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A gas-mechanical coupled constitutive equation for fractured coal containing gas

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ABSTRACT

A gas-mechanical coupled constitutive equation is developed for coal containing gas or CO_2 to predict the failure behavior based on fracture mechanics theory. A novel parameter of $|\partial \cos \alpha / \partial \Sigma_1|$ has been chosen as the failure characteristic parameter for coal containing gas. In addition, a closed-form gas-mechanical coupled constitutive equation is derived as $\sigma_1 = \sigma_3 + \sqrt{\frac{f}{\kappa + \frac{f \chi p}{\sigma_t}} \frac{\sigma_c}{\sigma_t} \sigma_c \sigma_3 + \sigma_c^2}$. The effects of the coal friction coefficient f, the gas pore pressure p, Biot's coefficient χ and the fracture parameter κ have been coupled in the proposed model. Without considering the effect of pore pressure, the equation wonderfully coincides with the original Hoek-Brown Empirical Strength Criterion. Sensitivity analysis indicates that under a determining confining pressure, the failure stress is an increasing function of f, in contrast, a decreasing function of p, κ and χ. Due to the low tensile strength of coal, the effects of different fracture parameter κ from different fracture criterions can nearly be ignored when the pore pressure p is high. At last, in order to further verify the gas-mechanical coupled model proposed in this study, the comparison between some laboratory data and theoretical values for coal containing gas have been carried out. It seems that the new model is in good agreement with the existing experimental data.

1. Introduction

Recently, coal has received renewed attention as a host porous media to adsorb CO_2 for greenhouse gas control. It is well known that the change of physical and mechanical properties of most coal depends on the confining pressure and pore gas pressure, especially for fractured coal. Confining pressure and gas pressure have opposite effects on coal properties in many cases. For example, both the failure strength and the elastic modulus of fractured coal increase with the confining pressure, but decrease with the pore gas pressure. The permeability and porosity of fractured coal, on the other hand, increase with the pore gas pressure but decrease with the confining stress respectively.

Most investigations have been focused on the limit strength of coal (Walton, 1958). Hoek and Brown (1980a, 1980b) proposed an empirical strength criterion for rock and rock masses. The nonlinear criterion includes the uniaxial compressive strength of the intact rock material and introduces two dimensionless parameters, m and s.

$$\sigma_1 = \sigma_3 + \sqrt{m \sigma_c \sigma_3 + s \sigma_c^2} \tag{1}$$

Hoek-Brown criterion is an empirical formula. m and s in Hoek-Brown criterion are hardness-softness and fragmentation degree of rock, respectively. Both m and s are empirical parameters. Kou et al. (1990) considered the effects of numerous microcracks on the mechanical behavior of structural coal and then derived a system of equations to describe the mechanical behavior of structural coal under loading. Some tests were carried out to study the effects of temperature and offset-notch location on fracture behavior of rock by an *in-situ* observation with Scanning Electron Microscope (SEM) (Zuo et al., 2010, 2014a and 2014b). Unfortunately, few investigations have been focused on the constitutive model for describing the whole deformation and failure process of fractured coal containing gas. Furthermore, most of the previous studies did not consider the effects of pore gas pressure.

From Terzaghi's effective stress theory, the constitutive model should consider the effects of pore gas and fluid pressure on the physical behavior and permeability of porous media. Li (1987) carried out some experiments to discuss the influence of pore gas

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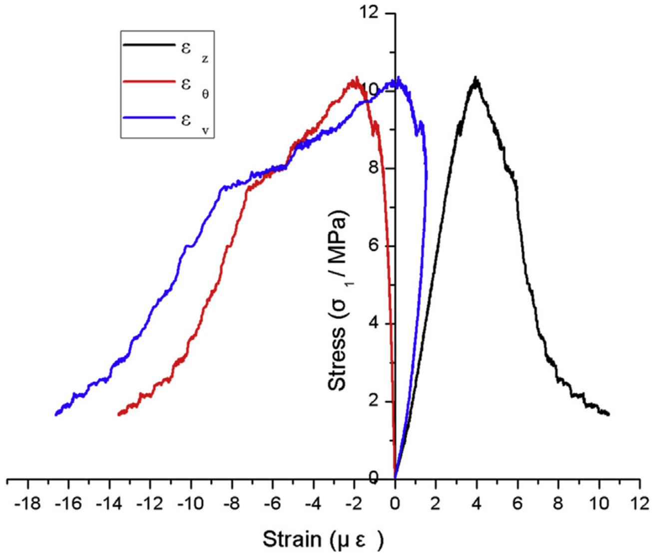

Fig. 1. The typical stress-strain curve of coal sample under uniaxial compression stress.

on the stress-strain curves of coal. Recent continued interests on the single and multiphase flow for fractured coal have been reported in numerous literature (Liu et al., 2011a, 2011b). Recently, carbon dioxide (CO_2) sequestration in deep coal seams has attracted more attention as a method of reducing the output of green house gases to the atmosphere (Saghafi et al., 2007, Chen et al., 2010). Therefore, it is very important to develop a rational constitutive model both for coal mining safety and CO_2 sequestration stability.

In the present work, the failure behaviors of fractured coal containing gas have been investigated in detail based on reported experimental data. Then a closed-form constitutive model has been developed to depict the failure criteria for fractured coal that considers the effects of gas. The proposed failure criterion of fractured coal containing gas generally includes three independent parameters which may be obtained by fitting the experimental stress-strain curves.

2. Typical failure characteristics and stress–strain relationship for fractured coal

The failure of coal specimens subjected to uniaxial or triaxial compressive stress have been studied in literature (Walton, 1958). A typical stress-strain curve of coal without gas is shown in Fig. 1. In this paper, the compressive stress and strain are defined as positive.

Rock brittle fracture under uniaxial compression can usually be viewed as a singular event, occurring after an essentially unrelated elastic deformation, and is characterized uniquely by the peak stress. Some literature also name the peak stress as the ultimate strength or fracture stress (Paterson and Wong, 2005). However, since there are a large number of microcracks and cleats distributing stochastically in coal sample, the whole failure process of coal has to be considered as a culmination of a progressive development of the critical microcracks and cleats. Fig. 1 clearly indicates that the stress-strain curve is approximately linear when the stress is below σp which is the proportion limit strength of coal. Therefore, the initial portion of the stress-strain curve is directly proportional to the strain ε which is known as Hooke's Law ($\sigma = E\varepsilon$). E is the modulus of elasticity, defined by the slope of the straight line portion of the stress-strain curve. With increasing load, the deformation becomes nonlinear elastic when the load reaches σe which is the elastic limit of the coal. Though the curve between σe and σp is nonlinear, the deformation is still recoverable once the external load is removed. This type of deformation involves stretching of the bonds between mineral particles or noncrystalline composition, but no slipping occurs between atoms. In this stage, there is no visible evidence of microcracks in coal. However when the load exceeds σe, many microcracks gradually appear. From Fig. 1, it can be seen that the stress-strain curve above σe is fluctuant which clearly indicates that numerous microcracks are induced by loading.

The peak stress of the coal can also be referred as the ultimate strength. It is well known that the ultimate strength of coal increases with the confining pressure. Brace and Byerlee (1967) showed that dilatant microcracks were strongly oriented parallel to the axis of maximum compression with increased confining

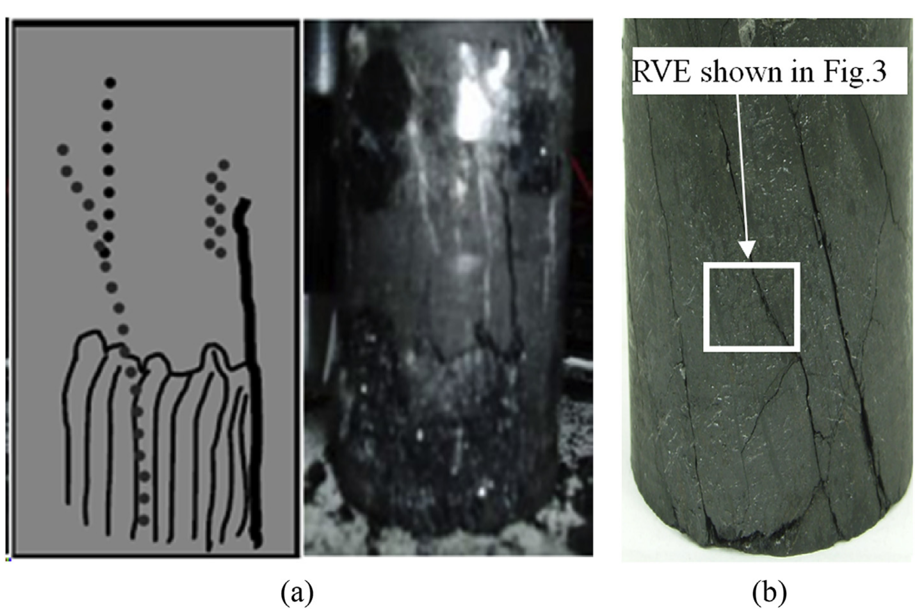

Fig. 2. Typical failure mode of coal sample.