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Testing Research on the Effect of Effective Stress on Coal Specimen

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Abstract: To have better understanding of the interaction mechanism for rock deformation and methane gas flow, the testing research on the effect of the effective stress on coal specimen under the action of 3-dimensional compression have been specially designed for this study. The triaxial compression tests to coal specimen containing methane gas are carried out with various confining stress and pore pressures. The result of this test showed that the empirical equations for effective stress coefficient are a bilinear function of variable with overall stress and pore pressure. The empiric equations can depict the dynamic deformation behavior of gassy coal under the action of pore pressure.

Key words: Triaxial compression, methane gas seepage, coal specimen, coupled effect, effective stress

INTRODUCTION

The effective stress coefficient (α) was defined as following by Terzaghi (1943) and Jeager and Cook (1979).

$$(\sigma_{ef})_{i,j} = \sigma_{i,j} - \alpha p \delta_{i,j} \quad (1)$$

Where, $(\sigma_{ef})_{i,j}$ is the effective stress tensor; $\sigma_{i,j}$ is the overall stress tensor; $\sigma_{i,j}$ is Kronecker function; p is pore pressure. It is interested by Bear (1972), Ettinger (1979), Walsh (1981), Borisenko (1985), Zhao *et al.* (1994), Zhao *et al.* (1994 a,b) Zhao and Hu (1995), Sun and Xian (1998, 1999), Valliappan and Zhang (1999), Sun (2002 a-c, 2005) and Zhao *et al.* (2004) that research on effect of gas pore pressure on stress in coal specimen. It is necessary to carry out the testing research of the law for effective stress on coal-mass under the action of in both pore pressure and overall stress in order to profoundly research the interaction coupled between gas leak flow and coal/rock mass deformation (Sun, 1998, 2000, 2002 a-c; Sun and Xian, 1998, 1999), which simulates the law of distributions for coal/rock mass stress and gas pore pressure of coal seam. Herein, the empirical equations of the effective stress coefficient (α) under the action of both total stress and pore pressure of coal specimen will systematically be investigated and fitted the empirical equation of α, which is the foundation of numerical simulations of the model coupled gas leak flow and coal/rock deformation in multi-coal-seams (Sun, 2002a-c, 2003, 2004, 2005; Sun and Wan, 2004; Sun and Guo, 2005).

MATERIALS AND METHODS

The homogenous coal specimen preparation: The coal specimen was collected from the 6th, 7th, 8th coal seam and intercalation of Shongzhao coal mining district in Chongqing of China according to the research aim. In the experiment, the molding specimen was adopted. In the process of molding coal specimen, firstly, the selected coal specimen was grinded and the coal powder whose diameter is 0.1~0.2 mm was selected. Then the coal powder was compressed and molded under 100 MPa, the size of molding coal specimen was Φ 50×95 mm±0.25 mm, and immediately put the specimen into a oven and dried under 80°C, it made the moisture in the specimen be equal to the moisture content in the coal seam. Finally the resistance strain sensor was plastered on the cylinder of the specimen on the base of request, and the specimen was put into the plastic bag in time in order to the testing.

The test device and method: The test device was made up of DLY-10 test machine as a loading on base of the rigid testmachine and the triaxial permeability cell that was made up of triaxial cell and measurement meters. The test device was showed Fig. 1. The axial pressure of the coal specimen was given by the machine of triaxial compression tests and the surrounding pressure was given by the oil pump; the coal specimen was separated from the oil route system and gas route system by silicon rubber. The methane gas was penetrated into the top ingoing hole of the triaxial permeability cell, which contains the specimen, from the high-pressure gas steel-bottle (the concentration of CH_4 is 99.0%) by triaxial compression chamber. It was flowed into the flow meter of the pipe from the outgoing hole in the bottom of the specimen and it was flowed out. The pore pressure in the coal specimen can be adjusted to the value we needed by the reductor. The high precision meter was used to measure the pore pressure and the surrounding pressure.

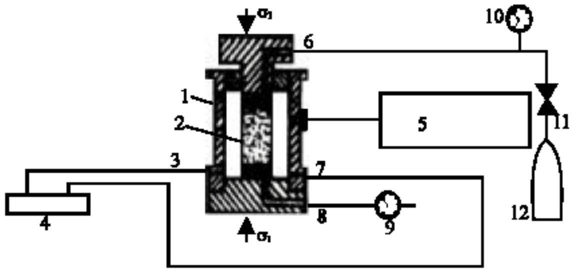

Fig. 1: Sketch of experimental device. 1- Traixial compression devices, 2- Coal specimen, 3- Oil flow out pipe, 4- Oil pump, 5- Strain-determining instrument, 6- Gas flow in pipe, 7- Oil flow in pipe, 8- Gas flow out pipe, 9- Gas flow rate meter, 10- Pressure meter, 11- Gas pressure reductor, 12- Steel bottle containing methane gas

The axial and the transverse strain of the coal specimen were measured by the static and dynamic resistance-strain-instrument in the whole compression process.

The test was carried out step-by-step according to the following. Firstly, the axial pressure was added a little and the specimen was fasten, then the surrounding pressure and the pore pressure was increased stepwise, and the surrounding pressure was not small than the pore pressure, which was kept in order to avoid that the methane gas was overflowed because of higher pore pressures. Secondarily, in the test, the sorption of the coal specimen for methane gas must be saturation, at this time, we could respectively measure the axial and cross direction strain value as well as the gas flow rate and so on. After measurement, the pore pressure of next level was added. Thirdly, after the surrounding pressure and the pore pressure both were adjusted equal to the value we needed; the next level axial pressure was thrown by the test machine. In the whole process, the loading rate was kept about 0.2 MPa sec^{-1} in order to keep the static loading.

THE MECHANICAL PROPERTY OF COAL SPECIMEN

The research by contrasting on the microstructure characterization between molding coal specimen and original coal specimen and the relation of mechanical property indicated that the variation law of original coal specimen and molding one was accordant though it is different to porosity volume, deformation rate and the intensity of peak of molding coal specimen and original coal specimen. Therefore, the similarity of variation law could exist between molding coal specimen and original one. It is feasible that the analysis result obtained from molding coal specimen was modified according to a similar coefficient and can be applied to original coal mass. In fact, the construction condition of original coal seam is complex including structural action, the action between overall stress and structural stress, and the different property of coal mass in different place, which shows the obvious inhomogeneous and anisotropic. However, the molding coal specimen not only possesses of the microstructure characterization of origin coal mass but also more homogeneous than original coal specimen and can represent the average homogeneous coal, which accords with the request of homogeneous materials model. Therefore, the molding coal specimens were used in this experiment. In order to indicate the similar relation between original coal specimen and molding one, Table 1 shows the contrastive results of the porosity between original coal specimen and molding coal specimen. From the Table 1, we can find that the difference of porosity between original coal specimen and molding coal specimen are 12 times though the real specific gravity and visual specific gravity are almost equal.

Table 1: Porosity of original and molding coal specimen

Parameter	Original specimen	Molding specimen
Real special gravity (g cm^{-3})	1.3217	1.3826
Visual special gravity (g cm^{-3})	1.3008	1.1182
Porosity (%)	1.5800	19.120

Table 2: Mechanical property for coal specimen

Coal seam remarks	E (Gpa) Original*	E (Gpa) Molding	ν Original*	ν Molding
Coal-seam 6	0.64	0.96	0.295	0.298
Coal-seam 7	0.43	0.65	0.292	0.294
Coal-seam 8	0.27	0.41	1.291	0.292

* The measured data of original coal specimen was made by Xie (1993)

In order to exactly analyze the experimental results, we measured the characteristic deformation parameter under the action of triaxial compression to each coal seam specimen at the same time including elastic modulus (E) and poisson ratio (ν) shown in Table 2. From the Table 2, the deformation characteristic parameter of original coal specimen under the single axis is similar to that of molding coal sample under the triaxial compression and the elastic modulus of molding coal sample under the triaxial compression is 1.5 times more than that of original coal specimen under the monoaxial compression.

TEST RESULTS

Test principle: The research on the effective stress law of coal specimen is based on the hypothesis by Zhao *et al.* (1994b) as following: (1) the homogeneous isotropy of coal specimen; (2) the deformation of coal specimen under the action of both solid framework stress (total stress)

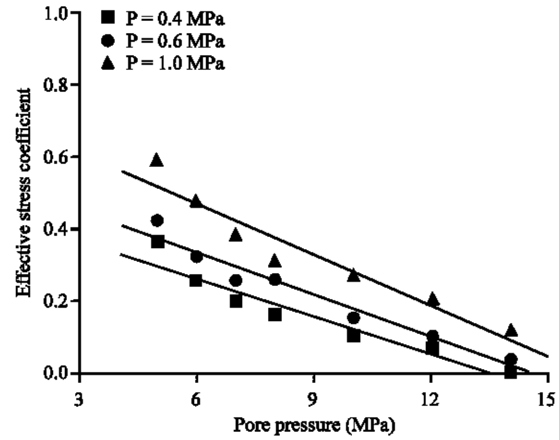

Fig. 2a: The relation for the effective stress coefficient and overall stress in coal seam 6

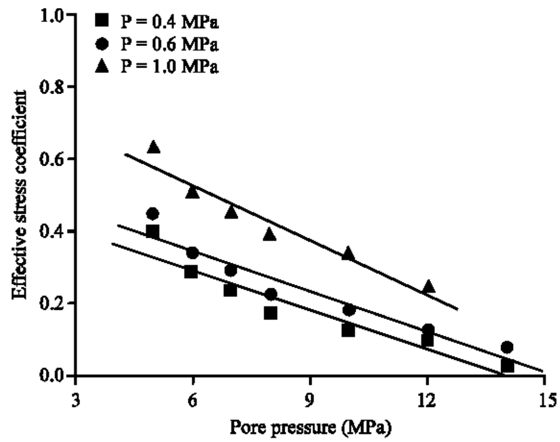

Fig. 3a: The relation for the effective stress coefficient and overall stress in coal seam 7 (case 1)

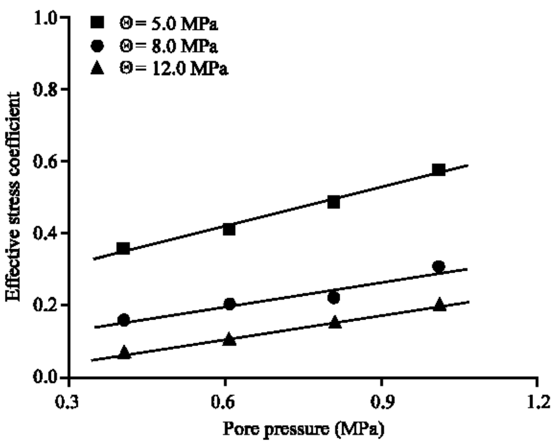

Fig. 2b: The relation for the effective stress coefficient and pore pressure in coal seam 6

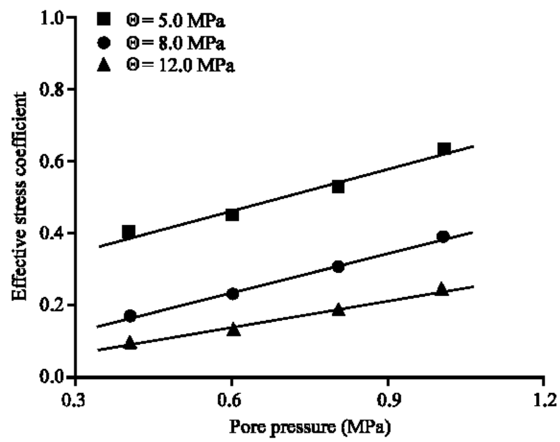

Fig. 3b: The relation for the effective stress coefficient and pore pressure in coal seam 7(case 1)

and pore pressure is linear elastic deformation; (3) the deformation is reversible. Therefore, the molding coal specimen is more according with basic hypothesis than the original coal specimen.

Although there is some differences between hypothesis above and the deformation of original coal seam, the experiment results indicate that the approximate degree is good. The axis deformation of coal specimen under the action pore pressure can be shown as following based on above hypothesis and from the Hooke's law expressed by the effective stress:

$$\varepsilon_1 = [(\sigma_{ef})_1 - 2\nu(\sigma_{ef})_2]/E = (\sigma_1 - 2\nu\sigma_2)/E - \alpha(1-2\nu)p/E \tag{2}$$

Where, ε_1 is axial strain; σ_1, σ_2 (where $\sigma_2 = \sigma_3$) are the component of total compression stress; p is pore pressure; E is elastic modulus and ν is poisson ratio. Because the deformation of coal specimen under the action of total compression σ_1, σ_2, σ_3 had been accomplished when the gas pore pressure of coal specimen was loaded; If the external loading is absent, i.e., $\sigma_1 = \sigma_2 = 0$, and the only loading is the pore pressure p, then we get the relation between the pore pressure and the deformation of coal specimen produced by gas pore pressure as following according Eq. 2:

$$\Delta\varepsilon_1 = -\alpha(1-2\nu)p/E \tag{3}$$

Where, $\Delta\varepsilon_1$ is axial strain of coal specimen caused by gas pore pressure. The experiment results can be obtained based on the Eq. 3 and the data of Table 2, the calculation method was shown following: the equivalent pore pressure (p_{ef}) can be calculated by the Eq. 3 based on the measured axial strain $\Delta\varepsilon_1$ and defined the effective stress coefficient (α) shown as following.

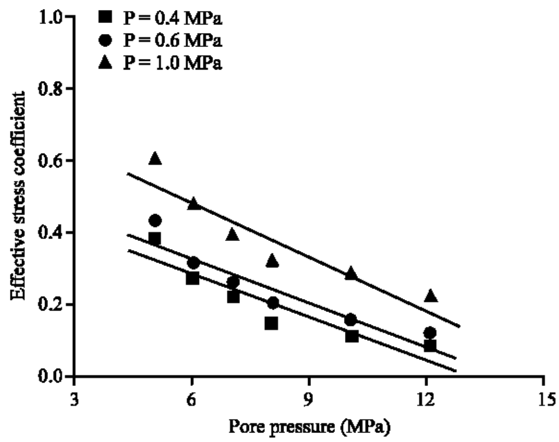

Fig. 4a: The relation for the effective stress coefficient and overall stress in coal seam 7(case 2)

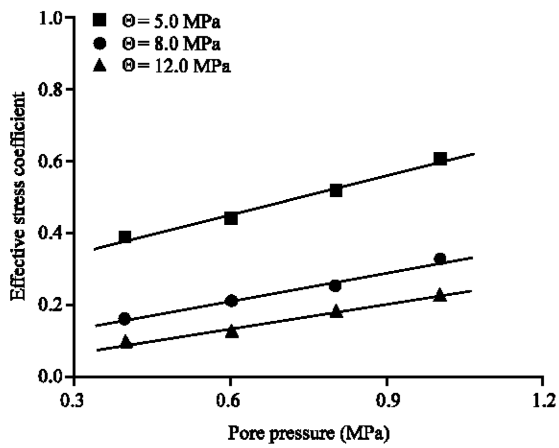

Fig. 4b: The relation for the effective stress coefficient and pore pressure in coal seam 7(case 2)

$$\alpha = p_{ef}/p \quad (4)$$

Where, pef = $-\Delta\varepsilon_1 E/(1-2\nu)$, it is called the equivalent pore pressure.

Experimental results: The experiment results of the relation curves for the effective stress coefficient (α) and overall stress (Θ) were shown in Fig. 2a-5a, and the relation curves for the effective stress coefficient (α) and pore pressure (p) were shown in Fig. 2b-5b.

DISCUSSION

It was shown in Fig. 2a-5a which are the relation curves for α-Θ and shown in Fig. 2b-5b which are the relation curves for α-p according to the variable feature for the effective stress coefficient (α) of coal specimens, which are collected from Datong coal mine 2 of

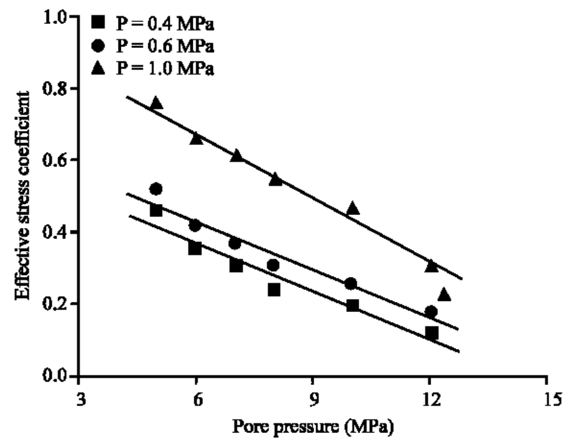

Fig. 5a: The relation for the effective stress coefficient and overall stress in coal seam 8

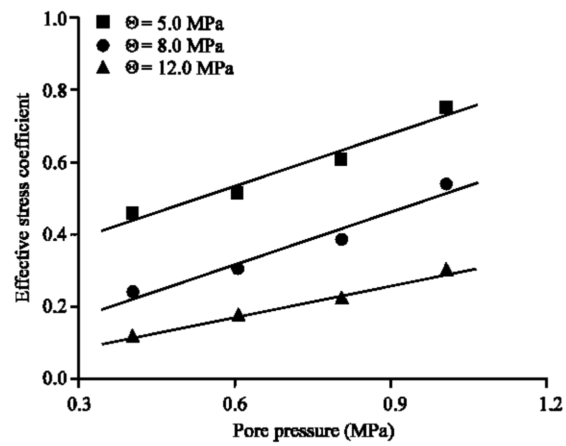

Fig. 5b: The relation for the effective stress coefficient and pore pressure in coal seam 8

Shongzhao, China, under the action of both overall stress (σ_1, σ_2, σ_3) and gas pore pressure (p). From the Fig. 2-5, the linear relation between the effective stress coefficient α and overall stress Θ, pore pressure p was obviously found and the bilinear functions were adopted to use simulation based on the data of the experiment results. The average empiric relations $\alpha = \alpha(\Theta, p)$ were shown in Eq. 5-7.

$$\alpha = 0.1298-0.0081\Theta+0.4545p-0.0285\Theta p \quad (5)$$
(for coal seam 6)

$$\alpha = 0.0233-0.0011\Theta+0.6686p-0.0323\Theta p \quad (6)$$
(for coal seam 7)

$$\alpha = 0.0543-0.0032\Theta+0.9748p-0.0578\Theta p \quad (7)$$
(for coal seam 8)

At final, the several laws and conclusions for this research can be drawn as following.

- With the increase of the overall stress, the effective stress coefficient of coal specimen was linearly decreased in Fig. 2a-5a. When the effective overall stress acted on the coal specimen is more than 30.0 MPa and pore pressure is less than 1.0 MPa, the action of pore pressure on the coal framework is almost equal to 0 i.e., $\alpha = 0$. The gas pore pressure of coal specimen is invalid from the macrocosmic.
- With the increase of the pore pressure, the effective stress coefficient of coal specimen was linearly increased and as the increase of the overall stress, the slope of the linear increase of the effective stress coefficient of coal specimen via pore pressure i.e. the range of α action is improved in Fig 2b-5b. When p is increased to specified value, $\alpha \to 1$, which shows the disintegrate action of pore pressure on the microstructure of coal specimen and the action of pore pressure is the most obvious at this time.
- When the coal specimen broke up to specified extent i.e., it was transfixion between pore and disintegrated pore, α is equal to 1. At this time, the microstructures of coal mass and soil mass were equal, which keep to the effective stress law of Terzaghi.
- When α is more than 0 and less than 1, the action of pore pressure is obvious in Fig. 2-5. This experiment results were similar to the one of research by Zhao and Hu (1995), which both confirmed the effective stress keep to the modified effective stress law of Terzaghi at this situation. The variety and distribution law of the effective stress coefficient of coal specimen in coal seam 6, 7, 8 of Shongzhao keeps to the bilinear function shown in Eq. 5-7.

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