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Effects of gas adsorption on mechanical properties and erosion mechanism of coal

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ABSTRACT

In order to study coal deformation and fractured mechanism under pore gas action, we chose gases N_2 and CH_4 as pore fluids, and carried out triaxial compression test of gas-bearing coal. To further explore the effects of gas erosion on coal deformation and failure, we tested the deformation and rapture process of coal during gas adsorption equilibrium under fixed axial load and confining pressure. The results showed that gas adsorption decreases coal's solid surface energy and lowers coal's compressive strength, leading to larger plastic deformation in coal and final rupture instability. From the physicochemical angle, we quantified the adsorbed gas erosion effects of coal based on both Griffith crack extension theory and Mohr–Columb strength criterion, explored the mechanical characteristics and erosion damage process of gas containing coals and put forwarded their mathematical models. These models can describe the experimental phenomena fairly.

1. Introduction

In order to solve the problems of mine gas disaster, explore coalbed methane resource and improve methane extraction efficiency, many researchers have carried out various theoretical and experimental studies on gas diffusion in coalbed (Vasyuchkov, 1985; Kuznetsov and Bobin, 1987; He and Nie, 2001), seepage flow (Yu et al., 1989; Wu et al., 1998; Bordier and Zimmer, 2000; Liu et al., 2003), and fluid–solid coupling (Tang et al., 2002; Yang et al., 2005; Liu et al., 2009; Pini et al., 2009; Jasinge et al., 2011). Among them, the deformation and mechanical response characteristics of gas-bearing coal are one of the key fluid–solid coupling problems of gas and coal. The occurrence form of gas adsorption in coal makes the mechanical properties of gas-bearing coal different from those of non-adsorption media (He and Nie, 2001). Thus, studies on the effect of gas adsorption on the mechanics properties of coal are of significance for revealing coal and gas coupling dynamic disasters mechanism so as to prevent and control these disasters.

Methane gas occurs in coal seams in free and adsorbed states (Gray, 1987; Harpalani and Chen, 1997; Pillalamarry et al., 2011). In studies on multi-or bi-phase medium, researchers have been applying the Terzaghi's effective stress principle or its related correction model to consider the interaction between pore fluid and solid skeleton. Although this principle can describe the pure mechanic interaction between pore fluid and solid skeleton, many modern physicochemical studies and experimental results have shown that there are more than mechanic interactions between them. Taking into account the gas adsorption swelling/desorption shrinkage and its erosion effects on coal mass (He, 1995), directly applying the effective stress theory of soil mechanics can not accurately describe the mechanism underlying the interaction between coal and gas. Some researchers (Harpalani and Chen, 1997; Gao et al., 1999; Zhou and Lin, 1999; Karacan, 2003, 2007; Liu et al., 2010) experimentally studied gas-adsorption induced swelling and found that coal would swell and deform after gas adsorption. Li et al. (2007) theoretically analyzed the relationship between swelling stress and effective stress induced by gas adsorption on coal. Some researchers (Jin et al., 1991; Liang et al., 1995; He et al., 1996) experimentally studied the effects of adsorbed gas on the mechanic properties of coal and found that after gas adsorption, both elastic modulus and coal strength are reduced. Jiang et al. (2007) utilized the mixture theory-based constitutive modeling approach to study the effects of both free and adsorbed gases on coal deformation. Previous research showed that the effect of gas adsorption on coal deformation involves two aspects: the

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mechanic effect and the non-mechanic effect (erosion). The former indicates that lowered effective stress is directly caused by the pore pressure and adsorption swelling stress and the latter indicates that decreased coal intensity is due to gas-adsorption from reduced solid surface energy. Therefore, in the study of both effective stress and mechanical properties of gas-bearing coal, it is necessary to consider the effects of both mechanic and non-mechanic actions of adsorbed gas on the mechanic properties of coal.

Additionally, to study the characteristics of coal's dual pore structure (Engler, 2000; Clarkson and Bustin, 2011; Liu et al., 2011), many researchers adopted the dual pore model to characterize the features of coal/rock mass (Warren and Root, 1963; Luo, 1998; Manik et al., 2002; Wu et al., 2010; Thararoop, 2010). Gas adsorbed on coal is mainly concentrated in micropores of coal, while gas in macropores and fractures resides in its free state. Gas in pores (mainly the adsorbed gas that produces pore pressure and adsorption induced expansion stress) and gas in fractures (mainly the free gas that only produce pore pressure) play different roles in the deformation mechanism of coal. The pore pressure induced by free gas is the volumetric force, thus, only its mechanic action is considered. Besides that, gas adsorption/desorption also exert the non-mechanical effect on coal (Jin et al., 1991; Liang et al., 1995; He et al., 1996). For studies on deformation of gas-bearing coal, considering both the dual pore structure of coal and clearly distinguishing pore deformation from fracture deformation are more fitting to the real mechanical response of gas-bearing coal.

Based on above, we performed both the loaded gas-bearing coal deformation and failure experiment and the adsorption induced swelling deformation and failure experiment, investigated the mechanical properties of coal samples in different adsorptive gases (nitrogen and methane) under different pressures. The results revealed the mechanism of interaction between gas and coal, thus are of significance for further understanding the mechanical deformation and failure characteristics of gas-bearing coal.

2. Gas-bearing coal/rock mechanical properties testing system and samples

2.1. Gas-bearing coal/rock mechanical properties testing system

Dual pore structure of coal and adsorption properties of gas make gas-bearing coal obviously different from the gas (or liquid) containing soil media or rock in mechanical properties. To more in-depth understand the mechanical properties of gas-bearing coal, two types of experiments, the loaded gas-bearing coal deformation and failure experiment and the adsorption-induced swelling deformation and failure experiment, were performed using a self-developed experiment system.

As shown in Fig. 1, the system is mainly composed of the loading system, the load displacement recording system, the parameters collection system, and the vacuum pumps and piping, etc. The test system of gas-bearing coal mechanic characteristics is capable of accurately controlling gas species, gas pressure, loading rate, and boundary conditions in the experimental process, real-timely acquiring the stress, displacement, and other experimental data in the process of coal sample deformation and failure, and providing the experimental support for the analysis of the deformation and failure process mechanic characteristics, and influencing factors of gas-bearing coal.

The process of the first experiment is described as follows. 1) According to the international society for rock mechanics (ISRM) standards, collect large lump coal masses from the underground mine with the body core tubes, process them into cylinders with 50 mm diameter and 100 mm length, and polish at both ends with an error of 0.02 mm; 2) Put the coal sample into the air tight cavity and check up the gas tightness, vacuum pump for 12 h; 3) Turn off the vacuum pump, open the gas cylinder valve, adjust the gas pressure and let adsorption for 12 h until reaching adsorption equilibrium; and 4) Continuously load onto the coal sample at the loading rate of 0.5 mm/min until its failure.

2.2. Samples and their preparation

In the experiment, two kinds of different coal samples were selected from two mines, the Daanshan (DAS) and the Sijiazhuang (SJZ) coal mines. To reduce the effect of the spatial distribution variability of cracks on the experimental results and increase the comparability, the briquettes were used first. In detail, the coal samples were crushed and filtered with a 40-mesh sieve to obtain coal grains with particle size less than or equal to 40 mesh. Then the filtered coal particles were modeled under high pressure into standard briquettes that bear 250 kN load and maintain pressure for 6 h Fig. 2 shows the standard briquettes prepared using samples from DAS and SJZ coal mines. During the experiment, the briquettes were processed into 50 mm × 100 mm standard samples which meet the standards of the International Society of Rock Mechanics.

3. Experimental contents and programs

3.1. Experimental contents

Gas adsorbility and pressure, coal pore structure, confining pressure and loading ways, etc., all affect the mechanical properties and damage process of coal. The aim of the experiment was to study the deformation and failure process of gas-bearing coal subject to stress through the following two experiments. Experiment 1 examined the effects of gas adsorbility and pressure on the mechanic characteristics of coal by measuring the stress–strain curve of gas-bearing coal during deformation and failure after reaching adsorption equilibrium under different pressures of different adsorptive gases; Experiment 2 was designed to simulate the effect of methane gas flow in coalbeds under coal mining that causes the accumulation or diffusion of methane gas on the mechanic properties of coal. It studied the adsorption-induced swelling deformation and failure and was performed on the basis of the above experiment to confirm the erosive action of adsorptive gas and test its effect on coal's deformation and failure process by measuring the deformation and failure process under the fixed axial pressure and effective confining pressure during adsorption equilibrium of methane gas.

3.2. Experimental procedures

3.2.1. The procedure of experiment 1

The experiment is the basic experiment testing the mechanic characteristics of coal/rock. The prepared 50 mm × 100 mm coal sample was first encapsulated with heat-shrinkable tube and put into the hermetically sealed cylinder tank to ensure that the pressure head of the tank was face to face contacted with the terminal face of the coal sample, as shown in Fig. 3. During the experiment, the effective confining pressure remained invariant (1.5 MPa) and the pressure of methane gas was set as 0 MPa, 0.75 MPa and 1.5 MPa, respectively. Table 1 lists 4 specific experimental parameters.

3.2.2. The procedure of experiment 2

In this experiment, the effective confining pressure was maintained at 1.5 MPa; the axial load was kept at 90% of the axial limit load on the gas-unbearing coal (the result of Experiment 1) and the axial stress was kept invariant. The corresponding methane gas was