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Experimental study on ultrasonic velocity and anisotropy of tectonically deformed coal

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ABSTRACT

Tectonically deformed coal (TDC) is defined as coal formed by various tectonic stresses. As one of the key concerns in the formation and recovery of coal bed methane (CBM) from the tectonic deformation coal seams, the texture and fractures of TDC present various features in different deformation environments and as a result the physical properties change. Therefore, the identification of TDC is significant and can be obtained from the physical properties. In this study, fourteen representative TDC and two undeformed coal samples from the Suzhou mining area in the east of north China plate were collected to investigate the geophysical recognition parameters of TDC by elastic properties, such as the velocities (P and S-waves), elastic parameters (V_p/V_s and Poisson's ratio) and velocity anisotropies. The results show that the elastic properties of undeformed coal and TDC samples from different deformation environments exhibit significant difference. Normally, the velocities and elastic parameters of undeformed coal have the highest values, while the velocity anisotropy has the lowest value. In brittle deformation environment, the velocity and elastic parameters decrease while the velocity anisotropy ascends with increased deformation extent. For the TDC samples from shear deformation environment, the velocity anisotropies present the significant high values among the selected TDC samples. In plastic deformation environment, the elastic parameters gradually decrease with the deformation extent ascending, while the velocity anisotropies are relatively high. Among the elastic properties, the V_p/V_s, Poisson's ratio and velocity anisotropy are sensitive to deformation type and extent of coal samples. Furthermore, the development characteristics of coal structural fractures have a significant impact on the elastic properties of measured coal samples from different deformation environments. In summary, the results may provide reference parameters for future studies in CBM rock physics from the tectonic deformation coal seams.

1. Introduction

As one porous medium which is sensitive to stress (Li and Ogawa, 2001; Cao et al., 2003; Green et al., 2011), coal can be damaged in different deformation environment and under various tectonic stress, resulting in different properties, such as mechanical characteristic, physical structure, and optical properties, from ordinary coals (Jiang and Ju, 2004; Qu et al., 2010; Li et al., 2011). These coals belong to tectonically deformed coal (TDC). According to some latest researches, the TDC distribution is one of the major concerns in the behaviors of gas outburst (Jiang et al., 2010; Qu et al., 2010; Pan and Luke, 2011). In China, TDCs are widely distributed with different deformation extents. Most TDCs exhibit brittle deformation, which is beneficial for coal bed methane (CBM) exploration (Jiang et al., 2010; Zhou, 2012). Therefore, identification of TDC distribution becomes one challenge in the seismic exploration of coalfields and is significant during CBM production and mining safety.

Various methods have been adopted for the prediction of TDC distribution in Coal Mine, including high stress areas monitoring, geophysical characteristics corresponding to the structural differences (Chen et al., 2015; Dou et al., 2012; Teng et al., 2015). For example, based on the difference between undeformed coal and TDC, the geophysical logging-based evaluation method is applied to the analyses of coal textures in the Zhengzhuang field of the southern Qinshui basin. The results show that undeformed coals are easily distinguished from TDCs (Teng et al., 2015). Though these methods are all useful, they are insufficient to predict the TDC distribution for lacking of the petrophysical foundation, such as the elastic velocities which have positive correlation with rock fabric (Mavko et al., 1995; Smeraglia et al., 2014). And the elastic velocities can be useful in the prediction of TDC

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distribution.

Currently, the elastic and mechanical parameters of coal, such as ultrasonic wave velocity, dynamic elastic parameter characteristics and their correlation with velocity, have been tested to study the density and development direction of cracks (Morcote et al., 2010; Dong et al., 2016; Wu et al., 2015) and the rock physics has become a focus of recent research (Wang, 2001; Mavko et al., 2009). However, among past studies involving dynamic tests of coal, most of these experiments focus on the elastic parameter characteristics of the undeformed coal (Dong et al., 2016; Wu et al., 2015). Few investigations were achieved on the elastic characteristics of TDC. As the textural structures of TDCs are highly heterogeneous and the strength of coal body exhibit significant differences due to the various characteristics of fractures. The complete TDC samples will be damaged under a larger pressure. Therefore, the TDCs are difficult to be processed into samples meeting the test requirements with machines. This led to the limited research on the elastic characteristics of TDC (Wang et al., 2014).

In this paper, the abrasive papers is used to carefully and slightly process the TDC samples into cylindrical samples and the secondary damage is avoided as much as possible. The study on the velocities, velocity anisotropies and elastic parameters of different TDCs is conducted using ultrasonic testing equipment under laboratory conditions. In addition, the influence factors of elastic properties are discussed based on the deformation features and basis test results of selected coal samples.

2. Study panel

2.1. General geology

Huaibei coalfield is located in the southeast margin of north China plate. The Xuzhou-Suxian arcuate double thrust-imbricate fan thrust fault system in Yanshanian (Jiang et al., 2010), which consisting of linear compactly closed folds and the thrust-imbricate fan faults, are the main structural features of Huaibei coalfield (Fig. 1). The strata involved in this nappe structure include Qingbaikou system and Sinian, Cambrian, Ordovician, Carboniferous and Permian, and lower Triassic. The axial lines of the folds and the distribution of faults horizontally exhibit shapes of arcs. Under the influence of regional tectonism, the structure of Huaibei area can be divided into north and south tectonic blocks by the north Suzhou fault. The south tectonic block, located between north Suzhou fault and Banqiao fault, can be divided into east and west tectonic zones by NW directed Xisipo fault. The east tectonic zone lies at the east part of Xisipo thrust fault and it is the front zone of the overlying thrust nappe structure. At the flanks of the east Suzhou syncline, coal seams experience strong compressional deformation, which led to extensive development of tectonically deformed coal. In particular, the coal body exhibited soft and granulates, the texture of coal is severely destroyed under the action of rheomorphism, including the cleats and fractures. The west tectonic zone locates at the west part of Xisipo thrust fault and it belongs to the underlying thrust nappe structure. The structural features of this zone are mainly brachy folds with near NS direction and faults with near EW trend. Furthermore, the tectonic deformation in south Suzhou syncline relatively fall off compared with that in east Suzhou syncline (Jiang et al., 2010).

Strata in the Huaibei coalfield consists of upper Proterozoic, Sinian, Cambrian, Ordovician, Carboniferous and Permian, Triassic, Jurassic and Cretaceous, Paleogene, Neogene and Quaternary. Among the strata, Shanxi Formation of the lower Permian and lower Shihezi Formation of the middle Permian are major coal-bearing strata. The main mineable coal seams of the Suzhou mining area are No 8 coal seam of lower Shihezi Formation and No 10 coal seam of Shanxi Formation as shown in Fig. 2.

2.2. Classification of TDC

Close attention has been paid to the TDC by many workers, resulting in various classification scheme of TDC by using different research perspective. These classification indexes mainly include the texture characteristic of coal body, the deformation environment and structure characteristic of coal body (Jiang and Ju, 2004), the deformation characteristic and strength of coal body (Qu et al., 2010), the deformation mechanism and structure evolution of coal body (Li et al., 2011). Among these classification indexes, the deformation environment and structure evolution are adopted in this paper for that these indexes reveal the cause and the evolution characteristics of TDC.

During the formation and evolution process of TDC, the deformation environments are mainly divided into Brittle, Shear and Plastic deformation environment (Fig. 3). The TDCs from brittle deformation environment can mainly be divided into the cataclastic, porphyroclastic and granulitic coal with increased deformation extent. In the shear deformation environment, the schistose coal forms from the cataclastic coal, and the scaly coal with squamous structure is developed due to the increased shear deformation extent. In the plastic deformation environment, the wrinkle coal with bending fractures develops. Noteworthy, the mylontic coal associated with ductile deformation is developed through two evolutionary processes. One is formed from wrinkle coal due to the strong action of rheomorphism in plastic deformation environment. The other is formed from scaly coal, which is associated with ductile brittle deformation (Fig. 3). The brief classification and deformation features are displayed in Table 1 and Fig. 4.

3. Sampling and experiment

3.1. Sample preparation

The samples in this study were collected at the working and heading faces in the Zhuxianzhuang, Taoyuan and Luling coal mine of Suzhou mining area, Huaibei coalfield, Anhui province, named by a number with a prefix “H” (e.g., H1, H2, H3, etc.). The collected samples were smashed and sieved to size fraction of 0.074–0.2 mm for proximate and elemental analysis, according to the China National Standard GB/T 212–2008, GB/T 214–2007, GB/T 476–2008, GB/T 19227–2008. The results are shown in Table 2. The porosity of coal samples obtained from mercury intrusion porosimetry measurements was corrected for coal compressibility (Giesche, 2006; Bergins et al., 2007) (Table 3). The maceral analysis and vitrinite reflectance of coal samples are displayed in Table 3.

The TDC samples in this study include cataclastic coal, porphyroclastic coal, granulitic coal, schistose coal, scaly coal, wrinkle coal and mylonitic structural coal. Two undeformed coal samples are selected for comparative analysis. To prevent coal samples from damaging during sample collection, the coal samples were carefully collected along the joint direction using a geologic hammer, enwrapped with soft paper and marked with adhesive tape. Then the undeformed coal and TDC samples were processed into cylindrical samples with abrasive paper under dry conditions and eight sets of data were obtained for each sample to study the elastic anisotropy (Fig. 5). Before testing, samples were left to dry at the room temperature for at least 72 h.

Notably, the coal samples used are selected based on the deformation features of TDC, following the description in Table 1. The coal samples have clear differences in deformation extent.

3.2. Experimental procedures

The ultrasonic speed experiment is conducted under normal temperature and pressure (298 K, 1 atm) with an OLYMPUS MODEL 5077PR Ultrasonic Pulser/Receivers at the Nanjing Sinopec Geophysical Research Institute. Pulse signals produced by an ultrasonic wave test instrument (Panametrics-NDT) are amplified, transformed,