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Relationship between macro-fracture density, P-wave velocity, and permeability of coal

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ABSTRACT

This study was undertaken to determine the quantitative relationship between macro-fracture density, P-wave velocity, porosity and permeability of different coal rank samples from mining areas in North China. The coal sample permeability shows an exponential growth with increasing fracture density. The relation between P-wave velocity and porosity is power function and P-wave velocity decreases with the increasing porosity. P-wave velocity linearly or nonlinearly decreases with the increase of fracture density in the selected coal samples (0.73–3.59% *Ro*). However, the overall trend is that P-wave velocity decreases with an increase in macro-fracture density. The permeability of coal samples linearly decreases with the increase of P-wave velocity. The quantitative relationship between P-wave velocity and permeability could provide reference for the further study of permeability predicting.

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1. Introduction

One of the key factors for the development of coalbed methane is the permeability of the coal reservoir, which directly determines the gas production rate. A number of factors can affect the permeability of a coal reservoir, including porosity (Liu et al., 2009; Yao et al., 2009), fracture density (Laubach et al., 1998; Karacan and Okandan, 2000; Pan et al., 2014), fracture aperture (Laubach et al., 1998; Karacan and Okandan, 2000) and orientation (Laubach et al., 1998; Karacan and Okandan, 2000; Paul and Chatterjee, 2011), mineral filling of fractures (Karacan and Okandan, 2000), tectonic stress (Chatterjee and Pal, 2010; Meng et al., 2011; Paul and Chatterjee, 2011), and other internal as well as external factors. Permeability variations within coal reservoirs, in turn, result in different acoustic wave characteristics.

The acoustic velocity characteristics of a rock formation contains a great deal of information related to rock properties, and damage-free analyses of rock mechanics using information carried by elastic waves are increasingly used in geological engineering (Khalil and Hanafy, 2008; Kassab and Weller, 2011; Donohue et al., 2013; Cardarelli et al., 2014). There are a number of factors influencing the acoustic velocity of a rock formation, which can roughly be divided into external and internal factors (Turk and Dearman, 1987). External factors mainly include porewater, water content, compressive and confining pressure, temperature and pore fluid properties, internal factors mainly include rock type, grain size, density and porosity (Turk and Dearman, 1987). In addition, joint development in a rock formation, including the number and trend of joints, influence the acoustic velocity (Boadu, 1997; Leucci and Giorgi, 2006; Nara et al., 2011). At present, research on acoustic velocity is mostly focused on the relationship between acoustic velocity and density (Ramachandran, 1992; Ravat et al., 1999; Louis et al., 2008; Khandelwal and Singh, 2009; Antonangeli et al., 2012; Rabbel et al., 2013), lithotype (Gaviglio, 1989), porosity (Popp and Kern, 1998; Brown et al., 2009; Wang et al., 2009; Kassab and Weller, 2011; Uyanik, 2011; Abraham et al., 2012; Jeanne et al., 2012; Maalej et al., 2013), permeability (Popp and Kern, 1998, 2000), temperature (Hampton, 1967; Krzesińska, 2000; Punturo et al., 2005), stress (Gardner et al., 1974; Punturo et al., 2005; Yang et al., 2014), the degree of water saturation (Ghorbani et al., 2009), and rock mechanic parameters (Yasar and Erdogan, 2004; Goueygou et al., 2009). Coal, as a rock with a complex component composition, is characterized by strong acoustic anisotropy. Coal rank, lithotype, carbon content, ash content, density, and physical and mechanical properties will affect the acoustic velocity of coal. Current research on the acoustic velocity of coal is mainly focused on the relationship between acoustic velocity and density (Peng et al., 2004; Meng et al., 2006; Wang et al., 2012) as well as coal's physical and mechanical properties (Meng et al., 2006; Pan et al., 2013), while studies examining the quantitative relationship between acoustic velocity and fracture density are lacking. The few existing studies on the relationship between acoustic velocity and fracture density (Boadu, 1997; Leucci and Giorgi, 2006; Nara et al., 2011) are mainly qualitative

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in nature or, if quantitative, were conducted using artificial fractures, which have led to results quite different from what would be expected from fracture formation under natural conditions.

For this study, four different ranks of coal samples were selected, including one high volatile bituminous coal sample, one low volatile bituminous coal sample and two anthracite coal samples. Macro-fracture density and the maximum reflectivity of vitrinite were measured, and porosity, permeability, and P-wave velocity tests were conducted. In order to provide a basis for predicting permeability in coalbed methane development areas, a qualitative and quantitative relationship between macro-fracture density, P-wave velocity, and permeability was established, with a special focus on the quantitative relationship between permeability and P-wave velocity.

2. Sample preparation and tests

Four groups of coal samples were collected from Wannian (WNK) and Xuecun colliery (XCK) in Fengfeng mining area, Hebei Province, the Gengcun colliery (GCK) in Yima mining area, Henan Province and Jincheng mining area (JC) in Shanxi Province. All samples are primary textured coal. The collected coal samples were processed and a series of experiments was conducted to obtain the required data. Specific sample preparation steps and analytical procedures are described below.

2.1. Sample preparation

Sample preparation was conducted according to the recommendations of the International Society for Rock Mechanics (ISRM). Coal samples were drilled according to the presence of vertical discontinuities and the end of each core was polished. Samples were cut into cylindrical specimens, as shown in Fig. 1. The maximum reflectance of vitrinite ($R_{O,max}$, %) measurement comply with China national standards GB/T 6948-2008 (method of determining microscopically the reflectance of vitrinite in coal). Sample information is summarized in Table 1.

2.2. Fracture density measurements

Fracture density reflects the degree of fracture development. We used a ruler to measure the length of each macro-fracture developed in the end faces and sides of each core and calculated the total length of the fractures. The area in which a fracture developed consists of the two end faces and the sides of each core. Average fracture density is the total length of fractures developed in an area divided by the area which fractures developed, was used to represent the degree of macro-fracture development. Data are summarized in Table 2.

2.3. P-wave velocity tests

P-wave velocity tests were conducted using an UTA-2000A ultrasonic analyser (Fig. 2). The sensor frequency was 35 kHz, sampling frequency was 10 MHz, with a timing precision of 0.1 μm. Butter was used to couple the sensor and the sample. Sample length L divided by the time it took for a P-wave to pass through the sample is the P-wave velocity. The coal core faces were labelled along their edges with 0, 1, 2, 3, and 4 in a counter-clockwise direction. The corresponding positions at the opposite end were marked 0′, 1′, 2′, 3′, and 4′ (Fig. 3). The average value of P-wave velocities from these five groups of position was used as the sample's P-wave velocity. P-wave velocities of the tested samples are shown in Table 2.

2.4. Porosity and permeability measurements

Helium porosity and air permeability were measured using routine coal analysis in Langfang Branch of Research Institute of Petroleum Exploration and Development, following the Chinese Oil and Gas Industry Standard (SY/T)5336-1996. The porosity measurement was conducted using a helium porosimeter (Ultrapore-200A) and the permeability measurement was conducted using a permeameter (ULTRA-PERMTM200). The measurements run up to a pressure of 1025 kPa, temperature of 23 °C and humidity of 50%. The test results are shown in Table 2.

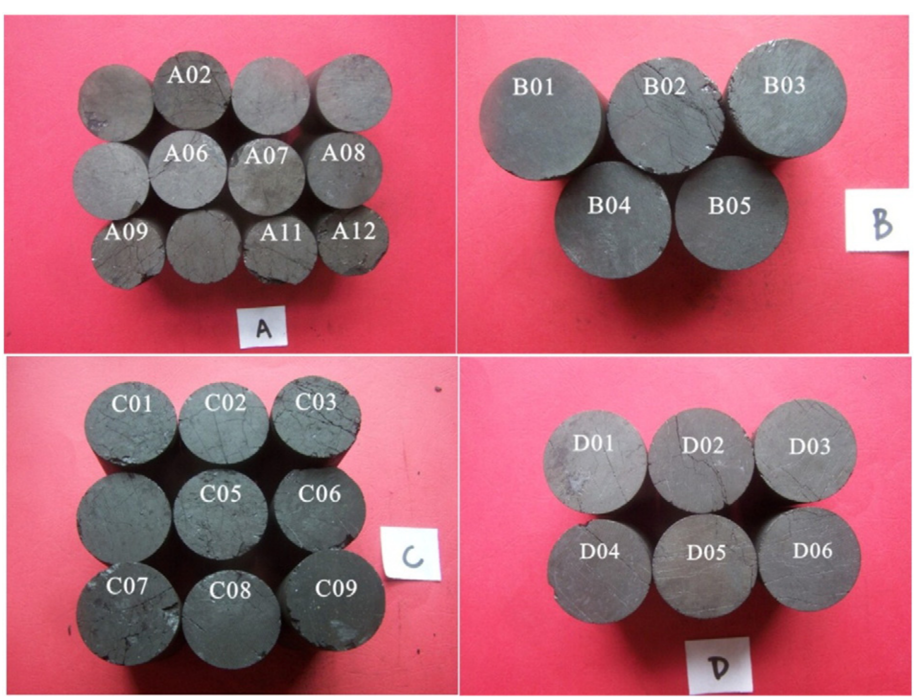

Fig. 1. Samples used in this study.

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