Experimental Study of Compressive Mechanical Behavior of Red Sandstone after Heating-Cooling Treatment

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Abstract: Investigation of compressive mechanical property of rock materials after heating-cooling treatment is of great significance for deep geothermal energy exploitation. This study conducted a series of uniaxial compressive experiments on red sandstone subjected to different heating-cooling treatments, i.e., heating temperature 25, 200, 400, 600, 800, and 1000°C and cooling temperature of 10°C. The experimental results showed that with an increase in the heating temperature, the peak strength of red sandstone after heating-cooling treatments attained a maximum value under the heating temperature of 400°C. Furthermore, the variations of instantaneous elastic modulus of treated samples are the same as that of primary wave velocity. To further reveal the failure characteristics of heating-cooling treated red sandstone, related scanning electron microscopy tests were also carried out to analyze the microstructure of red sandstone samples after various heating-cooling treatments, to provide a valuable reference for studying the mechanical properties of rock materials after heating-cooling treatments.

Keywords: Red sandstone; Heating-cooling treatment; Compressive stress-strain behavior; Microscope property
1 Introduction

During the development of green energy, geothermal energy has obtained much attention compared to traditional energy due to its high reliability and low cost [1-2]. Geothermal energy is generally stored in underground spaces at a 4 km depth and distributed in a rock mass with high temperatures [3-5]. During the extraction of geothermal energy, the heat-carrying fluid plays a significant role. When cold water is fed into the rock stratum, it encounters the high-temperature rock mass and cools it rapidly. Here the dry hot rock within the deep rock stratum is forced to cool, transferring energy to the thermal fluid [6-7]. These high-temperature water cooling actions will seriously influence the physical and mechanical properties of the rock mass (e.g., weak strength and instability of rock) [8-11]. Therefore, it is necessary to investigate the mechanical properties of rock after different heating-cooling treatments.

Much effort has been made to study the various mechanical properties of rock after high-temperature or heating-cooling treatment, and a lot of successes achieved [12-14]. Shao et al. studied the effect of cooling rate on mechanical properties of heated Strathbogie granite with different grain sizes [15]. Zhang et al. explored the influence of mineral components within a rock material on the physical and mechanical properties of rock [16]. The investigation of the primary wave velocity of Yantai granite after thermal treatment was conducted by Zhu et al. wherein they reported that increasing temperature caused attenuation of primary wave velocity [17]. Hu et al. conducted a series of uniaxial and tri-axial tests on sandstone after high-temperature treatment, and its rheological properties were also studied and modeled [18]. The effect of high-temperature water cooling on the rutting resistance of rock or asphalt mixture was investigated and a Bayesian method was presented to describe the dynamic stability and resistance of rock or asphalt mixture [19]. From these current researches, it can be demonstrated that different high-temperature treatments deeply affect the mechanical properties of rock materials. High-temperature treatment will weaken a rock material’s strength, elastic modulus, and primary wave velocity [20]. However, few studies are related to rock materials after heating-cooling treatment, and the corresponding research of mechanical behavior is limited. Heating-cooling treatment was applied to rock materials to conduct uniaxial and tri-axial experiments, and thermal and mechanical parameters of the treated rocks were obtained [22]. In addition, cyclic loading tests of rock after various heating-cooling treatments were also performed to achieve mechanical characteristics and deformation behavior [21].

Considering the afore-mentioned, this study is outlined as follows. First, experimental samples, apparatus, and procedures will be introduced in Section 2. Section 3 presents elastic modulus variations, stress-strain curves, and primary wave velocity of the samples under different heating-cooling treatments. And then, in Section 4, the compressive deformation mechanisms of the samples after heating-cooling treatments are discussed in terms of mineral components. Finally, several conclusions will be drawn.

2 Uniaxial compressive experiments

2.1 Experimental samples, program and apparatus

The red sandstone experimental samples were obtained from the Liuyang mountain of Hunan province, China. Cylindrical samples were drilled from full red sandstone rock mass with no obvious cracks and fractures on the surface, whose sizes are 100 mm in height and 50 mm in diameter. As shown in Fig. 1, to ensure initial samples’ uniformity, a series of primary wave (P-wave) velocity tests were performed on the initial red sandstone samples to select 30 experimental samples with consistent mechanical properties. Then the selected initial red sandstone samples were heated to 200, 400, 600, 800 and 1000°C with a heating rate of 5°C/min by industrial muffle furnace, after which the target temperature was kept for 4h. After continuous heating treatments on the samples, the heated red sandstone samples will be cooled by water in the absence of air in a 50 L glass container for 2h until set temperature of 10°C is achieved. Different target heating temperatures signify different cooling rates, where
an average cooling rate of 20°C min was obtained, which is greater than previous results reported by Chaki [23]. The experimental apparatus is the uniaxial-tri-axial compressive experimental system in the State Key Laboratory for Geomechanics and Deep Underground Engineering, and the testing procedures are controlled automatically by a computer software. During the uniaxial compressive tests, the loading style is set as strain loading with a constant strain rate of 0.003 mm/s until the sample fails.

![Initial red sandstone samples](image1)

![Red sandstone samples after high temperature water cooling](image2)

**Fig. 1** Experimental initial red sandstone samples and red sandstone samples after heating-cooling treatment

As shown in Fig. 1, with an increase in temperature under the same cooling conditions, fine white particles were increasingly deposited on the surface of red sandstone samples, possibly with changes in the mineral compositions induced by the heating-cooling treatment. As a result, the color of each treated sample changed to dark red, red, and white. To explore the influence of different heating-cooling treatments on the microstructure evolutions of red sandstone samples, a series of scanning electron microscopy (SEM) tests were conducted on each experimental sample. To simplify the analysis, the red sandstone samples subjected to 25, 200-10, 400-10, 600-10, 800-10, and 1000-10°C (heating-cooling) were selected. From Fig. 2(a), there are small initial cracks within the sample at room temperature with 25°C, indicating that the initial red sandstone sample has almost complete microstructure. And when the sample is heated to 200°C and cooled to a target temperature of 10°C, there are a small number of micro-cracks and particles generated on the surface of the sample and in the weak junction of aperture, signifying the effect of heating-cooling treatment. With the temperature increased from 400 to 600°C, many micro-cracks were generated, and long cracks within the apertures begin to connect and penetrate each other. In addition, when the heated temperature reached 800 and 1000°C, due to the softening effect of the montmorillonite in water by high-temperature water cooling, the sample was divided into small particles with clear cracks (trans-granular cracks), induced weakening of the red sandstone sample.
Fig. 2 SEM electro images of red sandstone samples after various heating-cooling treatments with 25, 200-10, 400-10, 600-10, 800-10 and 1000-10°C

2.2 Uniaxial experimental stress-strain curves

Fig. 3 Total stress-strain curves of red sandstone after different heating-cooling treatments

To explore the influence of different heating-cooling treatments on the axial stress-strain behaviors of the red sandstone samples, the self-developed uniaxial and tri-axial experimental system by SKLGDUE was employed with its vertical loading pressure reaching 2000 kN. To eliminate the errors of each treated sample, three prepared samples under the same treated conditions were tested, and the average value of their mechanical parameters was evaluated and analyzed. With the rise in heating temperature, the development of the compaction stage of the sample required more time. Moreover, when heated and cooled at 800-10°C and 1000-10°C, the peak strength exhibited a sudden drop, accounted for by the fact that the high-temperature water cooling reduces the components of quartz and clay minerals within red sandstone samples. In addition, the samples became ductile due to the decrease in the
bonding force of the sample.

Fig. 4 presents variations between the peak strength of the treated red sandstone sample and the different heating-cooling treatments. It was demonstrated that the peak strength of the sample increased by heating-cooling treatment and then decreased with an increase in heated temperature, which is the same as in other previous studies [8, 15]. Analyzing the effects of heating-cooling treatment on the sample, temperature-induced heating-cooling effects resulted in the development of initial cracks within the rock and a decrease in the peak strength. The maximum peak strength is 88.304 MPa, corresponding to a heating temperature of 400°C and a cooling temperature of 10°C. From this peak point, peak strength decreased sharply until it reached 40.569 MPa, signifying that this heating-cooling treatment condition (400-10°C) is the critical temperature condition for the red sandstone.

![Fig. 4 Variations of peak strength of red sandstone after different heating-cooling treatments](image)

2.3 Effect of heating-cooling treatment on elastic modulus and primary wave velocity

![Fig. 5 Variations of elastic modulus of red sandstone after different heating-cooling treatments](image)

Initial loading tangent modulus ($E_0$) is a significant parameter in the evolution of the mechanical properties of the red sandstone after heating-cooling treatment, which is the initial slope of the stress-strain curve after the compaction stage under compressive experiments. As shown in Fig. 5, the evolutions of average tangent modulus, i.e., the elastic modulus of red sandstone samples that subjected to different heating-cooling treatments (25, from 200-10 to 1000-10°C) were illustrated and $E_0$ increases with temperature until it reached 400°C and then decreased with a constant rate, whose changes correspond to evolutions of compaction stages of each treated sample. Meanwhile, it is well-known that the P-wave velocity is closely related to elastic modulus [17]. In Fig. 6, the evolutions of P-wave velocity under different heating-cooling treatments agree with elastic modulus variations.

![Fig. 6 Variations of P-wave velocity under different heating-cooling treatments](image)
3 Discussions

The main mineral composition of red sandstone include clastic and clay minerals, e.g., quartz, feldspar, montmorillonite, and illite. Different high-temperature treatments will cause variations in thermal expansion and contraction coefficient of mineral particles within the rock, which will lead to thermal stress due to the nonuniformity of thermal deformation [20]. Subsequently, an induced thermal rupture will affect the mechanical properties of the rock. Moreover, the interlayer water, crystal water, and structural water within the rock mass will evaporate when the rock is subjected to rising temperatures. Then a specific mineral composition with little water or no water is formed, which weakened rock’s physical and mechanical properties [22]. The micro-cracks surrounding the crystal particles extended, penetrated, and run through the whole rock sample by rapid water cooling impaction. It can be concluded that the surface of rock is intact, and many cracks and fissures have developed inside the rock mass. In summary, the changes in physical and chemical properties, e.g., microstructure, mineral composition, and growth of cracks, after heating-cooling treatment is the main reason for the weakness and damage of the mechanical properties of rock mass.

4 Conclusions

To study the compressive mechanical properties of red sandstone after heating-cooling treatments using five high-temperature points, a series of compressive experiments were conducted on red sandstone samples after heating-cooling treatments to investigate the evolution of mechanical property. The peak strength of treated red sandstone samples increased up to 400°C and then decreased thereafter. The evolution behavior of the elastic modulus are the same as that of P-wave velocity. Both experience a short increase and then decreased with an increase in heating temperature. The microstructures of different heating-cooling treated samples were analyzed by conducting SEM tests, and the various characteristics of pores and cracks were provided. Finally, the damage of red sandstone samples resulting from different heating-cooling treatments is accounted for by changing and transforming mineral composition and water content, which will provide a reference for the subsequent studies in mechanical properties of rock materials under heating-cooling treatments.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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