et al. Experimental study on permeability stress sensitivity of reconstituted granular coal with different lithotypes. Fuel. 2017;202:12-22.

20. Duan MK, Jiang CB, Yu H, et al. Experimental research on energy dissipation and seepage properties of coal under loading-unloading conditions at different stress levels. Rock and Soil Mechanics. 2018;39(4):1346-1354.

21. Vishal V, Ranjith PG, Singh TN. An experimental investigation on behaviour of coal under fluid saturation, using acoustic emission. J Nat Gas Sci Eng. 2015;22:428-436.

22. Vogler D, Amann F, Bayer P, et al. Permeability evolution in natural fractures subject to cyclic loading and gouge formation. Rock Mech Rock Eng. 2016;49(9):3463-3479.

23. Wang CL, Zhang XD, Li GZ, et al. Experimental study on the permeability of coal samples with different heights under cyclic loading and unloading. Chin J Rock Mech Eng. 2018;37(10):2299-2308.

24. Chen YL, Zhang YN, Tang JX, et al. Experimental study of the influence of bedding effect on methane adsorption-desorption
and seepage. *Journal of Mining & Safety Engineering*. 2018;35(04):859-868.

25. Wei JP, Sun LT, Wang DK, et al. Change law of permeability of coal under temperature impact and the mechanism of increasing permeability. *J China Coal Soc*. 2017;42(8):1919-1925.

26. Zhang XY, Wu CF, Liu SX, et al. Characteristic analysis and fractal model of the gas-water relative permeability of coal under different confining pressures. *J Petrol Sci Eng*. 2017;292:488-496.

27. Zhang QG, Fan XY, Liang YC, et al. Mechanical behavior and permeability evolution of reconstituted coal samples under various unloading confining pressures-implications for wellbore stability analysis. *Energies*. 2017;10(3):292.

28. Yu YJ, Zhang H, Zhang CH, et al. Effects of temperature and stress on permeability of standard coal briquette specimen. *J China Coal Soc*. 2013;38(6):936-941.

29. Li ZQ, Xian XF, Long QM. Experiment study of coal permeability under different temperature and stress. *J China Univ Min & Technol*. 2009;38(4):523-527.

30. Yang ZZ, Zhang YP, Jia M, et al. Experimental research on influence of low temperature on coal permeability. *Rock and Soil Mechanics*. 2017;2:354-360.

31. Xu J, Peng SJ, Yin GZ, et al. Development and application of tri-axial servo-controlled seepage equipment for thermo-fluid-solid coupling of coal containing methane. *Chin J Rock Mechan Eng*. 2010;36(2):112-117.

32. Coal Industry Ministry of the People's Republic of China. *Measuring methods of physico-mechanical properties for coal and rock*. Beijing: Standards Press of China; 1988:32-33.

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