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An experimental study on the physico-mechanical properties of two post-high-temperature rocks

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ABSTRACT

Using a hydraulic servo pressure testing machine, we investigated physical and mechanical properties of granite and sandstone samples after high-temperature treatment. Variations in apparent form, density, longitudinal wave velocity, damage, stress–strain curve, compression strength, peak strain, and elastic modulus with temperature are analyzed. We explored the differences in temperature effects on the physical and mechanical characteristics. Granite samples begin to gradually change from taupe to gray above 600 °C and sandstone samples start to gradually change from gray to brownish-red above 400 °C. 600 °C and 800 °C are respectively the brittle–ductile transition critical temperatures of granite and sandstone stress–strain curves. Rock density generally shows a gradual decreasing trend with temperature increasing. The influence of high temperature on sandstone density is much greater than granite. The decline rate of longitudinal wave velocity in granite is much greater than sandstone. Overall, damage increases gradually with temperature, but granite appears to suffer negative damage at 100 °C. Granite sample compression strength generally decreases with increasing temperature, while sandstone compression strength does not show obvious change between room temperature and 800 °C, but begins to decline rapidly above 800 °C. Peak strain increases with temperature and the increase rate of granite is similar to that of sandstone. Elastic modulus decreases with increasing temperature and decline rate of granite is much greater than sandstone. In addition, the temperature effect on the physical properties is much more intense than the effect on the mechanical properties of these two rock types.

1. Introduction

The interest for the mechanical behaviors of rock-like materials subjected to severe loading is growing (Caverzan et al., 2013). An appreciation of the influence of temperature on the mechanical behavior of rock has played a vital role in geological engineering (Funatsu et al., 2004; Alishaev et al., 2012; Liu and Xu, 2013). The mechanical characteristic of rock under high-temperature environments has become an important direction in rock mechanics research. Geological engineering areas, such as deep mining, geothermal resource development, high-level radioactive nuclear waste disposal and utilization of deep underground space, are all related to the mechanical properties of rocks under high-temperature environments (Logan, 1974; Voight, 2000; Watters et al., 2005; Shoko et al., 2006; Heap et al., 2011). Geological engineering may encounter sudden high-temperature events, and post-disaster reconstruction scenarios, assessment of which would also need to consider changes in the physical and mechanical properties of rocks exposed to high temperatures.

Hettema et al.(1999) performed a series of compaction experiments on well-sorted claystone grain aggregates at temperatures up to 1000 °C and under stresses up to 10 MPa to investigate the mechanisms controlling the compaction process. Zhang et al. (2001) measured the dynamic fracture toughness of Fangshan gabbro and Fangshan marble subjected to high temperature by means of the split Hopkinson pressure bar (SHPB) system. Lion et al. (2005) studied the influence of temperature on mechanical behavior and poro-mechanical properties of an oolitic limestone from Anstrude, France. Lam dos Santos et al. (2011) compared three types of artificial or engineered stones against two types of natural stones in what concerns to temperature, thermal aging and thermal shock effects on flexural strength and Young's modulus. Chen et al. (2012) conducted compression tests on granites mined from Ningbo, China, and obtained the influence of temperature on the fatigue life. Zhao et al. (2012) developed a servo-controlled triaxial rock testing system of high temperature and high pressure, for high temperature and high pressure rock testing. Ranjith et al. (2012) carried out uniaxial compressive strength testing of Hawkesbury sandstone at various temperatures between 25 and 950 °C to explore the mechanical response of the sandstone to significant changes in temperature. The testing results demonstrate a mechanical dependence on temperature whereby the compressive strength and elastic modulus for the sandstone increase

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Table 1
The mineral composition of rocks.

Mineral composition/%	Quartz	Calcite	Plagioclase	K-feldspar	Montmorillonite	Chlorite	Illite	Biotite	Amphibole	Diopside	Magnetite	Dolomite
Granite	17	–	37	8	–	–		18	12	4	4	–
Sandstone	52	27	8	6	1	2	3	–	–	–	–	1

with increasing temperature for temperatures less than c. 500 °C and decrease with increasing temperature for temperatures greater than c. 500 °C. Brotóns et al. (2013) investigated the effect of high temperatures in the mechanical properties of a calcarenite. The results show that uniaxial compressive strength and elastic parameters decrease as the temperature increases for the tested range of temperatures. Ozguven and Ozcelik (2013) studied the effect of heat in a fire and high temperatures on some properties of limestone and marble of different origins and textural characteristics were exposed to 200, 400, 600, 800 and 1000 °C temperature in the oven.

Given the existing studies discussed above, there is a consensus that under the influence of high temperatures below the rock melting point, rock mechanical properties change significantly. However, due to differences in mineral composition, and structure, including micro-fissures, the mechanical characteristics of rocks affected by temperature are complex. Various types of rocks under high temperature exhibit different mechanical characteristics of strength, and deformation, even if those of the same rock type under different geologic conditions, similarly, mechanical characteristics vary greatly. Although much knowledge has been gained through theoretical and experimental studies, the research has yet to meet the demands of practical engineering. Thus, the need to substantially increase knowledge of temperature effects on the physic-mechanical behaviors of rock is urgent. This paper adopts a hydraulic servo test system to carry out uniaxial compression tests on granite and sandstone after samples are subjected to temperatures from room temperature to 1000 °C. The variations in apparent form, density, longitudinal wave velocity, damage, stress–strain curve, compressive strength, peak strain, and elastic modulus of the two rock types with the change of temperatures are analyzed. Through regression analysis, we obtained the corresponding formulae, which provide a reference for problem-solving related to high-temperature rock engineering.

2. Mechanical tests on post-high-temperature rocks

Samples include two types of rock, granite and sandstone, with no visible flaws, collected from Qinling Mountains, China. In order to avoid laboratory bias, we maintained samples that bear average natural humidity. Rock samples with similar longitudinal wave velocity were selected prior to testing and processed to Φ 50 mm × 100 mm cylinders with a surface parallelism value within 0.05 mm, and surface flatness within 0.02 mm (ISRM, 2007). The average longitudinal wave velocities of granite and sandstone are, 4262 m/s and 2060 m/s, and the average densities are 2750 kg/m^3 and 2 650 kg/m^3. The main mineral compositions are shown in Table 1.

The heating device used herein is a RX3-20-12 box-type resistance furnace, composed of the control box and the furnace. The device has six built-in thermocouples used for heating, with automatic temperature control, silicon carbon rod heating elements, high-performance insulation fiber, and maximum operating temperature of 1200 °C, ensuring both stability and uniformity for heating of specimens from room temperature to 1000 °C. All the rock samples, before and after heating, must go through longitudinal wave velocity measurement with a RSM-SY5N non-metallic ultrasonic detection analyzer. We measure longitudinal wave velocity for each specimen 3 times, and take the average. The sensor frequency is 30 KHz, and sampling accuracy is within 1 μs. We use butter as a coupling agent between the sensor and the test specimen. We categorize sample test temperatures into 7 groups: room temperature, 100 °C, 200 °C, 400 °C, 600 °C, 800 °C and 1000 °C, each group equipped with no less than 3 specimens and with a heating rate of 10 °C/min. The predetermined temperature, once reached, is kept constant for 2 h. After that the specimens are left in the furnace to cool down to room temperature. For testing, we place samples carefully on the test machine and an axial load is applied with a loading rate of 0.8 MPa/s until failure occurs.

As can be seen from Figs. 1 and 2, with increasing temperature, changes have taken place in the color apparent form in the granite samples. Below 600 °C, the color change is not obvious, but granite samples begin to gradually change from taupe to gray and show increasing ringing above 600 °C. High temperature also has a significant effect on the apparent form of sandstone. Especially, above 400 °C, sandstone samples start to gradually change from gray to brownish-red. When the temperature reaches 800 °C, although apparent integrity remains good, one can intuitively feel that the internal damage is extensive. This is due to dehydration of the minerals in which physical and chemical changes take place.

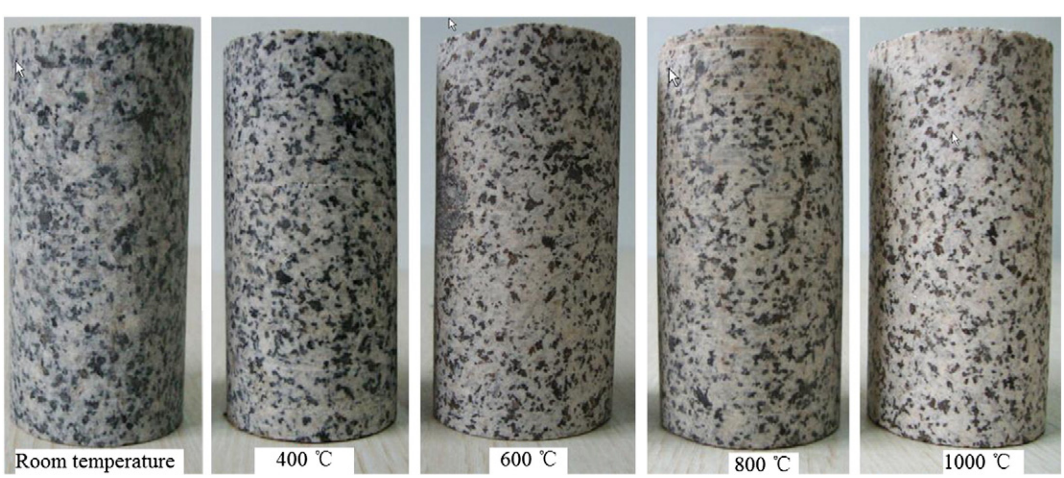

Fig. 1. Photos of granite specimens after typical temperatures.