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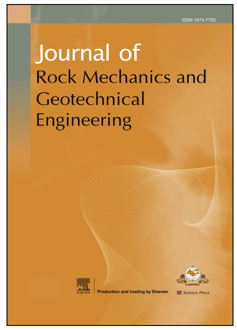

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Correlating mode-I fracture toughness and mechanical properties of heat-treated crystalline rocks

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Abstract: For the effect of thermal treatment on the mode-I fracture toughness (FT), three crystalline rocks (two basalts and one tonalite) were experimentally investigated. Semi-circular bend specimens of the rocks were prepared following the method suggested by the International Society for Rock Mechanics (ISRM) and were treated at various temperatures ranging from room temperature (25 °C) to 600 °C. Mode-I FT was correlated with tensile strength (TS), ultrasonic velocities, and Young's modulus (YM). Additionally, petrographic and X-ray diffraction analyses were carried out to find the chemical changes resulting from the heat treatment. Further, scanning electron microscopy (SEM) was conducted to observe the micro structural changes when subjected to high temperatures. These experiments demonstrate that heat treatment has a strong negative impact on the FT and mechanical properties of the rocks. From room temperature to 600 °C, mode-I FT values of massive basalt, giant plagioclase basalt, and tonalite were reduced by nearly 52%, 68%, and 64%, respectively. Also, at all temperature levels, FT and mechanical properties are found to be exponentially correlated. However, the exact nature of the relationship mainly depends on rock type. Besides, TS was found to be a better indicator of degradation degree than the mode-I FT. SEM images show that micro crack density and structural disintegration of the mineral grains increase with temperature. These physical changes confirm the observed reduction in the stiffness of heat-treated crystalline rocks.

Keywords: fracture toughness (FT); tensile strength (TS); ultrasonic velocity; Young's modulus (YM); crystalline rocks

1. Introduction

Climate change and energy security are the hot topics in the world. Rising economies like China and India are among the biggest consumers of energy in the present era. But concerns regarding the global warming have led to general consensus that greenhouse gas sources such as thermal power plants, cement factories, refineries, and hydrocarbon fuelled transports must be reduced substantially. Therefore, conventional energy must be replaced with renewable energy. In India, coal-based thermal power plant is still the major source of electricity. And the development of multiple renewable energies is the basis of the switch from coal-based power to alternative clean energy sources. Among these clean energy sources, geothermal energy holds a prominent position in India.

India has seven geothermal provinces with various lithological and tectonic settings. Among them, the Deccan Volcanic Province (DVP), which covers 50,000 km^2 of area in central and western India, is particularly interesting. Here, 18 geothermal springs with temperatures varying from 47 °C to 72 °C have already been investigated by Varun et al. (2012). Additionally, peninsular gneiss of South India has recently been identified as a new potential geothermal energy source (Singh et al., 2014). These two areas are shown in Fig. 1.

Development of any geothermal energy project needs an in-depth understanding of the geochemical and mechanical properties of the host rock. Fracture toughness (FT) and mechanical properties are particularly essential for designing the hydraulic fractures in enhanced geothermal systems. Additionally, these properties have tremendous implications in tunnelling, underground excavation, waste disposal site selection, and various problems in reservoir geomechanics. Therefore, it is required to have a good understanding of the effect of ambient geological conditions on FT and mechanical properties of crystalline rocks. One important geological parameter is the subsurface temperature. It is well documented that in geothermal systems, temperature can rise up to 200 °C; in underground nuclear disposal sites, temperature varies from 100 °C to 300 °C, if not properly sealed; and in drilling operations down-hole, temperature can be as high as 1000 °C (Paquet and François, 1980; Heuze, 1983; Maheshwar et al., 2015; Shao et al., 2015; Verma et al., 2015; Zhao, 2016).

Several researchers have investigated the temperature-dependent mechanical properties and FT of sedimentary and crystalline rocks (Funatsu et al., 2004, 2014; Nasseri et al., 2007; Kim and Kemeny, 2008; Meier et al., 2009; Vishal et al., 2011; Yin et al., 2012; Ranjith et al., 2012; Liu and Xu, 2014; Guha Roy and Singh, 2016). Meredith and Atkinson (1985) measured the FT value of the double torsion specimens of Westerly granite and Black gabbro. They reported that in both the rocks, FT increased slightly at the beginning, and then decreased steadily at temperature above 200 °C. Duclos and Paquet (1991) reported a similar decreasing trend of mode-I FT of basalt with increasing temperature. Nasseri et al. (2007) suggested that the FT of Westerly granite decreased by more than 90% from room temperature to 800 °C. Such pattern was also observed by Yin et al. (2015) for Laurentian granite at several loading rates. Investigation on the temperature-dependent strength of crystalline rocks also revealed similar pattern. Bauer and Johnson (1979), Homand-Etienne and Houpert (1989), Dwivedi et al. (2008), and Vishal et al. (2011) conducted experiments on different types of crystalline rocks and they all reported that the strength of rock decreased with increasing ambient temperature. Dwivedi et al. (2008) showed that the tensile strength (TS) of Indian granite was decreased by nearly 27% from room temperature to 150 °C, whereas Vishal et al. (2011) reported that TS of khondalite initially increased till 100 °C, and then declined steadily. Similar reduction in Young's modulus (YM) and ultrasonic velocities (P- and S-wave) has also been reported by other researchers for various kinds of rocks (Heuze, 1983; Rao et al., 2007; Wu et al., 2013; Zhang et al., 2015).

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