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Creep behaviour and constitutive model of coal filled with gas

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Abstract

Coal exhibits different creep behaviours when filled with different amounts of gas. Creep tests of coal filled with 0 and 0.5. MPa. gas were performed, and strain under different axial stress was compared. The three creep constitutive models which were analysed using the method fitting experimental data for determining which creep model can reflect the creep process of the test best. The results show that the deformation of coal filled with 0.5. MPa. gas is more higher than that of coal filled with 0. MPa. gas under the same axial stress. Gas plays a positive effect on the deformation of coal process and will accelerate creep process. And gas will reduce coal intensity and change coal creep properties. Compared with Nishihara Model and Extensional Nishihara Model, Burgers Model can reflect the three stages of creep process of coal filled with gas better. The research results can contribute to reveal coal and gas outburst mechanism.

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ABSTRACT

Coal exhibits different creep behaviours when filled with different amounts of gas. Creep tests of coal filled with 0 and 0.5 MPa gas were performed, and strain under different axial stress was compared. The three creep constitutive models which were analysed using the method fitting experimental data for determining which creep model can reflect the creep process of the test best. The results show that the deformation of coal filled with 0.5 MPa gas is more higher than that of coal filled with 0 MPa gas under the same axial stress. Gas plays a positive effect on the deformation of coal process and will accelerate creep process. And gas will reduce coal intensity and change coal creep properties. Compared with Nishihara Model and Extensional Nishihara Model, Burgers Model can reflect the three stages of creep process of coal filled with gas better. The research results can contribute to reveal coal and gas outburst mechanism.

1. Introduction

Creep properties of coal have an important significance for revealing the coal and gas outburst mechanism [1–5]. A considerable number of studies had been performed to understand creep process of coal [6–33]. He et al. brought up the generalized K-B model, which gave the entire creep curves of coal considering inhomogeneity in the accelerated creep stage of coal [34]. Liu and Zhao established the nonlinear viscous elastic-plastic creep model by adding the rheological index, and the index could better reflect the three creep stages of rock, fully describing the accelerated creep characteristics [35]. Moreover, analytical expressions of creep deformation, creep speed rate and the acceleration of creep were obtained. Xia et al. presented a unified rheological model and developed a method which can identify creep model of the rock according to creep experiment result [36]. Qin obtained the damage evolution equation and the mathematical relation between damage index and strain considering energy, and proposed that strain-time curve (the creep curve of coal-rock) could be obtained according to substitute the approximate solution of damage evolution equation into the mathematical relation between damage index and strain [37]. Pan et al. studied the creep model and delay instability of coal filled with gas and found that gas promoted the coal damage [38]. Yin and Wang studied the creep behaviour and the creep model of coal filled with gas and found gas pressure had the import effect on the coal creep and coal deformation [39–41].

From literature reviewed above, it can be seen that there are little research of creep behaviour of coal filled with gas. Although some creep models of coal are developed, there is no creep model of coal filled with gas. Therefore, creep behaviours experiment of coal filled with gas were performed, and strain of coal filled with different amounts of gas were compared in the paper. According to the experiment result, fitting value of three creep models were calculated and compared.

2. Creep behaviour of coal filled with gas

2.1. Experimental system

The creep experiments of coal filled with gas are performed in a self-designed CSCG-160 constant load creep seepage experiment system (Fig. 1). The experiment system consists of the loading system, gas system, vacuum system, control system and data acquisition system. The loading system is mainly composed of gravity storage device (Fig. 2), hand pump, reservoir, booster cylinder and its valve control system, sample holder. Meanwhile, the loading system has an independent axial and confining load mode for controlling different axial and confining. The gravity storage device is equipped with a number of gravity blocks, which provides long-term and stable axial and confining pressure. While the

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Fig. 1. Constant load creep seepage experiment device.

Fig. 2. Gravity storage device.

gravity loading can effectively avoid the influence on the experiment results caused by power outages and other malfunctions. The up and down of the gravity blocks is got by the hand pump. The top and end size of the piston in the booster cylinder is different. And the top area of the piston in the booster cylinder is larger than the end area of the piston. Thus, a lower pressure in the top area of the piston in the booster cylinder can be changed into a higher pressure in the end area of the piston, which will got the effect of pressure boost.

2.2. Coal sample

Raw coal samples used in this experiment are from Guzhuang Coal Mine located in Yangquan city. The coal is bright coal with strong luster and little endogenous fissure, and the density is 1.42 g/cm. According to requirement of the experiment system, raw coal samples were cut into cylindrical in shape with the same height (100 mm) and diameter (50 mm).

Before the creep experiment, the acoustic speed of coal is measured in acoustic test system. Four coal samples with approximately equal acoustic speeds are chosen for the creep experiment and uniaxial compression experiment. In order to determine the range of axial stress loaded on the coal, uniaxial compressive strength should be tested. Thus, two samples were used in uniaxial compression experiment, and the uniaxial compressive strength of the coal sample is 12.19 MPa.

2.3. Experimental methods

For safety, gas used in the experiment is carbon dioxide instead of methane. Coal is filled with two different amounts of gas: 0.5 and 0 MPa. The confined stress is 2 MPa in each experiment, but axial stress is incremented in stages. In the experiment of coal filled with 0.5 MPa gas, the following axial stress experiments are

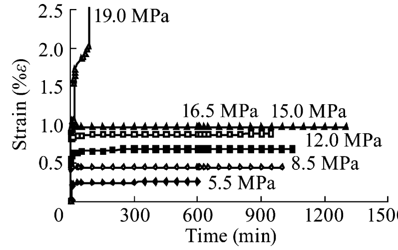

Fig. 3. Creep curves of coal filled with 0 MPa gas.

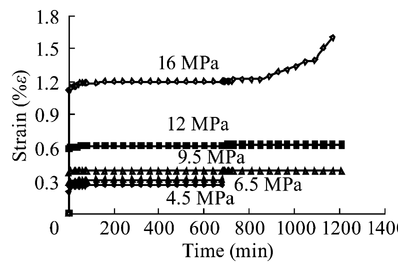

Fig. 4. Creep curves of coal filled with 0.5 MPa gas.

performed: 4.5, 6.5, 9.5, 12.0 and 16.0 MPa. In the experiment of coal filled with 0 MPa gas, the following axial stress experiments are performed: 5.5, 8.5, 12.0, 15.0, 16.5 and 19.0 MPa.

2.4. Experimental steps

Firstly, coal samples are put into the experiment device. Before loading, all pipe line must be connected with the vacuum pump which is used to pump the line and pressure cylinder to vacuum state. Hand pumps are used to bring the gravity energy storage device to the top. Then, the pressure cylinder is pushed to its initial state by hydraulic pressure; at the same time, the entire pipeline pressurization system should be filled with water. The weight block should then be placed in the gravity constant load storage device and different pressure ratios are chosen through the pressure cylinder. A predetermined value for loading the axial and the confining pressure of the coal sample can be set through the pipeline. The predetermined gas pressure of the coal sample is further added through the pipeline. At this time, the experiment begins and the axial deformation of coal and time is recorded. At last, experiments are carried on according to the pre-set axial stress.

2.5. Results and analysis

Creep curves of coal filled with 0 MPa gas under different axial stress is shown in Fig. 3 and creep curves of coal filled with 0.5 MPa gas under different axial stresses is shown in Fig. 4. From Figs. 3 and 4, the creep curves show the characteristics of "creep two stage", which means that creep curve characteristics are different in low and high axial stress. When the loaded axial stress is low, creep rate decreases, and stain will reach a certain value with the increase of time, which is called attenuation creep. When the loaded axial stress is high enough, stain will increased dramatically with time, and coal sample will transform into failure. The stage is called as non-attenuation creep.

Comparing the creep curves of coal filled with 0 MPa gas and creep curves of coal filled with 0.5 MPa gas, it can be clearly seen that failure strength of coal filled with different amount of gas is different, failure strength values of coal filled with 0 MPa gas are higher than that of coal filled with 0.5 MPa gas. Under the same axial stress, strains are different, and strain values of coal filled

Table 1
Fitting value of coal sample in Guzhuang.

Load (MPa)	Burgers	Nishihara	Extensional Nishihara
4.5	0.7398	0.7306	0.7306
6.5	0.9590	0.9656	0.9656
9.5	0.8939	0.7491	0.7491
12.0	0.8519	0.7603	0.7603
16.0	0.9748	0.9748	0.9731

with 0 MPa gas are lower than that of coal filled with 0.5 MPa gas. This phenomenon shows gas will make intensity of coal decrease. The period of time to failure is not equal, and gas will accelerate creep process. Gas pressure and migration, such as gas adsorption, diffusion and flow within the coal, will intensify extension and penetration of internal fissures, which will affect creep behaviour of coal indirectly and make strain values of coal increase.

It can be seen from the creep curves of coal filled with 0 MPa gas that coal filled with 0 MPa gas transform into failure at the stress values of 19 MPa. And it can be seen from the creep curves of coal filled with 0.5 MPa gas that coal filled with 0.5 MPa gas transforms into failure at the stress values of 16 MPa. This phenomenon shows that gas can make coal creep accelerate and make coal transform into failure much easier.

3. Creep constitutive model comparisons of coal filled with gas

Scholars have done a lot of research on creep theoretical models of coal. The creep constitutive models most commonly used are the Burgers, Nishihara and Extensional Nishihara model [6–41]. For fitting the experimental data, the parameters in the three model need to be simplified and the simplified equation can be shown as follow.

Burgers model can be simplified as follow

$$\varepsilon = a\exp(-bt) + ct + d \tag{1}$$

Nishihara model can be simplified as follow

$$\begin{cases} \varepsilon = a\exp(-bt) + c \quad \sigma < \sigma_f \\ \varepsilon = a\exp(-bt) + ct + d \quad \sigma > \sigma_f \end{cases} \tag{2}$$

Extensional Nishihara model can be simplified as follow

$$\begin{cases} \varepsilon = a\exp(-bt) + c \quad \sigma < \sigma_f \\ \varepsilon = a\exp(-bt) + c[\exp(-dt) + \exp(dt)] + et + f \quad \sigma > \sigma_f \end{cases} \tag{3}$$

The above three models are used for fitting experimental data. Matlab software is used to calculate the fitting value of the experiment data in Fig. 4. The fitting value is shown in Table 1.

It can be seen from Table 1 that in the non accelerated creep stage, the fitting value of Burgers model is better than other models generally. And in the accelerated creep stage, the fitting values of Burgers model and Nishihara are better than Extensional Nishihara model. Thus, it can be known that Burgers model can effectively describe the creep phenomenon of coal samples.

The fitting curve of creep constitutive model of coal filled with gas can be seen in Fig. 5. From the fitting curve and the residual error curve, it can be known that the fitting curve of Burgers model is consistent with the experimental data in the deceleration creep stage. And Burgers model has an excellent fitting effect for the creep accelerated phenomenon of coal sample, and the residual error is very low.

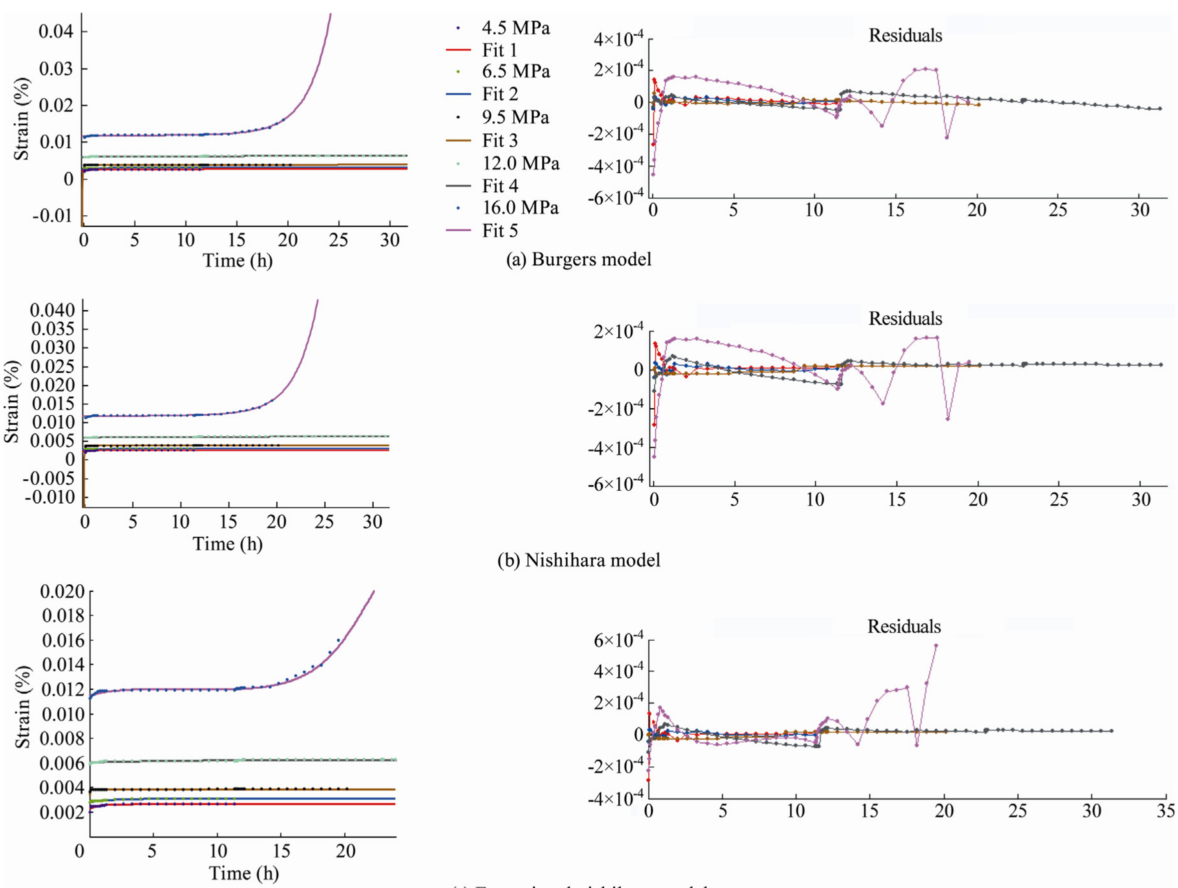

Fig. 5. The fitting result of Guzhuang coal sample.

Table 2
Fitting result comparison of coal sample in Guzhuang.

Load (MPa)	Burgers	Nishihara	Extensional Nishihara
4.5	√̲	√̲	√̲
6.5	√	√	√
9.5	√	√̲	√̲
12.0	√	√̲	√̲
16.0	√	√	√

When the fitting curve is not consistent with the experimental data according to the fitting degree and the curve prediction criterion, the model will directly be denied and is represented by "×". If the prediction trend of fitting curve is good and the fitting value is between 0.7 and 0.8, the model will be regarded as good and is represented by "√̲". If the prediction trend of fitting curve is good and the fitting value is above 0.8, the model will be regarded as very good and is represented by "√". According to the principle, the fitting result comparison of three constitutive model of coal filled with gas is done. The fitting result comparisons of the three model can be seen in Table 2.

The fitting result comparisons show that Burgers model, Nishihara model and Extensional Nishihara model have good fitting values. In the non accelerated creep stage, the fitting value of Burgers model is generally higher than the Nishihara model and Extensional Nishihara model. And in the accelerated creep stage, Burgers model also has the higher fitting value. The fitting result comparisons show that Burgers model can effectively describe the creep phenomenon of coal samples. Thus, the fitting result of Burgers models can be accepted. And the fitting value of Burgers model is slightly higher than that of Nishihara and Extensional Nishihara. Compared with Nishihara Model and Extensional Nishihara Model, Burgers Model can reflect the creep process of coal filled with gas better.

4. Conclusions

In the present study, the creep properties of coal filled with 0 MPa gas and coal filled with 0.5 MPa gas are studied. The results show that failure strength of coal filled with different amount of gas is different, failure strength values of coal filled with 0 MPa gas is higher than that of coal filled with 0.5 MPa gas. Under the same axial stress, strains are different, and strain values of coal filled with 0 MPa gas is lower than that of coal filled with 0.5 MPa gas. This phenomenon shows gas will make intensity of coal decrease. The period of time to failure is not equal, and gas will accelerate creep process. Gas pressure and migration, such as gas adsorption, diffusion and flow within the coal, will intensify extension and penetration of internal fissures, which will affect creep behaviour of coal indirectly and make strain values of coal increase. By using the test results, the Burgers, Nishihara and Extensional Nishihara model are used to explain the creep behaviour. Matlab software is used to fit experimental data. From the fitting results of the three model it can be known that Burgers Model can reflect the three stages of creep process of coal filled with gas better. Although the number of coal samples in this study is limited, the results show that more laboratory tests are needed to validate the laboratory results and creep constitutive model.

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