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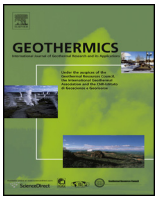

Experimental and numerical studies on the mechanical behaviour of Australian Strathbogie granite at high temperatures: An application to geothermal energy

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ABSTRACT

The effect of temperature on the mechanical behaviour of Strathbogie granite (fine-grained) was studied under unconfined stress conditions. Fracturing behaviour of test specimens was studied using an acoustic emission (AE) detection system and some crack propagation was also performed using electron microscopy scanning (SEM). The stress–strain curves showed plastic and post-peak behaviour for temperatures above 800 °C and the brittle–plastic transition was observed to occur between 600 and 800 °C for the uniaxially tested Strathbogie granite at a strain rate of 0.1 mm/min and room humidity. Specimens were heated at a rate of 5 °C/min with a 1 h holding period before testing. The AE results showed that the increasing temperature reduces the stress thresholds for crack initiation and crack damage and extends the duration of stable crack propagation. Prevalence of ductile properties with increasing temperature was also observed from AE results. The stress–strain and AE results reveal that the failure modes of Strathbogie granite specimens changed from brittle fracturing to quasi-brittle shear fracturing and eventually to ductile failure with increasing temperature. Temperature was observed to influence the colour of granite, and the initial white/grey colour changed to an oxidated reddish colour with increasing temperature. The stress–strain data of tested specimens were incorporated into a finite element model (ABAQUS 6.7.1), so that both plastic and ductile behaviour of the Strathbogie granite could be predicted over a wide range of temperatures.

1. Introduction

Geothermal heat is now a recommended renewable energy resource on the time-scales of both technological and societal systems, with cost, reliability and environmental advantages over conventional energy resources (Rybach, 2003; Gallup, 2009; Axelsson, 2010). Exploration of geothermal resources has posed new challenges for engineers and geologists to counter rock engineering problems at high temperatures. Laboratory testing is an important aspect of rock mechanics, which provides essential input data for the design of engineering structures in the Earth's crust and mantle subjected to tectonic forces. Since the 1970s, a large number of laboratory studies have been carried out to investigate the effect of temperature on the physical and mechanical properties of rocks in engineering applications, such as deep mining, underground chambers for nuclear disposal storage (at temperatures which generally vary from 100 to 300 °C and will increase over the storage period) and high-temperature thermal cracking of rocks during mechanical drilling (at temperatures as high as 1000 °C), as well as the design of enhanced geothermal systems (EGSs) (at temperatures about 200 °C) (Francois, 1980; Bauer et al., 1981; Paquet et al., 1981; Heuze, 1983; Hirth and Tullis, 1989). The mechanical behaviour of rock can be significantly influenced by elevated temperatures in such underground projects. In addition, different types of underground engineering applications encounter different temperatures, which vary from room temperature to extremely high temperatures. Therefore, understanding the effect of temperature on the physical and mechanical properties of rock is of great importance for the design of rock structures and safety assessment in underground rock engineering.

During the 1970s–1980s, investigations mainly focused on understanding the natural processes in the Earth's crust, such as rock deformation (faulting, folding and shearing), geothermal activity and magmatic intrusions. Most of these studies reported

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the influence of temperature on the mechanical behaviour of granite (Heuze, 1983; Wang et al., 2002; Dwivedi et al., 2008; Xu et al., 2008a,b). For example, a review study (Heuze, 1983) reported that some mechanical, physical and thermal properties of granitic rocks, including deformation modulus, Poisson's ratio, tensile strength, compressive strength, cohesion and internal friction angle and viscosity, all vary considerably with increasing temperatures. Although some other scholars have also studied the physical and mechanical properties of rocks under high temperatures, the vast majority of previous experimental studies have been performed by heating the specimens to predetermined temperature levels, but testing them at room temperature (Xu et al., 2008a,b, 2009; Zhang et al., 2009). Since rocks in natural geothermal reservoirs are subjected to continuous heating conditions, these preheating test conditions may not exactly reproduce the in situ temperature conditions. In addition, when pre-heated rock specimens are cooling down to room temperature, micro-structural changes and irreversible thermally induced micro-cracking can take place. Therefore, the results of experimental studies performed on pre-heated specimens at room temperature are insufficient to represent the essential characteristics of rocks at high temperature in geothermal applications. The aim of this paper is to investigate the mechanical behaviour of granite, which is a common rock type in the Earth's crust, at high temperatures (with continuous heating) under unconfined stress conditions using both experimental and numerical studies.

A review of the most pertinent studies in the literature regarding the basic mineralogy of granite, brittle–plastic transition of granite and fracturing behaviour of rock is presented in the following subsections, followed by the results and discussion of the experimental work and numerical simulation undertaken for the present paper.

1.1. Basic mineralogy of granitic rocks

Granites are generally medium- to coarse-grained igneous crystalline rocks that form by crystallization of certain slow-cooling magma. The main minerals that form granite are quartz, plagioclase feldspars and alkali feldspar, and some amount of biotite, muscovite and/or hornblende (Farndon, 2010). Granite is rich in elements with heat-producing radioactive isotopes (K, Th, U), and is thus commonly associated with temperature anomalies and elevated geothermal gradients within the crust. This feature makes it a suitable geothermal reservoir rock. It also has extremely low permeability and high strength, which also make it a good potential storage site for nuclear waste.

1.2. Brittle–plastic transition of granitic rocks

Brittle to plastic transition in response to increasing temperature has been studied for different types of rocks. The experimental results of Tullis and Yund (1987) demonstrated a transition from dominantly micro-cracking to dominantly dislocation at approximately 300–400 °C for quartz and 550–650 °C for feldspar. Hueckel et al. (1994) reported that the confining pressure at brittle to plastic transition is generally reduced by elevated temperatures. According to their study, when westerly granite is subjected to triaxial conditions, the confining pressure at brittle to semi-brittle transition drops from 2000 MPa at 360 °C to about 500 MPa at 800 °C, and the compressive strength also drops as the temperature increases, with a dramatic drop at 668 °C.

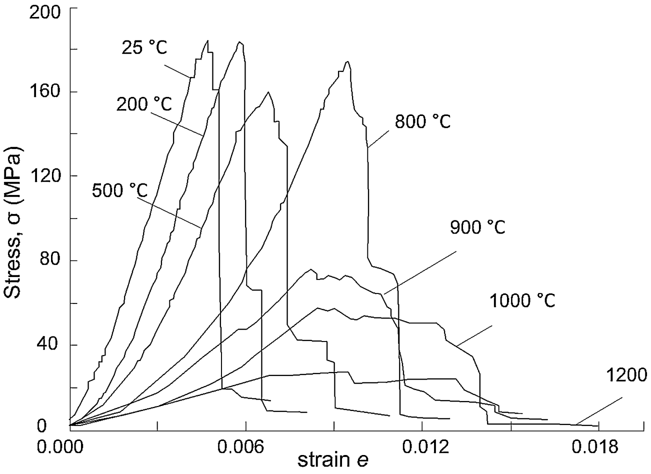

Fig. 1. Stress–strain curves of granite after high temperature (Xu et al., 2008a,b).

Xu et al. (2009) had used different temperatures ranging from room temperature to 1200 °C for their testing. The results showed that the phase-changing behaviour of brittle–plastic transition appears around 800 °C and the mechanical properties of the granite samples did not significantly vary before that (Fig. 1). This transition temperature is higher than that of westerly granite, which was found to be 668 °C by Hueckel et al. (1994). Therefore, it is clear that the brittle–plastic transition temperature can be significantly different, even for the same type of rock. This is understandable, considering the variation of rock mineral composition and micro-structural properties for the same rock type obtained from different sources.

1.3. Fracture development behaviour in rock

1.3.1. Stages of fracture development

Based on the characteristics of the axial stress–axial strain and axial stress–lateral strain curves of uniaxial compression tests, Hoek and Bieniawski (1965) found that the crack propagation process of brittle materials consists of three main stages: (1) crack closure followed by an elastic region; (2) crack initiation followed by a stable crack propagation region; (3) crack damage followed by unstable crack propagation until ultimate failure. In previous studies, various methods such as stress–strain analysis, scanning electron microscopy, photoelasticity, and acoustic emission have been used to identify these crack development stages (Bieniawski, 1967; Eberhardt et al., 1998; Ranjith et al., 2008). When the material is subjected to compressive loading, closure of pre-existing micro-cracks that are inclined to the applied loading direction takes place (Bieniawski, 1967). Linear elastic deformation occurs after the majority of pre-existing cracks have closed. This marks the beginning of the stable crack propagation region and the stress at the transition stage is known as the crack initiation stress threshold (σ_{ci}). In the stable crack propagation region the material deforms elastically. As the loading is further increased, unstable crack propagation begins and the stress at the transition from stable crack propagation to unstable crack propagation is referred to as the crack damage stress threshold (σ_{cd}) (Eberhardt et al., 1998).

1.3.2. Acoustic emission (AE) detection method to study fracturing development

Acoustic emission (AE) detection is a non-destructive evaluation method to study the crack propagation of a brittle material subjected to a stress field (Ranjith et al., 2008). Brittle material suddenly releases strain energy when a crack develops, which creates an elastic stress wave travelling from the location of energy release to the sample's surface. AE is used to detect and measure the transient wave that is generated from the discrete acoustic waves produced by each micro-crack, which can produce event data to interpret the crack propagation of the material. AE detection is able to monitor micro-crack slip and formation relative to the stress–strain response.