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Damage and permeability evolution law of coal mass during confining pressure relief

In order to research the damage and permeability evolution law of coal mass under fluid-solid coupling during confining pressure relief, the permeability coefficient determination test on coal samples with transient pressure pulse method has been conducted under the condition of false triaxial and constant axial pressure. The experiment results indicated that the deformation of coal sample is mainly radial expansion deformation during confining pressure relief. When axial pressure is between uniaxial compressive strength and triaxial compressive strength, the typical curve of "confining pressure relief-volume strain" contains three stages: elastic deformation recovery, plastic deformation and failure stage. The damage and permeability coefficient variation has a confining pressure relief threshold. Below this threshold, permeability coefficient increases slowly and steady; above this threshold, it rises rapidly. It also has a inflection point for confining pressure relief. When confining pressure relief exceeds inflection point, coal sample gets macro rupture and permeability coefficient increases sharply.

Keywords: *Coal mass; fluid-solid coupling; transient pressure pulse method; confining pressure relief; damage; permeability coefficient; radial expansion deformation; plastic deformation*

1. Introduction

In colliery and rock excavation engineering, because of engineering excavation, surrounding rock stress state of excavation cavern is certainly changed, from primary 3D stress state to plane stress state, even uniaxial stress state. Surrounding rock horizontal stress in the side of excavation cavern decreases, namely confining pressure reduces and returns to the original rock stress state until it goes deep into surrounding rock in a certain depth. As for the coal wall on mining face and coal strata on both sides of roadway, stress state variation causes rupture of surrounding rock and structure change, such as fracture zone and limit equilibrium area of coal wall, loose circle (Dong 2011) of roadway surrounding rock, and then causes their permeability change. When pore fluid pressure exists in surrounding rock, it also plays a part in surrounding rock rupture and structure change and causes permeability variation jointly, such as coal seam gas desorption and diffusion (Zhou and Lin 1998; Zhu et al. 2007) on mining face, water bursting in mine, pressure relief gas extraction and slope excavation stability, etc.

Deformation damage characteristics of rock under unloading condition differ greatly from that under loading condition, which is studied more at present (Li and Wang 1993; Hua et al. 1995; Zheng et al. 2010; Palmer and Vaziri 1995; Chen et al.1979). However, only a few researches cover deformation damage characteristics of rock under unloading condition. More studies (Hubbert 1957; Zhang and Xue 2009; Yang et al. 2007; Morrow and Lockner 2013) aim at permeability character of porous media such as rock and coal and permeability evolution law during overall stress and strain, some studies (Wang 2005; Huang and Wang 2007) involve the effect of confining pressure increase on permeability. Traditional researches (Yang et al. 2011) on fluid-solid coupling have gone deep into fluid-solid damage coupling. Under the condition of unloading, there is little research on permeability evolution law. For this reason, it is necessary to deeply research on rupture (damage) and permeability evolution law of coal and rock mass under the condition of fluid-solid coupling during confining pressure relief, which possess theoretical and realistic significance at safety and high effective production in colliery and much other engineering.

2. Experimental plan

Coal briquettes for test are taken from 3# coal seam in Dayang colliery, Jincheng. They are made into 3 cylindrical coal samples with 5 cm in diameter and 9 cm in height for permeability experiment. Meanwhile, in comparison with rock, a sandstone briquette is processed into cylindrical sandstone sample with 5 cm in diameter and 9 cm in height for permeability experiment.

2.1 Experimental equipment

The permeability test machine adopts MTS815.02 electro-hydraulic servo rock mechanics test system, which is shown

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in Fig.1. It is equipped with three separate sets of closed-loop servo control system of axial pressure σ_1, confining pressure σ_3 ($\sigma_2 = \sigma_3$) and pore water pressure P_w, and possesses computer control and automatic data acquisition function. The axial strain of sample can be calculated based on pressure plate displacement monitored by test machine and the radial strain is monitored by ring displacement sensor. As MTS test system is provided with such characteristics as hydraulic servo control, high data acquisition frequency (5 kHz) and huge frame stiffness (10.5×109 N/m), it is fully qualified for compression test after sample failure. In addition, the response frequency of hydraulic servo control system is 290 Hz, hydraulic source power 18 kW and the flow of hydraulic oil source system 31.8 L/min.

On the top and bottom end of samples, each has a water penetration steel plate with many uniformly distributed small holes. It can make water pressure uniformly act on the entire sample section so as to ensure that liquid can permeate into sample evenly on the whole sample surface. Top end water pressure of sample remains on the upper part of top permeable steel plate, bottom end water pressure on the lower part of bottom permeable steel plate. In the centre of each plate, there is a small vertical hole as water flow channel.

In order to avoid oil-water mix, every sample must be seal up well. First of all, prepare some sticky electric tape that can be tightened up, twine a layer of electric tape on the entire sample except both ends, twine another layer on the whole sample so as to connect top and bottom pressure head. Secondly, warp a layer of thin film and twine a layer of electric tape. Once again, warp a layer of thin film and seal up both ends of thin film by electric tape. At last, warp another layer of thin film and seal up both ends of thin film by electric tape. The well-packaged coal sample is installed as shown in Fig.1(b).

2.2 Experimental principle

Basic principle (Fig.2) of measuring permeability by transient pressure pulse method is as follows. According to experimental design, exert a certain axial pressure σ_1, confining pressure σ_3 and pore water pressure P_{w1} (always keep $P_{w1} < \sigma_3$, or else it can make heat shrinkable plastic seal failure and then experiment fails). Finally, reduce bottom end water pressure (P_{w2} ($P_{w2} = P_{w1}$ at the start) so as to form osmotic pressure difference Δp (equipment maximum differential pressure is less than 2 MPa) between both ends, thus water can seep into sample. In the process of seepage, decrease Δp ceaselessly. The decreasing speed relates to rock type and structure, sample height (seepage path) and section size, fluid viscosity and density, stress state and stress level, etc.

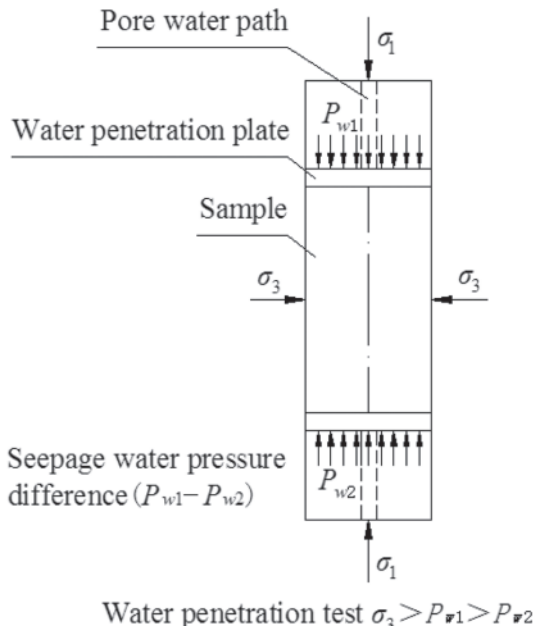


Fig.2 Schematic plan of permeability test principle

On the basis of experimental data collected automatically by computer, rock permeability is:

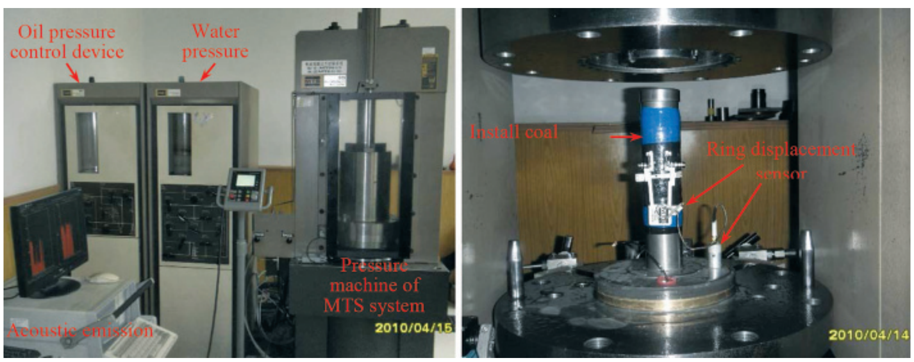
$$k = \frac{1}{5n}\sum_{i=1}^{n} 526\times10^{-6}\times\lg[\Delta p(i-1)/\Delta p(i)] \quad \text{... (1)}$$

Where n is data acquisition line number; $\Delta p(i-1)$ is osmotic pressure difference of the $(i-1)$ line, MPa; $\Delta p(i)$ is osmotic pressure difference of the $i$line, MPa.

In order to avoid the effect of initial water absorption and gap gas of coal on top and bottom water pressure difference, every sample must be soaked in water over 48 h before experiment so as to keep it saturated state.

2.3 Experimental process

Based on conventional mechanical parameters test of coal sample taken from big coal briquette by intensive drilling method, physico-mechanical properties of coal sample for permeability test are shown in Table 1. Initial confining



(a) Test system (b) Install well-packaged coal sample

Fig.1 MTS815 system for permeability test

Table 1: Physic-mechanical properties of coal sample

	Porosity (%)	Compression strength (MPa)	Elastic modulus (GPa)	Tensile strength (MPa)	Cohesive force	Internal friction angle
Nature	4.7058	12.82	1.62	1.067	1.943	41.36
Saturated state	-	-	-	1.192	2.9196	15.38

pressure of cylindrical permeability coal sample and rock sample (5 cm in diameter, 9 cm height) is 10 MPa. Axial pressure stays at 18.44 MPa (No.1 coal sample), 12.24 MPa (No.2 coal sample) and 26.41 MPa (sandstone sample) separately. Because of incorrect operation, test results of No.3 coal sample are invalid. Proportionally apply axial pressure and confining pressure in step so as not to break sample during loading. When loading pressure reaches initial stress state, permeability test on sample begins, seepage water pressure difference keeps at 1.5 MPa. Then, confining pressure relief remains at about 0.5 MPa every time and permeability coefficient variation with confining pressure relief is test.

Every 3D stress state point for permeability test can be divided into four stages. At first stage, confining pressure relief keeps at about 0.5 MPa. At second stage, apply water pressure on top and bottom end of sample at the same time for the purpose of the same value of 4.5 MPa. At third stage, reduce bottom water pressure to 3 MPa. At fourth stage, test the variation of seepage water pressure difference with time until water pressure goes steady or reaches a stable value. At this stage, data acquisition time interval is 1s.

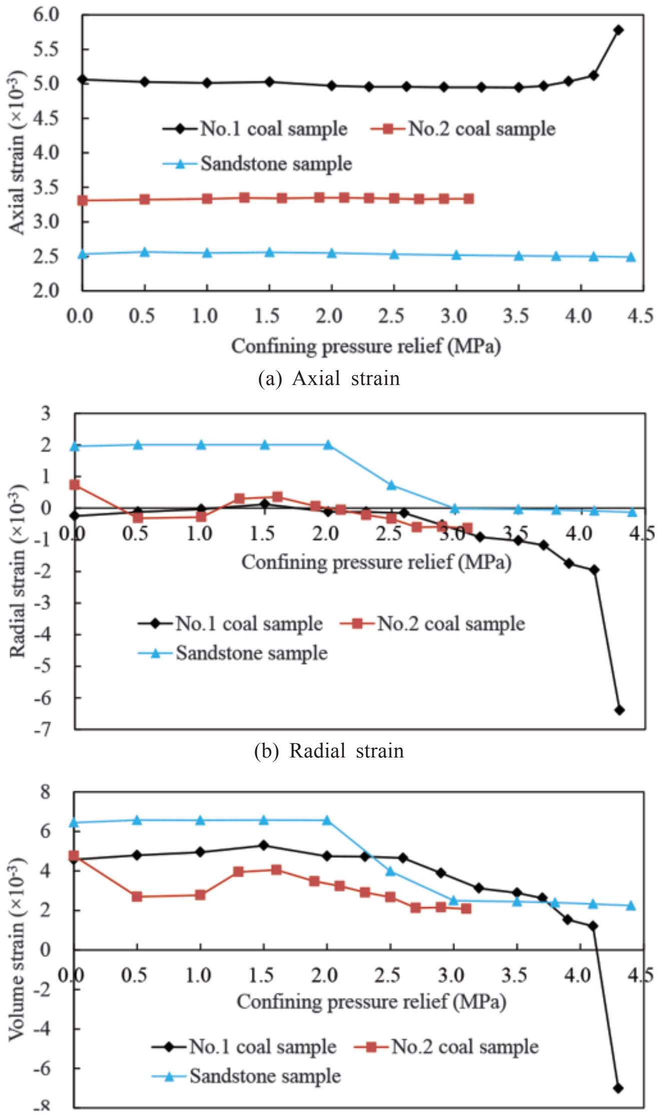
3. Analyses of experimental results

3.1 Deformation and failure law of samples during confining pressure relief

Under the condition of false triaxial and constant axial compression, with the increase of confining pressure relief, axial strain of each sample remain unchanged basically (Fig.3, compression is positive and tension negative). Only when sample breaks, axial compression deformation increases significantly, such as No.1 coal sample. As confining pressure reduces gradually, radial compression deformation of sample recovers gradually. When confining pressure reduces to a certain value, sample goes from radial compression deformation to radial tension deformation. It shows that sample deformation is mainly radial expansion deformation in the process of confining pressure relief (Fig.4). Along with confining pressure reduction, sample volume increases gradually as a whole and expands in volume, which is called volume-expanding phenomenon. When confining pressure relief rises, volume strain of sample can be divided into three stages roughly (Figs.3 and 4).

The elastic deformation recovery stage: volume strain of sample slowly increases towards positive without great fluctuation. With the increase of confining pressure relief, previously closed joint fissures inside coal and rock open up by degrees and then sample volume rises. In this stage, the confining pressure relief range of No.1 coal sample, No.2 coal sample and rock sample are relatively close, which are 0~1.5 MPa, 0~1.6 MPa and 0~2.0 MPa respectively.

The plastic deformation stage: volume strain of sample significantly improves towards positive and approximately varies linearly. With the further increase of confining pressure relief, previously joint fissures inside coal and rock expand distinctly. Fissures begin to rupture and propagate along with new cracks initiation is possible at the same time. In this

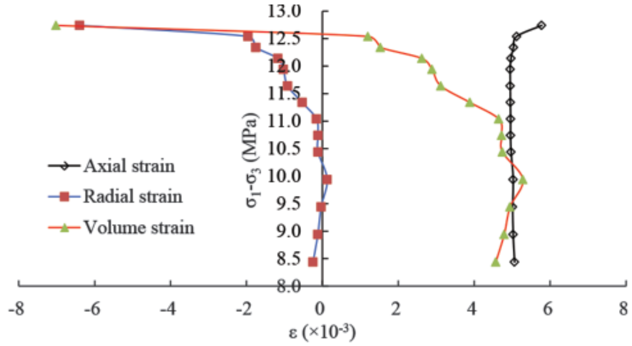


(a) Axial strain

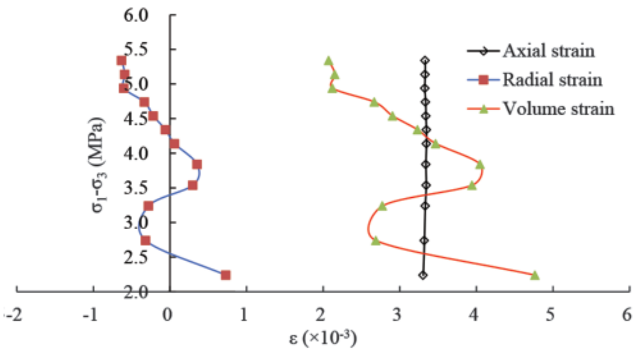
(b) Radial strain

(c) Volume strain

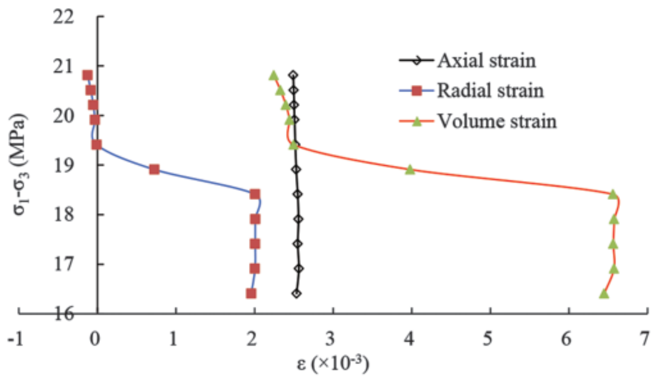
Fig.3 Relationship of strain and confining pressure relief for samples



(a) No.1 coal sample



(b) No.2 coal sample

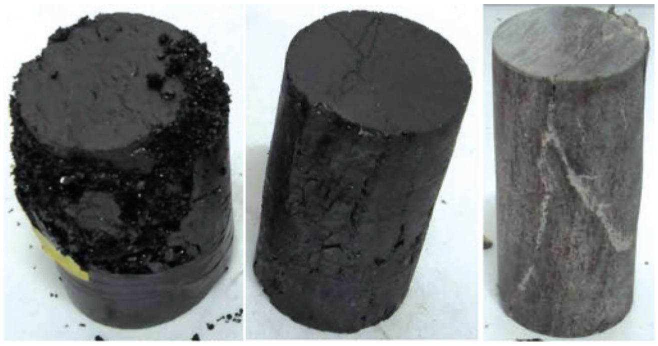


(c) Sandstone sample

Fig.4 Relationship of principal stress difference and strain for samples

stage, due to the variance of axial pressure and lithological characters of each sample, the confining pressure relief range of No.1 coal sample, No.2 coal sample and sandstone sample goes away, which are 1.5~3.9 MPa, 1.6~3.1 MPa and 2.0~3.0 MPa respectively.

The failure stage: volume strain of coal sample increases sharply towards positive. Owing to well-developed native joint fissures of coal, when confining pressure relief improves to a certain value, fissures rupture and expand and communicate mutually to fracture network, and may produce fracture plane. For this reason, coal sample swells and breaks (Fig.5(a)), volume strain rises sharply such as No.1 coal sample when confining pressure relief exceeds 3.9 MPa. Because axial pressure for No.1 coal sample is much greater than its uniaxial compressive strength, and axial compressive pressure for No.2 coal sample is slightly lower than its uniaxial compressive strength, volume strain increment of No.2 coal sample is much less than that of No.1 coal sample under the condition of same confining pressure relief. Moreover, No.2 coal sample has no macro fracture plane (Fig.5(b)) and the failure stage cannot be test out. Due to high homogeneous degree, sandstone sample forms two shear fracture planes (Fig.5(c)) during confining pressure relief. Because there is still confining pressure effect, sliding deformation gives priority to fracture planes and opening degree changes inconspicuously. As a result, sandstone sample volume increases slowly and less obviously in the failure stage (confining pressure relief surpasses 3.0 MPa).



(a) No.1 coal sample (b) No.2 coal sample (c) Sandstone sample

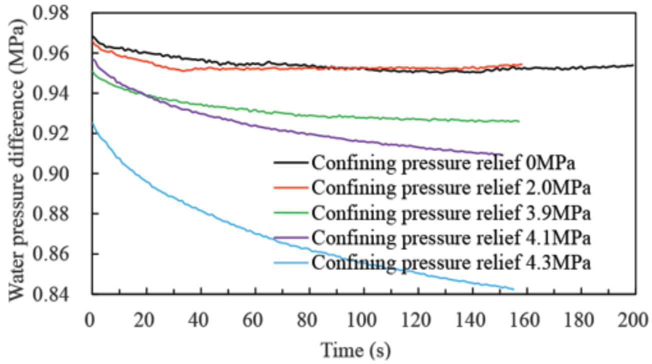
Fig.5 Sample failure shape of permeability experiment during confining pressure relief

According to the material mechanics, with the gradual decrease of confining pressure, normal stress on any inclined section inside sample declines gradually, but shear stress reverses and reaches the maximum at the angle between inclined section and axial stress. Obviously, the principal stress difference of sample rises by degrees in the process of confining pressure relief and sample transits from 3D stress state to uniaxial stress state. If axial pressure is lower than its uniaxial compressive strength, confining pressure relief is unable to give rise to sample failure. For example, No.2 coal sample has no macro failure (Fig.5(b)). Consequently, in the 3D stress state, axial pressure of sample must be higher than its uniaxial compressive strength so that sample is possible to fail during confining pressure relief.

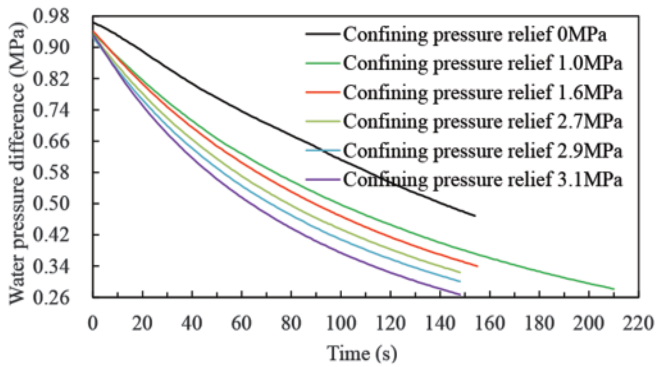
3.2 Damage evolution law during confining pressure relief

With the increase of confining pressure relief, the opening degree, number and range of fissures inside sample increase, propagating and connecting to form fracture planes, which cause volume change. Therefore, sample volume strain variation can reflect its internal damage evolution. Meanwhile, sample permeability is determined by the number, opening degree and connectivity of internal fissures. When transient pressure pulse method is used to measure sample permeability, the more internal fissures are, the greater damage is and then the more unimpeded water flow channel is. Thus, the descent speed of seepage water pressure difference becomes higher. In consequence, the descent speed of seepage water pressure difference can reflect sample damage degree during confining pressure relief (Fig.6).

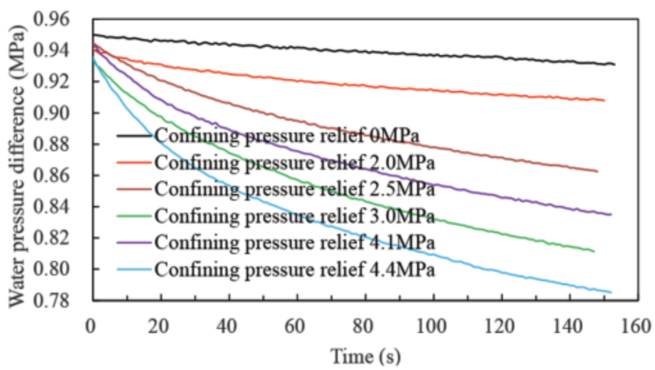
Seepage water pressure difference of each permeability test point varies with time and its descent speed declines gradually as a whole along with time extension. Thus, the tangent slope of initial point of water pressure difference and time curve can be used to reflect sample damage degree. Along with the increase of confining pressure relief, initial water pressure difference becomes higher and higher. The descent speed variation rule of initial water pressure difference just reflects damage evolution law.



(a) No.1 coal sample



(b) No.2 coal sample

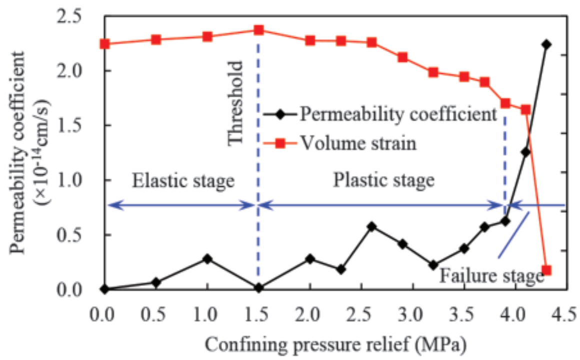


(c) Sandstone sample

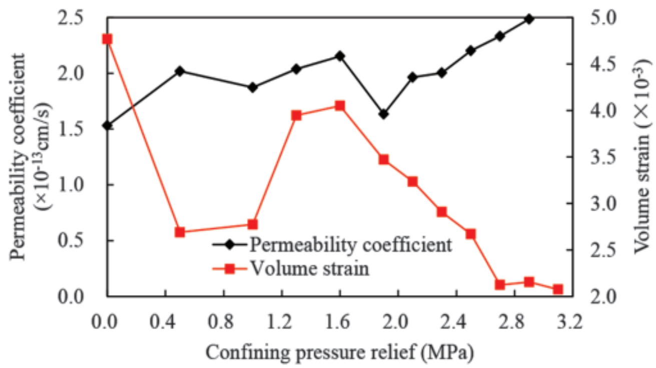
Fig.6 Relationship between seepage water pressure difference and time

3.3 Permeability coefficient variation law during confining pressure relief

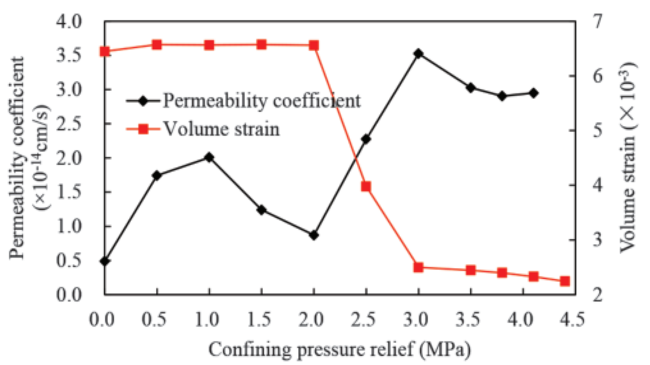
The damage evolution law decides the permeability coefficient evolution law, and volume strain variation reflects damage evolution law. Sample permeability coefficient variation quite agrees with its volume strain variation (Fig.7). As confining pressure relief rises, sample volume and permeability coefficient overall increase, namely the aggravation of sample damage degree induces permeability coefficient indrease gradually. Based on the diversity of variation degree, typical permeability variation during confining pressure relief contains three stages (Fig.7(a)). Take No.1 coal sample for example, permeability coefficient is 0.004×10^{-14}cm/s at initial confining pressure relief. At elastic



(a) No.1 coal sample



(b) No.2 coal sample



(c) Sandstone sample

Fig.7 Relationship among permeability coefficient, volume strain and confining pressure relief for samples deformation recovery stage, the average is 0.117×10^{-14}cm/s, which is 26.42 times of the initial stage. At plastic deformation stage, the average is 0.363×10^{-14}cm/s, which is 82.21 times of the initial stage. When confining pressure relief gets to 4.3 MPa at failure stage, the average of permeability coefficient is 2.238×10^{-14}cm/s, which is 507.32 times of the initial stage.

Confining pressure relief threshold (the cutoff point of elastic stage and plastic stage) exists in sample permeability coefficient variation. Below this threshold, permeability coefficient increases slowly and steady; above this threshold, it rises rapidly. Under the condition of initial stress state of this experiment, the threshold of No.1 coal sample, No.2 coal sample and sandstone sample are 1.5 MPa, 1.6 MPa and 2.0 MPa respectively. Mechanical properties and initial stress state of sample are crucial factors in confining pressure relief threshold. In general, the greater is the initial damage of coal sample and the lower is the strength, the lower will be the confining pressure relief threshold. Because of lesser initial damage and higher strength of rock sample, under the same condition, its confining pressure relief threshold is high and much greater than that of coal sample. The presence of confining pressure relief threshold has great significance at judging sample damage evolution and permeability coefficient variation. Sample damage and permeability coefficient variation has confining pressure relief inflection point (the cutoff point of plastic stage and failure stage). When confining pressure relief exceeds the inflection point, sample gets macro rupture and permeability coefficient increases sharply.

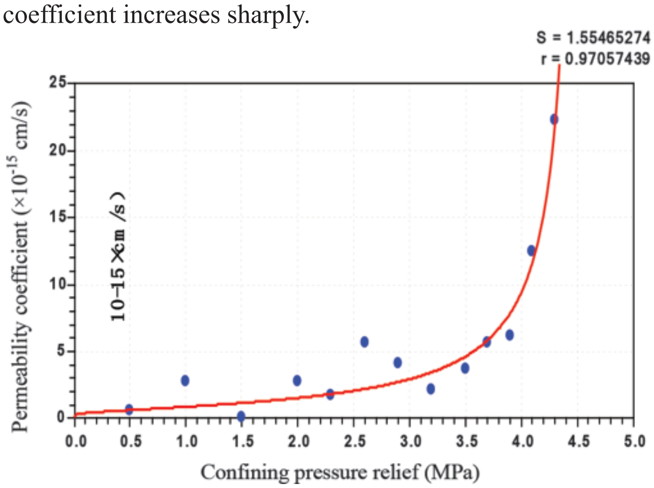


Fig.8 Fitting curve of permeability coefficient and confining pressure relief

Based on the test data of No.1 coal sample, the nonlinear relationship between coal sample permeability coefficient and confining pressure relief is matched as Fig.8 (Harris Model). The fitted equation is:

$$K = 1/(5.130 - 3.996\,\sigma^{0.165}) \quad \dots (2)$$

Where K is permeability coefficient, $\times 10^{-15}$cm/s, σ is confining pressure relief, MPa. As for No.2 coal sample, when its permeability coefficient units converts to ($\times 10^{-13}$cm/s), this equation roughly agrees with the relationship between its permeability coefficient and confining pressure relief. As a result, this fitted equation is valid for estimating coal permeability coefficient variation rule with confining pressure relief. However, it is incorrect for sandstone.

4. Conclusions

1. Under the condition of false triaxial and constant axial compression, the deformation of coal samples is mainly radial expansion deformation in the process of confining pressure relief; axial strain remains unchanged basically. Only when coal samples break, axial compression deformation increases significantly.
2. When axial pressure is between uniaxial compressive strength and triaxial compressive strength, the typical curve of "confining pressure relief-volume strain" contains three stages: elastic deformation recovery, plastic deformation and failure stage.
3. During confining pressure relief, volume strain comprehensively reflects coal sample damage of crack growth and expansion, volume strain variation reveals damage evolution law. The variation rule of permeability coefficient accords with that of coal sample volume strain and possesses stages.
4. Coal sample damage and permeability coefficient variation has confining pressure relief threshold. Below this threshold, permeability coefficient increases slowly and steady; above this threshold, it rises rapidly. Mechanical properties and initial stress state of coal sample determine the value of confining pressure relief threshold.
5. Coal sample damage and permeability coefficient variation has confining pressure relief inflection point. When confining pressure relief exceeds the inflection point, coal samples get macro rupture and permeability coefficient increases sharply.

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(Continued on page 460)