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Experimental research on the permeability of high-rank coal under a varying stress and its influencing factors

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A B S T R A C T

In order to investigate the permeability behavior of high rank coal during early depletion of CBM and its influencing factors, we collected 14 coal samples from Ordos Basin in northwest China and determined their air permeability under a varying effective stress of 2.5–20 MPa in laboratory. We used effective confining pressure to simulate effective stress. It turns out that high rank coal permeability is susceptible to effective stress. Permeability of coal samples declines exponentially with the rise of effective stress on the whole. When effective confining pressure variation ranges from 2.5 MPa to 10 MPa, permeability varies dramatically; when effective confining pressure rises to above 10 MPa, the curve of permeability decline gets gentle and the stress sensitivity becomes relatively weak. Coal permeability is also affected by coal moisture, maceral, fracturing and metamorphism degree. Permeability rises with the increase of vitrinite content and fracturing degree and decreases with the increase of moisture content. Permeability of wet and fractured coal samples is more sensitive to effective stress than dry intact ones and the irreversible permeability loss rate of fractured coal cores is significant, over 80%. Comparison of tests results of medium and low rank coal samples and high rank ones shows that, the stress sensitivity coefficient decreases with the increase of the maximum reflectance of vitrinite; if experiencing the same load-relief process, the irreversible permeability loss rate of low rank coal is less than that of medium and high rank coals.

1. Introduction

China has abundant coal bed methane (CBM) resources, especially in its high rank coal basins, such as Ordos Basin, Qinshui Basin and so on. Due to multiple tectonic movements, high rank coal has its special features in matrix porosity, fracturing, petrology, gas adsorption/desorption, permeability and geomechanics (Meng et al., 2009, 2010, 2011; Meng and Hou, 2012). Permeability is a key parameter for CBM reservoir and its temporal and spatial variation will affect the gas production significantly. Not until 1950s did people come to make experimental and theoretical researches on hydrologic features of fractured rock mass. The seepage model of fractured rock mass was founded and the basic relation of rock mass effective stress and seepage flow was obtained (Enever and Henning, 1997; McKee et al, 1998; Zhang et al., 1997, 2000, 2007; Zhang and Roegiers, 2010). Permeability changes during depletion of CBM wells because effective stress increases with the decrease of pore pressure due to pumping water in early stage and coal matrix shrinks due to gas desorption in later stage. Permeability variation is significant during depletion of CBM wells in the San Juan basin (Palmer, 2009). The influencing factors of CBM reservoir permeability are various, including in-situ stress, geological structure, burial depth of the coal, coal mass structure, petrographic characteristics, coal quality, coal rank, development degree of natural fracture and so on. The magnitude and direction of in-situ stress exert important influences towards CBM reservoir permeability (Meng et al., 2010). Stress-dependent permeability has been extensively studied in fractured rocks (Zimmerman and Bodvarsson, 1996, 2000; Min et al., 2004). Spatially, variations in in-situ permeability values to water are likely a function of the maceral composition, mode of deformation, and degree of shearing of the coal seams (Gentzis et al., 2007). Based on geophysical log data and well test in Huainan and Huaibei coalfields, China, Fu et al. (2009) established a correlation between permeability and structure of coal. Several analytic perm-change models were proposed and widely used in some CBM reservoir simulation (Shi and Durucan, 2005; Connell, 2009; Connell et al., 2010; Chen et al., 2012; Pan and Connell, 2012). In Palmer–Mansoori and Shi–Durucan models, the cleat compressibility keeps the same during drainage, but some experimental research indicated that cleat compressibility changes with the type of gas and gas pressure during enhanced CBM recovery (Pan et al., 2010; Jasinge et al., 2012). Laboratory measurements show that coal permeability decreases exponentially with the increase of effective stress (Somerton et al., 1975; Durucan and Edwards, 1986; Enever and Henning, 1997; McKee et al, 1998).

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Mitra et al. (2012) and Liu et al. (2012) considered that permeability exponentially increases with depletion due to coal matrix shrinkage and permeability change is small at high pore pressure and then accelerates because the coal matrix shrinkage effect is significant only when substantial desorption occurs. Zeng et al. (2011) reported that the permeability of coal samples under triaxial compression tends to decrease with the increase in effective stress in each loading direction and is controlled by the evolution of cracks in coal. Broken coal sample under higher stress level shows higher permeability than the intact coal under lower stress. Permeability was strongly stress-dependent decreasing by more than two orders of magnitude in the stress range of 250–2000 psi, whether hydrostatic or triaxial stress; the mean effective stress was the controlling factor in permeability reduction (Somerton et al., 1975; Liu, 2011). The study on the influence of in situ stress on the CBM reservoir permeability has not been widely investigated due to the lack of CBM reservoir stress and permeability data. Thus the understanding of the permeability variation during the exploration and development of CBM was still poor. However, the CBM reservoir has low permeability and strong gas adsorption capacity, which is quite different from the conventional oil and gas reservoirs. Dual porosity is a significant feature of coal seam, the coal matrix is considered to be the low permeability, high storage capacity in primary porosity system and the cleat system is believed to be the high permeability, low storage secondary porosity system. The primary porosity is mainly controlled by coal deposition, while the secondary porosity by cleats and fractures. CBM reservoir permeability changes a lot under different stress states (Wang and Park, 2002; Palchik, 2012; Schatzel et al., 2012). The permeability of CBM reservoir is usually affected by drilling, well completion and operation which will unavoidably induce local stress concentration and even rock mass failure in the vicinity of the well.

Reported experimental researches are mainly on low-medium rank coal (Somerton et al., 1975; Enever and Henning, 1997; McKee et al., 1998; Pan et al., 2010; Liu, 2011; Jasinge et al., 2012; Mitra et al., 2012) and researches on permeability of high rank coal have not been widely reported (Meng and Hou, 2013). In early stage of CBM depletion, improper pumping water may induce an abnormal increase in effective stress and a significant irreversible reduction in permeability but little matrix shrinkage and thereby impair later stage gas production. Our experimental study aims to understand the air permeability behavior of high rank coal at a varying effective stress of 2.5–20 MPa and tries to correlate the permeability and effective stress, fracturing, maceral and moisture in laboratory scale and to give some suggestions on early groundwater extraction.

2. Experimental method

2.1. Experiment samples

Ordos Basin in north China extends across five provinces, including Inner Mongolia, Shanxi, Shaanxi, Ningxia and Gansu (Yang et al., 2008). Tectonically, controlled by the basement configuration, the basin comprises six major subdivisions: the Yimeng upwarping in the north, the fold–thrust belt in the western margin, the Tianhuan downwarping, the Shanbei slope, the Jinxi fold belt in the east, and

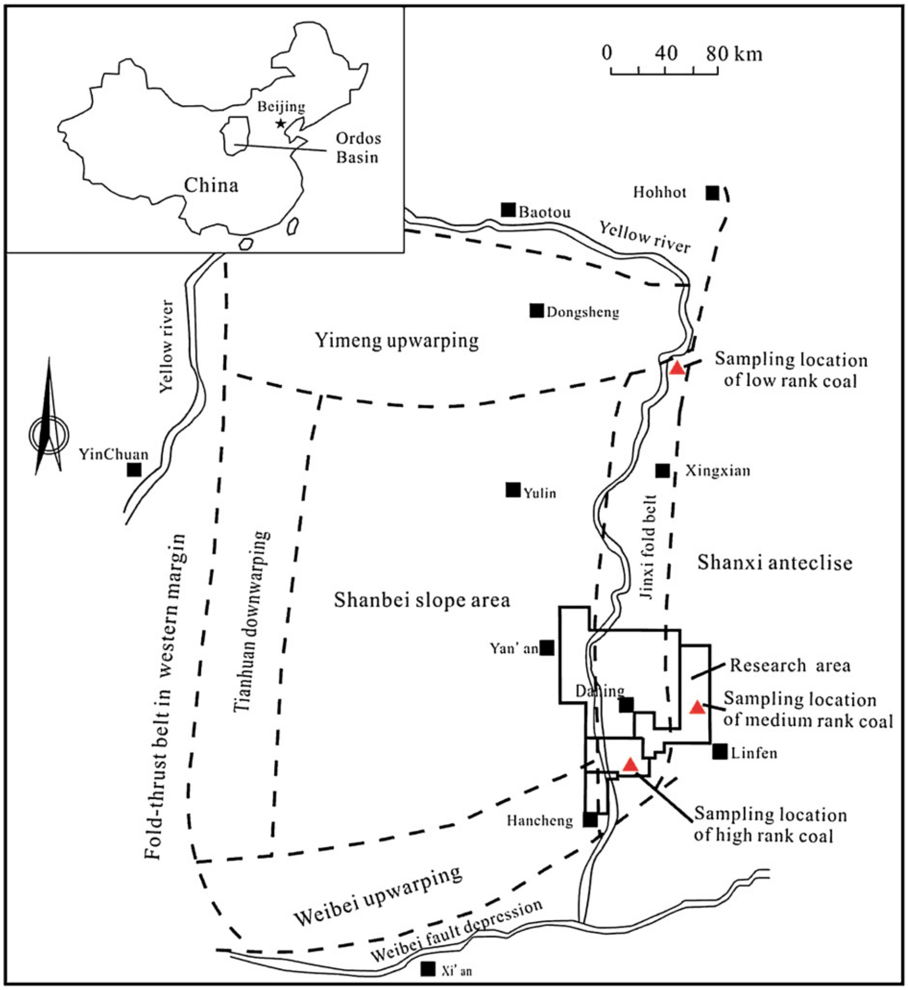

Fig. 1. Location of study area and sampling sites.