Journal of Natural Gas Science and Engineering 34 (2016) 55–63

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

An experimental study of fractured sandstone permeability after high-temperature treatment under different confining pressures

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A R T I C L E I N F O

Article history:
Received 21 March 2016
Received in revised form
10 June 2016
Accepted 13 June 2016
Available online 16 June 2016

Keywords:
Experimental study
Fractured sandstone
Permeability
High temperature
Confining pressure

A B S T R A C T

A detailed understanding of the effects of temperature and confining pressure on permeability is critical for projects such as underground coal gasification, reconstruction after a gas disaster, and disposal of nuclear waste. In this study, uniaxial compression experiments were conducted on sandstone after exposure to high temperature, and water flow tests were then performed on the fractured sandstone. A non-Darcy method was adopted to calculate the permeability. The mechanical properties were enhanced and the permeability slowly decreased when the temperature was below 400 °C. When the temperature exceeded 400 °C, the formation of new cracks and the extension of existing cracks were observed using a scanning electron microscope; the volume increased rapidly, and the mechanical properties significantly decreased. The permeability increased rapidly as the temperature increased from 400 to 600 °C, while the change in permeability was modest at temperatures above 600 °C. An exponential function was used to fit the permeability and temperature data above 400 °C. As the confining pressure increased from 2 to 8 MPa, the permeability initially decreased sharply and then decreased at a considerably slower rate. Temperature slightly affected the change in permeability at a higher confining pressure.

1. Introduction

Underground mining has long been considered a high-risk activity (Wang et al., 2013). Violent mining disturbances cause stress concentrations and separation along strata planes that can cause the bending and subsequent fracturing of rock layers (Adhikary and Guo, 2015). A number of studies have demonstrated the mechanics of strata deformation induced by underground mining (Ropski and Lama, 1973; Kesserü, 1984; Singh et al., 1986). The permeability of fractured rocks is considerably higher than that of rocks that remain intact. Forster and Enever (1992) conducted field tests in a coal mine in Australia and showed that permeability increased by three orders of magnitude in a fractured zone.

Many coal mines are threatened by groundwater during the mining process (Wang and Park, 2003; Wu et al., 2004; Zhang, 2005). One of the most dangerous hazards is water inrushes from Ordovician limestone under Permo-Carboniferous coal seams (Zhang et al., 2014b) where the resident aquifer contains a large amount of water under high pressure (Bieniawski, 1982; Zhang and Shen, 2004; Zhang and Peng, 2005). Mining activities cause strata failures and form fractured zones (Xiao and Xu, 2000); these fractures can become water flow channels and affect the stability of excavated structures (Chegbeleh et al., 2009). Many studies have indicated that high-pressure groundwater can break through fractured strata and burst into the working face (Li and Zhou, 2006; Wu and Zhou, 2008; Li et al., 2011; Zhu and Wei, 2011; Zhu et al., 2013). These challenges are correlated with fracture density, rock mechanical properties, and enhanced fluid flow (Davoodi et al., 2013; Barani et al., 2014). Zhang et al. (2013) demonstrated that the permeability of brittle rocks was significantly higher at the critical failure point due to fracture formation during compression. Zhu et al. (2002) showed that the water flow properties of integrated and fractured rocks differed significantly and that permeability is closely related to the style of deformation destruction.

Previous research has shown that permeability is closely correlated with fracture evolution (Larsen et al., 2010; Larsen and Gudmundsson, 2010; Thararoop et al., 2012; Wang et al., 2015;

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http://dx.doi.org/10.1016/j.jngse.2016.06.034

Zou et al., 2015), which is affected by ambient conditions, such as temperature (Cai et al., 2014). Ferrero and Marini (2001) studied the behavior of two types of marble after high-temperature treatments of up to 600 °C using microscopic analyses and open porosity tests; they found that new cracks formed and that open porosity increased with increasing temperature. Numerous studies have demonstrated that high temperature affects the physical and mechanical properties of rocks (Géraud et al., 1992; Chopra, 1997; Zhang et al., 2001; Zhao et al., 2012; Ozguven and Ozcelik, 2014; Zhang et al., 2014a; Shao et al., 2015a; Ding et al., 2016).

Many countries, including the USA, China, and India, have reported underground coal fires (Coates and Heffern, 2000; Michalski, 2004; Coates et al., 2005; Chatterjee, 2006; Kuenzer and Stracher, 2012; Zeng et al., 2015). The spontaneous combustion of coal seams is a hazard that causes not only resource loss and environmental pollution but also other hazards, such as gas explosions and water inrushes (Hu et al., 2015; Lu and Qin, 2015; Shao et al., 2015b). Qin et al. (2009) conducted in site tests in a coalfield fire area and showed that the maximum temperature reached 1200 °C. In addition, the rapid development of in site gasification techniques (Shackley et al., 2006; Khadse et al., 2007; Stanczyk et al., 2011) provides an excellent opportunity to use coal resources where the temperature of the working face can exceed 1000 °C (Niu et al., 2014). Rock masses involved in projects such as post-disaster reconstruction after coal fires and underground coal gasification have experienced high-temperature treatments that caused fractures and changes in seepage behavior in the strata as a result of the combustion process (Otto and Kempka, 2015). Along with the mechanical behavior deterioration caused by excavation effects, thermal stress causes permeability changes. Few studies on water flow properties have considered both stress changes and high-temperature effects.

In this paper, we performed uniaxial compression tests on sandstone after high-temperature treatment and water flow tests on fractured sandstone using an MTS815.02 Material Testing System and a self-made water flow device to investigate the effect of temperature and confining pressure on permeability. These experimental results offer an accurate understanding of water inrushes in underground projects related to high temperature.

2. Experimental materials and testing procedures

2.1. Experimental materials

The sandstone used in this study was fine-grained and collected using a 165-mm vertical drill core from a depth of 192 m in the Pingshuo coalmine located in Shuozhou City, Shanxi Province, China, as shown in Fig. 1. The Shuozhou sandstone was composed of feldspar, quartz, kaolinite, illite, chlorite, calcite, siderite, and small amounts of other minerals. The sandstone density and porosity were approximately 2.51 g/cm^3 and 3.4×10^{-2}, respectively. All experiments were conducted on cylindrical specimens with diameters of 50 mm and lengths of 100 mm in accordance with the ISRM standard (Fairhurst and Hudson, 1999).

2.2. Experimental equipment and testing procedures

2.2.1. Experimental equipment

Compression tests were performed using an MTS815.02 Material Testing System with a maximum loading capacity of 1700 kN. A GWD-02A electric furnace was used to heat the specimens to a maximum temperature of 1100 °C.

The seepage properties were tested using an MTS815.02 and a self-made water flow device, as shown in Fig. 2. The perforated plate (5) ensured that the liquid flowed regularly, and the felt pad (6) prevented the fluid from polluting the MTS815.02 system. Epoxy resin was used to separate the specimen and the cylindrical barrel (8) and to inhibit the radial flow of the liquid. The triaxial cell was connected to the cylindrical barrel (8) via a one-way valve that included a valve core (13), a valve chest (14), a spring (11), a plate (10) and a screw (15). The self-made pipes (1 and 12) were used to vary the confining pressure.

The fluid starts from the pore water pressure load system, flows through globe valves S12 and S14 and the one-way valve, reaches the specimen, and then flows out via globe valves S1 and S15.

The water flow velocity is controlled by the pore water pressure load system. A controller, including a distributor, a personal computer and software, is used to collect and analyze the data.

2.2.2. Testing procedures

The experimental methods for testing mechanical behavior and permeability vary according to the research background, including tests conducted during the process of high-temperature treatment and after high-temperature treatment; the latter method was studied in this paper. Both axial stress and confining pressure affect rock in underground projects, and mechanical properties in uniaxial tests and triaxial tests differ. We conducted uniaxial compression experiments to study the effect of high-temperature treatment on the mechanical behavior of sandstone.

(1) We performed uniaxial compression tests on the sandstone after high-temperature treatment. Seven temperature levels were set: 20 (room temperature), 200, 400, 500, 600, 700 and 800 °C. The temperature settings are closely correlated to the site conditions, and the temperature of a fire in a coalfield is approximately 800 °C (Burton et al., 2006; Couch, 2009). Each temperature was tested on three specimens. These samples were numbered, and their mass and dimensions were measured before the compression tests. The specimens were heated to their designated temperature at a rate of 20 °C/min, held at that temperature for 2 h to ensure that the materials were fully heated, and subsequently cooled back to room temperature. The mass and dimensions were then measured again. After high-temperature treatment, the specimens underwent uniaxial compression tests that were performed by displacement control at a rate of 0.2 mm/min. The mechanical properties, including the peak strength, Young's modulus and peak strain, were obtained.

(2) We performed water flow tests on the fractured sandstone. The specimens were first heated to the target temperature at a rate of 20 °C/min, maintained at that temperature for 2 h, and finally cooled back to room temperature. After high-temperature treatment, the specimens were uniaxially compressed to a given strain value that was 1.3 times greater than the average peak strain obtained in the uniaxial compression test at the same temperature. The deformation values before and after unloading were considered identical because after reaching peak strength, the deformation could not recover. The pre-fractured specimens were circumferentially wrapped in PVC bands and thermo-shrinking plastic covers to prevent fragments from separating from the integrated structure. After the specimens were placed on the testing platform, confining pressures σ_3 ($\sigma_3 = 2$, 5, and 8 MPa) were applied at a rate of 0.08 MPa/s; then, constant axial loads were applied. The confining pressure settings are correlated to the site conditions. Stress meters were distributed in the 21,105 working face of the Pingshuo coalmine where the sandstone was collected, and the monitoring results indicated that most of the stress values ranged from 2