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REVIEW

Experimental study of coal flow characteristics under mining disturbance in China

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Abstract
With annually increased coal mining depth, gas extraction becomes more and more problematic. The gas extraction effect depends on coal seam permeability, which, in turn, is affected by many factors, including loading and unloading stresses and strains in the coal seam. Stresses induce internal cracks, resulting in cleats and gas emission channels, the coal seam permeability permanently changes accordingly. To clarify the stress-induced effects on coal seam permeability, this survey summarized the available approaches used to link the stress path and seepage law in the coal body seepage law, which can be classified into two design methods: single load variation and combined field mining method. The characterization methods used to observe the surface of coal samples and three-dimensional reconstruction include electron microscopy, CT scanning, and Nuclear Magnetic Resonance (NMR). According to the stress paths designed by the above two approaches, the seepage laws and similarities of three kinds of coal samples with the fractured structure were summarized in this paper. The following directions are recommended to study the seepage law of coal bodies with three kinds of fractured structures under stress. Firstly, the stress path of the experimental coal body should be designed by the combined field mining method. The stressed environment of a deep coal seam is complicated, and the axial and confining pressures change simultaneously. Therefore, one cannot fully reflect the real situation on-site by studying permeability evolution alone. Secondly, during the coal seam mining, the stressed state changes from time to time, and the development of coal seam fractures is affected by mining. When studying the stress effect on seepage of coal samples, the fractured structure of coal samples should be considered. Finally, the available structural characterization methods of coal samples can be combined with the 3D printing technology, which would produce artificial samples with the fractured structure characteristics of natural coal.

Keywords Stress loading and unloading · Structural characterization · Permeability · Fracture structure · Broken coal

The occurrence and mining conditions of underground coal seams become more complex with increasing mining depth, making mining gas extraction more and more problematic (Chen et al. 2020; Wang et al. 2021a, b). Gas extraction efficiency directly depends on the coal seam permeability, which, in turn, is controlled by several internal factors (such as coal strength, stress loading–unloading methods, and bedding structure) and external factors (such as temperature, moisture, and buried depth) (Liu et al. 2020). In the process of coal seam mining, the coal strength, bedding structure, and external factors exhibit no significant fluctuations, the loading–unloading stress range is relatively wide. Therefore, its variation and adjustment can be used to optimize the permeability of coal seams, effectively alleviating the problems of low coal seam permeability and high ground stress.

Loading and unloading stress paths have a significant impact on the development of coal seam cracks and cleats, i.e., perpendicular sets of fractures, whereas the dominant cleat or "face cleat" is oriented parallel to the maximum horizontal compressive stress. Certain folds and cracks on the surface of coal seams will promote the development of coal seam cleats, and the generation

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and development of cracks and fissures, thereby increasing the permeability of coal seams. Therefore, stresses and coal seam fissure structure are the main factors controlling permeability characteristics of coal seams. This paper analyzes possible loading and unloading stress paths based on previous studies, taking three types of coal samples (namely, intact, cracked/fractured, and broken ones) as the research objects. Permeability evolution patterns of these three types of coal samples under various stress paths are compared and quantitatively expressed. The advantages and disadvantages of the available permeability research approaches, as well as future research trends and directions, are discussed in detail to provide theoretical references in coal permeability optimization. In order to accurately obtain the change of the seepage state of the coal seam during the longwall mining process, we must first understand the stress changes experienced by the coal seam during the mining process, and judge the development of the internal fractures in the coal seam according to the stress state around the coal seam. Therefore, this paper summarizes the stress paths and seepage laws of coal bodies set by some scholars for coal bodies with different fracture structures, and makes prospects and future research directions.

1 Test coal sample selection and preparation

Longwall mining or Pressure Relief Mining (PRM) provides stress re-distribution and creates fractures in the surrounding rock mass, thus adjusting the permeability distribution. As shown in Fig. 1, PRM mining causes the surrounding rock mass to be damaged, whereas the degree of damage is inversely proportional to the distance from the PRM longwall panel. Specifically, from the inside to the outside, the degree of damage gradually reduces from the caving zone, fracture zone, and swelling deformation zone to the original zone, as shown in the upper part of Fig. 1 (Zhang and Zhang 2019; Zhang et al. 2019a, b, c, d, e, f).

Significant differences in fracture distribution and stress state are found in these zones. The caving zone is composed of broken rock and coal mass, and it gradually compacts with the advance of the longwall face, but the final stress is lower than the initial one. In the fracture zone, coal and rock mass break and contain fully developed fractures. As the longwall face advances, the stress gradually increases to the initial state. Therefore, caving and fracture zones are within a pressure relief state for a long time after their formation. Consequently, the permeability in each direction

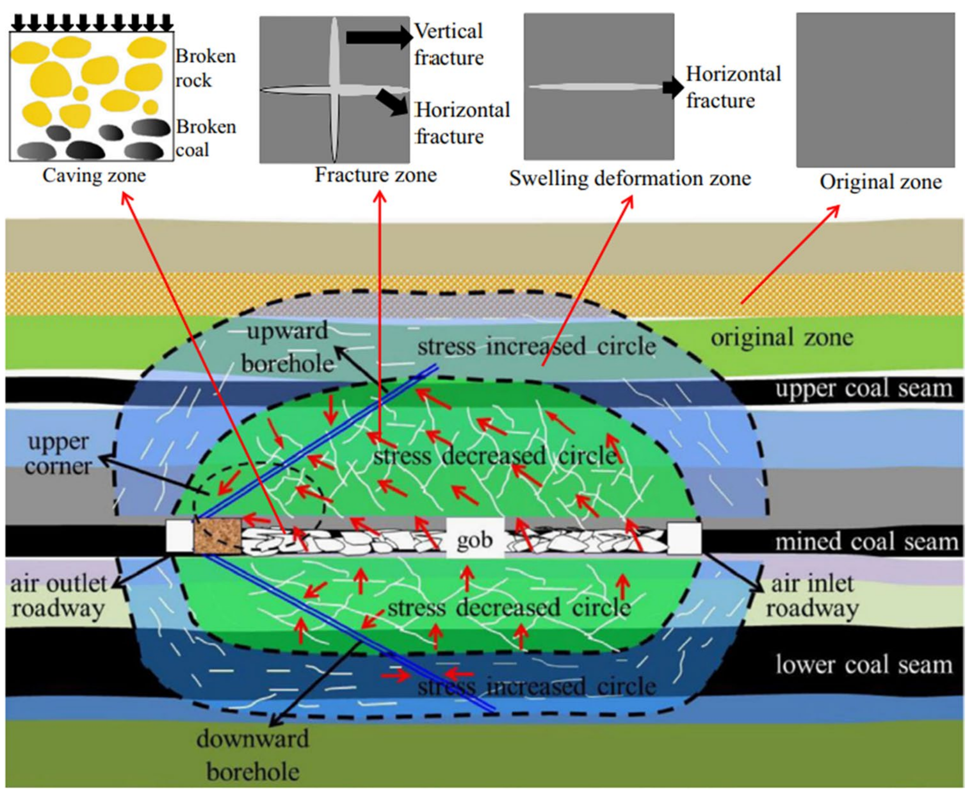


Fig. 1 Different damage zones in pressure relief mining (PRM), modified after (Zhang et al. 2019a, b, c, d, e, f; Zhang et al. 2020a, b, c, d)

significantly increases, yielding primary channels of gas migration, as shown in Fig. 1. In the swelling deformation zone, the vertical stress is considerably reduced due to the subsidence of the fracture zone. The developed horizontal fractures lead to a considerable increase in horizontal permeability. However, coal and rock mass in this zone does not completely fail, which usually produces a high-stressed structure (Tang et al. 2022; Zhang et al. 2015a, b, c, 2016a, b, c, d; Zhang et al. 2019a, b, c, d, e, f). In this zone, the horizontal stress increases, thus reducing the vertical permeability. Stresses and permeability in the original zone roughly remain unchanged. Therefore, to simulate permeability changes and coalbed methane (CBM) migration during longwall mining, it is necessary to grasp permeability-stress dependencies in different zones. The permeability of coal and rock mass in each zone was tested in this study to elaborate on the relevant permeability model. In order to discuss the above problems in depth, this review summarizes the seepage laws of different types of coal samples, elaborates the stress paths designed by some scholars, and lists the experimental instruments and structural characterization methods used by some scholars to study the seepage laws of coal bodies.

1.1 Test coal sample preparation

Test coal samples include common coal samples, briquettes, and new material coal samples (Fig. 2). Test coal samples can be classified by their shape (cylinder and box) and size: cylindrical samples of 50 mm in diameter and height of 50 mm; cylindrical samples of 50 mm in diameter and height of 100 mm; box samples of 50 mm × 50 mm × 50 mm or 50 mm × 50 mm × 100 mm dimensions, etc.

The method of making ordinary coal samples is to take out large coal blocks from the coal seams, drill the coal samples according to the horizontal or vertical bedding directions, maintaining the integrity of the coal samples, and adjust them according to the experimental requirements. Coal briquettes are produced by press molding from coal particles as the main raw material, according to the mix ratio, mechanical strength, sample shape, and size requirements (Gu et al. 2020). Yin et al. revealed some similarities in the mechanical parameters and of raw coal and coal briquettes and their evolution patterns under the same test conditions (Yin et al., 2009). The coal blocks are treated coal bodies with different sizes of coal particles ranging from 0.25 to 3.00 mm, which particles are mixed with different mix ratios to obtain a variety of coal briquettes. Physical and mechanical parameters of coal briquettes are experimentally determined in loading–unloading tests (Xu et al. 2021; Tian et al. 2013).

With the continuous development of 3D printing technology and printing materials (Li et al. 2021), it is possible to quickly make complex 3D solid models, which have been widely used in geotechnical and engineering applications. Huang et al. used three-dimensional reconstruction and 3D printing technology to prepare samples from photosensitive resin materials, which simulated natural coal rock specimens with complex fractures (Huang et al. 2021). Ju et al. used the 3D printing technology to produce a smooth crack network specimen with cracks' length, tendency, and inclinations complying with the preset random distributions (Ju et al.

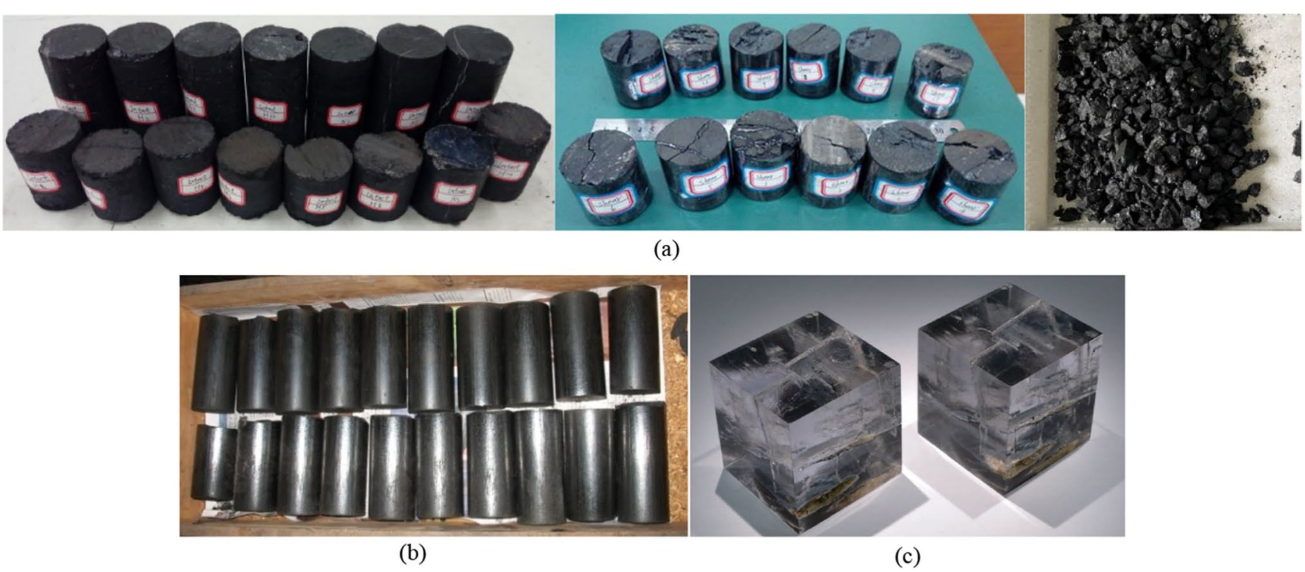


Fig. 2 Macroscopic comparison of three coal types: **a** Common coal samples (Zhang et al. 2018a, b; Kan et al. 2021), **b** Briquettes, **c** New material coal samples

2014). Jiang et al. prepared physical analog models with single, double, and porous fractured structures, a natural rough joint model, and a tunnel model with complex geological structure or support structure, which extended the application prospects of 3D printing technology in complex model elaboration and rock mechanics testing (Jiang and Song 2018). Wang et al. obtained a three-dimensional crack network model by stretching the two-dimensional plane and using polylactic acid polymer plastic as the printing material, printed by layer stacking (Wang et al. 2018a, b, c). Zhang et al. used water-soluble materials for printing a crack network model and then soaking water to remove water-soluble materials, forming an open crack network specimen (Zhang et al. 2020a, b, c, d). Wang et al. used the 3D printing technology to make a rough cross-crack model with different crack inclination angles, subjected the produced specimen to uniaxial compression test and explored its rupture mechanism (Wang et al. 2021a, b).

At present, 3D printing technology and printing materials have gradually matured. The main difficulty in using this technology to make crack rock samples lies in the digital model with real three-dimensional crack network structure in the pre-printing stage (Zhu et al. 2018). In the above-mentioned studies, the fracture network was generally reduced to models with smooth surface, quasi-three-dimensional form, or simple intersecting relationships, which differed from the irregular undulating surface and intersecting pattern of the actual fracture. Therefore, the preparation of samples that can characterize the complex structure inside the natural rock fracture needs further exploration.

1.2 Structural characterization of damaged coal

The fractured structure of a coal rock body is the key factor linking stress and seepage. Therefore, characterization and reconstruction of coal rock fractured structures are very topical. It generally starts from the description and statistical analysis of the distribution characteristics of fractured structures, the experimental reconstruction in a laboratory or numerical simulation based on statistical results, and the verification and correction of the reconstruction model against the original coal sample (He et al. 2022). Structural characterization methods can observe the microscopic development of coal fractures, thus facilitating the intuitive perception of coal bodies in the field.

Currently, coal samples are observed by scanning electron microscopy (SEM), computer tomography (CT), X-ray, thermal analysis, transmission electron microscopy (TEM), and scanning tunneling microscopy (STM). SEM images are used to observe pore structures on coal surfaces. Xu et al. performed a series of laboratory tests, including nondestructive low-field nuclear magnetic resonance (NMR), scanning electron microscopy (SEM), X-ray computed tomography (CT) and core tests were carried out to characterize the physical structure properties of coal (Xu et al. 2016). Ni et al. was discussed connectivity of pores and propose an improved permeability estimation method based on multiple binary images (Ni et al. 2021). Ramandi et al. (2015) used wet and dry micro-CT imaging and scanning electron microscopy to capture the complex coal cleat network. The literature used CT to observe the changes in coal and shale fissures(Zhang et al. 2016a, b, c, d; Hou et al. 2021; Fan et al. 2020). The literature used NMR to observe the changes in coal cracks. Figure 3 shows several structural characterization methods, including the used equipment and the obtained images (Xue et al. 2021; Ai et al. 2021; Zhou et al. 2021; Zhao et al. 2017).

Among the three structural characterization methods, they all have their own applicability.

(1) NMR is good at observing the microscopic pore type and shape of shale, and has a relatively strong ability to observe local samples, but NMR is not good at reflecting the overall situation of rock samples;
(2) NMR can finely analyze the porosity of the sample, analyze the pore connectivity and movable fluid, and reflect the overall situation of the sample. Compared with SEM, NMR lacks the expression of sample details;
(3) CT scanning technology can quantitatively analyze the sample, identify pores and high-density substances in the sample, and use 3D reconstruction technology to reconstruct the three-dimensional model of the sample. However, there is no fixed standard for the selection of CT number threshold during 3D model reconstruction, which is a major drawback of CT;
(4) In the process of analyzing the pore structure of the sample, it is suggested to use scanning electron microscope to observe the pore type and shape of shale, measure the porosity with nuclear magnetic resonance, analyze the pore size distribution, pore connectivity and movable fluid, cooperate with CT scanning to reconstruct the three-dimensional model of the sample, and obtain more perfect pore structure data of shale reservoir by observing the spatial structure characteristics of pores and fractures.

2 Stress path designing

2.1 Single load-induced stress path

According to the cracked/fractured structure, coal can be subdivided into three categories: intact, fractured and broken. The first category corresponds to coal bodies with no obvious surface cracks or those affected by the mining.

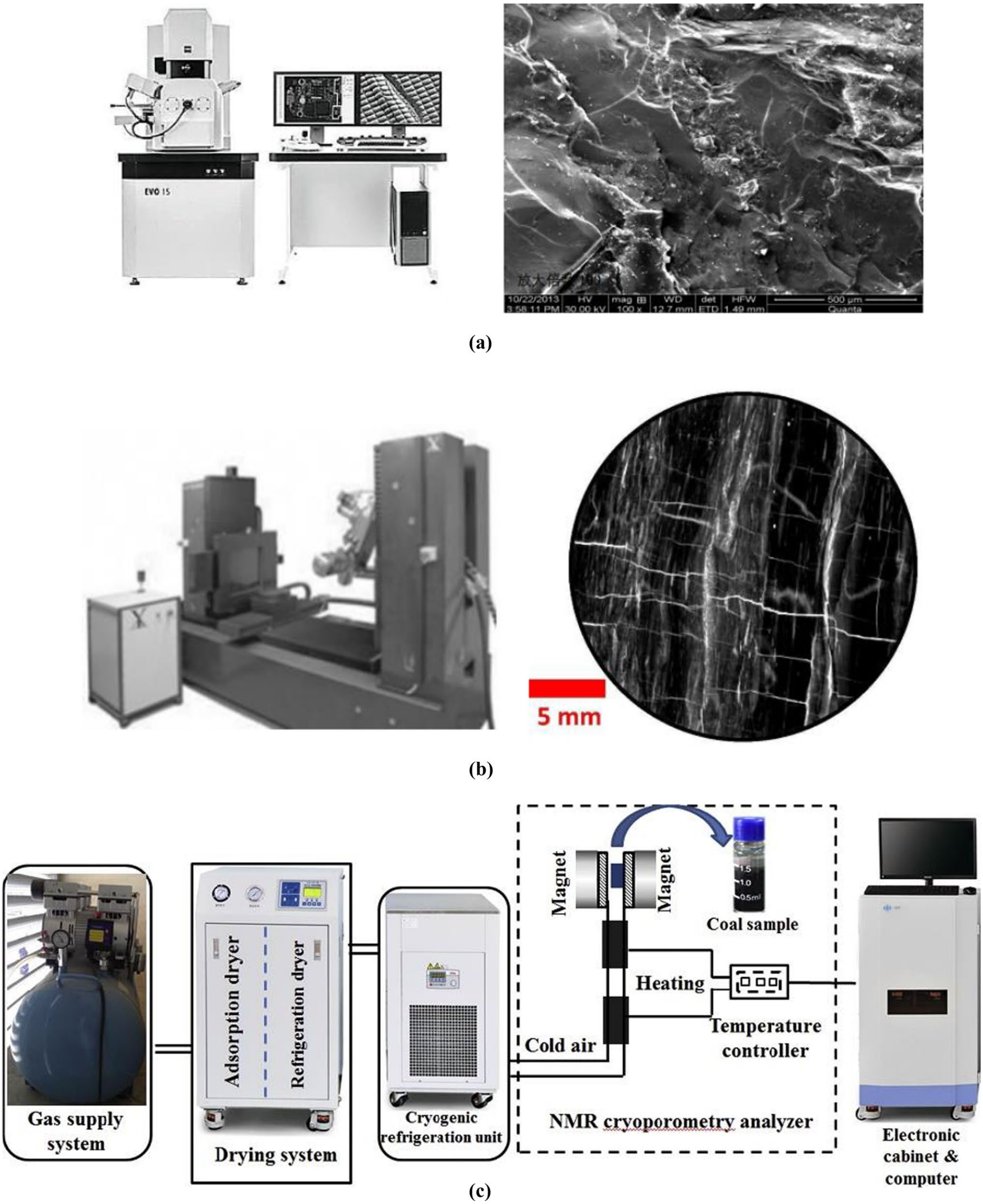


Fig. 3 SEM/CT/NMR microsystem. **a** SEM (Zou et al. 2016), **b** CT (Jing et al. 2017; Wang et al. 2019a, b, c, d), **c** NMR (Zhao et al. 2017)

Scholars have set up different stress paths to obtain the seepage laws of intact coal samples under stress. For intact coal samples, Zhang et al. set up two sets of stresses, one set simulated the stress of coal and rock when it was unloaded, and the other set was used as a control group for observation (Zhang et al. 2019a, b, c, d, e, f). Tian and Li set the unloading stress path of intact coal samples by dropping the confining pressure after their simultaneous loading by axial and confining pressures (Tian and Li 2018). They compared the seepage laws of inclined, vertically and horizontally stratified coal samples under the same stress path. To simulate the seepage law of fractured coal samples under stress, scholars used self-made fractured coal bodies. Thus, Wang et al. have compared the self-made horizontally and vertically fractured coal samples with intact ones, set up the stress path of stepped loading and unloading axial pressure, and applied three loading–unloading cycles (Wang et al. 2019a, b, c, d). Due to the stress concentration in front of the workface, there were too many cracks in the coal seam, resulting in the breakage of the coal sample. Zhang et al. prepared ten groups of coal samples with different Talbot grading structures and applied five kinds of loads to these samples in the axial direction (Zhang et al. 2019a, b, c, d, e, f). Jia et al. carried out research on raw coal and briquette samples, and set the stress path of fixed confining pressure, air pressure and loading and unloading axial pressure for the two coal samples. The research results show that the permeability of raw coal samples changes greatly in the low confining pressure stage and small in the high confining pressure stage, while the permeability of briquette samples changes almost equally in the whole loading and unloading process (Jia et al. 2020). Wang et al. used 3D printing to make coal samples of new materials, and obtained that the preparation of complex fracture network model can be realized by using 3D printing technology, which can provide an effective way for repeated production and test comparative analysis of complex fracture samples in laboratory test (Wang et al. 2018a, b, c).

The above stress path only changed the axial or confining pressures, revealing the variation law of coal permeability under the influence of axial pressure and confining pressure. However, due to the combined effect of in-situ stresses and other factors, the coal body in the actual site is subjected to the cyclic loading and unloading of multiple axial confining pressures. Therefore, the above load variation schemes failed to reflect the real situation of the mining site fully.

2.2 Stress paths realized via conventional triaxial equipment

The conventional triaxial equipment mainly applies axial and confining pressures to cylindrical coal samples. Zhang et al. combined the actual background of coal seam group mining and realized a step-by-step loading–unloading path in three kinds of coal by varying the axial and confining pressures, whereas the path stress difference increased gradually (Zhang et al. 2017a, b). To simulate the mining effects of the increased abutment pressure in front of the workface and the decreased horizontal stress in the process of mining, Lv et al. simulated the stress environment of single coal seam without pillar mining, and obtained the seepage law of coal seam (Lv et al. 2012). To simulate the goaf state in different stages, Zhang et al. set up a stress path which increase the axial pressure, reduce the confining pressure, and reduce the axial pressure (Zhang et al. 2017a, b). Yin et al. set a fixed confining pressure to increase the stress path of the axial pressure (Yin et al. 2015). Fang et al. set the stepped loading and unloading axial pressure and confining pressure, and fixed the stress path of the pore pressure (Fang and Liu 2019). Peng et al. set up a stress path that first increases step by step and then decreases step by step (Peng et al. 2020). Jiang et al. set up a stress path that increases the axial pressure, reduces the confining pressure, and then reduces the axial pressure and the confining pressure at the same time (Jiang et al. 2020a, b). Xie et al. (2011) further considered the effect of the protective layer mining method on the stress state in the coal body of the protected layer, obtained the stress path suitable for different mining methods through field measurement and data analysis. Finally, they revealed the following four stages of stress variation of the protected layer: preloading stage, axial compression stage, pressure relief expansion stage, and stress recovery stage. This work promoted further in-depth studies on the influence of mining methods on coal and rock mechanical properties, failure mechanisms, and gas seepage capacity, the stress curves of the three mining methods are shown in Fig. 4. Ren et al. used physical analog models and materials to realize the stress path of the protected layer under the disturbance of protective layer mining (Ren et al. 2019). They analyzed the confining pressure effect in protective layer mining on permeability evolution. The permeability change was analyzed for two stress paths in the unloading stage: with the unloading stress higher or lower than the initial stress before mining. The conventional triaxial equipment instrument is shown in Fig. 5.

2.3 True triaxial stress path

True triaxial equipment can apply pressure from three directions simultaneously to better simulate the stress environment of the coal seam. Generally, coal samples required for tests via true triaxial equipment are square-shaped (box-shaped) compared to conventional triaxial cylindrical ones. In 2014, Yin et al. designed a triaxial loading scheme with a fixed σ_1 principal stress component and varied the stress paths of σ_2 and σ_3, respectively. The results showed that an

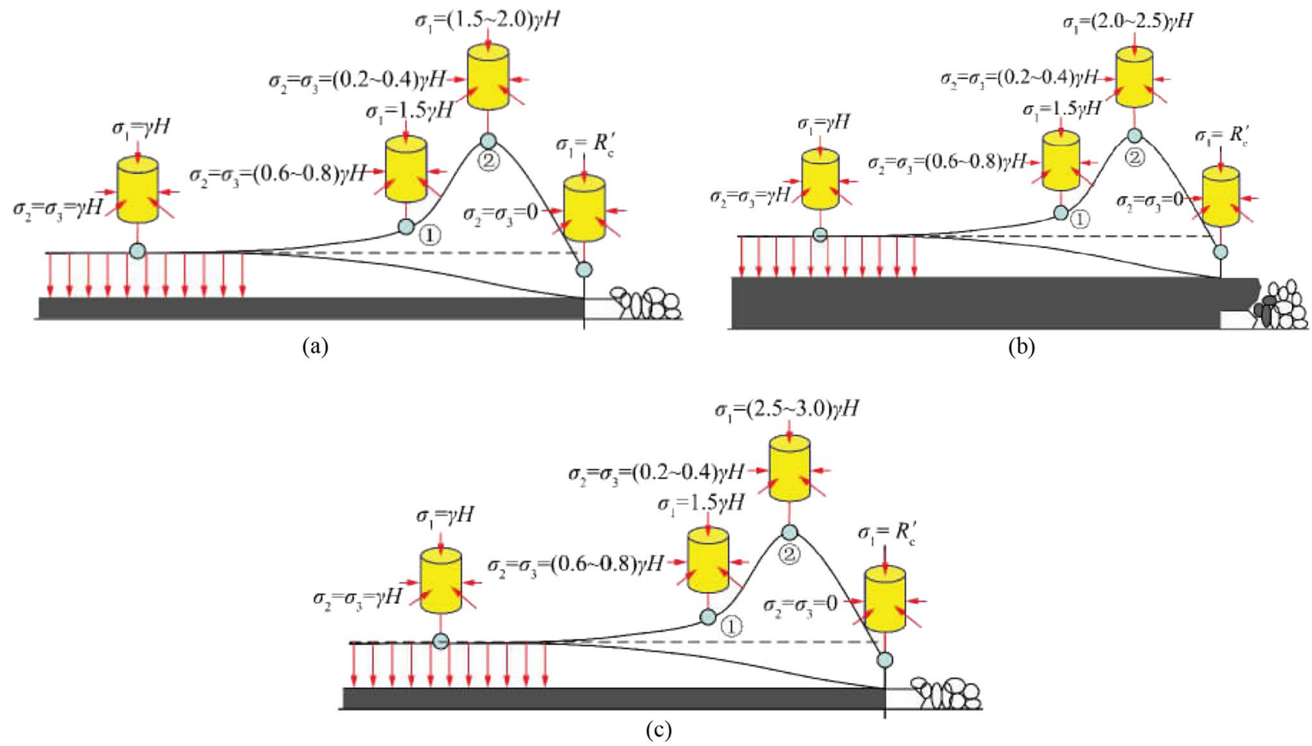
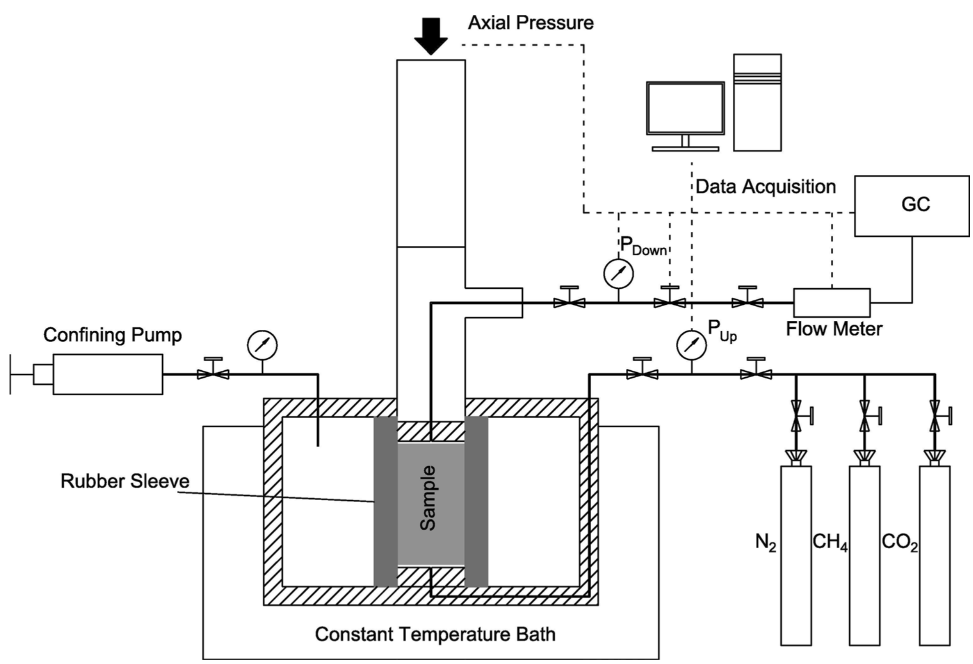


Fig. 4 Three kinds of mining actual stress paths (Xie et al. 2011): **a** Protected coal seam mining, **b** Top-coal caving mining, **c** Non-pillar mining

Fig. 5 Conventional triaxial equipment (Zhang et al. 2016a, b, c, d)



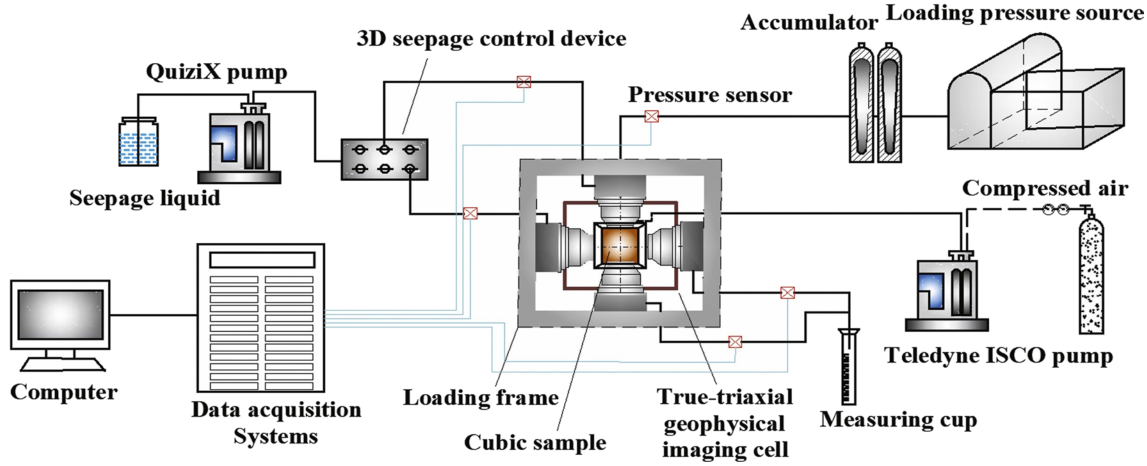


Fig. 6 True triaxial equipment

increase in any of the principal stresses σ_1, σ_2, and σ_3 inhibited the permeability of the rock, while the stress σ_2 had the most significant impact on the permeability of fractured coal (Yin et al. 2014a, b). In 2018, Yin et al. modified the above approach and designed the stress path with gradually increasing stresses σ_1, σ_2, and σ_3. They revealed that the true triaxial stress paths strongly influenced the deformation, strength characteristics, and permeability evolution of raw coal (Yin et al. 2018). In order to determine the stress change mechanism that affects the evolution of stratified coal cracks under true triaxial conditions. Liu et al. conducted experimental studies on different stratifications (vertical, horizontal and inclined stratification) based on gas permeability (Liu et al. 2019) (Fig. 6).

The above three stress paths are set for different purposes and applicable conditions.

(1) True triaxial equipment is suitable for cubic specimens and can simultaneously apply stress in the triaxial directions of the specimen. Under the influence of geological structure, faults, folds and artificial excavation, reservoir coal and rock are subject to different stresses in three directions, so the use of true triaxial equipment is more suitable for on-site mining.
(2) Conventional triaxial is suitable for cylindrical specimens, and can only apply stress in two directions: confining pressure and axial pressure.
(3) The stress path of changing a stress is mostly used in laboratory experiments to explore the influence of a stress on the permeability of the sample.

3 Experimental equipment and permeability test method

The test equipment used to study the seepage changes in coal rock under loading and unloading conditions can be subdivided into conventional and true triaxial equipment, according to the applied stress loading schemes. Thus, Brace et al. used conventional triaxial testing machines to study the permeability of granite under high pressure (Brace et al. 1968). Peng et al. studied the mechanical properties of raw coal with an MTS815 rock mechanics testing system and external gas seepage control system (Peng et al. 2003). The latter consisted of a gas supply system, gas stabilization and temperature increase control system, measurement system, and pipeline vacuum control system. They analyzed the permeability and porosity changes in small-sized sandstone cylindrical specimens under different confining pressure values during the full stress–strain process. To analyze the energy evolution law and permeability characteristics of coal body damage during coal mining and the seepage law under full stress and strain, Wang et al. and Zhang et al. also used an MTS815 Flex Text GT rock mechanical test system improved by the Water Resources and Hydropower Laboratory of Sichuan University (Wang et al. 2018a, b, c; Zhang et al. 2015a, b, c).

Alternatively, He et al. used an RMT-150B rock mechanics testing machine to conduct acoustic emission (AE) tests under conventional triaxial cyclic loading and unloading on coal samples (He et al. 2014). They conducted AE tests under true triaxial cyclic loading and unloading. To study the mechanical properties and seepage laws of sandstone under stress, Zhang et al. used a rock automatic triaxial seepage test system to conduct conventional triaxial compression experiments on sandstone under anhydrous conditions and with different confining pressure gradients (Zhang et al. 2019a, b, c, d, e, f).

The above-mentioned scholars used conventional triaxial equipment to research coal and rock's mechanical properties and seepage laws. However, in the process of deep coal resource mining, due to the influence of ground stress and engineering disturbances, coal and rock masses are often in a true triaxial stress state ($\sigma_1 > \sigma_2 > \sigma_3$) with unequal pressures in three directions, while the conventional triaxial loading stress path ($\sigma_1 > \sigma_2 = \sigma_3$) can hardly reflect the actual stress state of the coal rock mass. Therefore, some scholars used true triaxial equipment to study coal rock's mechanical characteristics and seepage laws: Yin et al. developed a rock stress-seepage coupling true triaxial test system according to the stress environment of the rock, which provided independent servo control to apply three-dimensional stress (Yin et al. 2014a, b). Besides, an acoustic measurement system was used to track the specimen's crack propagation and evolution process under the action of three-dimensional stress and seepage water pressure in real time. Liu et al. successfully developed the RPT3 true triaxial rock seepage meter, which could independently apply the principal stress and water pressure in three directions to realize the coupling test of rock fracture seepage under triaxial stress (Liu and Chen 2007). The seepage system used high-pressure nitrogen to apply stable water pressure, and its maximum seepage pressure could reach 1.5 MPa. Wang et al. designed a stress path that kept stresses σ_1 and σ_3 unchanged, while stress σ_2 was subject to cyclical variation (Wang et al. 2019a, b, c, d). The results showed that the total dissipated energy of coal increased exponentially, and the damage variable of coal exhibited an obvious S-shaped deceleration → acceleration → re-deceleration trend. To study the impact of coal mining on the mechanical characteristics of coal rock, they used the true triaxial test module in the RTX-3000 test system developed by the GCTS company (USA). This equipment could conduct single-axial, three-axial, and true three-axial rock mechanics tests with various stress paths corresponding to compression, relaxation, creep, and cyclic stress conditions. Liu et al. used true triaxial test instruments to conduct permeability experiments on Sandstone, shale and coal specimens (Liu et al. 2021). Jiang et al. used a true triaxial test instrument to conduct a permeability test on the sampled reservoir sandstone (Jiang et al. 2020a, b). Pan et al. used a new experimental setup for anisotropic permeability measurement in triaxial rigs to measure cubic rock sample with 3D printing membrane to simulate a standard core sample (Pan et al. 2015).

When studying the influence of pressure on coal seepage under mining disturbance, the steady-state method, transient method, capillary balance method, and slab model method are used to measure coal rock permeability. The most widely used methods are the steady-state method and transient method:

(1) The test principle of the steady-state method is Darcy's law, which is used to test the permeability expression of sandstone samples as follows (Wang et al. 2019a, b, c, d)

$$K_i = \frac{\mu \Delta Q_i L}{A \Delta P \Delta t_i} \tag{1}$$

where, K_i is the average permeability of sandstone in Δt_i time; μ is the fluid viscosity coefficient, which is taken as $\mu = 100.5 \times 10^{-5}$ Pa s; ΔQ_i is the volume of water flowing through the sandstone sample in Δt_i time, m^3; L is the height of the sandstone, m; A is the cross-sectional area of the sample, m^2; P is the seepage pressure difference between the upstream and downstream of the rock sample.

Some scholars used the steady-state method to study the permeability of coal samples. For the process of sandstone seepage-stress-damage gradual cracking, Liu et al. used the multi-functional rock triaxial test system of Top-Industrie (France) and measured the samples with the steady-state method under conventional triaxial (Liu et al. 2008). Zhang et al. used a rock full-automatic triaxial seepage test system and applied the steady-state method to study the seepage law of sandstone under stress (Zhang et al. 2019a, b, c, d, e, f).

(2) The basic principles and steps of the transient-flow method are as follows. The transient pressure pulse method was first proposed by Brace et al. in 1968 and used to measure the permeability coefficient of rock (Brace et al. 1968). It implied that, firstly, equal constant water pressures were applied to the upper and lower ends of the rock sample, and pulsed water pressure was applied through the downstream flow pump to reduce the downstream water pressure to close and fix the pressure vessel. Under the action of the pressure difference, a bottom-up seepage flow was generated in the core, and the water flew from the downstream container to the upstream one through the sample. After that, the upper water pressure gradually decreased, and the lower water pressure gradually rose until the pressure balance was reached. Permeability is calculated by the law of differential pressure attenuation.

$$\Delta P_t = (\Delta P_0) e^{-\alpha t} \tag{2}$$

$$k = \frac{a \mu L C_1 C_2}{A (C_1 + C_2)} \tag{3}$$

where, k is the core permeability, m^2; ΔP_t is the measured value of the upstream and downstream pressure difference, MPa; ΔP_0 is the initial pressure difference, MPa; t is the elapsed time, s; A is the cross-sectional area of the rock sample, m^2; μ is the viscosity coefficient of water, Pa s; L is the length of the sample, m; C_1 and C_2 are the water capacity values of the upstream and downstream pressure vessels, whereas capacity $C_1 = dv_1/dp_1$ and has the order of 10^{-14} m^3/Pa; a is the slope of the pressure difference-time curve in semi-logarithmic coordinates.

Some scholars used the transient method to measure the permeability of coal and rock. Thus, Liu et al. used three methods (conventional permeability test, variable confining pressure permeability test, and transient method) under triaxial compression for the same kind of mudstone in deep formations to carry out the permeability test (Liu et al. 2014). The test study revealed that the mudstone characteristics obtained by the above three methods were quite different, and those of the conventional method exceeded two others by 3–5 orders of magnitude, the advantages and disadvantages of the above three methods are as follows: (1) The conventional test cannot reflect the actual stress state of the formation, and it is not recommended to use this method to carry out a permeability test as a deep mudstone. (2) The transient method test and the variable confining pressure permeability test method under triaxial compression can better reveal the variation law of permeability with pressure. Zhang et al. used the steady-state and transient methods and reported that the permeability under different confining pressure conditions experienced four stages: slow decline, approximately stable, slow increase, and rapid increase (Zhang et al. 2020a, b, c, d). Fang et al. proposed an applicability of a novel transient technique, and through the proposed transient technique, the impact of gas compressibility is minimized (Fang et al. 2020).

4 Seepage characteristics

Based on the available results on the stress path and structural characterization of the three types of coals, several scholars established various models by coupling the three factors of stress, cracking, and seepage. Thus, the permeability of coal during loading and unloading was investigated, simulated by a permeability model, and modified for actual mining conditions on site in studies (Cui and Bustin 2005; Palmer et al. 2007; Shi and Durucan 2010; Zhang et al. 2016a, b, c, d; Chen et al. 2013).

Besides, based on conventional uniaxial or triaxial compression-shear experiments in the laboratory, and with the help of scanning electron microscope (SEM), CT three-dimensional reconstruction, acoustic emission, and nuclear magnetic resonance equipment, researchers studied the evolution mechanism of the crack structure under stress for the stress-seepage characteristics of the three types of coal. The permeability of the coal sample can be calculated through laboratory data (Zhang et al. 2018a, b, 2020a, b, c, d; 2021a, b, c). The main parameter is the permeability k (md), and the calculation formula is:

$$k = \frac{2\mu p_0 Q_0 L}{[p_1^2 - (p_0 - p_2)^2]s} \tag{4}$$

where, μ is the gas dynamic viscosity coefficient, Pa; P_0 is the standard atmospheric pressure, Pa; Q_0 is the seepage flow under standard atmospheric pressure, cm^3/s; L is the length of the coal sample, cm; P_1 is the gas pressure at the upper end of the coal sample, Pa; P_2 is the negative pressure at the outlet of the lower end of the coal sample, Pa; S is the cross-sectional area of the coal sample, cm^2.

4.1 Seepage law of intact coal samples under loading stresses

The available findings on the stress path effect on seepage can be summarized as follows. Zhu et al. reported that the seepage characteristics of coal obtained by different stress-loading methods were different (Zhu et al. 2018). The permeability of coal samples decreased with axial and confining pressures and increased with air pressure. Zhang et al. applied axial and confining pressures to assess their influence on the seepage of the intact coal sample: the radial permeability of the intact coal sample exceeded its axial permeability, and the permeability varied with the number of cycles (Zhang et al. 2017a, b).

As for the stress paths obtained by combined mining methods. In particular, the permeability under the mining stress of the protective layer generally exceeded that of the top coal but decreased faster. Xie et al. systematically analyzed the coupling mechanisms of mining stress-fracture-seepage of the three (top coal caving, pillarless, and protective layer-based) mining methods (Xie et al. 2011). They explored the expansion and permeability changes of coal samples in various stages of different mining methods, providing a theoretical basis for on-site coal and gas co-mining. Based on the protective layer mining stress path, Ren et al. realized the confining pressure variation in analog model experiments and obtained a more accurate stress path (Ren et al. 2019). It was found that the confining pressure effect on permeability during the mining process of the protected layer exceeded that of axial pressure. Yin et al. investigated the unloading rate effect of confining pressure on the permeability of gas-containing coal and found that higher unloading rates of confining pressure promoted the increase in coal permeability (Yin et al. 2011a, b).

4.2 Seepage law of fractured coal samples under various stress paths

Since coal bedding is directional, the coal permeability values in the bedding and normal directions differ, implying the anisotropy of permeability. Li et al. reported that the permeability of coal samples in the parallel bedding direction was higher by one order of magnitude than that in the vertical bedding direction (Li et al. 2015). According to Tian et al. under the designed stress path, the permeability of the horizontally layered fractured coal sample exhibited the largest drop during the loading process, indicating that this kind of coal was easier compacted than the inclined, vertically layered coal seam during the mining process (Tian and Li 2018).

Due to the influence of tectonic stress, the primary cracks in the coal seam continued to develop, forming a fracture zone and leading to the formation of tectonic cracks due to stress concentration. In the process of coal seam mining, the coal seam was prone to stress concentration, and cracks continued to develop and eventually formed a coal seam with obvious cracks on the surface. Wang et al. have studied the permeability of prefabricated fractured coal samples. Under the set stress path, the permeability and stress sensitivity coefficient of vertically fractured coal samples were significantly higher than those of intact and horizontally fractured coal samples (Wang et al. 2019a, b, c, d). The method of dimensionless analysis was used to eliminate the influence of initial permeability and analyze the difference between different fractured and intact coal samples in the mining process. Under the cyclic stress path, Zhang et al. found that the permeability of the fractured coal sample under the same stress state during the first loading and unloading process was two orders of magnitude higher than that of the intact one, and the permeability loss of the fractured coal samples significantly exceeded that of the intact ones (Zhang et al. 2019a, b, c, d, e, f). Wang et al. effectively used the industrial CT scanning experimental system to obtain the degree of development of the internal fracture structure of the coal sample. The larger fractal dimensions corresponded to more developed crack and higher permeability (Wang et al. 2020).

Fractured and intact coal samples had the same permeability variation patterns under the stress action, whereas the stress and permeability exhibited a negative exponential relationship. The permeability changed rapidly in the early stage of loading, which process was slowed down in the later stage and decreased with the number of repeated mining cycles.

4.3 Seepage law of broken coal samples under various stress paths

Because the internal structure of broken coal samples is heterogeneous and discontinuous, its permeability change differs from those of intact and fractured coal samples. The internal fracture channel of the broken coal sample has a large volume, so when the stress is applied, the internal fractured coal particles will break and fill the original fracture again, the sample is reduced as a whole, and the volume of the fracture channel is reduced. Liu et al. reported that the permeability coefficient of broken sandstone increased by one order of magnitude compared to the intact one under high pressure (Liu et al. 2002). Under the same pressure, the smaller the particle size, the smaller the permeability coefficient, while the permeability coefficient of the mixed-sized particle sample was the smallest. Huang et al. and Sun et al. established the functional relationship between permeability and load and revealed that the permeability of broken rock was mainly determined by porosity (Huang et al. 2005; Sun et al. 2003). Zhang et al. used the circulation path to find that the permeability of broken coal samples decreased with the effective stress and increased with porosity (Zhang et al. 2019a, b, c, d, e, f). There was also a big difference in the unloading processes of intact and broken coal samples. Chao et al. obtained that the permeability and porosity of the broken coal sample are negative exponential functions of the axial stress (Chao et al. 2019). Under the same stress, the porosity and permeability decrease with the increase of the particle size and particle size range of the coal sample. Shang et al. used a self-made triaxial seepage test system to conduct seepage tests on broken coal under triaxial stress (Shang et al. 2019). They reported that the permeability of broken coal samples decreases with the confining pressure. Zhang et al. prepared ten groups of cemented and broken coal models with different gradation structures and obtained the relationship curve between effective stress and coal permeability under triaxial compression (Zhang et al. 2019a, b, c, d, e, f). The coupling model proposed by the above-mentioned scholars provided a theoretical basis for the gas drainage of cracks and broken coal seams in the protective layer. Li et al. obtained that under the same stress, the strain of a single-particle coal sample is lower than that of a mixed-particle coal sample (Li et al. 2019).

According to the above findings, the seepage changes in broken and intact coal samples differed as follows: (1) The permeability of broken coal samples was higher than that of intact ones under the same pressure values. (2) The broken coal sample body did not have a structure, and the permeability increased slowly during the unloading process. As the number of cycles increased, the change in permeability decreased. (3)

Broken coal samples with different Talbot exponents had different permeability changes under the same stress.

5 Other factors

Besides the fractured structure of coal samples, their permeability also depends on coal rank, temperature, moisture, and gas pressure.

(1) Coal rank. The degree of coal metamorphism varies from lignite to anthracite, resulting in different internal components of coal seams and differences in gas content, thickness, and permeability. Wang et al. compared the differences in the mining of low, medium, and high rank coals and proposed an evaluation system for the permeability characteristics of different coal ranks (Wang et al. 2019a, b, c, d).

(2) Temperature. Due to the influence of geothermal, gas adsorption and desorption, and other factors, the actual temperature of the coal body changes. Yang et al. reported that an increase in coal temperature improved the permeability and flow rate, while higher temperatures promoted the adsorption and desorption of the coal, thereby improving its permeability (Yang et al. 2009).

(3) Moisture. The water in coal can have gaseous and liquid forms. Both forms can co-exist in the cracks and pores of the coal and affect the gas permeability patterns in the coal. Experiments of Yin et al. revealed that permeability linearly decreased with the water content (Yin et al. 2011a, b). Yuan et al. and Wei et al. experimentally proved that the coal permeability and moisture content had a negative exponential relationship (Yuan et al. 2012; Wei et al. 2014).

(4) Gas pressure. During underground coal mining, coal and rock mass permeability is affected by complex conditions such as different gas pressures and three-dimensional stress states. Therefore, the gas pressure effect on the permeability of coal seams is particularly important. Zhang et al. designed and conducted experiments on five sets of coal samples with five different gas pressure values. They reported that the gas permeability of coal and rock first increased and then decreased with the gas pressure (Zhang et al. 2015a, b, c).

6 Discussion

(1) When studying the permeability of three types of coals (intact, fractured, and broken), scholars often analyzed changes in coal permeability for different stress paths of coal samples. The required loading and unloading stress paths were mainly realized by unilaterally changing the axial and confining pressures in the coal sample or its stress environment. To simulate the cyclic pressure during mining, various cyclic loading and unloading stress paths were designed to fully reflect the real situation of the site compared to the change in permeability under a single load of confining pressure and axial pressure (Zhang et al. 2016a, b, c, d). However, the reliability of applying such schemes to actual mining is low.

During on-site mining, the stress environment in front of the workface is complicated, and the stress environment cannot be accurately simulated by changing the axial or confining pressures. Therefore, the combined on-site mining method has been used to set the stress path of the coal sample during the test. Different mining methods provide different stress distributions in coal and rock mass. Common mining methods include top coal mining, protective layer mining, and pillarless mining. Huang et al. realized the stress path of the protective layer during mining, proposed the mining stress path of the coal seam group in the Xutuan mining area of China, and studied the gas migration law in the above coal seam group for the above (Huang et al. 2019). Besides, physical analog methods have been used to adjust the confining pressure and determine the true stress path. The latter obtained through field practice can provide a reference for field operations. At the same time, the coal seam is affected by the three-dimensional stress during the mining process, while most scholars only considered the effect of σ_1 and σ_3 stresses, ignoring that of σ_2. The use of true triaxial equipment in the respective experiments can effectively simulate the true stress environment of the coal seam. Therefore, it is expedient to set the stress path in combination with the actual mining method of the coal seam or use true triaxial equipment for experimental research.

(2) The above survey strongly indicated that the permeability patterns of intact and fractured coal samples under the same stress path were roughly the same. The comparative analysis revealed that the permeability change in fractured coal samples exceeded that in the intact ones. The permeability of broken coal samples differed from those of the above two kinds: under high stress, it could exceed 100 md, while the porosity was still high. Since a broken coal sample had no fractured structure, its pore recovery ability after loading and compaction was poor, the permeability increased very slowly during the unloading process, and the later period of permeability change was short. Most studies were focused on the permeability changes of intact coal samples under stress. In contrast, those devoted to fractured and broken coal samples under stress were quite scarce and did not fully reflect the real situation on site. Scholars should introduce the fractured structure of coal into permeability research and compare the permeability evolution patterns of

intact, fractured/cracked, and broken coal samples under the same stress path to provide theoretical guidance for the gas migration prediction in the coal seam and its most efficient extraction.

(3) Besides the conventional coal sample preparation, one should take advantage of the 3D printing technology to prepare coal rock physical models with the fissure structure characteristics and mechanical performance index close to that of natural fractured coal. Recent studies used CT imaging, three-dimensional reconstruction, and 3D printing technology to prepare a natural coal rock model containing complex fractures. With the help of three-dimensional stress freezing and photo elastic technology, the internal stress field distribution of complex fractured coal rock under uniaxial compression load can be intuitively and quantitatively grasped and visualized. In the structural characterization of coal, in-depth research can be combined with 3D printing technology.

7 Conclusions

(1) When studying the permeability changes in intact, fractured, and broken coal bodies under stress, they should be observed in combination with on-site mining methods to provide theoretical guidance for the on-site gas extraction and improve the coal seam permeability.
(2) When studying the factors affecting the permeability of coal samples, especially the fractured and broken ones, the main focus should be on the fractured structure of the coal samples. The difference in permeability changes of intact, fractured, and broken coal bodies should be analyzed for the same loading–unloading stress paths.
(3) In addition to the SEM, CT, and NMR observations, the coal structure characterization can be combined with the 3D printing technology to produce physical analog samples with fractured structures close to the actual fractured coal.

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