

# Study on the Failure Mechanism and Permeability Characteristics of Gas Containing Sandstone Intercalated Coal

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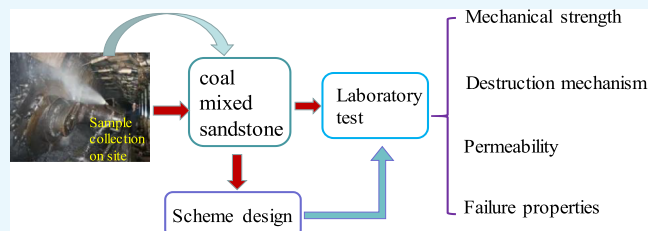
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**ABSTRACT:** The deformation failure mechanism and permeability characteristics of loaded coal sandstone samples under triaxial stress loading were analyzed based on the experimental platform of the coal-rock fluid solid coupling triaxial servo system. The results show that the stress–strain curve of coal intercalated sandstone can be divided into five stages: compaction closure, elastic deformation, stable fracture expansion, unstable fracture expansion, and post-peak strain softening. With the increase of confining pressure, the peak strength and residual strength of the sample increase linearly with the confining pressure. The permeability of the sample decreases slowly with the increase of axial strain, increases rapidly after reaching the stage of unstable fracture propagation, and changes in “V” shape. The relationship between initial permeability and confining pressure can be fitted with exponential function. Based on the fracture volumetric strain model, the progressive failure mechanism of damage expansion of coal mixed sandstone is discussed. The fracture volume strain of each sample under different stress states is given, and the failure mode and crack distribution characteristics of the sample are obtained. The research results can provide reference for reasonable, safe, and efficient coal mining and gas disaster control.



## 1. INTRODUCTION

Coal resource is an important energy source in China. In 2020, the total energy consumption is about 4.98 billion tons of standard coal, with an increase of 2.2% over the previous year. Coal consumption accounts for 56.8% of the total energy consumption. It is estimated that coal consumption will still account for 50 to 52% by 2025.<sup>1</sup> Coalbed methane is an associated gas in coal, also known as gas. It is a colorless, odorless, tasteless, flammable, and explosive gas, which seriously affects the safe and efficient mining of coal resources. When the concentration of underground gas is 5.5 to 16%, it can cause gas explosion and pose a serious threat to personnel and equipment.<sup>2,3</sup>

The only way to reduce or eliminate the occurrence of gas and other disasters in coal is to effectively extract the gas in coal. However, due to the complex and changeable occurrence conditions of coal, the permeability of coal becomes poor under the combined action of water, in situ stress, and temperature, so it is difficult to effectively eradicate the geological disasters caused by gas. At present, scholars at home and abroad have conducted a lot of research on the permeability characteristics of coal and rock and found that the existence of water could weaken the strength of coal body and block the migration channel of gas in the coal body, resulting in further degradation of permeability.<sup>4–8</sup> The high gas content in the coal body would increase the gas pressure in the coal body in a remarkable way. The vibration of gas pressure can also change the distribution characteristics of the pore structure in the coal body. The

increase of gas pressure can widen the seepage channel in the coal body, which further enhances the permeability of the coal body and weakens the strength of the coal body. The decrease of gas pressure can narrow the seepage channel in the coal body, weaken the permeability of the coal body, and strengthen the strength of the coal body.<sup>9–14</sup> With the recovery of coal resources, the coal and rock mass in front of the working face can be divided into stress reduction area, stress increase area, and original rock stress area. The change of the stress state changes the permeability of the coal body. With the increase of stress, the pores and fissures in the coal body close slowly, the gas migration channel closes, and the permeability becomes worse. With the decrease of stress, the pores and fissures in the coal body slowly open, the gas migration channel expands, and the permeability becomes better.<sup>15–20</sup> In fact, the migration characteristics of gas in coal and rock are closely related to the damage evolution degree generated in coal and rock mass during loading.<sup>21</sup> Wang et al.<sup>22</sup> expounded the mechanical and nonmechanical effects of different gas occurrence states on holes and fractures and revealed the internal relationship between gas bearing coal hole

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and fracture damage and macrostrength loss. Wang et al.<sup>23,24</sup> compared and analyzed the dynamic changes of coal fracture development morphology under uniaxial and triaxial loadings. Shang et al.<sup>25</sup> carried out the seepage test of damaged coal under triaxial stress and obtained the evolution law of seepage characteristics of broken media with confining pressure and porosity.

In summary, domestic and foreign scholars have carried out many studies on the mechanical and permeability characteristics of coal and rock mass under different axial pressures, confining pressure and fluid pressure. The abovementioned research was carried out for a single coal sample or rock sample; however, research on samples containing coal in the rock has been rarely reported. Due to the different occurrence conditions of coal resources, the deformation and permeability characteristics of coal and rock in different regions are quite different. Therefore, based on this, according to the engineering background of  $K_2$  coal seam in Nantong Coal Mine, Chongqing, China, triaxial seepage tests of coal intercalated sandstone samples were carried out to discuss the mechanical, deformation, and permeability characteristics and the damage expansion and progressive failure mechanism of sandstone intercalated coal based on the fracture strain model. This study is expected to provide some reference value for deep coalbed methane mining.

## 2. TEST DEVICE AND SCHEME

**2.1. Sandstone Intercalated Coal.** The sample is taken from the coal mixed sandstone sample of  $K_2$  coal seam roof of Nantong Coal Mine in Chongqing, China. The standard cylindrical sample is made in the laboratory to meet the rock mechanics test requirement.<sup>26</sup> The coal mixed sandstone sample is shown in Figure 1.



Figure 1. Standard sample.

**2.2. Experimental Device.** “Gas bearing coal thermal fluid solid coupling triaxial servo seepage device”<sup>27</sup> was adopted. The equipment can simultaneously apply axial pressure (maximum 1000 kN), confining pressure (maximum 60 MPa), and gas pressure (maximum 6 MPa) and can synchronously monitor axial deformation, radial deformation, and gas flow. The experimental equipment is shown in Figure 2.

**2.3. Scheme Design.** Conventional triaxial compression tests under different confining pressures are carried out as follows:

- (1) The axial stress and confining pressure are set as 3 MPa.
- (2) Gas pressure is set as 2 MPa.
- (3) When the confining pressure and gas pressure are constant, the axial stress is loaded until the sample is damaged.
- (4) The sample is replaced and the confining pressure is changed to 6, 9, 12, 15, 18, and 21 MPa.

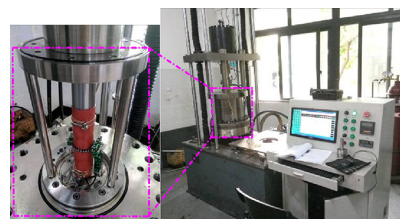


Figure 2. Gas bearing coal thermal fluid solid coupling triaxial servo seepage device.

## 3. MECHANICAL PROPERTIES OF GAS CONTAINING SANDSTONE INTERCALATED COAL

According to the test results, the calculation formula of sample volumetric strain is

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \quad (1)$$

where  $\varepsilon_v$  is the volumetric strain,  $\varepsilon_1$  is the axial strain, and  $\varepsilon_3$  is the radial strain.

The calculation formula of the principal stress difference of specimen  $\sigma'$  is

$$\sigma' = \sigma_1 - \sigma_3 \quad (2)$$

where,  $\sigma'$  is the deviatoric stress (MPa),  $\sigma_1$  is the axial stress (MPa), and  $\sigma_3$  is the confining pressure (MPa).

According to the experimental results, the total stress–strain curves of coal mixed sandstone under different confining pressures are given, as shown in Figure 3.

It can be seen from Figure 3 that the total stress–strain relationship curve of the sample under each confining pressure shows similar variation characteristics, and the residual strength appears after the peak. The total stress–strain curve can be roughly divided into five stages. Stage I is the compression closure stage. In this stage, the pores and cracks in the sample are compacted and closed during axial compression, and the stress–strain curve is concave. Stage II is the elastic deformation stage. In this stage, the deformation of loaded and unloaded axial compression specimens recovers to the original state, and the stress–strain curve is approximately a straight line. Stage III is the stage of stable crack propagation. In this stage, microcracks begin to appear slowly in the sample, and the sample produces unrecoverable plastic deformation. The stress value corresponding to the end point of this stage is called damage dilatancy stress. Stage IV is the unstable crack propagation stage. In this stage, the internal cracks of the sample are generated rapidly, and the cracks expand and extend through the whole sample, resulting in instability failure and unrecoverable failure deformation of the sample. The end point at this stage corresponds to the peak stress of the sample. Stage V is the post-peak strain softening stage, in which the stress decreases with the increase of strain, and finally, the residual strength appears. It shows that the specimen can withstand a certain strength even if it is damaged.

According to the Coulomb criterion,<sup>28</sup> the strength of rock is equal to the bonding force of rock itself against shear friction and the friction force generated in the normal direction on the shear plane, that is

$$\tau_s = c_0 + \sigma_n \tan \varphi \quad (3)$$

where  $\tau_s$  is the maximum shear stress carried by the rock;  $c_0$  is cohesion,  $\varphi$  is the internal friction angle, and  $\sigma_n$  is the normal stress.

Equation 3 is expressed by principal stress as

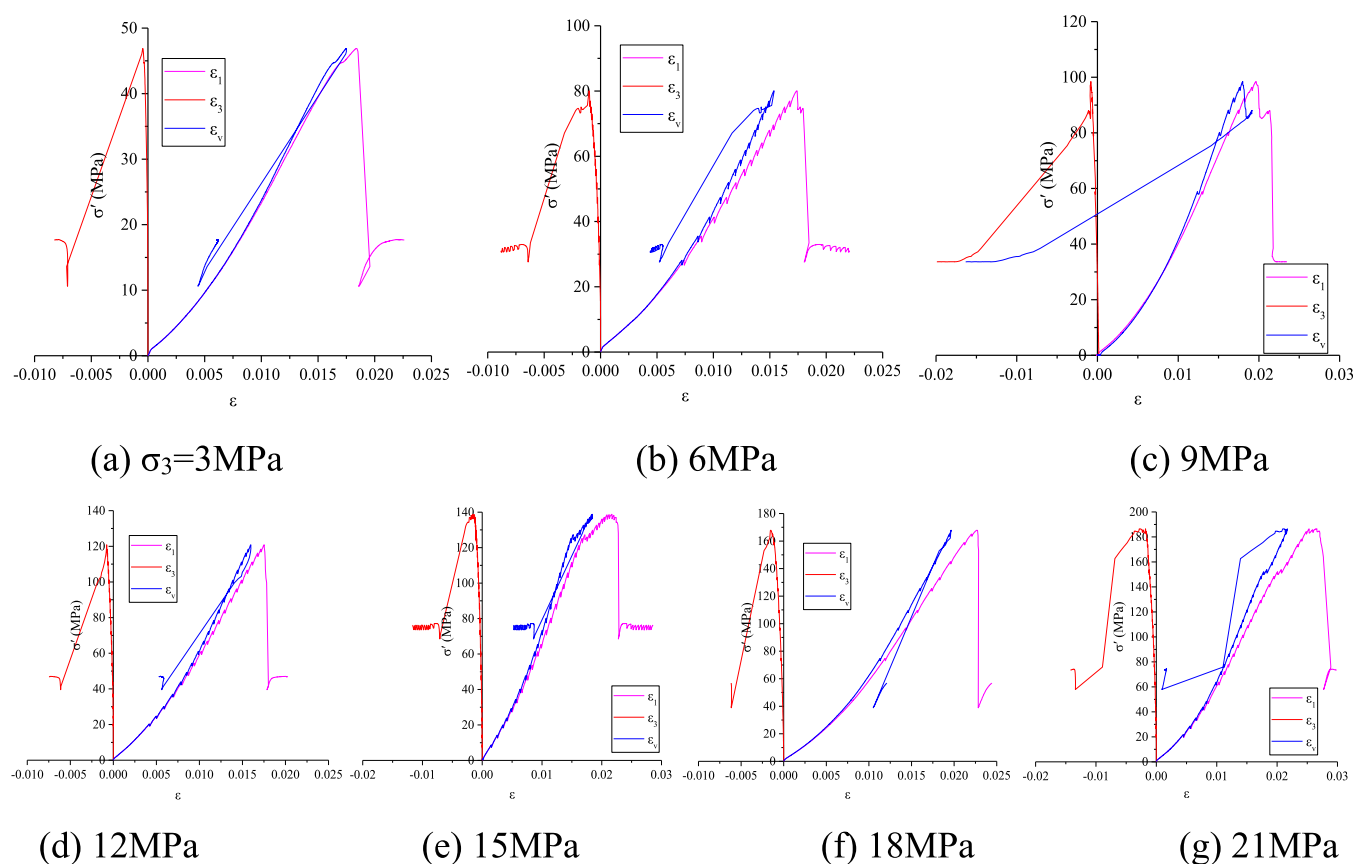


Figure 3. Total stress–strain curves of specimens under different confining pressures.

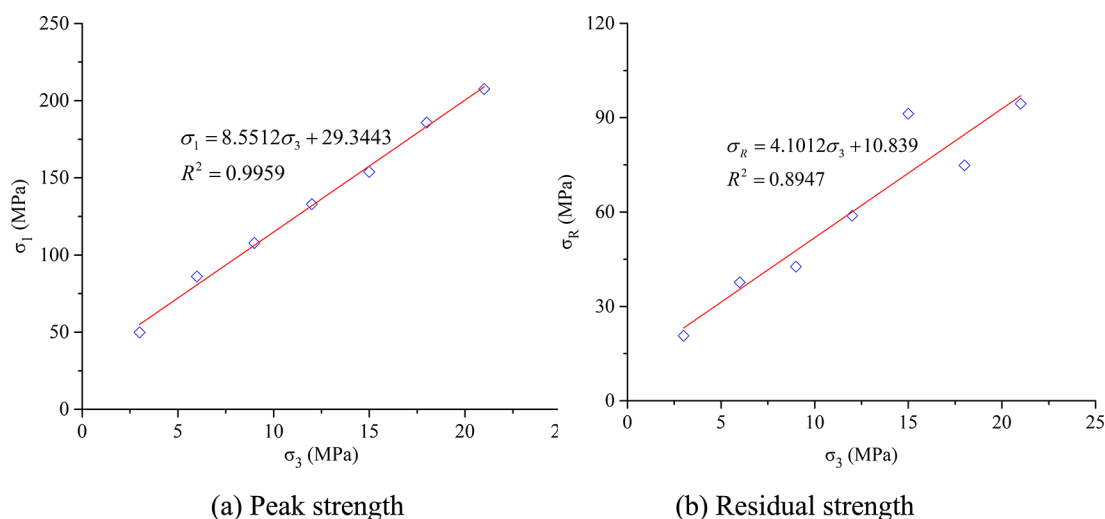


Figure 4. Relationship curve between peak strength, residual strength, and confining pressure.

$$\sigma_1 = K\sigma_3 + Q \quad (4)$$

where  $K$  and  $Q$  are material parameters,  $K$  is the slope of the intensity line in the coordinate, which can be solved according to  $(1 + \sin \varphi)/(1 - \sin \varphi)$ ; and  $Q$  is the theoretical uniaxial compressive strength (MPa), which can be solved according to  $2c_0 \cos \varphi/(1 - \sin \varphi)$ .

The relationship curve between peak strength and confining pressure of the fitting curve sample is shown in Figure 4a. Combined with formula 4,  $c_0$  is 5.02 MPa and internal friction angle  $\varphi_r$  is 52.4°. With the increase of confining pressure, the residual

strength of coal intercalated sandstone gradually increases. The fitting relationship between residual strength and confining pressure of coal intercalated sandstone under different confining pressures is shown in Figure 4b.

According to the abovementioned experimental results, the Mohr stress circle and envelope of the sample under different gas pressures are drawn, as shown in Figure 5. It can be seen that with the increase of confining pressure, the Mohr stress circle of the sample gradually moves to the right, indicating that the axial stress required for the failure of the sample increases with the increasing confining pressure.

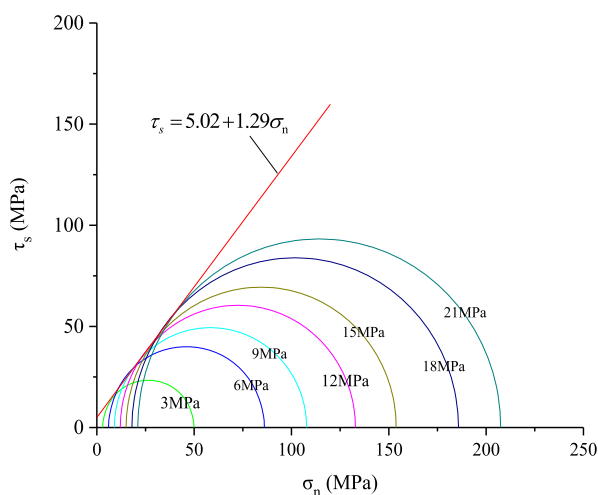


Figure 5. Mohr stress circle of the raw coal sample containing gas.

#### 4. PERMEABILITY CHARACTERISTICS OF GAS CONTAINING SANDSTONE INTERCALATED COAL

In the study on the seepage characteristics of sandstone intercalated coal, it is considered that the migration of gas in the samples obeys Darcy's law, and the calculation formula is as follows<sup>16,27</sup>

$$k = \frac{2\nu\mu L p_{\text{out}}}{A(p_{\text{int}}^2 - p_{\text{out}}^2)} \quad (5)$$

where,  $k$  is permeability (mD);  $\nu$  is the gas seepage velocity of coal body ( $\text{cm}^3/\text{s}$ );  $\mu$  is the gas dynamic viscosity coefficient, which is taken as  $1.087 \times 10^{-5}$  Pa·s;  $L$  is the length of the coal rock sample (cm);  $A$  is the cross-sectional area of the sample

( $\text{cm}^2$ );  $p_{\text{int}}$  is the gas inlet pressure (MPa); and  $p_{\text{out}}$  is the gas outlet pressure (MPa), that is, atmospheric pressure (0.1 MPa).

Figure 6 shows the total stress–strain permeability curve of each sample under different confining pressures.

It can be seen from Figure 6 that the permeability characteristics of sandstone intercalated coal are closely related to the axial stress and confining pressure on the sample. During the axial loading process, the microporous fractures in the sample are slowly compacted and closed, the seepage channel becomes narrow, the ability of gas to pass through the real sample decreases, and the permeability decreases nonlinearly with the increase of deviatoric stress. Moreover, the initial permeability of coal inclusion samples under different confining pressures decreases slowly with the increase of confining pressure, and the fitted relationship between the initial permeability and confining pressure meets the exponential function, as shown in Figure 7. In the yield stage, cracks have been formed in the coal intercalated sandstone and expand slowly with the continuous increase of load. In this process, the permeability of the sample begins to increase slowly. When the internal crack of the sample gradually extends and penetrates the whole sample, the permeability of the sample increases rapidly. It can be seen that the development of permeability shows a “V” shape, with a gentle decrease at the initial stage and a rapid increase after the axial strain reaches the bottom.

#### 5. RESULTS AND DISCUSSION

**5.1. Specimen Failure Mechanism.** Due to the anisotropy of sandstone with coal, there are different forms of defects in the sample. Under the action of external load, a large number of microcracks are generated in the sample, which slowly expand and connect to form macrocracks. Based on this, this paper discusses the progressive failure mechanism of sandstone

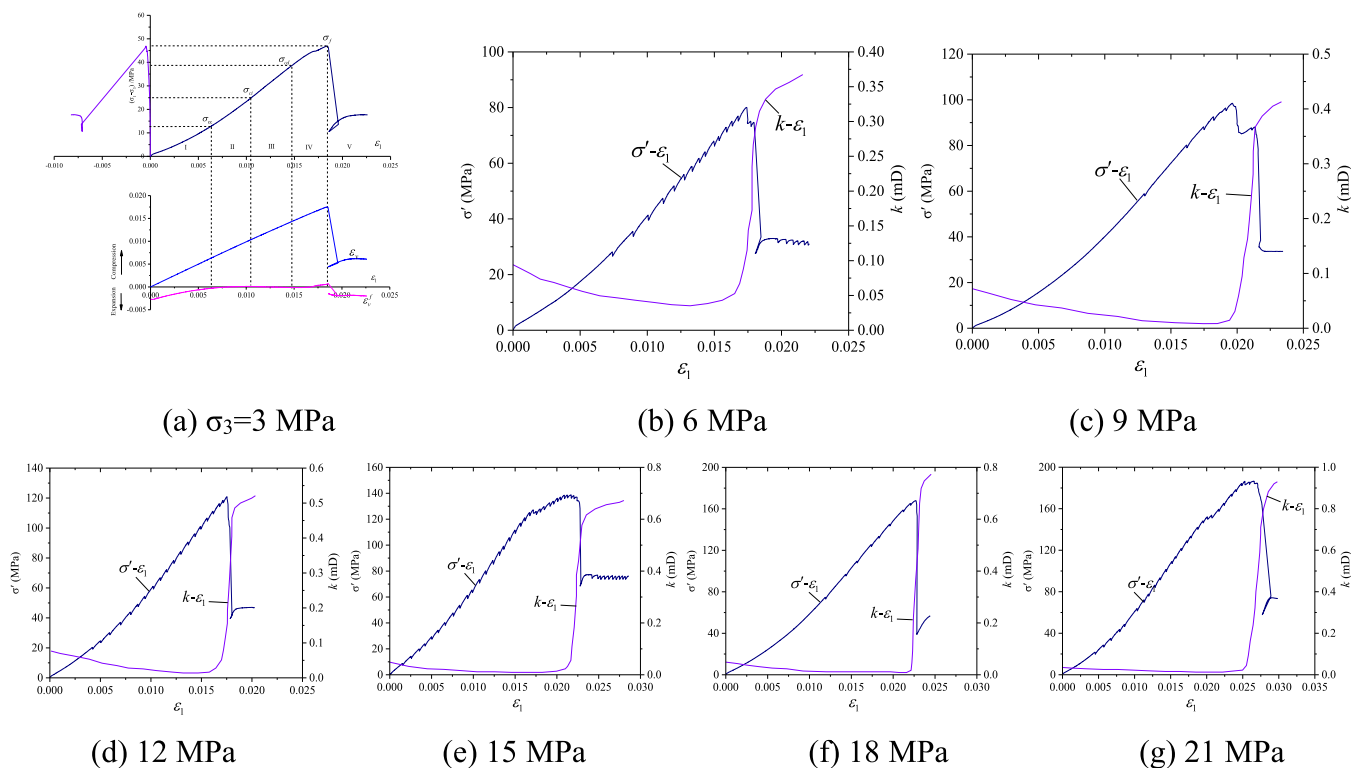
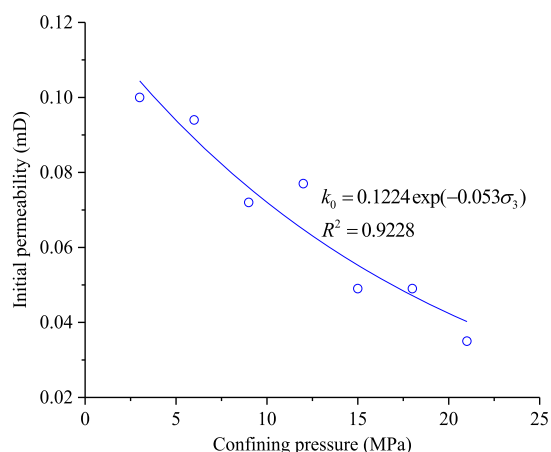


Figure 6. Total stress–strain permeability curve of each sample under different confining pressures.



**Figure 7.** Relationship curve between the initial permeability and confining pressure.

intercalated coal with the idea of the fracture strain model.<sup>29</sup> Figure 8 shows the total stress–strain relationship curve and fracture strain curve of the coal mixed sandstone sample under the confining pressure of 3 MPa.

As shown in Figure 8, according to the difference of the internal microfracture evolution state of coal mixed sandstone samples under different load levels, the stress–strain relationship curve before the peak can be divided into five stages: stage I is the compaction closure stage, and the stress corresponding to the end point of this stage  $\sigma_{cc}$  is called fracture closure stress. Stage II is the elastic deformation stage, and the end point of this

stage corresponds to the crack initiation stress  $\sigma_{ci}$ . Stage III is the stage of stable fracture expansion, and the end point of this stage corresponds to the damage dilatancy stress  $\sigma_{cd}$ . Stage IV is the unstable fracture expansion stage, and the end point of this stage corresponds to the peak stress  $\sigma_f$ . Stage V is the post-peak failure stage. In this stage, the sample has macroconnected cracks, and the sliding dislocation between the fracture surfaces leads to the instability and failure of the sample.

Fracture volume strain refers to the change of coal and rock volume deformation caused by the initiation and expansion of primary fractures in coal and rock mass and new fractures under load. It is calculated by eq 6

$$\varepsilon_v^f = \varepsilon_v - \varepsilon_v^g \quad (6)$$

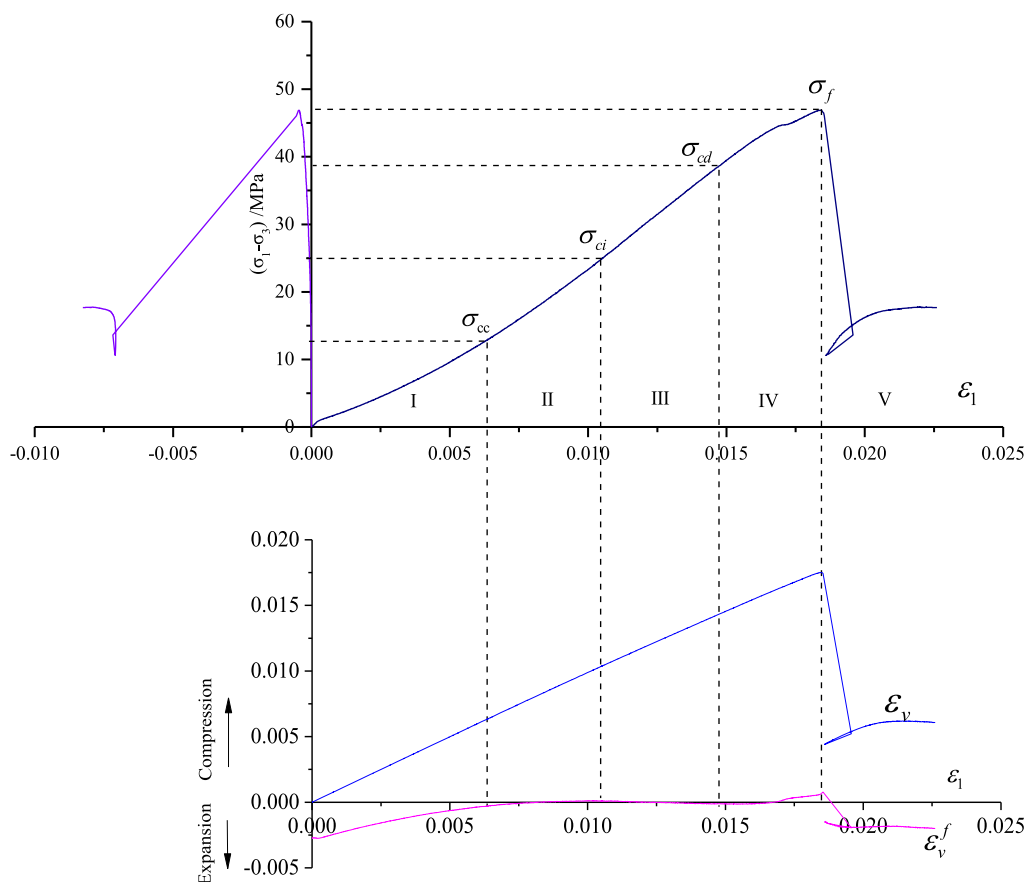
where  $\varepsilon_v$  is the total volumetric strain, which is calculated by formula 1, and  $\varepsilon_v^g$  is the elastic volumetric strain of the coal rock skeleton.

The volumetric strain of coal and rock skeleton can be calculated by generalized Hooke's law, which can be obtained under the condition of the conventional triaxial experiment

$$\varepsilon_v^g = \frac{1 - 2\mu}{E}(\sigma_1 + \sigma_3) \quad (7)$$

Therefore

$$\varepsilon_v^f = \varepsilon_v - \frac{1 - 2\mu}{E}(\sigma_1 + \sigma_3) \quad (8)$$



**Figure 8.** Relation curve of deviatoric stress–strain and fracture strain of the sample.

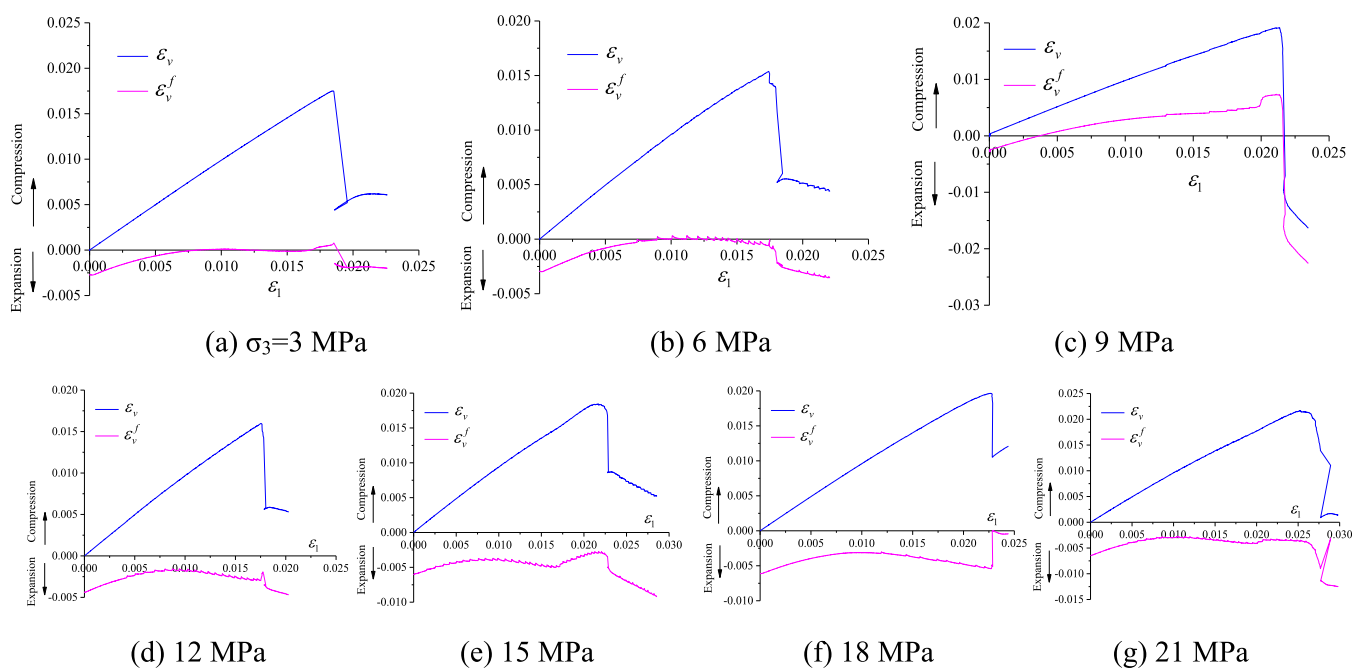


Figure 9. Volumetric strain and fracture strain curves of sandstone with coal.

Table 1. Volume Strain and Crack Volume Strain of Each Sample under Different Stress Values

$\sigma_3/\text{MPa}$	$\sigma_{cc}/\text{MPa}$		$\sigma_{ci}/\text{MPa}$		$\sigma_{cd}/\text{MPa}$		$\sigma_t/\text{MPa}$	
	$\varepsilon_v/\%$	$\varepsilon_v^f/\%$	$\varepsilon_v/\%$	$\varepsilon_v^f/\%$	$\varepsilon_v/\%$	$\varepsilon_v^f/\%$	$\varepsilon_v/\%$	$\varepsilon_v^f/\%$
3	5.977	-0.372	7.799	-0.052	13.805	-0.098	18.390	0.572
6	5.484	-0.660	7.431	-0.118	13.042	-0.085	15.353	-0.582
9	6.545	1.348	8.543	2.226	14.454	3.691	17.659	4.707
12	5.532	-2.180	7.485	-1.829	13.261	-2.461	15.977	-2.959
15	5.202	-4.241	7.134	-4.020	13.292	-4.699	18.411	-2.973
18	6.974	-3.383	9.338	-3.126	16.553	-4.321	19.626	-5.422
21	7.570	-3.241	9.733	-2.983	17.039	-4.108	21.709	-3.655

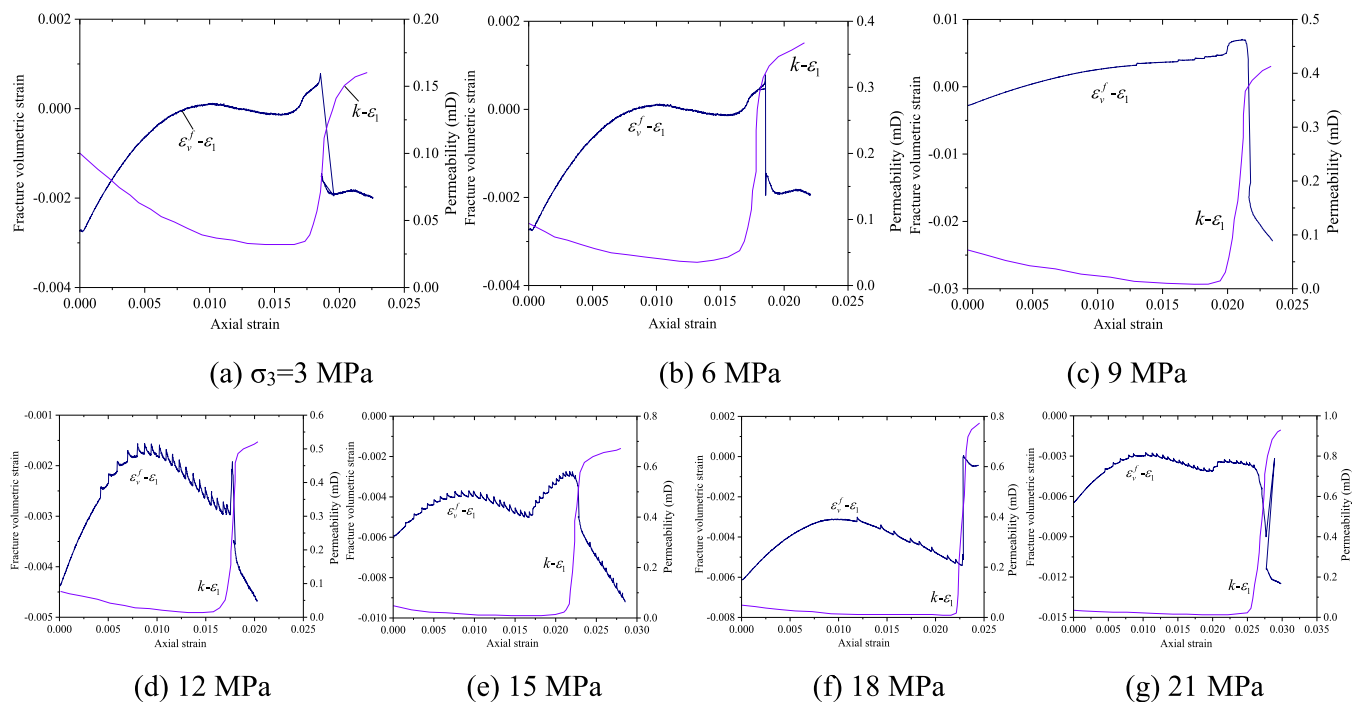


Figure 10. Fracture volume strain–axial strain–permeability relationship curve of sandstone intercalated coal.



**Figure 11.** Sketch diagram of failure mode and crack of the coal mixed sandstone sample under triaxial compression.

The relationship curve between volumetric strain, fracture volumetric strain, and axial strain of each sample under different stress conditions according to formula 8 is shown in Figure 9.

It can be seen from Figure 9 that the volumetric strain of each sample gradually increases with the increase of axial strain (compression is positive), indicating that the volume of the sample is compressed. In the initial compaction deformation stage, the primary pores and cracks in the sample are compacted, and the structure and properties of the sample change irreversibly. With the continuous increase of axial strain, the volumetric strain of each sample continues to increase. When the peak strength is reached, the volumetric strain drops rapidly, but only the volumetric strain of the sample under the confining pressure of 9 MPa changes from positive to negative, indicating that the sample has damage expansion deformation and sample volume expansion deformation. The fracture volumetric strain of each sample is negative in the initial compaction deformation stage, indicating that expansion deformation of the sample occurs. With the increase of axial strain, the fracture volume strain of the sample decreases gradually and continues to increase in the positive direction after the fracture volume strain of the individual sample decreases to zero, indicating that the fracture volume strain of the sample changes from expansion to compression.

Table 1 shows the crack closure stress of each sample  $\sigma_{cc}$ , crack initiation stress  $\sigma_{ci}$ , damage dilatancy stress  $\sigma_{cd}$ , and the volume strain and crack volume strain of each sample under the condition of peak stress  $\sigma_f$ .

**5.2. Permeability Analysis.** Figure 10 shows the fracture volumetric strain–axial strain–permeability curve of each sample under different confining pressures. It can be seen that the permeability characteristics of the gas-containing coal sandstone sample are closely related to the evolution and expansion characteristics of its internal cracks. With increasing axial stress, the axial deformation gradually increases under the action of axial pressure. During this process, the fracture volumetric strain gradually decreases, and the rate of decrease slows down. This is due to the slow closure of the internal pores and cracks of the sample, and the gas seepage channel becomes smaller. As the axial deformation continues to increase, the fracture volume strain of most specimens continues to show expansion deformation during this process, and individual specimens continue to show compression deformation, while the permeability continues to decrease. When the axial load reaches the yield strength of the sample, the permeability of the sample changes from a slow decrease to a slow increase. When the axial load reaches the peak strength of the sample, the permeability of the sample increases rapidly.

**5.3. Specimen Failure Characteristics.** The failure mode of triaxial compression of the coal mixed sandstone sample is

shown in Figure 11, and the sketch diagram of crack is given at the same time.

In the triaxial compression test, the failure of sandstone with coal is relatively simple, and most of them show typical shear failure. There is powdery material on the main control shear surface with obvious friction marks. Most of the sample shear surfaces appear in horizontal or inclined cracks perpendicular or oblique to the loading direction, and most of them are damaged along the coal inclusion position. This is because the strength of the coal inclusion is low, and the inclined cracks are formed first under high load. From the fracture sketch, the failure angle  $\alpha$  of each sample can be calculated, and the internal friction angle of the coal mixed sandstone sample can be calculated according to the Coulomb strength criterion. Through analysis and calculation, the average value of the internal friction angle of the coal mixed sandstone sample is  $57.6^\circ$ , which is close to the calculated value of  $52.4^\circ$ .

## 6. CONCLUSIONS

Triaxial compression tests are carried out for gas bearing sandstone with coal under different confining pressures. The permeability characteristics and deformation and failure mechanism of the sample during loading are analyzed, and the following conclusions are drawn:

The stress–strain curve of coal intercalated sandstone can be divided into compression closure, elastic deformation, stable fracture expansion, unstable fracture expansion, and post-peak strain softening stages.

With the increase of confining pressure, the peak strength and residual strength of the sample increase linearly with the confining pressure. The development of permeability shows a “V” shape, with a gentle decrease at the initial stage and a rapid increase after the axial strain reaches the bottom. The relationship between the initial permeability and confining pressure can be fitted with the exponential function.

Based on the idea of fracture strain model, the progressive failure mechanism of damage dilatancy of coal mixed sandstone is discussed, and the fracture volume strain of each sample under different stress states is calculated. The failure mode and crack distribution characteristics of the sample are obtained, and the calculated internal friction angle of the sample is close to the theoretical value.

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## Notes

The authors declare no competing financial interest.

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