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Experimental study on shear and creep behaviour of green tuff at high temperatures

Guan-lin Ye [a,*], Tomohiro Nishimura [b], Feng Zhang [b]

[a] Department of Civil Engineering and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China
[b] Department of Civil Engineering, Nagoya Institute of Technology, Nagoya, Japan

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ABSTRACT

The long-term stability of soft rock under high temperature conditions is very important to the safety of high-level radioactive waste (HLW) disposal. This study presents a series of triaxial compression tests and triaxial creep tests on green tuff in a temperature range of 20–80 °C. Repeated tests showed that the influence of temperature was more apparent on the peak strength and creep failure time than on the residual strength and volume change. The thermal effect on creep failure time was significant and became more prominent in higher creep stress. A linear correlation between the creep failure time and the minimum axial steady-strain rate at different temperatures was obtained. A thermal reversion behaviour, in which the peak shear strength and the creep rupture time of soft rocks are not monotonic functions of temperature, was observed. X-ray diffraction analysis showed that neither zeolite reduction nor hydrothermal alteration was the reason for thermal reversion.

1. Introduction

In the geologic disposal of high-level radioactive waste, the radioactive waste is solidified within a metal container, and the container is covered by cement or concrete and further covered by clayey material. These components are called the engineered barrier. And the surrounding clayey or rock ground is served as a natural barrier. Since the half-life of nuclear waste can be as long as tens of thousands of years,[1] the long-term stability of natural barriers under high temperature conditions is a key factor in disposability assessment. The purpose of this study is to identify the thermo-mechanical properties of green tuff, which are act as natural barriers in some disposal sites, such as the Rokkasyo-mura in Japan.

It is well known that the influence of temperature on the mechanical properties of rocks is very important for geotechnical engineering and geophysical science. Some experimental research has been carried out in recent decades.[2–8] The object of the rock tests was to investigate the effect of temperature on creep, strength and deformation. Additional factors need to be considered in investigating the thermal-mechanical properties of rocks, such as mineralogy, moisture content, pore fluid and hydrothermal alteration. An extensive literature review of the high-temperature mechanical properties of granitic rocks was undertaken by Heuze.[9] He summarised that the elastic modulus, tensile strength and compressive strength of granites decreased as temperature increased. Mollo et al.[10] investigate the influence of temperature on the deformation of a limestone. Heap et al.[3] investigated the influence of temperature on the creep properties of sandstone under triaxial stress conditions. They also found that the shear strength reduced, while creep strain rate increased by several orders of magnitude, as the temperature rose from 20 °C to 75 °C. Yang and Daemen[2] conducted uniaxial creep tests on tuff at room temperature and at elevated temperature (204 °C), and found that the creep of tuff increased with increasing temperature. Heap et al.[4] show the impact of high temperatures on the mechanical behaviour of a variety of tuffs (some containing zeolites). Later, Heap et al.[11] showed the impact of high temperatures on the permeability of tuff containing zeolites and zeolite-free tuff. In recent years, porosity change has become a major concern in rock testing. For instance, Heap et al.[3] paper showed the porosity change of sandstones deforming at constant stress and temperatures of 25, 45, and 75 °C.

Previous experimental studies found that the shear strengths and creep failure times of most rocks show a decreasing trend with increasing temperature. The change of shear strength was linked to the subcritical crack growth. Many researches suggest that growth of pre-existing cracks and flaws by the mechanism of stress corrosion is the dominant mechanism of subcritical crack growth in rocks (e.g.,[12]).

Little research on the thermo-mechanical properties of green tuff is available. Green tuff is a kind of soft rock, having a strength

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* Corresponding author.
E-mail address: ygl@sjtu.edu.cn (G.-l. Ye).

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between that of rocks and clays. It can be treated as a heavily overconsolidated geomaterial with a preconsolidation pressure generally greater than 10 MPa[13–19]. High-temperature undrained triaxial compression tests and uniaxial creep tests on green tuff were conducted by Okada[20–21] and Shibata et al.[22] The experimental findings can be summarised as follows: (1) As the temperature decreased, the peak value of shear stress increased and the stress-strain curve relationship changed from ductile to brittle. (2) As the temperature increased by about 40 °C, the uniaxial creep failure time could decrease by 2 to 4 orders of magnitude. These changes of strength and creep failure time are similar to those of rock. (3) The decrease of the shear strengths is a monotonic function of the temperature. There were several limitations in their research: (1) Only two temperatures (20 °C and 60 °C) were considered in the triaxial compression tests; (2) The stress and temperature conditions in the creep tests were not the same as in the triaxial tests. In order to obtain a proper insight into the thermal–mechanical properties of soft rock, it is necessary to carry out drained triaxial compression and creep tests.

This paper presents a series of drained triaxial compression tests and drained triaxial creep tests on green tuff under temperatures ranging from 20 °C to 80 °C. A temperature-controlled triaxial test apparatus and specimen preparation method is introduced. The thermal effects on the shear strength, volume change and the creep failure time will be analysed in depth. Additionally, a new phenomenon in which the shear strengths and the creep rupture times of soft rock are not monotonic functions of temperature will be described and discussed in detail.

2. Testing apparatus

The temperature-controlled triaxial test apparatus consists of a triaxial cell with a heating system, a loading control unit for axial load and cell pressure, and a data acquisition unit.

The design of the triaxial cell is shown in Fig. 1. A heater and a temperature sensor are installed inside the triaxial cell. An external temperature control unit monitors the temperature of the cell water. An inclined propeller (incline angle of 45°) driven by a motor is used to circulate the cell water. Compared with vertical propellers that have been used in other apparatuses, the inclined one can provide not only vertical but also horizontal water circulation, ensuring a uniform water temperature throughout the triaxial cell.

The axial load can be applied by either stress or strain controlled mode. In the stress controlled mode, the load is applied by an air-pressure actuator. In the strain controlled mode, the base of the triaxial cell is jacked up by a speed-controlled motor. The cell pressure is applied through a piston type water pressure amplifier. The maximum available cell pressure is 10 MPa. The axial load (stress control mode only) and cell pressure are controlled by two electro-pneumatic (E/P) regulators.

The axial load is read from an internal temperature-compensated load cell. The axial displacement is measured by a pair of external displacement transducers. The volumetric strain of a saturated porous geomaterial during drained shearing can be calculated using the volume of water expelled from a specimen.[23–24] A burette type volume change device with differential pressure measurement is used to measure the volume change.

The measured values of axial load, axial displacement, cell pressure and pore-water pressure and volume change are sent to a PC through a data-logger. Based on the measured values, a computer programme adjusts the necessary pressures and sends out voltage signals to the E/P regulators through a D/A (Digital/Analogue) board.

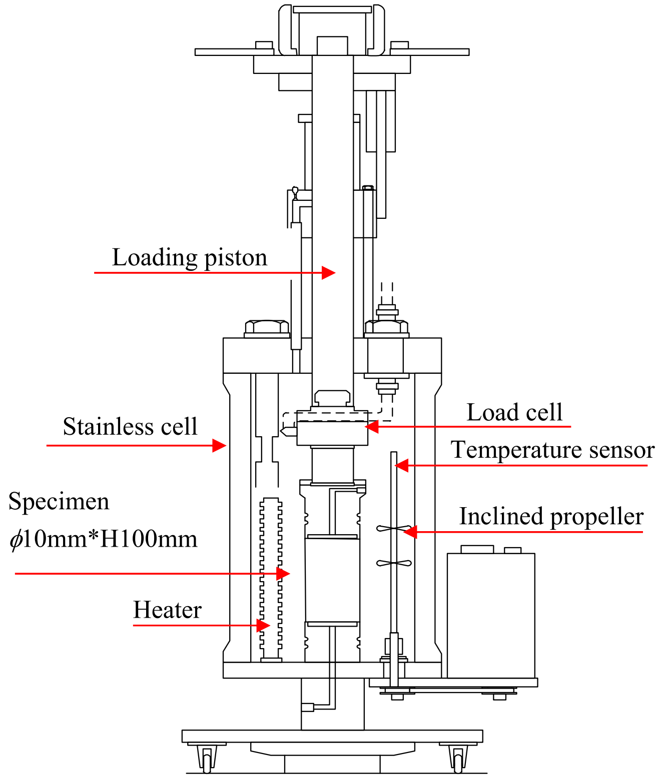

Fig. 1. Triaxial cell with heater and propeller.

The testing temperature range for the water-saturated specimen is 20 to 80 °C, because previous studies[20–21] suggest that this range is sufficient to significantly influence the shear strength and creep rate. Water is used as confining fluid for the sake of convenience. A latex jacket (membrane) is used for tests at temperatures of 20 °C and 40 °C. A Neoprene jacket that can endure temperatures up to 130 °C is used for tests at temperatures of 60 °C and 80 °C.

3. Test procedure

3.1. Soft rock specimen preparation

The green tuff sample used in this study is Ohya stone, which is a kind of rhyolitic welded tuff of the Miocene epoch (20 million years ago). Ohya stone has a uniaxial compressive strength of less than 20 MPa,[13] a porosity of 0.333, a water content of 20%, and a permeability k of 1.0×10^{-8} m/s. The stone consists of a large amount of glass and zeolite, with some plagioclase and quartz, as shown in Table 1 (data from the Ohya Stone Industry Cooperative Association). The rock was mined from a quarry in Tochigi Prefecture, Japan, at a depth of 30–60 m. Blocks with the fewest crevices or pockets and of the best quality were chosen for the specimens. Because the shear strength of soft rock will change considerably due to weathering, the rocks were kept in a wet state immediately after sampling, and avoided exposing to air for a long time.

The specimens were placed in a desiccator filled with de-aired water, then a vacuum was applied for seven days to obtain a high rate of saturation. By this procedure, a Skempton's *B* value greater than 0.95 can be achieved. The detailed procedure of specimen preparation can be referred to in Ye et al.[25] The dimensions of the cylindrical specimens are 50 mm in diameter and 100 mm in height, as shown in Fig. 2. Constant-rate-of-strain (CRS) oedometer tests with a strain rate of 3.3×10^{-7}/s (0.002%/min) were carried