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Mechanical behavior and failure mechanism of pre-cracked specimen under uniaxial compression

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A R T I C L E I N F O

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A B S T R A C T

As a desirable permeability enhancement method, hydraulic slotting has been widely used for enhanced coal bed methane (ECBM) recovery in China. Aiming at the problem that the action mechanism of the slot on the mechanical properties of the slotted coal is still unclear, this paper investigates the effects of flaw inclination on the strength, deformation and cracking process of the pre-cracked specimens. The result shows that the stress-strain curves can be divided into three categories based on the stress behaviors, dropping step by step or dropping sharply, after the peak. With an increase of the flaw inclination, the strength and elastic modulus of the pre-cracked specimen increases gradually, which is verified by the numerical simulation and theoretical results. Analysis of the cracking processes indicates that the initiation position of the first crack in specimens with various flaw inclinations is different, which is caused by the various distributions of tensile and compressive stress concentration zones. The distribution of the stress field controls the cracking process which will in turn affect the stress field distribution. With the propagation of the cracks, the tensile stress concentration zones expand and the concentration degree lowers gradually, while the compressive stress concentration zones show the opposite variation trend. Based on the above results, an optimized slot arrangement method has been proposed for the field application of hydraulic slotting.

1. Introduction

Gas drainage, a basic method for gas disaster control, contains ground well gas drainage and underground borehole gas drainage (Xue et al., 2017). In 2014, the total coal bed methane (CBM) extracted in China is 17,000 Mm^3, and that extracted from the underground is 13,300 Mm^3, accounting for 78.2% of the total, implying that underground gas drainage is still the main method for gas control in China. Besides, the utilization amount of CBM extracted from the underground is 4500 Mm^3, the utilization rate is only 34%. The reason is that the permeability of most coal seams in China is in the range of 10^{-19}–10^{-18} m^2, which is three orders lower than that in Austria and four orders lower than that in America (Zhou et al., 2016; Meng et al., 2015). Such a low permeability of the coal seam prevents the gas from flowing to the borehole, lowering the concentration of the CBM extracted. Generally, gas with the concentration <20% cannot be used directly and will be discharged into the atmosphere, leading to the greenhouse effect (Li et al., 2015; Warmuzinsli, 2008; Bibler et al., 1998). Therefore, to improve the gas utilization rate, CBM with a higher concentration should be extracted, which requires larger coal seam permeability (Zhang and Li, 2017).

Exploitation of the protective coal seam has proven to be the most effective method for stress relief and permeability enhancement in coal seam group (Liu et al., 2016b; Kong et al., 2014). However, more commonly, the coal seam exists in the form of single coal seam, a protective coal seam cannot be found. In addition, with an increase of the mining depth, the initial coal seam gradually turns into coal and gas outburst seam. To solve the problem, that is the outburst elimination of the single and the initial coal seams, hydraulic slotting has been developed and applied (Liu et al., 2016a, 2016b; Lin et al., 2012).

In the past decades, much research on the hydraulic slotting technique has been conducted and some meaningful results have been achieved. Lin et al. (2015) investigated the cracking modes and the corresponding energy evolution rules in slotting disturbed zones under different stress conditions. The research result contributed to the borehole arrangement in the field. Lin and Shen (2015) studied the coal-permeability enhancement mechanism of multilevel slotting by high-pressure waterjet. The result indicated that with slot number increases from 0 to 3, the coal strength decreases about 40%; and the porosity near the flaw increases about 30%, which was indirectly verified by the field application. Aiming at the problem of hole collapse in the soft coal seam, Lu et al. (2010) proposed a technique of drilling holes by waterjet in the

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roof/floor until the soft coal seam was reached. This technique was reported to be able to improve the drilling length and gas flow significantly. Lu et al. (2009, 2011) used the hydraulic slotting to release the energy stored in the soft and high gassy coal seam so as to improve the gas drainage efficiency and eliminate the outburst risk, which in turn increased the roadway driving speed. Liu et al. (2016b) investigated the pore structure and the resulting adsorption and seepage capacities variations of coal in the slotting disturbed zone. Based on the results, a microscopic model on permeability enhancement and outburst elimination was developed. Based on the framework of coal-methane co-exploitation, Zou et al. (2015) proposed an integrated technique, a combination of drilling-slotting-separation- sealing, to enhance coal permeability and CBM recovery. The field test result indicated that the gas concentration in the slotted borehole was 1.05–1.91 times higher than that in the traditional borehole, implying the effectiveness of the technique.

The review about the hydraulic slotting indicates that the research to date has tended to focus on the adsorption and seepage characterizations, cracking modes of the slotting disturbed zone and the application effect in the field. Research about the effects of the spatial arrangement of the slot, especially the flaw inclination, on the mechanical properties and its guiding significance to the field application of hydraulic slotting is rarely reported.

In this work, we investigated the effect of flaw inclination on the mechanical properties, especially the strength, deformation and cracking processes of the pre-cracked coal specimens by laboratory test and numerical simulation. In addition, the stress filed around the flaw was also studied to explore the action mechanism of the flaw on the mechanical characteristics of the coal. At last, based on the research result, an optimized slot arrangement was proposed for the field application of hydraulic slotting.

2. Research methods

In order to investigate the mechanical properties and cracking process of specimens containing combined flaws with various inclinations, the uniaxial compression tests were conducted in the laboratory combining with the acoustic emission detection. In addition, the numerical simulation was also adopted to further explore the corresponding mechanical mechanism and verify the rationality of the experimental results.

2.1. Laboratory test

2.1.1. Test material

The specimens used in the laboratory tests are artificial coal samples with the size of 120 mm × 60 mm × 30 mm (Fig. 1) and an average porosity of 4.3%. The mix proportion of the synthetic coal sample is coal: cement: binder: water = 108:27:9:20. The samples were pressed under a constant pressure of 40 MPa for 30 min and then transferred to the thermostat with a constant temperature of 25 °C for 30 days. After consolidation, a combined flaw was drilled at the center of the specimen. The circular hole is 6 mm in diameter, and the rectangular flaw is 20 mm long and 2 mm wide. Notice that the surfaces of the specimens were painted white to get a better observation of the crack initiation, propagation and coalescence processes.

2.1.2. Test methods and apparatus

Uniaxial compression tests were conducted on the pre-cracked specimens to obtain the mechanical properties. In the tests, the loading rate was set as 0.1 mm/min, the stress-strain curve, UCS (Uniaxial Compressive Strength) and E (Elastic modulus) of each specimen were monitored. The loading processes were recorded by a digital camera to observe the crack initiation, propagation and coalescence in the specimens. In addition, the intensity characteristics of AE (acoustic emission) during the cracking process of each specimen were also monitored using an AE detector. Notice that each test was conducted for three times to reduce the experimental error caused by sample variability.

2.2. Numerical simulation

2.2.1. Fundamentals of PFC^{2D}

In PFC^{2D} (Particle Flow Code in two dimensions), two kinds of particle bond models (PBM) are embedded, namely contact bond model (CBM) and parallel bond model (PBM) (Cho et al., 2007; Yoon, 2007). The PBM can transmit both force and moment between particles, while the CBM can only transmit the force acting at the contact point (Itasca, 2002; Lisjak and Grasselli, 2014). For the CBM, a marked reduction of the macro-stiffness will not be observed after the breakage of the bond as long as the particles still remain in contact. While for the PBM, the breakage of the bond will result in an immediate decrease of the macro-stiffness because the stiffness consists of both contact and bond stiffness (Liu et al., 2016a; Lee and Jeon, 2011). This property implies that the PBM is more realistic for rock-like material modeling. Therefore, the PBM is adopted in the current work to model the coal specimens.

2.2.2. Calibration of mesoscopic parameters

To generate a parallel-bond model, a set of mesoscopic parameters should be determined. The model generated with the specified parameter set should reproduce the macro mechanical properties of the coal samples obtained in the laboratory (Wang et al., 2014). Here the stress-strain curve, UCS, E and the failure mode (macroscopic rupture plane) obtained from our laboratory tests were selected as the target variables and the ultimate goal of calibration is to minimize the gap between the variables. In the current work, a series of calibration schemes were conducted and the comparation between the final calibration results and laboratory test results has been depicted in Fig. 2. It can be seen that the shapes of the stress-strain curves are similar, even though a notable difference was observed in peak strains (with an error of −

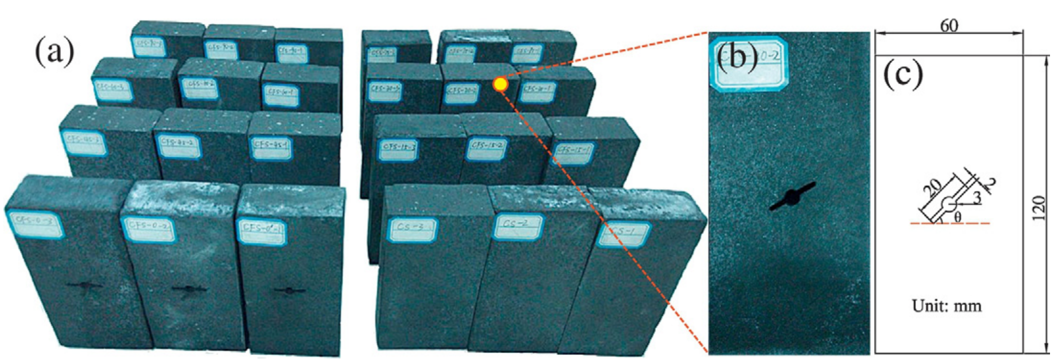

Fig. 1. Coal samples used in the laboratory test. (a) physical map of coal samples with different flaw inclinations; (b) physical map of coal sample with a flaw inclination of 30°; (c) sketch map of coal sample.