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# Permeability evolution in fractured coal — Combining triaxial confinement with X-ray computed tomography, acoustic emission and ultrasonic techniques

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## ABSTRACT

Cyclic loading of coals impacts permeability due to reversible deformation and irreversible damage and extension to pre-existing fracture networks. These changes in permeability influence the effectiveness of degassing of coal prior to mining, the recovery of coalbed methane by both conventional and enhanced methods and potential for sequestration of $CO_2$. We explore these interactions of stress and damage that contribute to changes in permeability through imaging with X-ray computed tomography (X-ray CT), acoustic emission (AE) profiling together with the concurrent measurement of P-wave velocities. We use these techniques to examine the evolution of the 3D fracture network during stressing through failure. A total of five semi-anthracite/anthracite coal cores (~40 mm in diameter and 80 mm in length) are sequentially loaded to failure (~37.53 MPa) with concurrent measurements of permeability. Intermittent scanning by X-ray CT, AE profiling and measurement of the evolving P-wave velocity effectively determine changes in the 3D fracture network with applied stress. These results are correlated with the "V-shaped" variation of permeability with increasing axial stress under the imposed triaxial stress conditions. This is consistent with observations on hard rocks where increasing stresses initially close fractures before fractures ultimately dilate, propagate and coalesce as the peak strength is reached. The increase in fracture volume is non uniform within the sample and is largest at the end platens. The permeability evolution was similarly dynamic with coal permeability reduced by one to two orders of magnitude in some cores (0.18–0.004 mD) until increasing dramatically as failure is approached (14.07–37.53 MPa).

## 1. Introduction

Potential unconventional natural gas resources, including coalbed methane (CBM) and shale gas, are estimated to be of the same order as the known conventional gas reserves (Karacan and Okandan, 2000). There are multiple locations where the recovery of CBM can be economically viable. However its accumulation, retention and recovery involve significantly different mechanisms to those involved in the concentration of conventional gas reserves (Ertekin, 1995; Karacan and Okandan, 2000; Vinokurova, 1978). Most significant among these is the role of matrix storage as the principal reservoir for the gas — both in free state and sorbed. Generally, in bituminous coals, CBM is produced by diffusion from the matrix micropore system to the cleats and then by Darcy flow from the fracture system to the wellbore. From the viewpoint of gas production, the most important structural features of the coal are the features of the permeable fracture network (including cleats), including mineral occurrences, fracture morphology, fracture density and relating to macroscale fracture permeability (Nick et al., 1995). For CBM extraction, knowledge of the properties of the cleats is necessary as they influence the local and regional fluid flows (Close, 1993; Laubach et al., 1998). The dynamic cleat behavior influences the permeability as fractures are the major fluid pathways. Identifying the characteristics of these fractures, including their permeability anisotropy and magnitude, and their evolution with gas pressure and effective stress, are key unknowns in the recovery of CBM. Field and laboratory studies have shown that fluid flow through natural fractures in coal and rock differs significantly from their idealization as smooth parallel plates — due principally to the heterogeneous distribution of apertures (Cacas et al., 1990; Nemoto et al., 2009; Watanabe et al., 2008, 2011a,b).

Previous research (Kendall and Briggs, 1933; Stach et al., 1982) found variations in fracture intensity depending on maceral and mineral matter contents. Fracture density depends on coal rank (Law, 1993; Pattison et al., 1996) and exhibits a reverse U-shaped relationship with rank — progressing from lignites (low fracture densities) through bituminous coals (high fracture densities) to anthracite (lower fracture densities). Fracture characteristics (e.g. density, connectivity and geometry) may be acquired by image analysis of cores from CBM reservoirs

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**Table 1**
Coal composition and proximate analysis of the coals tested.

| Coals | Colliery | $R_{o,m}$ (%) | Proximate analysis (ad. %) | | | | Coal composition (%) | | | Micro-fractures analysis | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | C | H | A | Moisture | V | I | M | D (per 9 cm$^2$) | Connectivity |
| A (CC3#-2) | Changcun, Changzhi | 1.94 | 82.12 | 3.16 | 0.73 | 8.98 | 89.2 | 9.6 | 1.2 | 9 | Good |
| B (SJZ9#-1) | Shenjiazhuang, Gaoping | 2.24 | 79.62 | 3.32 | 1.04 | 10.84 | 86.7 | 10.9 | 2.4 | 75 | Very good |
| C (WTP15#-2) | Wangtaipu, Jincheng | 3.28 | 79.85 | 2.32 | 2.47 | 11.34 | 89.5 | 6.2 | 4.3 | 8 | Good |
| D (YC4#-1) | Yangcheng, Yicheng | 2.68 | 82.24 | 3.1 | 1.65 | 10.52 | 18.5 | 81.4 | 0.1 | 14 | Not good |
| E (ZLS3#-1) | Zhulinshan, Yangcheng | 2.20 | 82.78 | 3.08 | 1.16 | 9.06 | 69.8 | 28.9 | 1.3 | 15 | Not good |

Note: $R_{o,m}$, Maximum vitrinite reflectance; C, Carbon; H, Hydrogen; A, Ash; V, Vitrinite; I, Inertinite; M, Minerals; D, Density.

and outcrops (Wolf et al., 2004). Techniques at the sub-meter scale were employed to measure cleat densities, or cleat spacing distribution, by using X-ray CT and image analysis (Mazumder et al., 2006; Wolf et al., 2008). X-ray CT is an effective nondestructive method for analyzing internal structures in rock materials, such as fractures in coals (Cnudde and Boone, 2013; Karacan, 2009; Karpyn et al., 2009; Ketcham and Carlson, 2001; Kumar et al., 2011; Polak et al., 2003; Zhu et al., 2007). Previous studies have demonstrated the ability to determine fracture aperture distributions using X-ray CT. (Bertels et al., 2001; Johns et al., 1993; Karpyn et al., 2009; Keller, 1998; Kumar et al., 2011; Montemagno and Pyrak-Nolte, 1999; Watanabe et al., 2011a).

To better understand the factors contributing to the dynamic evolution of permeability in coal subject to variable stresses, where fracture deformation and extension may be important, monitoring and imaging via acoustic emission (AE) may provide important constraint (Backers et al., 2005; Butt, 1999; Chang and Lee, 2004; Fu, 2005; Ganne et al., 2007; He et al., 2010). However, flows in naturally fractured coal cores, which often contain distributed fractures of different apertures and at multiple length-scales, are usually difficult to evaluate. Although fracture flow analyses by numerical fracture models with heterogeneous aperture distributions may be effective (Nemoto et al., 2009; Watanabe et al., 2011b), the determination of the evolution of the fracture aperture remains an important challenge. Thus for the effective development of CBM reservoirs an understanding of fracture characteristics, including an evaluation of fracture evolution with effective stress is important. The characterization of fracture-size patterns, network geometries, and the response of fracture systems to changing effective stress conditions is an area of principal need (Laubach et al., 1998). In addition, there are limited data on cleat apertures, widths, lengths, and connectivity. In this work, five cores from the most active CBM play in China (Qinshui Basin, North China) were investigated to evaluate the effects of the evolution of fracture heterogeneity (including cleat morphology, cleat density, and cleat aperture) under variable mechanical stresses (0–37.53 MPa) on permeability. X-ray CT, AE, P-wave velocities, and optical microscopy were combined for fracture analysis and to determine the influence of fracture network evolution on permeability as tri-axial stresses (axial differential stress in the range of 0–37.53 MPa) were incremented on naturally fractured coals.

## 2. Methods

### 2.1. Sampling and acoustic measurements

Five fresh block samples of coal (Table 1) of dimension ~30 × 30 × 30 cm$^3$ each were obtained directly from underground mines at depths between ~400 m and ~1200 m in the Qinshui Basin, North China using the channel method.

AE is a useful method to determine the interior dynamic change (Deng et al., 2011; Wu et al., 2011; Zhao and Jiang, 2010) of rocks. Here the AE monitoring of fracture evolution was performed using an advanced AE21C system using a single sensor with a resonant frequency of 140 kHz. The sensor was glued to the cores and further secured with spring clips or adhesive tape (Fig. 1). The AE signals were amplified by a 40 dB fixed-gain preamplifier with 110 V adaptive voltage. The detection interval was 300 μs. The AE data included: ring-down count rates, energy rates, duration and rise time (Chang and Lee, 2004) under axial compression during the cyclic loading process. Only the ring-down count rates and energy rates were used in the present study as they directly relate to fracture generation (Zhao and Jiang, 2010). P-wave velocity of coal cores was captured using a ULT-100

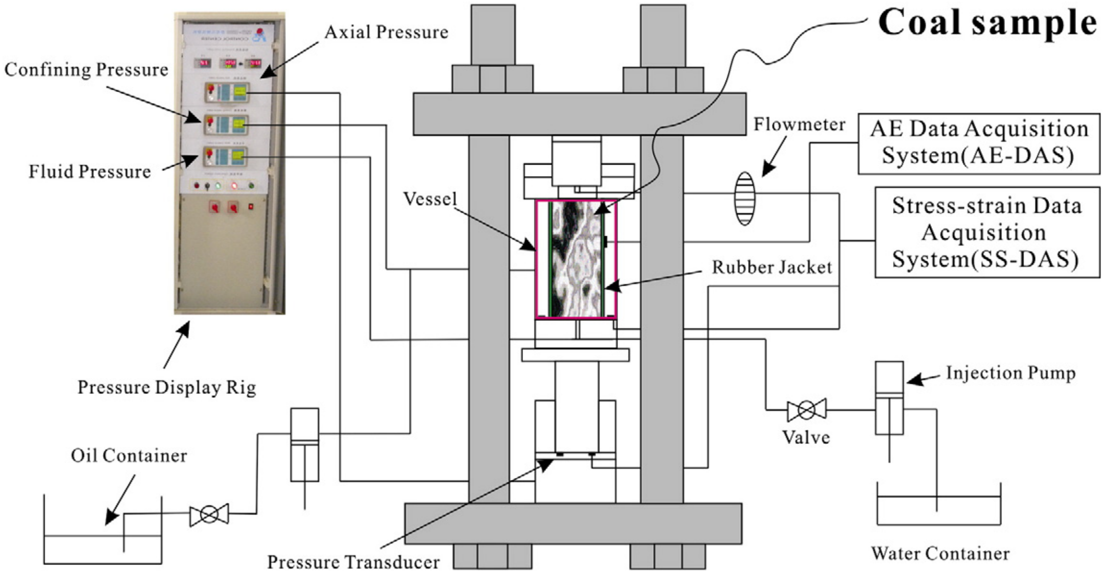

**Fig. 1.** Schematic plot of experimental apparatus (GAW-2000).