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Technical Note

Damage model of coal under creep and triaxial compression

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1. Introduction

With the gradual increase of depth in coal mines, deep tunnels in rocks are under high triaxial stress state, resulting in increased numbers of engineering disasters. Therefore, in order to ensure the stability and safety of deep underground rock engineering, it is necessary to investigate the mechanical behaviors of rocks under triaxial stress.[1] Since laboratory testing is a main method to study the mechanical behaviors of deep rocks, in the past several decades, extensive laboratory investigations[2,3] have been carried out on the mechanical behavior of all kinds of rocks under triaxial compression in order to predict the short and long-term deformation of deep rock masses.

Coal is a special kind of rock material. In the laboratory, the short-term strength, deformation and acoustic emission (AE) behaviors of coal have been extensively investigated. Medhurst and Brown[4] carried out a series of triaxial compression tests on coal specimens with diameters of 61, 101, 146 and 300 mm, to investigate the effects of scale on the strength and yield behavior of the coal specimens in accordance with the nonlinear Hoek–Brown criterion. Feng et al.[5] performed an experimental study on the deformation behavior of coal under thermo-mechanical coupling conditions, which indicated that the process of temperature-dependent deformation of coal could be divided into three stages: thermal dilatation with the temperature rising from room temperature to 200 °C, slow volume compression from 200 °C to 400 °C and serious volume compression from 400 °C to 600 °C. Li et al.[6] investigated the strength, deformation and AE behaviors of coal under confining pressure and pore water pressure and argued that the triaxial strength and residual strength of coal increased with the increase of confining pressure but reduced with the increase of pore water pressure. Xie et al.[7] analyzed the influence of different mining layouts on the mechanical behavior of coal, and their results indicated that the trend of the coal deformation decreased with the increase of the buried depth under the same mining layout, while the strength and deformation modulus increased, and the failure mechanism under three mining layouts was dominated by shear/tensile failure.

However, very few test results have been reported regarding the creep behavior of coal under uniaxial compression and conventional triaxial compression. Cao et al.[8] carried out experiments on outburst- hazardous coal under uniaxial compression creep to study the AE characteristics of coal at different creep stages. However, the creep time of coal was too short, being only four hours. Wang et al.[9] used a self-creep testing apparatus to carry out triaxial creep tests on outburst coal specimens from the Songzao coal mine, and found that the attenuation creep property was shown under the condition of less than its long-term strength load, and the non-attenuation creep property for greater stress conditions. Yin et al.[10] carried out triaxial creep experiments on coal containing gas under unloading conditions. The results showed that unloading could accelerate failure and the macro-fissures induced by unloading could increase the gas flow velocity significantly. Xu et al.[11] analyzed the influence of creep on the permeability of gas-bearing coal by means of experiments on coal seepage. The results showed that the influence of creep on coal permeability differ with different temperatures and effective stress coupling. Mohsen et al.[12] conducted a series of triaxial compression tests and found that CO_2 can significantly change the mechanical properties of coal. The experimental results showed that the elastic modulus of coal can decrease up to 19% when CO_2 is injected into coal specimens and the strength of coal can be reduced by 20%.

The above creep test results of coal offer a foundation for the construction of creep models of coal. In recent years, few advances

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on triaxial creep modeling of coal have been reported. Based on the triaxial creep test results of out burst prone coal, by introducing a visco-elasto-plastic body to describe the deformation property of non-Newtonian fluids, Wang et al.[9] proposed the visco-elasto-plastic creep model of out burst prone coal combined with a Poyting–Thomson model. On the basis of triaxial creep experimental data for coal containing gas, Yin et al.[10] modified the Chaboche viscoplasiticity constitutive relation, which describes the short-term creep failure of coal containing gas. However, since existing triaxial creep models do not take into account time scale effect and verify the predicted effect of the models with various differential stress levels, they cannot be used to predict the long-term creep deformation of coal. To date, triaxial creep models of coal materials have not been very mature, and triaxial creep modeling of coal is still one of the most difficult problems in rock rheological mechanics.

Therefore in this paper, we report the results of a series of short-term and creep experiments on coal under different confining pressures. The aims are (i) to put forward a new damage evolution equation of coal, ii) to construct a new short-term damage model for coal, and (iii) to propose a new nonlinear creep damage model for coal.

2. Damage evolution equation

2.1. Analysis of damage evolution process

Damage mechanics is a developing science, and there are various definitions of damage variable. For example, Xie and Chen[13] and Xie[14] demonstrated that damage results from the gradual weakening of material cohesion under monotonic or cyclic loading, leading to the failure of volume elements. The usual damage variable (D) can be expressed as follows[15]:

$$D = \mu \frac{A - A_e}{A} \tag{1}$$

where A is the total area of material interface, A_e is the effective area of material interface; μ is the influence coefficient related to the distribution of the defects, generally equal to one. $D=0$ corresponds to undamaged intact material, $D=1$ corresponds to materials with completely fractured volume elements in the normal plane, and therefore $0<D<1$ corresponds to materials with various extents of damage.

In accordance with the stress–axial strain curve of coal specimens under compressive loading, the compression deformation of coal can be divided into five stages (Fig. 1): (I) pore and fissure closure; (II) elastic deformation; (III) crack growth; (IV): post-peak softening; and (V) residual strength. In Fig. 1, σ_{cc}, σ_{ci} and σ_{cr} are respectively the critical threshold of coal at stages I, II and IV, and σ_{cf} is the peak strength of coal. In the past, the damage evolution process of coal at the stage of pore and fissure closure was often not taken into account and the damage evolution curve of coal under compression was regarded as approximately same as that under tension. However, due to the existence of many original fissures and pores in the coal specimen, the damage evolution process of coal at the stage of pore and fissure closure cannot be ignored.

Under compression loading, the open micro-fissures and pores inside the coal specimen gradually close, resulting in the increase of the effective force bearing area of the material. According to Eq. (1), damage variable D decreases with the increase of the strain at the stage of pore and fissure closure. It should be noted that due to the existence of open micro fissures and pores, the initial damage variable $D|_{\sigma=0}>0$. However, for some dense rock material (e.g. granite), it can be approximately regarded as $D|_{\sigma=0}=0$ due to there being no obvious stage of fissure and pore closure. However, at the stage of elastic deformation, the stress–axial strain curve of coal is approximately linear. Assuming the coal's loading modulus is equal to its elastic modulus, we find that the damage variable D equals zero according to Eq. (1). At this time, the original fissures and pores in the coal specimen have been compressed and new cracks are not initiated. After the stage of elastic deformation, the coal specimen enters the stages of crack evolution and post-peak softening, and the damage variable increases nonlinearly with the axial strain, which results mainly from the initiation, propagation and coalescence of new cracks in the coal specimen. When the coal specimen is loaded to the stage of residual strength and supports the axial capacity by friction. At this time, the damage variable reaches the maximum value, i.e. it equals 1.

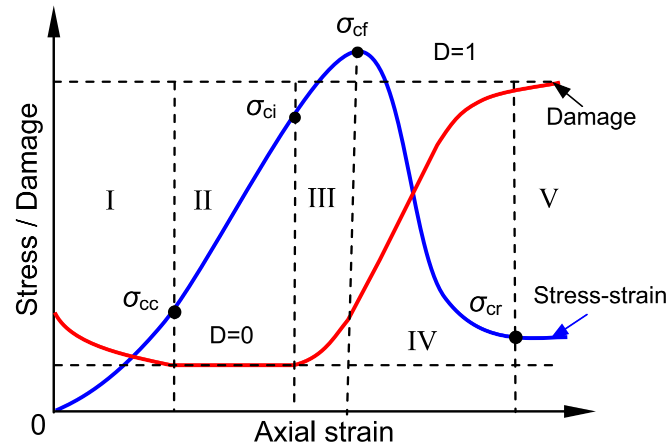

Fig. 1. Typical evolution characteristics of stress–axial strain and damage for coal under compression.

2.2. Construction of damage evolution equation

On the basis of many micro-flaws in the rock material, Xie[14] considered that the damage of the rock has two main causes: the propagation and coalescence of original micro-flaws; and the initiation of new microcracks due to nucleation along the crystal interfaces and the fracture of the crystal joint. Xie[14] suggested that the relation between the damage evolution of rock and energy dissipation can be expressed as follows.

$$D = 1 - \exp\left(-\alpha\left|U^d - U_0^d\right|^{\beta}\right) \tag{2}$$

where α and β are the parameters related to material properties; U^d is the dissipated energy causing rock damage; $U_0{}^d$ is the dissipated energy corresponding to the initial damage.

The absolute value function $|U^d - U_0{}^d|$ in Eq. (2) is to ensure that the exponential function is tenable. Because During the initial loading, $U^d < U_0{}^d \neq 0$, which does not satisfy the basic requirement that the base of the exponential function should be greater than zero. This means that the parameters α and β cannot be determined, and consequently, the numerical realization cannot be accomplished. Therefore, Tian et al.[16] simplified Eq. (2) to the following equation.

$$D = 1 - \exp[-\alpha(U^d)^{\beta}] \tag{3}$$

Therefore, the problem mentioned above can be solved. But the damage evolution equation shown in Eq. (3) has the same function form as the statistical damage evolution equation proposed by Li et al.[17,18] In the past, the established damage constitutive model could not well describe the brittle drop after the peak and the residual strength characteristics.