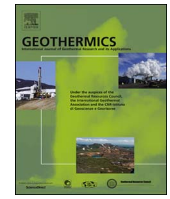
Geothermics 69 (2017) 93–109

Contents lists available at ScienceDirect

Geothermics

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



Experimental investigation on triaxial mechanical and permeability behavior of sandstone after exposure to different high temperature treatments

Sheng-Qi Yang*, Peng Xu, Yan-Bao Li, Yan-Hua Huang

State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, 221116, PR China

ARTICLE INFO

Keywords:
Sandstone
High temperature
Strength
Deformation
Permeability
Thermal damage

ABSTRACT

Geothermal energy offers great advantages in cost, reliability and environmental friendliness compared with conventional fossil fuels; geothermal energy is recommended and has been identified as a renewable and alternative energy source. Two of the pre-requisites for the exploitation of geothermal energy are reservoir and cap rock, and the mechanical properties and permeability behavior of reservoir and cap rock have a great influence on the exploitation of geothermal energy. This study presents a series of experimental results that analyze the effects of temperature (25, 100, 200, 300, 400, 500, 600, 700 and 800 °C) on the physical properties and mechanical and permeability behavior of sandstone. According to the physical test findings, the critical temperature (T_c) that induces changes in the mechanical and permeability behavior of sandstone was identified as 400–500 °C. A more obvious decreasing trend in those physical properties, i.e., weight, density, P-wave velocity, S-wave velocity, dynamic elastic modulus and Poisson's ratio, can be observed with the increase in temperature after T_c compared to that observed before T_c. The triaxial compression coupled with the transient pulse permeability test results showed that increasing temperature leads to an increase of cohesion and decrease of internal friction angle before T_c, and the opposite trends were observed after T_c. A decrease of nearly 20% in elastic modulus was observed after 800 °C compared with room temperature. The initial permeability of sandstone under certain pressure conditions was found to increase nonlinearly with the increase in temperature. Those findings are further discussed in the SEM and XRD analysis, according to which the material composition and state of sandstone as well as the micro-structure changed dramatically with the increase in temperature. Furthermore, a series of empirical relations between the temperatures and physical and mechanical properties of sandstone were derived, and are expected to aid in geothermal energy extraction from super-critical temperature resources.

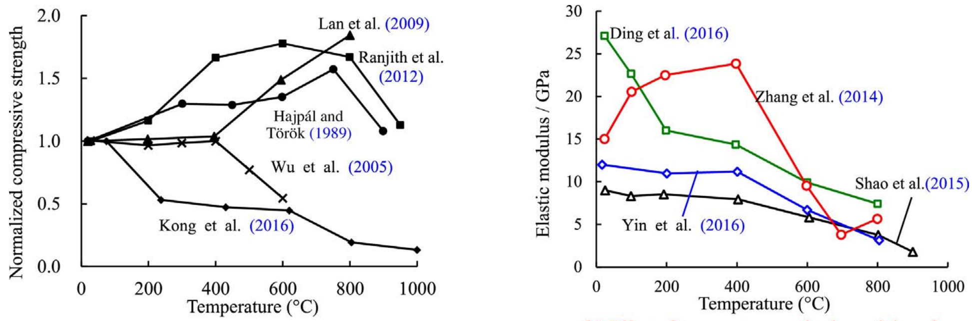
1. Introduction

Compared with conventional fossil fuels such as coal and oil, geothermal energy offers great advantages in cost, reliability and environmental friendliness (Martín-Gamboa et al., 2015; Axelsson, 2010), given the release of acid rain and greenhouse gases created by the use of fossil fuel (Lund et al., 2005), and geothermal energy is now recommended and identified as a renewable and alternative energy source (Kumari et al., 2017). As a common deeply buried rock, deep sandstone reservoirs with adequate temperatures are developed to serve as geothermal reservoirs (Gong et al., 2011). For exploitation of geothermal energy, four pre-requisites are needed, namely, a heat source, heat-carrying fluid, permeable or fractured rock that acts as reservoir and cap rock, and an impermeable insulation cover (Chandrasekharam and Chandrasekhar, 2010; Shao et al., 2014).

The mechanical and permeability behaviors of reservoir rock and cap rock have a great influence on deep geothermal energy extraction (Angelo et al., 2008). An increase in the permeability of reservoir rock favors heat-carrying fluid extraction, but an increase in the permeability of cap rock leads to loss of heat-carrying fluid, which is not beneficial for full exploitation of a geothermal resource. For this reason, analysis of the mechanical properties of geothermal reservoir and cap rock under high pressure and temperature conditions (geothermal conditions) can be helpful in basic predictions. Laboratory experiments conducted at high temperature can better represent practical situations than those conducted with high-temperature treatment, and if sub-

* Corresponding author.
E-mail address: yangsqi@hotmail.com (S.-Q. Yang).

http://dx.doi.org/10.1016/j.geothermics.2017.04.009
Received 10 January 2017; Received in revised form 3 April 2017; Accepted 17 April 2017



(a) Effect of temperature on normalized compressive strength of rock

(b) Effect of temperature on elastic modulus of rock

Fig. 1. Uniaxial compressive strength and elastic modulus of rock after heat treatment.

jected to the experimental technical conditions, few triaxial compression tests of rock at high temperature (above 500 °C) can be conducted, much less analysis of micro-structure and permeability. As a result, experiments performed on rock after thermal treatment are conducted as an alternative to reduce the difficulty and costs of laboratory experiments.

In recent decades, the influence of temperature on physical (Mambou et al., 2014), thermal (Tang et al., 2015) and mechanical properties (Li et al., 2016); microstructures (Török and Hajpál, 2005); failure mechanisms (Shao et al., 2015); and thermo-mechanical models (Yao et al., 2016) have been investigated. In addition, extensive laboratory research has been performed on different types of rock materials exposed to high temperatures including marble (Peng et al., 2016a, 2016b), sandstone (Kong et al., 2016; Zhu et al., 2016), claystone (Tian et al., 2014), shale (Morteza and Richard, 2016), granite (Liu and Xu, 2014; Yin et al., 2016; Yang et al., 2017), salt rock (Liang et al., 2006), and mudstone (Luo and Wang, 2011), among others. Fig. 1 shows the normalized peak strength and elastic modulus versus high temperature from references (Shao et al., 2015; Kong et al., 2016; Yin et al., 2016; Ranjith et al., 2012; Zhang et al., 2014; Lan, 2009; Hajpál and Török, 1989; Ding et al., 2016a,b). Fig. 1 also indicates that rock properties can be highly dependent on temperature, and the characteristics of temperature dependency vary with the rock types. Even for the same type of rock material, the critical temperature is not a constant, and might result from initial rock features such as micro-cracks and microstructure. Moreover, the effect of the testing temperature on the mechanical behavior of rock under different test methods (such as uniaxial compression, the Brazilian test and the three-point bedding test) has also been widely studied. Taking sandstone material as an example, the experimental results from sandstone can be briefly described as follows. The results of uniaxial compression tests on heat treated sandstone demonstrated that the compressive strength and elastic modulus for sandstone are increased at 500 °C, before decreasing up to the maximum temperature of 950 °C (Ranjith et al., 2012). Sirdesai et al. (2017) performed a series of Brazilian test on heated sandstone specimens and found that the physical properties and tensile strength are closely related to the treatment temperature. Mahanta et al. (2016) examined Indian sandstones after thermal treatment at different temperatures under three-point bedding tests. The experimental results showed that the fracture toughness of rock first increases and subsequently decreases as the temperature increases. Ding et al. (2016a,b) investigated the strength and deformation parameters of sandstone after high temperature treatment under unloading conditions and found that when the temperature is higher than 400 °C, the peak ductile deformation increased rapidly with increasing temperature or initial confining pressure. Li et al. (2016) conducted a number of dynamic compression tests on thermal-treated sandstone specimens using split Hopkinson pressure bar test system. The experimental results indicated that a critical value exists for the dynamic mechanical parameters, e.g. 500 °C for the tested sandstone. From the literature, it is clear that the evolutionary law of mechanical behavior of heated rock at high temperature shows different responses under different geological and stress conditions even for the same types of rocks (Meng et al., 2006).

Although the effects of heat treatment on the mechanical properties of rock have been studied systematically in the above-mentioned reports, limited experiments on conventional triaxial compression test results are available for heated sandstone with respect to different high temperature treatments. Moreover, for permeability of rock under both stress changes and high-temperature effects, little information has been reported in the literature (Ding et al., 2016a,b). Consequently, the aim of this paper is to investigate the physical, mechanical and permeability properties of sandstone exposed to high temperatures. In the present study, sandstone material was used to study the physical, mechanical and permeability properties of rock exposed to high temperatures through a suite of laboratory tests involving thermal treatment at temperatures up to 800 °C and triaxial compressive tests under confining pressures of 5, 10, 20 and 30 MPa. First, the physical properties (weight, volume, density and dynamic parameters) of the sandstone specimens were analyzed after high temperature treatment. Second, the influences of thermal treatment temperature on the strength and failure behaviors were analyzed in detail based on the triaxial compression results. Furthermore, the permeability evolution behavior of sandstone during the complete stress-strain process after exposure to different high temperature treatments was also investigated using the transient pulse technique. Finally, the microscopic mechanism of high temperature on the physical, mechanical and permeability behaviors of the tested sandstone were revealed using X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis. Furthermore, a series of empirical relations between the temperatures and the physical and mechanical properties of sandstone were derived and are expected to aid in geothermal energy extraction from super-critical temperature resources.

2. Experimental material and testing procedure

2.1. Sandstone material and heating procedure

The material used throughout this research was sandstone collected from Rizhao city in China, which is located near the Yellow Sea in the Circum-Pacific geothermal belt. In this area, the primary surface formations are the Paleoproterozoic Fenzishan group and Jingshan group and the Cretaceous period Wangshi group consisting mainly of dolomite marble, purple sandstone and silty mudstone that can be easily identified. Rizhao sandstone is a high-level hard stone with good homogeneity and high porosity (Yang et al., 2014).

In the present research, high temperature treatments were administered to the specimens with a high-temperature furnace using the following procedure. First, the specimens were heated to their target temperature (100, 200, 300, 400, 500, 600, 700 and 800 °C) at a rate of