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Mesomechanics coal experiment and an elastic-brittle damage model based on texture features

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ABSTRACT

To accurately describe damage within coal, digital image processing technology was used to determine texture parameters and obtain quantitative information related to coal meso-cracks. The relationship between damage and mesoscopic information for coal under compression was then analysed. The shape and distribution of damage were comprehensively considered in a defined damage variable, which was based on the texture characteristic. An elastic-brittle damage model based on the mesostructure information of coal was established. As a result, the damage model can appropriately and reliably replicate the processes of initiation, expansion, cut-through and eventual destruction of microscopic damage to coal under compression. After comparison, it was proved that the predicted overall stress-strain response of the model was comparable to the experimental result.

1. Introduction

Coal is a type of brittle solid material, and its deformation and failure are closely related to the extension and evolution of internal mesoscopic damage. The study of the coupling mechanisms of cracking and stress through the analysis of a constitutive model that reflects the deformation and failure of coal has traditionally been a contentious issue. The solution to this problem is to study progressive deformation from the perspective of mesoscopic mechanics by combining the development of mesoscopic damage with the macro-fracture damage mechanics of coal.

Kassner et al. [1] indicated that a multi-scale mechanical model covering the macro- and meso-scales must be built to study the failure mechanism of rock material in depth. The closure law of cracks was studied by Batzle et al. [2], who observed rock specimens under uniaxial compression. Robina et al. [3] researched the effects of initial micro-cracks and rock grain size on the uniaxial compression strength of marble. Hatzor et al. [4] found that the initial cracking stress of rock was influenced by porosity as well as grain arrangement and structure. Using the result of triaxial compression tests of different grain sizes and an embedded dolomite structure, Wu et al. [5] analysed the anisotropic damage of sandstone under variable confining pressures with an optical microscope and scanning electron microscopy (SEM). They also studied the evolutionary process of anisotropic damage using the slip wing-tip model. Erarslan et al. [6] studied the relationship of fatigue damage and the fracture toughness of tuff by using electron microscope scanning image information. Zhu et al. [7] studied the damage process of marble by using microscope data; quantitative information for micro-crack geometric parameters were obtained from the SEM images, and the quantitative relationship between stress and inelastic strain caused by the micro-cracks was established. Yang et al. [8] developed the nonlinear constitutive equation by considering the nonlinear deformation properties of coal, introduced the idea of the compressive energy of gas in view of the compressible property, assumed that the damage variable has a power function relationship with porosity according to the continuous damage theory and mesoscopic damage theory, and deduced a new nonlinear damage constitutive model of coal containing gas by applying the thermodynamics energy conservation laws. Cao et al. [9] carried out coupled coal-gas mesomechanics experiments of the destruction process, obtained images and identified the damage evolution of cracks based on fractal theory. Nie et al. [10] observed the mesostructure and fracture process of the coal interior by using the computerized tomography (CT)

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scanning experimental system. Li et al. [11] investigated damage evolution in rockburst testing from two aspects, including fracture surface crack and fragment characteristics. Scanning electron microscopy was used to observe micro crack information on a fragment surface. Xue et al. [12] discussed the pore structure characteristics of tectonic coals based on SEM observations.

Constitutive models of the deformation and failure process of rock material have always been a fundamental, yet challenging, area of study in the field of rock mechanics, which scholars have intensively analysed for many years. Their efforts have led to impressive progress in the understanding of these processes. Generally speaking, there are two study methods of rock constitutive models that simulate the whole process of rock material deformation and failure; one uses statistics to simulate damage, and the other bases the process of rock deformation on microscopic evidence and the theory of the destruction of the localization zone. Tang et al., Cao et al., Xu et al., Deng et al., and Wang et al. have studied the strain-softening behaviour of rock by using the former method [13–19]. In contrast, Zhang et al. [20] built a constitutive model reflecting the strain-softening process of rock using the latter technique.

For underground mining, the study of the coupling mechanism of crack and stress fields using constitutive models that reflect the entire deformation and failure process of coal has been an important yet challenging issue. Previous studies have failed to reflect the complete process of coal deformation and failure due to the different mechanical properties of coal and rock. Limitations and deficiencies in the methods mentioned above also exist, which means that the methods used to research the physical properties of coal still need to be studied. Various distribution types of micro-unit strength have been introduced in the statistical damage simulation method, such as the two-parameter Weibull distribution, lognormal distribution, normal distribution, power function distribution and so on. These types of distribution are mostly theoretical hypotheses, and they do not fully correlate with the actual distribution types of micro-unit strength. As for the different deformation processes, there are some deficiencies in the constitutive model built on microscope-based information and the theory of the destruction of the localisation zone. It has been difficult to identify a unified function to reflect these processes; at the same time, there are many parameters in the models, and those parameters are difficult to calculate.

The above studies mostly focused on rock material. Less research has focused on a mesoscopic damage constitutive equation for coal. The damage parameters for coal (or rock) were obtained by measuring the mesostructure of coal by digital image processing. Neither of these methods are accurate because they do not comprehensively consider the shape information or distribution relationship of the mesostructure. Because there is a partially repeated sequence on the surface image of coal, which is a sequence that is not random at the mesoscopic scale, image texture features can be used to study the characteristics of the mesoscopic structure of coal. This process is valuable [21] to the description of image content.

To reduce the identified deficiencies in historical models, the research described in this paper was carried out using mesoscopic damage mechanics experiments on coal and shooting real-time mesoscopic images of the coal surface using a stereo microscope. Those images were quantified utilizing digital image processing technology, and the texture characteristics on the coal's surface were identified. The images texture features were innovatively introduced to describe the mesoscopic damage of coal and used to define the damage variable. Finally, a novel damage constitutive model using the defined damage variable was established, which accurately reflects the deformation and failure of coal.

2. Mesomechanics test

2.1. Testing scheme

Coal specimens used in the test were cored from the 8th coal seam of the Yuyang coal mine in Chongqing, Southwest China. The self-developed experimental device, named the "coupled solid-gas mesomechanics device with stereo microscope", was used. This device system is shown in Fig. 1a.

The experimental equipment and observation conditions required the use of 20 coal specimens 20 mm × 20 mm × 40 mm in size, as shown in Fig. 1b. The preparation and testing procedures followed those used in a previous publication by Cao et al. [9].

2.2. Experimental results

The stress-strain curves were similar for all samples. For simplicity's sake, only the No.5 sample would be analysed hereafter. Its stress-strain curve under uniaxial compression is shown in Fig. 2. Its uniaxial compressive strength is 7.13 MPa, and its elastic modulus is 5.1217×10^8 Pa.

The images of the specimen were shot with the stereo microscope during the loading process. It should be noted that 40 images were taken and that 15 min were required to obtain a single mesoscale image of the specimen's surface. To minimize the influence of the loading pause, only photos at an axial displacement of 0.30 mm, 0.40 mm, 0.50 mm, 0.55 mm and 0.60 mm, indicated in Fig. 2 as points *A-E*, respectively, were taken. The images for each of these points after integration are shown in Fig. 3.

3. Quantification of mesocracks

Before image processing, wear scars and impurities on the specimen surface were identified. These impurities are very clear at the meso-scale, as shown in Fig. 4, but they are obviously not cracks.

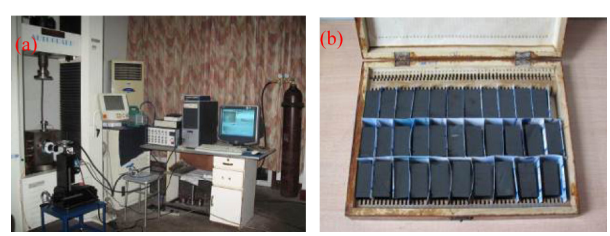

Fig. 1. The experimental device (a) and coal samples (b).

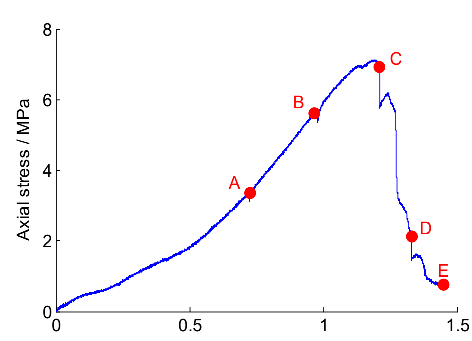

Fig. 2. The stress-strain curve.

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