**Experimental study on strain behavior and permeability evolution of sandstone under constant amplitude cyclic loading-unloading**

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**Abstract**  
The coupling of in situ stress, seepage, and fracture makes the strata exhibit complex strain behavior and permeability evolution under the stress path of cyclic loading-unloading. In this study, the cyclic loading-unloading experiments of constant amplitude axial stress of sandstone under the combination of different initial confining pressures and loading-unloading rates are conducted. The experimental results show that the heterogeneity of sandstone, Poisson’s ratio produced by adjacent loading-unloading, and confining pressure determine the deformation characteristics of sandstone in lateral and axial directions. Sandstone can produce significant shear dilatancy at a low rate; this is because stress perturbation can activate more particle slippage and fracture structure changes. However, the fracture preferentially propagates along the end or edge of the crack with strong stress sensitivity to form a shear failure plane at high rate. The normalized permeability of sandstone decreases with an increase in the loading-unloading rate before failure. The evolution of normalized permeability is closely related to the shear slip of fracture structure and sandstone particles. For the prevention of rock engineering disasters, the high loading-unloading rate results in lower normalized permeability, which favors the prevention of gas-type disasters in rocks with higher gas potential energy; however, it is not conducive to the prevention of rockburst.

**Keywords**  
constant amplitude cyclic loading-unloading, loading-unloading rate, normalized permeability, shear effect, volumetric strain

1 | INTRODUCTION

In rock engineering activities, cyclic loading-unloading is a common stress loading path, for example, the coal pillar subjected to periodic loading-unloading behavior undermining perturbation, the strata movement caused by the periodic weighting above the working face, the dynamical changes in radial stress and circumferential stress in roadway excavation, the load acting on the railways, roads, and bridges as foundations, and the slope rock mass under periodic large fluctuation of reservoir water.

Many scholars have studied the mechanical properties of rock under cyclic loading-unloading stress paths. Liu et al. performed cyclic loading-unloading experiments on...
sandstone under different confining pressures and loading frequencies. The experimental results showed that the dilatancy of sandstone under low confining pressure is more evident, and the failure mode of sandstone is shear failure. Jiang et al. performed the tiered cyclic loading experiments of axial stress on raw coal. It was found that the cumulative dissipated energy increased exponentially during cyclic loading-unloading. Liu et al. performed cyclic loading tests on rock salt under different axial stress regimes and considered that the damage initiates when the axial stress level exceeds the elastic limit. The accumulation of damage accelerates after the point of volume expansion. Martin & Chandler performed cyclic loading tests on granite under different stress regimes and analyzed the law of crack initiation stress. It was concluded that the crack initiation stress is basically unchanged and has nothing to do with the damage accumulated in the rock; however, the crack damage stress is closely related to the accumulated damage. Fuenkajorn & Phueakphum performed uniaxial cyclic loading tests on salt rock, revealing the dilation strength and critical shear strain of rock. Both determined the maximum deformation before dilation strain or accelerated creep rate occurs under given shear stress. It was also concluded that the effect of loading frequency on rock salt strength is less than that of the magnitudes of the maximum load and the loading amplitude. Eberhardt et al. performed uniaxial cyclic loading tests on Lac du Bonnet granite and investigated the microcrack propagation law and damage mechanical properties of rock. The results show that the rock failure occurs by a process in which small cracks coalesce into larger cracks, which in turn coalesce together to form a critical failure plane.

In addition, the engineering disasters encountered in rock engineering are often induced by the multifield coupling of in situ stress, temperature, and fluid flow. Permeability is an important parameter to evaluate the seepage effect and fracture connectivity of rock strata. Mckee et al. considered that the permeability of coal has a negative exponential relationship with the increase in buried depth and in situ stress. Brace et al. investigated the permeability evolution of granite under high confining pressure and pore pressure. It was concluded that the permeability of granite has a strong dependence on effective stress and decreases with an increase in the effective confining pressure. Stormont & Daemen performed permeability tests on rock salt and concluded that low confining pressure contributed to the growth of secondary cracks, and the rock salt permeability is greater. Zhang et al. conducted permeability tests of Carrara marble and calcite, which showed that the permeability increases more obviously with an increase in strain. The increase in permeability during deformation is closely related to the formation of microcracks and the interconnection between microcracks.

Most previous studies have not investigated the permeability evolution of different types of rocks under cyclic loading-unloading tests, as well as the dilatancy behavior of rock and its effect on the permeability under different initial confining pressure and loading-unloading rate. Sandstone is a common sedimentary rock in the roof above the coal seam. Therefore, the mechanics and seepage experiments of cyclic loading-unloading of axial stress with constant amplitude were conducted to investigate the effects of cyclic numbers, loading-unloading rates and initial confining pressures on the deformation behavior and permeability evolution of sandstone.

2 | EXPERIMENTAL APPARATUS AND SCHEME

2.1 | Experimental apparatus

The cyclic loading-unloading experiment was conducted with the servo-controlled seepage apparatus for the
thermal-hydrological-mechanical coupling of coals and rocks,17,18 as shown in Figure 1. The experimental apparatus was able to provide a maximum force of 1000 kN in the axial directions and a maximum confining pressure of 60 MPa. The axial stress could be applied by displacement control or force control, while the confining pressure could only be applied by force control. The precision of the axial stress and confining pressure was ±1% of the stress target value. The axial displacement sensor and lateral extensometer monitored the axial and lateral deformation, respectively. The dimensions of cylindrical specimens that could be satisfied in the loading cell were \( \phi 50 \text{ mm} \times 100 \text{ mm} \) and \( \phi 100 \text{ mm} \times 200 \text{ mm} \).

### 2.2 Experimental specimens

Experimental specimens were obtained from an outcrop of feldspar sandstone in Chayuan New Area, Chongqing. The sandstones were drilled, cut, and polished into \( \phi 50 \text{ mm} \times 100 \text{ mm} \) cylinder. The uniaxial compressive strengths (UCSs) of sandstone are 46.90 MPa. The porosity of sandstone measured by mercury intrusion method was 4.15%. The Poisson’s ratio \( \nu \) and Young’s modulus \( E \) is 0.34 and 5.3 GPa, respectively. The two ends of the cylindrical specimen were finally ground to meet the requirements of the ISRM.19 The sandstone specimens are shown in Figure 2.

### 2.3 Experimental scheme

Cyclic loading-unloading is a common stress path. In the study, the effects of different initial confining pressures, loading-unloading rates and cyclic numbers on the deformation behavior and permeability evolution of sandstone were investigated by cyclic loading-unloading of axial stress in the form of a constant amplitude. The range of cyclic loading-unloading of axial stress was from the designed initial hydrostatic pressure to 70% of the conventional triaxial compression strength under the designed confining pressure. In the experiment, \( \text{CH}_4 \) flowed through the sandstone and the outlet pressure was the atmospheric pressure. The gas pressure was 3 MPa. First, the conventional triaxial compression strength of sandstone under gas pressure of 3 MPa was determined, as summarized in Table 1. Then, the cyclic loading-unloading experiment of axial stress was conducted on the sandstone.

The details are as follows: Step 1—axial stress and confining pressure were applied to a hydrostatic pressure state of 10, 20, 25, and 30 MPa, at the identical rate of 0.05 MPa/s. Step 2—The gas inlet valve was opened, and a gas pressure of 3 MPa was applied to the sandstone specimens under different confining pressures. Step 3—When the flow rate was stable, the axial stress was applied up to approximately 70% of the peak stress measured by conventional triaxial compression test at a rate of 0.05 MPa/s. Step 4—The confining pressure was kept constant, and the experiment of cyclic loading-unloading axial stress was performed at the rate of 0.2, 0.4, 0.8, and 1.2 MPa/s. The cyclic number was 10. Step 5—After the cyclic loading-unloading experiment, the axial force control was switched to the displacement control immediately, and the axial loading was continued at the rate of 0.1 mm/min until the residual strength was stable.

The experimental stress path is shown in Figure 3.

### 3 EXPERIMENTAL RESULTS

#### 3.1 Stress-strain relationship

Figures 4-7 show the relationship between the strain (including axial strain \( \varepsilon_a \), lateral strain \( \varepsilon_l \), and volumetric strain \( \varepsilon_v \)) and cyclic loading-unloading number for different initial confining pressures \( (\sigma_3 = 10, 20, 25, 30 \text{ MPa}) \) and loading-unloading rates \( (v = 0.2, 0.4, 0.8, \text{ and } 1.2 \text{ MPa/s}) \). The strains in Figures 4-7 correspond to the maximum value for each cyclic loading of axial stress. An increase in strain implies that the sandstone tends to be compressed, whereas a decrease implies that sandstone tends to be expanded. It can be seen that the sandstone specimen showed a compressive trend with an increase in cyclic loading-unloading number.
Because of the heterogeneity and incomplete elasticity of the rock, the axial strain and lateral strain could not be fully recover under the unloading path, that is, there was residual deformation. It may be due to local damage in the area where the future failure plane may be formed, resulting in irreversible deformation. Essentially, the stress-induced fracture and the sliding of sandstone particles were still present. With the further loading of axial stress, the axial strain continued to increase, showing that the sandstone was compressed in the axial direction. Equation (1) shows that the lateral strain of sandstone is determined by the Poisson's effect, that is, lateral deformation ability of sandstone and axial displacement. The cyclic loading peak and number of axial stress designed in the experiment did not result in the yielding of the sandstone. With an increase in cyclic loading-unloading number, the sandstone tended to be more elastic, and the increment of axial strain decreased gradually, that is, the slope of axial strain in Figures 4-7 decreased. Therefore, the capacity of axial displacement in \( (i+1) \)-th loading was not greater than that in \( i \)-th unloading, that is, \( \Delta l_{i,\text{unloading}} \geq \Delta l_{i+1,\text{loading}} \). In addition, \( \nu_{(i+1),\text{loading}} \leq \nu_{i,\text{unloading}} \), which together determine that the sandstone was also compressive in the lateral direction.

It is worth noting that the lateral expansion of sandstone also occurred under an initial confining pressure of 10 MPa. The author considers that this behavior was induced by a lower confining pressure. The low confining pressure made the sandstone suffer from weak horizontal constraints, and there were still many natural flaws in the sandstone. The homogeneity of the sandstone was not as good as that under high confining pressure regimes. The Poisson's effect was significant under

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**Figure 3** Stress path under the condition of \( \sigma_3 = 10 \text{ MPa} \) and \( v = 0.2 \text{ MPa/s} \)

**Figure 4** Relationship between strain and cyclic loading-unloading number under \( \sigma_3 = 10 \text{ MPa} \)
low confining pressure regimes, which shows that the lateral strain of sandstone decreased. However, when the number and size of natural flaws in sandstone decreased, its homogeneity was enhanced, and the lateral direction was converted into a compressed state with the increase of cyclic loading-unloading number.

\[
\begin{cases}
\nu_{i\text{loading}} & \geq \frac{\Delta l_{\text{unloading}}}{\Delta l_{(i+1)\text{loading}}}, & \text{Expansion} \\
\nu_{i\text{unloading}} & \leq \frac{\Delta l_{\text{unloading}}}{\Delta l_{(i+1)\text{loading}}}, & \text{Contraction}
\end{cases}
\]

where $\Delta l_{\text{unloading}}$ and $\Delta l_{(i+1)\text{loading}}$ are the change in axial displacement at the $i$th unloading and $(i + 1)$th loading, respectively. $\nu_{i\text{loading}}$ and $\nu_{i\text{unloading}}$ are the Poisson’s ratios at the $i$th unloading and $(i + 1)$th loading, respectively.

Rock is an incomplete elastic and nonlinear material, and each loading and unloading behavior can result in residual deformation, that is, the loading and unloading curves cannot form a closed loop. This is similar to the experimental results obtained by Jiang et al.\(^{(21)}\) This implies that energy dissipation occurs, and the change in volumetric strain is closely related to it. The elastic energy accumulated in the sandstone was released during unloading, and the dissipation energy was used for the frictional sliding between the sandstone particles and the stress response of natural flaws. The energy expression of sandstone obtained by area method is as follows

\[
W_1 = \int \sigma_1 d\varepsilon_1 = \sum_{i=1}^{n} \frac{1}{2} \left( \sigma_{1j} + \sigma_{1j-1} \right) \left( \varepsilon_{1j} - \varepsilon_{1j-1} \right)
\]

\[
E_{\varepsilon_1} = \sum_{i=1}^{n} \frac{1}{2} \left( \sigma'_{1j} + \sigma'_{1j-1} \right) \left( \varepsilon'_{1j} - \varepsilon'_{1j-1} \right)
\]

\[
W_3 = \int \sigma_3 d\varepsilon_3 = \sum_{i=1}^{n} \frac{1}{2} \left( \sigma_{3j} + \sigma_{3j-1} \right) \left( \varepsilon_{3j} - \varepsilon_{3j-1} \right)
\]

\[
E_{\varepsilon_3} = \sum_{i=1}^{n} \frac{1}{2} \left( \sigma'_{3j} + \sigma'_{3j-1} \right) \left( \varepsilon'_{3j} - \varepsilon'_{3j-1} \right)
\]
where \( W_1 \) and \( W_3 \) are the total work done by the axial stress and confining pressure during loading in MPa, respectively. \( E_{e1} \) and \( E_{e3} \) are the elastic energies released in the axial and lateral directions during unloading in MPa, respectively. \( \sigma_{1j} \) and \( \sigma_{3j} \) are the stresses at each point of the stress-strain curve of the loading stage in MPa. \( \epsilon_{1j} \) and \( \epsilon_{3j} \) are the strains at each point of the stress-strain curve of the loading stage. \( \sigma'_{1j} \) and \( \sigma'_{3j} \) are the stresses at each point of the stress-strain curve of the unloading stage in MPa. \( \epsilon'_{1j} \) and \( \epsilon'_{3j} \) are the strains at each point of the stress-strain curve of the unloading stage.

Figure 8 shows the relationship between the hysteretic loop area, volumetric strain, and cyclic loading-unloading number under \( \sigma_3 = 25 \text{ MPa} \) and \( \nu = 0.4 \text{ MPa/s} \). The dissipation energy of sandstone decreased with an increase in cyclic loading-unloading number, which showed that the slope of volumetric strain decreased and the sandstone was more elastic. The energy dissipated during crack propagation also increased accordingly. Further, the continuous release of dissipation energy indicated that the frictional sliding between the sandstone particles and the dynamical adjustment of fracture structure was always in progress under deviator stress.

Figure 9 shows the change of volumetric strain with loading rate at the first peak of applied axial stress, and the moment of sandstone failure. Figure 10 shows the relationship between dilatancy capacity \( (\Delta \epsilon_{v,j}) \) and loading-unloading rate \( (\nu) \). The experimental results show that the dilatancy capacity decreased with an increase in loading rate. The low loading rate allowed the fracture structure and particle arrangement in sandstone to be adjusted in time. In this case, the stress perturbation can spread to a more extensive and larger number of sandstone particles and internal fractures, making it easier to form crack populations. At a low loading rate, rocks underwent a low-stress state for a relatively long period, and there was relatively sufficient time for pore and fracture structure adjustment, sandstone particle sliding, and secondary crack development. A reasonable explanation for the relationship between loading rate and strain behavior of sandstone can also be obtained from the change of permeability. The permeability evolution is closely related to the formation of microcracks and the interconnection between microcracks. The permeability
evolution of sandstone is discussed in Section 4. Further, the maximum of axial stress was 70% of the triaxial compressive strength in cyclic loading, and it is likely that the cracks inside the sandstone did not reach the threshold of crack damage stress.\(^7\) A higher loading rate produced a larger stress increment, which played a significant role in the change of fracture structures with more sensitive stress response. The bond and sliding between sandstone particles, as well as the fractures that had not yet responded to the stress change in time, were in a relatively calm period; that is, the range of stress perturbation caused by the high loading rate was small. Sandstone is equivalent to the assembly of particles. Only by activating more particles of sandstone, it may induce significant shear dilatancy, which ultimately results in shear failure due to the formation and development of local shear zone. Therefore, the sandstone produced significant shear dilatancy at a lower rate. Similarly, Su et al\(^2\) considered that high loading rates cause insufficient crack propagation in rock before failure; that is, the energy consumed by sandstone decreases. Correspondingly, the elastic strain energy gathered before peak stress increases, and the kinetic energy released at the moment of rockburst was greater.

From Figure 10, it can be seen that the dilatancy capacity decreased with an increase in the confining pressure under the same rate, which is consistent with some research results.\(^2\) Under high initial confining pressure, a large number of natural flaws in sandstone have been compacted, and the connections between particles are tighter. The increase in the normal stress acting on the fracture surface and sandstone particles resulted in a decrease in shear slip under the action of deviator stress. Moreover, a large number of
fractures were subjected to tensile stress or shear stress at their ends and edges to produce branch cracks, in turn, to communicate with adjacent fractures under low confining pressure. Therefore, the dilatancy capacity was negatively correlated with the confining pressure. Similarly, Stormont & Daemen\textsuperscript{12} considered that the initial porosity of rock salt develops with the sliding along the grain boundaries, and the lower confining pressure causes the sliding accompanied with the dilation of the rock salt to be easier.

3.2 Shear fracture energy

The sandstone produced significant shear dilatancy behavior before shear failure, and the breakdown zone size was small relative to the overall fracture size.\textsuperscript{22} Inspired by the integral path independent of $J$ integral,\textsuperscript{23} the shear fracture energy of sandstone before the peak stress was as follows:

\[
\Gamma = \Delta \tau \times \Delta u \quad (8)
\]

\[
\tau = \frac{1}{2} (\sigma_1 - \sigma_3) \sin (2\theta) \quad (9)
\]

\[
\Delta u = \frac{\Delta \varepsilon_u \times L}{\cos \theta} = \frac{\Delta \varepsilon_d \times d}{\sin \theta} \quad (10)
\]

\[
\Gamma = \frac{\Delta \tau \times L \times \Delta \varepsilon_V}{\cos \theta (1 + 4 \tan \theta)} \quad (11)
\]
where $\Gamma$ is shear fracture energy in MPa, $\tau$ is shear stress in MPa, $u$ is the slip displacement of the shear band before the shear failure plane is formed in m, $d$ is the diameter of the specimen in m (Figure 11), $L$ is the length of the specimen in m, $\theta$ is the fault angle of sandstone derived from the Mohr’s stress circle in degree. Combined with the strength in Table 1, the average of $\theta$ is 41.65°.

The shear fracture energy ($\Gamma$) is proportional to the shear stress ($\tau$) and dilatancy capacity ($\Delta \varepsilon V$) in Equation (11), that is, the $\Gamma$ increased with the increase of $\Delta \varepsilon V$. The relationships between shear fracture energy and dilatancy capacity, loading-unloading rate obtained by substituting the experimental results into Equation (11) are shown in Figures 12 and 13. High shear fracture energy can lead to an evident shear slip of sandstone grain and fracture relative surface, which is more likely to induce engineering geological disasters (such as landslides and earthquakes). As mentioned earlier, stress perturbation can activate more particle motion and fracture structure change at low rates. Only larger shear fracture energy allows these activated particles to shear slip and connect natural fractures and activated fractures, eventually forming a shear failure plane. However, the main fracture/secondary fracture preferentially propagates along the end or edge of the flaw with strong stress sensitivity to form the shear plane at high rates. In this case, no redundant shear fracture energy is required to trigger the frictional sliding of non-dominant fractures and sandstone particles farther away from dominant fractures. Therefore, lower loading-unloading rate requires more shear fracture energy for shear failure of sandstone.

As shown in Figure 12, there was no good regularity between shear fracture energy and confining pressure. The shear fracture energy was the largest in the case of $\sigma_3 = 10$ MPa, but not the least in the case of $\sigma_3 = 30$ MPa in the experiment. This was caused by the fact that the deviator stress corresponding to the failure of sandstone was not the maximum deviator stress ($\sigma_1-\sigma_3$)$_{\text{max}}$ under the designed confining pressure. Sandstone still has a strong bearing capacity from the ($\sigma_1-\sigma_3$)$_{\text{max}}$ to the adjacent brittle drop, that is, ($\sigma_1-\sigma_3$)$_{\text{max}}$ may decline to a certain extent before the brittle drop occurs. However, due to the inevitable discreteness and heterogeneity between the tested sandstone specimens, the decreasing magnitude of ($\sigma_1-\sigma_3$)$_{\text{max}}$ was uncertain. In the axial stress loading, the shear stress ($\tau$) and volumetric strain ($\varepsilon V$) changed simultaneously, and both affected the shear fracture energy.
Therefore, on the one hand, there was a regular change between dilatancy capacity and confining pressure; on the other hand, owing to the uncertain change in \((\sigma_1 - \sigma_3)_{\text{max}}\) before brittle drop, there was no good regularity between shear fracture energy and confining pressure.

## 4 | PERMEABILITY EVOLUTION

Rock engineering often faces the problem of multiphysical field coupling. The migration of fluid in coal and rock cannot be ignored and may even cause dynamic disasters, such as coal and gas outburst. Therefore, it is necessary to investigate the permeability evolution of sandstone under cyclic loading-unloading.

In addition, the internal pore and fracture structure of the tested sandstone was uncomplicated, and there was no obvious bedding. The measured gas flow rate was greater than...
where the permeability in Equation (12) is normalized as follows:

$$k_N = \frac{k}{k_0}$$

where $k_N$ is the normalized permeability, $k_i$ is the real-time permeability in m$^2$, $k_0$ is the initial permeability in m$^2$, which was recorded as the permeability at the starting point of the first cyclic loading-unloading of axial stress.

Figure 14 shows the relationship between normalized permeability ($k_N$) and cyclic loading-unloading number ($N$). It can be seen that the confining pressure is negatively correlated with $k_N$. It is widely agreed that a lower confining pressure implies that the sandstone is weakly constrained horizontally, which is beneficial to fluid flow. Further, $k_N$ decreases with an increase in the loading-unloading rate. The normalized permeability was lower because of the insufficient development of the fractures and incomplete sliding of sandstone particles under high loading rate, which may be conducive to the excavation of strata with high potential energy of gas, such as coal and gas outburst seam. Liu et al. also considered that permeability evolution is closely related to strain.

However, the normalized permeability did not show regularity with an increase in cyclic loading-unloading number. $k_N$ fluctuated within a small range under each stress condition. The volumetric strain increased with an increase in the loading number, which indicates that the sandstone was in a compressed state; however, the normalized permeability did not decrease. The author considers that the effective pores and fractures play a decisive role in permeability. These effective seepage channels may not change regularly with a change in $v$ and $N$. The evolution of normalized permeability may be related to the dilatancy capacity between adjacent cyclic loading-unloading. This dilatancy capacity indicates that the fracture structure of the sandstone was being dynamically adjusted and was affected by the in situ stress and particle distribution, intergranular fillers, and fracture structure of sandstone. However, no significant fatigue damage was produced due to the smaller prepeak axial stress than the peak strength.

In addition, although the fractures and particles in sandstone were compressed during the increase in volumetric strain, the shear slip inside the sandstone also affected the permeability evolution under the deviator stress. Therefore, there was no good regularity between normalized permeability and loading-unloading number.

FIGURE 15  Relationship between normalized permeability and volumetric strain increment

$10^{-7}$ m$^3$/s. Therefore, the flow of CH$_4$ in the sandstone can be characterized by Darcy's law in the experiment. The fracture permeability equation is as follows:

$$k = \frac{2q\mu LP_2}{A \left(P_1^2 - P_2^2\right)}$$

FIGURES 15 and 16 show the relationship between normalized permeability ($k_N$) and dilatancy capacity ($\Delta\varepsilon_V = \varepsilon_{V-1} - \varepsilon_{V-2}$), loading-unloading rate ($v$), respectively. Volume expansion is induced by the development of microcracks. The permeability is sensitively dependent on the strain, and high dilatancy capacity also results in a corresponding increase in plastic strain, which in turn leads to an increase in the apparent connected porosity and normalized permeability. Furthermore, high in situ stress (ie, the increase in initial confining pressure in experiment) determines the greater ultimate energy-storage capacity of the rock, which increases the possibility of rockburst. Combined with the experimental results, when the engineering activities are conducted at mining depths of kilometer levels or the special rock formations, such as the top coal caving and large mining height technology, it is necessary to design the advance rate such that the rate level is sufficiently low to prevent rockburst, and yet high enough to prevent coal and gas outburst. It is worth noting that due to the inevitable
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discreteness and heterogeneity between the tested sandstone specimens, the permeability increases with the loading rate and then decreases at $\sigma_3 = 10$ MPa. Under this confining pressure, the permeability of sandstone is the smallest when the loading-unloading rate is the maximum (Figure 16), which satisfies the purpose of our research.

Figure 17 shows the relationship between normalized permeability and shear fracture energy ($\Gamma$). Zhang et al.\textsuperscript{40} considered that there is a strong correlation between porosity and strain energies. It can be seen that $k_N$ increased with an increase in $\Gamma$ under identical confining pressure. Shear action plays an important role in the permeability of rock, and a small shear displacement can cause a significant increase in permeability.\textsuperscript{41}

FIGURE 16 Relationship between normalized permeability and loading-unloading rate

FIGURE 17 Relationship between normalized permeability and shear fracture energy

2. Dilatancy capacity decreases with an increase in confining pressure under an identical loading rate. Low loading rates make the sandstone produce significant shear dilatancy under identical confining pressure.
3. Normalized permeability of sandstone decreases with an increase in loading-unloading rate at the moment of failure. The evolution of normalized permeability is closely related to the dilatancy capacity of sandstone, which is determined by the shear fracture energy.
4. High loading rate is beneficial for the prevention of gas-type kinetic energy disasters in strata with high gas potential energy; however, it is not conducive to the prevention of rockburst.

5 | CONCLUSION

Under the combination of different initial confining pressure and loading-unloading rate, the cyclic loading-unloading experiment of axial stress with constant amplitude was conducted to investigate the deformation behavior and permeability evolution of sandstone. The main conclusions drawn from this study are as follows:

1. With an increase in cyclic loading-unloading times, sandstone tends to be compressed under high confining pressure. The axial compression is induced by the residual deformation of sandstone at each unloading, and the lateral compression is determined by the Poisson's ratio and axial displacement. Under low confining pressure, the Poisson's effect is more evident because of weaker horizontal constraint of sandstone, which shows lateral expansion.

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CONFLICT OF INTEREST

We declare we have no competing interests.

ETHICAL APPROVAL

It is not relevant to this work.

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DATA AVAILABILITY STATEMENT

Data are available within the article or its supplementary materials.

REFERENCES

1. Hu X, Su G, Chen G, et al. Experiment on rockburst process of borehole and its acoustic emission characteristics. Rock Mech Rock Eng. 2018;52:783-802.
2. Liu E, Huang R, He S. Effects of frequency on the dynamic properties of intact rock samples subjected to cyclic loading under confining pressure conditions. Rock Mech Rock Eng. 2011;45(1):89-102.
3. Liu E, He S. Effects of cyclic dynamic loading on the mechanical properties of intact rock samples under confining pressure conditions. Eng Geol. 2012;125:81-91.
4. Liu E, He S, Xue X, Xu J. Dynamic properties of intact rock samples subjected to cyclic loading under confining pressure conditions. Rock Mech Rock Eng. 2011;44(5):629-634.
5. Jiang C, Duan M, Yin G, et al. Experimental study on seepage properties, AE characteristics and energy dissipation of coal under cyclic loading. Eng Geol. 2017;221:114-123.
6. Liu J, Xie H, Hou Z, Yang C, Chen L. Damage evolution of rock salt under cyclic loading in uniaxial tests. Acta Geotech. 2013;9(1):153-160.
7. Martin CD, Chandler NA. The progressive fracture of Lac du Bonnet granite. Int J Rock Mech Min Sci Geomech Abstr. 1994;31(6):643-659.
8. Fuenkajorn K, Phueakphum D. Effects of cyclic loading on mechanical properties of Maha Sarakham salt. Eng Geol. 2010;112(1-4):43-52.
9. Eberhardt E, Stead D, Stimpson B. Quantifying progressive pre-peak brittle fracture damage in rock during uniaxial compression. Int J Rock Mech Min Sci. 1999;36(3):361-380.
10. McKee CR, Bumb AC, Koenig RA. Stress-dependent permeability and porosity of coal and other geologic formations. SPE Form Eval. 1988;3(01):81-91.
11. Brace WF, Walsh JB, Frangos WT. Permeability of granite under high pressure. J Geophys Res. 1968;73(6):2225-2236.
12. Stormont JC, Daemen J. Laboratory study of gas permeability changes in rock salt during deformation. Int J Rock Mech Min Sci Geomech Abstr. 1992;29(4):325-342.
13. Zhang S, Cox SF, Paterson MS. The influence of room temperature deformation on porosity and permeability in calcite aggregates. J Geophys Res. 1994;99(B8):15761.
14. Tan YL, Yu FH, Chen L. A new approach for predicting bedding separation of roof strata in underground coalmines. Int J Rock Mech Min Sci. 2013;61:183-188.
15. Yao Y, Liu D, Tang D, Tang S, Che Y, Huang W. Preliminary evaluation of the coalbed methane production potential and its geological controls in the Weibei Coalfield, Southeastern Ordos Basin, China. Int J Coal Geol. 2009;78(1):1-15.
16. Shabanimashcool M, Li CC. A numerical study of stress changes in barrier pillars and a border area in a longwall coal mine. Int J Coal Geol. 2013;106:39-47.
17. Li W, Zhang D, Li M. Failure criteria of gas-infiltrated sandy shale based on the effective stress principle. Energies. 2016;9(11):972.
18. Yin G, Jiang C, Wang JG, Xu J. Combined effect of stress, pore pressure and temperature on methane permeability in anthracite coal: an experimental study. Transp Porous Media. 2013;100(1):1-16.
19. ISRM. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. In: Ulusay R, Hudson JA, editors. Prepared by the Commission on Testing Methods. Ankara: ISRM; 2007.
20. Munoz H, Taheri A. Local damage and progressive localisation in porous sandstone during cyclic loading. Rock Mech Rock Eng. 2017;50(12):3253-3259.
21. Su G, Jiang J, Feng X, Mo C, Jiang Q. Experimental study of ejection process in rockburst. Chin J Rock Mech Eng. 2016;35(10):1990-1999 [in Chinese].
22. Ougier-Simonin A, Zhu W. Effect of pore pressure buildup on slowness of rupture propagation. J Geophys Res: Solid Earth. 2015;120(12):7966-7985.
23. Rice JR. A path independent integral and the approximate analysis of strain concentration by notches and cracks. J Appl Mech. 1968;35(2):379.
24. Sultan N. Comment on “Excess pore pressure resulting from methane hydrate dissociation in marine sediments: a theoretical approach” by Wenxue Xu and Leonid N. Germanovich. J Geophys Res. 2007;112:B02103. https://doi.org/10.1029/2006JB004527
25. Fan C, Elsworth D, Li S, Zhou L, Yang Z, Song Y. Thermo-hydro-mechanical-chemical couplings controlling CH4 production and CO2 sequestration in enhanced coalbed methane recovery. Energy. 2019;173:1054-1077.
26. Wu W, Reece JS, Gensterblum Y, Zoback MD. Permeability evolution of slowly slipping faults in shale reservoirs. Geophys Res Lett. 2017;44(22):11368-11375.
27. Liu C, Yin G, Li M, Shang D, Deng B, Song Z. Deformation and permeability evolution of coals considering the effect of bedding. Int J Rock Mech Min Sci. 2019;117:49-62.
28. Fan C, Elsworth D, Li S, et al. Modelling and optimization of enhanced coalbed methane recovery using CO2/N2 mixtures. Fuel. 2019;253:1114-1129.
29. Sutherland W. J.L. The viscosity of gases and molecular force. The London, Edinburgh, and Dublin Philosophical Magazine and J Sci. 1893;36(223):507-531.
30. Lu S, Zhang Y, Sa Z, Si S. Evaluation of the effect of adsorbed gas and free gas on mechanical properties of coal. Environ Earth Sci. 2019;78(6):218. https://doi.org/10.1007/s12665-019-8222-3.
31. Taheri A, Royle A, Yang Z, Zhao Y. Study on variations of peak strength of a sandstone during cyclic loading. Geomech Geophys Geo-Energy Geo-Resources. 2015;2(1):1-10.
32. Shao JF, Chiarelli AS, Hoteit N. Modeling of coupled elastoplastic damage in rock materials. Int J Rock Mech Min Sci. 1999;36(4-5):444.
33. Lu S, Zhang Y, Sa Z, Si S, Shu L, Wang L. Damage-induced permeability model of coal and its application to gas predrainage in combination of soft coal and hard coal. Energy Sci Eng. 2019;7:1352-1367. https://doi.org/10.1002/ese.3.355
34. Su G, Feng X, Wang J, Jiang J, Hu L. Experimental study of remotely triggered rockburst induced by a tunnel axial dynamic disturbance under true-triaxial conditions. Rock Mech Rock Eng. 2017;50(8):2207-2226.
35. Lu S, Li L, Cheng Y, Sa Z, Zhang Y, Yang N. Mechanical failure mechanisms and forms of normal and deformed coal combination containing gas: model development and analysis. Eng Fail Anal. 2017;80:241-252.
36. Xie H, Chen Z, Wang J. Three-dimensional numerical analysis of deformation and failure during top coal caving. Int J Rock Mech Min Sci. 1999;36(5):651-658.
37. Wang J, Zhang J, Li Z. A new research system for caving mechanism analysis and its application to sublevel top–coal caving mining. *Int J Rock Mech Min Sci*. 2016;88:273-285.

38. Ju J, Xu J. Structural characteristics of key strata and strata behaviour of a fully mechanized longwall face with 7.0 m height chocks. *Int J Rock Mech Min Sci*. 2013;58:46-54.

39. Wang F, Jiang B, Chen S, Ren M. Surface collapse control under thick unconsolidated layers by backfilling strip mining in coal mines. *Int J Rock Mech Min Sci*. 2019;113:268-277.

40. Zhang J, Deng H, Taheri A, Ke B, Liu C. Deterioration and strain energy development of sandstones under quasi-static and dynamic loading after freeze-thaw cycles. *Cold Reg Sci Technol*. 2019;160:252-264.

41. Lee H, Park Y, Cho T, You K. Influence of asperity degradation on the mechanical behavior of rough rock joints under cyclic shear loading. *Int J Rock Mech Min Sci*. 2001;38(7):967-980.

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