Experimental study on seepage characteristics of coal under truly triaxial loading and unloading based on different minimum principal stress properties

Zhiyuan Liu¹, Gang Wang², Weimin Cheng², Xiangjie Qin¹, Dongyang Han¹

1 Shandong University of Science and Technology, College of Safety and Environmental Engineering, Qingdao, PR China
2 Shandong University of Science and Technology, Mine Disaster Prevention and Control-Ministry of State Key Laboratory Breeding Base, Qingdao, PR China

E-mail: gang.wang@sdust.edu.cn

Abstract: China’s coal-mining industry has developed from shallow mining to deep mining. Consequently, coal under unloading conditions is becoming increasingly complicated. In this study, seepage experiments are conducted for different minimum principal stress properties and levels of coal using a self-developed truly triaxial fluid–solid coupling seepage experimental system. In the experiment, the maximum and intermediate principal stresses correspond to the rigid stress and the minimum principal stress corresponds to the flexible stress. Experimental results show that the flexible minimum principal stress is conducive to coal deformation during axial compressive loading, whereas the rigid confining pressure inhibits coal deformation. For coal under stress unloading, the deformation and permeability of coal show a recovery change. In the initial stage of unloading, the permeability of coal shows a relatively large increase; this increase is evident in the unloading tests for rigid minimum principal stress. However, the level of the minimum principal stress is not related to the unloading effect. The findings of this study aid the prevention and control of dynamic disasters caused by coalbed gas in deep coal mining.

Key words: Truly triaxial stress loading and unloading; Minimum principal stress; Stress properties; Coal; Permeability characteristics

1. Introduction

Underground coal mining induces complex loading and unloading stresses of coal and rock mass, and the unloading condition tends to destroy coal mass. Therefore, the influence of stress unloading on the deformation, damage, and permeability evolution of coal must be investigated.

Some scholars have studied the mechanical and seepage characteristics of coal and rock mass. Heping Xie et al. [1] analyzed the distribution law of support pressure on the working face under three typical mining conditions (i.e., caving coal, nonpillar, and protective layer mining) by increasing axial stress and reducing confining pressure. Jiang Xu et al. [2] studied the deformation and permeability characteristics of coal and rock under loading and unloading conditions using their self-developed thermal–fluid–solid coupling triaxial servo seepage test system for gas-bearing coal; they reported that the permeability, stress difference, and strain of coal and rock during the loading and unloading
processes present a staged change. Changbao Jiang et al. \cite{3,4} conducted an experimental study on the mechanical and permeability characteristics of gas-bearing coal on the basis of the influence of loading and unloading speed; they showed that the permeability of some coal samples under loading and unloading conditions presents a v-shaped change of first decreasing and then increasing. Guangzhi Yin et al. \cite{5} conducted experiments on the mechanical properties of gas-bearing coal under different loading and unloading conditions, and their results indicated that the load bearing strength of coal samples under loading and unloading conditions is lower than the peak strength of coal samples under conventional loading. Chao Xu et al. \cite{6} studied the characteristics of coal damage and permeability variation under three stress paths: increasing axial pressure at constant confining pressure, unloading confining pressure at constant axial pressure, and simultaneously increasing axial pressure and unloading confining pressure. Xiaoyuan Li et al. \cite{7} conducted seepage tests of coal under cyclic loading at constant gas pressure and different confining pressures and found that permeability gradually increases during unloading and decreases during loading. Xiaochun Xiao et al. \cite{8} examined the influence of loading rate on the mechanical properties and fracture laws of coal. Chao Liu et al. \cite{9} conducted confining pressure unloading tests at different stress levels and found that when axial stress decreases, confining pressure plays a leading role in permeability, and coal pore and fissure structures are mainly developed, expanded, and extended. Dengke Wang et al. \cite{10} studied the characteristics of the deformation and permeability variation of coal under unloading confining pressure and indicated that the permeability of coal increases with the decrease in confining pressure, and permeability changes exponentially. According to their unloading confining pressure test, Anzeng Hua et al. \cite{11} pointed out that instability failure occurs when axial stress is greater than the uniaxial compressive strength of coal. Yi Xue et al. \cite{12} conducted tests under loading and unloading confining pressure and pointed out that the greater the unloading rate of confining pressure, the more complex the destroyed structure of coal, the greater the fractal dimension, and the greater the permeability after fracturing. Guangzhi Yin et al. \cite{13} conducted deformation and permeability evolution tests of coal under confining pressure for four periods and compared and analyzed the deformation characteristics during loading. They found that the compressive strength and strain of coal gradually decreases with the unloading of confining pressure. S.Q. Yang et al. \cite{14} investigated the deformation and failure characteristics of marble under six paths and emphasized the influence of stress paths on peak strength and failure pattern. S. R. Swanson and W. S. Brow \cite{15} explored the effect of loading paths on the fracture and maximum strength of rock. Shengqi Yang et al. \cite{16} investigated the strength and deformation behavior of red sandstones under simple and complex loading paths, which are important for ensuring the stability and safety of deep underground rock engineering.

The above scholars studied the deformation and permeability characteristics of coal and rock mass under various loading and unloading paths through stress and displacement control methods to utilize the loading and unloading stress law of coal and rock mass in the process of coal mining. In this study, a self-developed truly triaxial fluid–solid coupling seepage test device was used to analyze the seepage characteristics of coal under the condition of axial stress loading and unloading. The analysis was performed for different minimum principal stress loading properties, with the working face supported and unsupported during pressure relief. The results suggested that the effect of confining pressure on deformation and seepage characteristics during loading and unloading is worthy of further exploration.

2. Test design

2.1 Test equipment and test pieces
A truly triaxial fluid–solid coupling seepage test system for coal is adopted in the test equipment \cite{17}. The coal sample for the test is taken from the N2808 working face of No. 8 anthracite coal seam in the Yuyang coal mine of Chongqing Songzao Coal Power Co., Ltd. \cite{18}. The size of the sample is 100 mm × 100 mm × 200 mm.
Figure 1. Truly triaxial fluid–solid coupling seepage test apparatus for coal

2.2 Test design and implementation

To study pressure relief on the working face in coal mining, the influence of axial pressure loading and unloading on the deformation and seepage characteristics of coal is analyzed under two types of stresses, with the stress in the direction of minimum principal stress loaded through the soft hydraulic oil and the rigid compressive block. The specific test steps are as follows:

(1) In accordance with the connection requirements for the test system, the coal sample and each pipeline are connected tightly to ensure the air tightness of the test system.

(2) ① Loading test: The axial stress $\sigma_1$ (maximum principal stress) and confining principal stress $\sigma_2$ and $\sigma_3$ (intermediate principal stress and minimum principal stress) are set to 4 MPa at the hydrostatic pressure level, and then $\sigma_1$ and $\sigma_2$ (or $\sigma_3$) are separately set to 6 MPa. Lastly, $\sigma_1$ is applied separately to form a truly triaxial stress environment. After the stress is stabilized, the 1-MPa gas is injected into the coal. When the coal displacement and gas flow are unchanged, $\sigma_1$ is applied to its peak strength ($\sigma_u$) via the force control method at a rate of 0.01 N/s. After the coal sample is destructed, loading is continued via the displacement control method at a rate of 0.01 mm/s until the end of the test.

② Unloading test: The process of forming a truly triaxial stress environment is basically the same. The only difference is that $\sigma_1$ is applied to 80% of $\sigma_u$. Then, during the unloading of $\sigma_1$, the deformation and destruction of the coal samples are observed and recorded.

(3) After the tests, the test device is cleaned and checked to change the minimum principal stress level for the next control experiment.

(4) Four sets of test data are collected, compared, and analyzed.
3. Test results and analysis
3.1 Loading seepage test of coal for different minimum principal stress properties
To compare and analyze the influence of axial loading on the deformation and seepage characteristics of coal for different minimum principal stress properties, an axial loading seepage test is designed. The coal sample undergoing compression deformation has positive strains, and the coal sample undergoing expansion deformation has negative strains.

3.1.1 Deformation characteristics of coal under loading stress path
Fig. 2 shows the adjustment of the flexible and rigid stress of the minimum principal stress through the different stress loading modes of the minimum and intermediate principal stress. In other words, when the direction of the minimum principal stress is rigid, intermediate principal stress must be converted into minimum principal stress.

![Figure 2. Designed adjustment of stress for tests](image-url)
Fig. 3 shows the stress–strain curves of coal from the horizontal axial compression tests for different minimum principal stress properties at a gas seepage pressure of 1 MPa. In the two axial compressive loading tests, when the gas pressure is 1 MPa and the minimum principal stress is 4 MPa, the deformation and volumetric strain of the coal sample in the direction of the maximum principal stress first increase and then decrease with the increase in maximum principal stress. In the truly triaxial stress environment with a minimum principal stress of 4 MPa, the minimum principal stress is rigid, and the minimum principal stress is flexible. In the axial compressive loading tests, the peak strength is 19.30 MPa for the former coal sample and 17.70 MPa for the latter, which is reduced by 8.3% compared with that of the former. The strains in the directions of the maximum principal stress and the minimum principal stress corresponding to the peak strength are increased by 9.9% and 0.002%, respectively, whereas the volumetric strain corresponding to the peak strength is decreased by 26.5%. As shown in Table 1, when the minimum principal stress is 5 MPa, the strains of the coal sample change similarly to different degrees, and the degree of deformation is much greater than that at the stress level of 4 MPa. This result indicates that flexible minimum principal stress is conducive to coal deformation under axial compressive loading, whereas rigid confining pressure inhibits coal deformation. Moreover, the greater the flexible minimum principal stress, the greater the deformation degree of coal.

**Table 1.** Comparison of coal deformation for different minimum principal stress properties

|                | $\sigma_3 = 4$ MPa | $\sigma_3 = 5$ MPa |
|----------------|-------------------|-------------------|
| $\sigma_u$ (MPa) | 19.30             | 21.81             |
| $\varepsilon_1$ ($10^{-2}$) | 7.15              | 7.86              |
| $\varepsilon_3$ ($10^{-2}$) | -4.15             | -3.92             |
| $\varepsilon_v$ ($10^{-2}$) | 2.53              | 2.17              |

3.1.2 Permeability variation of coal under loading stress path

Fig. 4 shows the permeability variation of coal samples during axial compressive loading for different minimum principal stress properties.
Figure 4. Permeability variation of coal under loading for different confining pressure properties

In the rigid stress axial loading test with a gas pressure of 1 MPa and a minimum principal stress of 4 MPa, the initial permeability ($K_0$) of the coal sample is $1.88 \times 10^{-15} \text{ m}^2$, the peak permeability ($K_u$) is $0.34 \times 10^{-15} \text{ m}^2$, and the final permeability ($K$) is $0.59 \times 10^{-15} \text{ m}^2$. Similarly, in the flexible stress axial loading test with a minimum principal stress of 4 MPa, the initial permeability ($K_0$) of the coal sample is $1.73 \times 10^{-15} \text{ m}^2$, the peak permeability ($K_u$) is $0.33 \times 10^{-15} \text{ m}^2$, and the final permeability ($K$) is $0.50 \times 10^{-15} \text{ m}^2$. The initial, peak, and final permeability in the latter test are decreased by 8.0%, 3.0%, and 15.2%, respectively.

When the minimum principal stress is loaded to a stress level of 5 MPa, the permeability of the coal sample, particularly the peak and final permeability whose values significantly vary, also changes similarly. In the axial compression loading tests, the minimum principal stress properties and stress levels significantly influence the permeability characteristics of coal. Furthermore, the greater the minimum principal stress, the greater the effect of its properties. Therefore, the effects of the supporting material properties on the evolution of coal seam deformation and permeability should be considered when the working face in the mining area is supported.

Table 2. Comparison of permeability of coal for different minimum principal stress properties

|                  | $\sigma_3 = 4 \text{ MPa}$ | $\sigma_3 = 5 \text{ MPa}$ |
|------------------|--------------------------|--------------------------|
|                  | Rigid | Flexible | Rigid | Flexible |
| $K_0 \left(10^{-15} \text{ m}^2\right)$ | 1.88  | 1.73     | 2.02  | 1.97     |
| $K_u \left(10^{-15} \text{ m}^2\right)$ | 0.34  | 0.33     | 0.34  | 0.21     |
| $K \left(10^{-15} \text{ m}^2\right)$ | 0.59  | 0.50     | 0.54  | 0.39     |
3.2 Unloading seepage test of coal for different minimum principal stress properties

The axial compression loading test indicates that the minimum principal stress properties and levels greatly influence the deformation and seepage characteristics of coal. To study the effects of axial pressure unloading on mechanical properties and permeability evolution, an axial pressure unloading seepage test of coal is designed. Specifically, the first 80% of the peak axial pressure is loaded on the coal sample at the truly triaxial stress level, and then the axial pressure is unloaded through the displacement control method at a rate of 0.1 mm/min. Lastly, the deformation of the coal sample is observed, and the permeability variation is analyzed.

3.2.1 Deformation characteristics of coal under unloading stress path

Figs. 5 (a)–(d) show the stress–strain curves from the axial pressure unloading tests at a constant gas pressure of 1 MPa for different minimum principal stress properties and levels consistent with those of the loading tests.

![Stress–strain curves](image)

(a) Rigid confining pressure of 4 MPa  (b) Flexible confining pressure of 4 MPa

(c) Rigid confining pressure of 5 MPa  (d) Flexible confining pressure of 5 MPa

**Figure 5.** Stress–strain curves of coal from unloading tests under different confining pressures

As shown in Fig. 5, the recovery of deformation and permeability occurs in the coal sample with the unloading of the axial pressure. However, the rate of change is relatively smaller than that in the loading tests.

When the gas pressure is 1 MPa and the minimum principal stress is 4 MPa, the axial pressure unloading test is started after 80% of the peak axial pressure of the coal sample is reached. In the truly triaxial compression-unloading test for the rigid minimum principal stress, the initial strain ($\varepsilon_{1,1}$) in the direction of the maximum principal stress is $6.5 \times 10^{-2}$, the final strain ($\varepsilon_{1,2}$) is $3.8 \times 10^{-2}$, and the strain difference is $2.7 \times 10^{-2}$. Moreover, the initial volumetric strain ($\varepsilon_{v,1}$) is $2.38 \times 10^{-2}$, the final volumetric strain ($\varepsilon_{v,2}$) is $2.31 \times 10^{-2}$, and the strain difference is $0.07 \times 10^{-2}$. In addition, the initial strain ($\varepsilon_{3,1}$) and final strain ($\varepsilon_{3,2}$) in the direction of the minimum principal stress are $-3.51 \times 10^{-2}$ and $-1.54 \times 10^{-2}$,
respectively, and the strain difference is $-1.97 \times 10^{-2}$. In the truly triaxial compression-unloading test for the flexible minimum principal stress, the difference of the strain in the direction of the maximum principal stress is $3.3 \times 10^{-2}$, the volumetric strain difference is $-0.41 \times 10^{-2}$, and the difference of the strain in the direction of the minimum principal stress is $-2.3 \times 10^{-2}$. The unloading effects of the flexible minimum principal stress are more evident than those of the rigid minimum principal stress. Moreover, flexible stress can facilitate pressure relief and produce large deformation to achieve pressure relief in a large range of coal seams.

Table 3. Comparison of coal deformation for different minimum principal stress properties

|                  | $\sigma_3 = 4$ MPa |                  | $\sigma_3 = 5$ MPa |
|------------------|--------------------|------------------|--------------------|
|                  | Rigid              | Flexible         | Rigid              | Flexible         |
| $\varepsilon_{11}$ ($10^{-2}$) | 6.50               | 7.00             | 8.64               | 5.74             |
| $\varepsilon_{12}$ ($10^{-2}$) | 3.80               | 3.67             | 3.13               | 2.92             |
| $\varepsilon_{31}$ ($10^{-2}$) | -3.51              | -3.67            | -4.91              | -3.20            |
| $\varepsilon_{32}$ ($10^{-2}$) | -1.54              | -1.42            | -1.23              | -1.50            |
| $\varepsilon_v$ ($10^{-2}$)   | 2.38               | 2.02             | 1.70               | 1.96             |
| $\varepsilon_v$ ($10^{-2}$)   | 2.31               | 2.43             | 1.81               | 2.14             |

3.2.2 Permeability variation of coal under unloading stress path

Fig. 6 shows the permeability variation of coal from the truly triaxial unloading axial pressure seepage tests for different minimum principal stress properties and levels at a gas pressure of 1 MPa and a minimum principal stress of 4 MPa. As indicated in this figure, the permeability of the coal sample increases to different degrees with the unloading of axial pressure. The increase is evident at the beginning of the unloading, whereas the rate of increase decreases as the unloading continues.
Figure 6. Permeability variation of coal from unloading tests under different confining pressures. Specifically, when the minimum principal stress is 4 MPa as rigid stress, the initial permeability \( (K_0) \) of the coal sample is \( 0.30 \times 10^{-15} \) m\(^2\), the final permeability \( (K) \) is \( 2.25 \times 10^{-15} \) m\(^2\), and the permeability difference is \( 1.95 \times 10^{-15} \) m\(^2\). When the minimum principal stress is 4 MPa as flexible stress, the initial permeability \( (K_0) \) of the coal sample is \( 0.32 \times 10^{-15} \) m\(^2\), the final permeability \( (K) \) is \( 2.21 \times 10^{-15} \) m\(^2\), and the permeability difference is \( 1.89 \times 10^{-15} \) m\(^2\). Similarly, the permeability difference of the coal sample is \( 1.78 \times 10^{-15} \) m\(^2\) for the minimum principal stress of 5 MPa as rigid stress and \( 1.87 \times 10^{-15} \) m\(^2\) for the minimum principal stress of 5 MPa as flexible stress. Therefore, the increase in the initial hydrostatic pressure level of the minimum principal stress reduces the degree of change in coal permeability in the unloading axial pressure tests. However, no evident correspondence is found between the differences in permeability at different minimum principal stress levels.

Table 4. Comparison of the permeability of coal for different minimum principal stress properties

| \( \sigma_3 = 4 \text{ MPa} \) | \( \sigma_3 = 5 \text{ MPa} \) |
|----------------|----------------|
| \( K_0 (10^{-15} \text{ m}^2) \) | 0.30 | 0.32 |
| \( K (10^{-15} \text{ m}^2) \) | 2.25 | 2.21 |

4. Conclusions

In this study, truly triaxial seepage tests of coal are conducted for different minimum principal stress properties and levels at constant seepage pressure. The influences of the initial stress levels and properties on coal deformation and seepage characteristics are analyzed, and the following conclusions are drawn:

(1) In the truly triaxial compressive loading tests, the flexible minimum principal stress is conducive to coal deformation during axial compressive loading, whereas the rigid confining pressure inhibits coal deformation. Moreover, the greater the flexible minimum principal stress, the greater the deformation degree of coal. However, when the values of the two types of stresses are equal, the flexible minimum principal stress inhibits the permeability change of coal.

(2) For coal under stress unloading, the deformation and permeability of coal show a recovery change, i.e., the deformation and permeability are restored toward their initial states; however, they cannot be restored to their original state because the rate of change is smaller than that during loading, particularly in the unloading tests for the rigid minimum principal stress.

(3) The unloading of axial pressure can increase the permeability of coal, particularly in the initial stage of unloading. Moreover, the increase in the permeability of coal is evident in the unloading tests for the rigid minimum principal stress. However, the level of the minimum principal stress is not related to the effects of pressure relief.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 51674158, 51574158, 51934004, and 51974176), the Taishan Scholar Talent Advantage Unique Subject Team Support Program, the Major Program of Shandong Province Natural Science Foundation (No.ZR2018ZA0602), the Science and Technology Support Plan for Youth Innovation of Colleges and Universities in Shandong Province (No. 2019KJH006), the Special fund for Taishan scholars project (No. TS20190935).

References

[1] XIE H P, ZHOU H W, LIU J F et al. Mining-induced mechanical behavior in coal seams under different mining layouts[J]. Journal of the China Coal Society, 2011, 36(7): 1007-1007.
[2] XU J, LI B B, ZHOU T et al. Experimental study of coal deformation and permeability characteristics under loading-unloading conditions[J]. Journal of the China Coal Society, 2012, 37(9): 1493-1498.
[3] JIANG C, YU H, DUAN M et al. Experimental study of mechanical and permeability characteristics of coal with methane containing due to different loading-unloading speeds[J]. Journal of Mining and Safety Engineering, 2017, 34(6): 1216–1222.

[4] BAO J C, GUN H, XIANG H Q. Experiment on deformation failure and permeability evolution law of gas-containing coal under multi stage unloading confining pressures[J]. Journal of China Coal Society, 2011, 36(12): 10–13.

[5] YIN G, LI W, LI M et al. Experimental study of mechanical properties of coal containing methane under different loading-unloading conditions[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(5): 891–901.

[6] CHAO X, QIANG F, KAI W et al. Effects of the loading methods on the damage-permeability aging characteristics of deep mining coal[J]. Journal of China University of Mining & Technology, 2018, 47(1): 197–205.

[7] XIAOQUAN L, GUANGZHI Y, BO C. Experimental study on deformation and seepage properties of outburst coal samples under cyclic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29: 3498–3504.

[8] XIAO X C, DING X, ZHAO X et al. Experimental study on acoustic emission and charge signals during coal failure process at different loading rates[J]. Rock and Soil Mechanics, 2017, 38(12): 3419–3426.

[9] CHAO L, DONG MING Z, DE LEI S et al. Influence of confining pressure unloading at post-peak on deformation and permeability characteristics of raw coal[J]. Rock and Soil Mechanics, 2018, 39(6): 2017–2034.

[10] WANG D, ZHANG P, WEI J et al. The seepage properties and permeability enhancement mechanism in coal under temperature shocks during unloading confining pressures[J]. Journal of Natural Gas Science and Engineering, Elsevier B.V., 2020, 77: 103242.

[11] HUA A Z, YOU M Q. Rock failure due to energy release during unloading and application to underground rock burst control[J]. Tunnelling and Underground Space Technology, 2001, 16(3): 241–246.

[12] XUE Y, RANJITH P G, GAO F et al. Mechanical behaviour and permeability evolution of gas-containing coal from unloading confined pressure tests[J]. Journal of Natural Gas Science and Engineering, Elsevier B.V., 2017, 40: 336–346.

[13] YIN G, JIANG C, WANG J G et al. Geomechanical and flow properties of coal from loading axial stress and unloading confining pressure tests[J]. International Journal of Rock Mechanics and Mining Sciences, Elsevier, 2015, 76: 155–161.

[14] YANG S Q, JING H W, LI Y S et al. Experimental Investigation on Mechanical Behavior of Coarse Marble Under Six Different Loading Paths[J]. Experimental Mechanics, 2011, 51(3): 315–334.

[15] SWANSSON S R, BROWN W S. An observation of loading path independence of fracture in rock[J]. International Journal of Rock Mechanics and Mining Sciences and, 1971, 8(3): 277–281.

[16] YANG S Q, JING H W. Evaluation on strength and deformation behavior of red sandstone under simple and complex loading paths[J]. Engineering Geology, 2013, 164: 1–17.

[17] WANG G, WANG P, GUO Y et al. A Novel True Triaxial Apparatus for Testing Shear Seepage in Gas-Solid Coupling Coal[J]. Geoﬂuids, 2018, 2018: 1–9.

[18] WANG G, LI W, WANG, PENGFEI et al. Deformation and gas flow characteristics of coal-like materials under triaxial stress conditions[J]. International Journal of Rock Mechanics and Mining Sciences, 2016, 91(November 2016): 72–80.