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Temperature-dependent mechanical behaviour of Australian Strathbogie granite with different cooling treatments

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ABSTRACT

Understanding the mechanical behaviour of reservoir rock under different temperatures with different cooling conditions is necessary for safe and effective deep geo-engineering applications, including geothermal energy extraction, deep geological disposal of nuclear waste, deep mining and coal gasification projects. The aim of this study is, therefore, to investigate the effect of increasing temperature (from room temperature to 800 °C) followed by two cooling methods (both rapid and slow) on the mechanical behaviour of Australian Strathbogie granite under uniaxial conditions. Further, a separate experimental program was conducted under continuous heating conditions without cooling the samples to compare the results of cooled samples. In order to investigate the strain developments in granite subjected to heating following slow and rapid cooling, ARAMIS photogrammetry technology was adopted, and the corresponding fracture propagation patterns were investigated using an acoustic emission (AE) system. Optical microscopic imaging technology was used to identify the corresponding micro-structural alterations and crack-formation patterns. According to the results, once the rock mass is subjected to higher thermal stresses, strength and elastic characteristics are significantly reduced, mainly due to thermally-induced damage in terms of both inter-granular and intra-granular cracks. The stress-strain response revealed that the failure mode of granite is changed from brittle to quasi-brittle fracturing with increasing temperature. The following cooling causes the strength and elastic characteristics of the granite to be further decreased through the enhancement of crack density, and the influence of rapid cooling is much greater than that of slow cooling, due to sudden thermal shock. This is evidenced by the AE results, according to which both high pre-heated temperatures and high cooling rates cause much quicker crack initiation and propagation in granite with lesser seismicity in the quasi-brittle region.

1. Introduction

In recent years, due to the demand for high temperature applications in geological sciences and geotechnical engineering, many research studies have focused on understanding the temperature-dependent mechanical behaviour of reservoir rocks. Investigation of temperature-dependent reservoir behaviour is critical for many deep geological applications, including deep geothermal energy exploitation (enhanced geothermal systems), deep mining, deep geological disposal of nuclear waste and coal gasification projects.

With the presence of heat-producing radioactive isotopes and thus elevated geothermal gradients, granite has become an important reservoir material for enhanced geothermal systems (EGSs) (up to 350 °C) (Barla, 2017; Breede et al., 2013). Traditionally, water is used for fracturing and heat-carrying process in EGSs. During the injection of cold water into hot rock, around the borehole, the hot rock is subjected to sudden temperature changes, resulting in the generation of thermal stresses, and with increasing distance from the borehole, the corresponding cooling rates decrease. These thermal stresses significantly influence the mechanical characteristics of the reservoir rock, and reservoir rocks subjected to different heating and cooling conditions, therefore, exhibit very different mechanical characteristics compared to intact rock, and these effects can critically affect the stability of the borehole. Also, the high-temperature mechanical response of formation rocks (mainly granite) is critical for geological nuclear disposal facilities (Ramspott et al., 1979). These facilities experience significant

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temperature rises, generally in the range of 200 °C to 1500 °C during the decomposition of radioactive substances (Gibb, 2000). Therefore, for the safe storage of nuclear waste under deep geological locations, the mechanical characteristics of the formation rock under high temperature conditions need to be precisely understood. In addition, under coal gasification process, once coal is burnt by injecting oxygen and steam, upper rock layers experience thermal stresses up to 1300 °C (both slow and rapid cooling conditions), and, therefore thermo-mechanical behaviour of cap rock need to be investigated for the safe and effective operational process (Ocampo et al., 2003). However, it should be noted that the cap rock layers in the coal gasification process are mostly sedimentary layers with few granite formations (Qi et al., 2016).

Once the rock mass experiences temperature differences, thermal stresses are generated, these are generally tensile stresses at the cooling surface and compressive in the interior of the rock (Collin and Rowcliffe, 2002). The highest tensile stresses are experienced on the surface of the rock and decrease with increasing crack depth. With increasing temperature the number of thermally-induced cracks increases, resulting in the increased crack density of the rock mass. According to David et al. (2012), once the Peyratte granite is heated from room temperature to 600 °C, crack density increases from 0.2% to 4.4%. Further, due to the anisotropic expansion of different mineralogical constituents of the rock matrix, thermal cracks are nucleated and significant enhancement of crack density has been reported above 600 °C, which is mainly due to the α to β transition of quartz, which occurs at 573 °C (Ohno, 1995). These induced thermal stresses alter the mechanical response of the reservoir rock, and these influences are highly dependent on the micro-structural characteristics of the rock, including the mineralogical and grain size distributions. Further, the cooling rate has a significant influence on this mechanical response of the rock, and, depending on the cooling rate, the rock can be thermally shocked after a certain critical quenching (Fellner and Supancic, 2002). Therefore, an understanding of the temperature-dependent mechanical behaviour in reservoirs rock together with quenching effects is necessary for safe geological applications.

Since 1970, a large number of laboratory experiments have been conducted to investigate the effect of temperature on the mechanical behaviour of granite. However, most of the experiments have been conducted by pre-heating the specimens to the corresponding temperature ranges and then testing them at room temperature (Chen et al., 2017; Liu and Xu, 2015; Singh et al., 2015). Many deep geotechnical applications experience continuous thermal stresses together with different cooling rates including 'thermal shocks'. Only a few experiments have been performed under continuous heating using appropriate test facilities (Kumari et al., 2017; Shao et al., 2015). Limited studies have captured the effect of cooling rate on the mechanical behaviour of the rock (Brotóns et al., 2013; Shao et al., 2014), and none of them has captured the overall influence of continuous thermal stresses and the effect of cooling rate on the mechanical behaviour of reservoir rock. This study, therefore, intends to fill this gap, and offer an important contribution to many deep geological applications.

2. Experimental methodology

2.1. Testing material

For the present study, granite samples were collected from the Strathbogie batholith located 150 km north-east of Melbourne. It is a 1500 km^2 large granitic intrusion in Victoria, mainly consisting of S-type granite. Quartz, feldspar, cordierite, garnet, biotite, and tourmaline are the main constituents of these granites (Phillips and Clemens, 2013). Fig. 1 illustrates a close view of a sample of the tested granite with its grain size distribution. The selected Strathbogie granite is a coarse-grained type of granite with grain sizes mainly ranging from 0.2 mm to 0.5 mm, with only a few larger grains (> 3 mm). Therefore, the selected granite type has a moderate strength (uniaxial compressive strength at room temperature of 120.9 MPa) with a bulk density of 2703 kg/m^3. Based on mercury intrusion testing, it has around 1.16% porosity and based on XRD analysis, alpha quartz is the dominant mineral (around 50% of the mass), followed by plagioclase, biotite and K-feldspar (16%, 15% and 13% of the mass, respectively). Small amounts of clinochlore, muscovite, ankerite, talc and serpentine can also be identified. In relation to its mineralogical composition, the selected granite is representative of the majority of the granite in the earth's crust (Best, 2013).

2.2. Sample preparation

In order to prepare specimens from the granite block obtained from the field, cylindrical cores were first prepared, following the ASTM recommendations for compressive strength and elastic modulus (ASTM, 2014) for uniaxial compressive strength (UCS). Rock samples were then uni-directionally cored into 22.5 mm cores, applying a very small coring rate, and samples with visible cracks and layers were discarded, in order to eliminate differences in orientation of the granite structure and the influence of macro-scale cracks and bedding on the test results. The cylindrical cores were then cut into 45 mm lengths, so the diameter-to-length ratio was 1:2. After making the cylindrical samples, the two ends of each were ground using a surface grinder to produce two parallel surfaces perpendicular to the loading axis.

2.3. Slow and rapid cooling treatments

In order to study the cooling effect on granite, thermal stressing was first created by heating the sample to the target temperature using the high-temperature furnace available in the Monash University Civil Engineering laboratory. A low heating rate of 5 °C/min was employed to avoid the possible thermal shock that may occur under rapid heat development in the sample. Samples were then kept for 2 h under the final temperature in the furnace to uniformly distribute the assigned temperature. Two cooling treatments (i.e. rapid cooling and slow cooling) were then adopted for the specimens at two different rates. Under the rapid cooling treatment, heated samples were put into a water bath to provide quenching to simulate fluid circulating through hot rock surfaces. For the slow cooling treatment, the temperature of the furnace was turned off and allowed to cool at a very small controlled cooling rate, simulating the cooling of the surrounding rocks. In order to obtain the required cooling rates, some specimens were tested with installed thermal couples to detect surface temperature changes. A ceramic paste was applied to ensure the contact between the thermal couple tip and the specimen. Fig. 2 illustrates the typical temperature changes of the surfaces of the specimens over time for rapid and slow cooling treatments.

2.4. Uniaxial compressive testing with ARAMIS photogrammetry and acoustic emission technology

Uniaxial compressive tests were then conducted on the thermally-treated samples using a Shimadzu compression testing machine available in the Monash University Civil Engineering laboratory. For all the tests, a loading rate of 0.1 mm/min was adopted to fail the sample under compression within 5–12 min. Load vs. deformation was measured in each test during axial compression using a data acquisition system. Further, the sample displacement (both axial and lateral displacements) was obtained using ARAMIS photogrammetry. ARAMIS is a non-contact optical 3-D deformation measuring system consisting of two high-resolution cameras and the ARAMIS photogrammetric software. In this technology, the movements of pixels in a photograph are translated into displacement vectors. It is therefore necessary to create discrete correlation areas in the captured stereo images to track the deformation of the specimen. Therefore, samples were painted white prior to testing and then black paint was sprayed on them to achieve the