Effect of thermal cycles on mechanical properties of a moderately weathered granite

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Abstract. The friction between the hard rock and milling wheels of a tunnel boring machine generates high temperatures. The high-temperature bedrock was then cooled down by circulating slurry. Therefore, thermal cycles were initiated within bedrocks. Understanding the response of mechanical properties of hard rock to these thermal cycles can be helpful in improving the drilling efficiency. In this study, uniaxial compressive strength and elastic modulus of a moderately weathered granite after various thermal cycles were determined. Results show that, for the specimens treated at a temperature of lower than 300°C, uniaxial compressive strength and elastic modulus decreased with the increasing numbers of thermal cycles. For the specimens treated at a temperature of higher than 400°C, uniaxial compressive strength and elastic modulus increased in the first six thermal cycles, and the tendencies reversed as the thermal treatment was further proceeded. For a given numbers of thermal treatment, uniaxial compressive strength and elastic modulus peaked at 200°C and began to decrease as the temperature further increases. These findings can be used to optimize the rotating speed of milling wheels during excavating granite bedrock.

1. Introduction
With an increasing demand for natural resources such as petroleum, coal, and geothermy, the depth of excavation would continue to increase. As the geological conditions are complex at a great depth, tunneling in deep rock formations becomes even more difficult. For example, the friction between the hard rock and milling wheels of a tunnel boring machine generates high temperatures. It is essential to investigate the mechanical behaviors of bedrock under these abnormal conditions.
The physical and mechanical properties of hard rock at high temperatures and the damage mechanism at moderate temperatures had been previously investigated [1-3]. Specifically, the uniaxial compressive strength of granite was decreased after heated to high temperatures [4]. The longitudinal wave velocity of granite was decreased after subjected to heating; the higher the temperature, the greater the drop in the longitudinal wave velocity [5-7]. In addition, the peak strength and elastic modulus of hard rock were found to change nonlinearly with the temperature [8, 9]. Test results also show that, changes in physical and mechanical properties are not obvious at moderate temperatures; when the temperature was raised to a given value, uniaxial compressive strength, elastic modulus, shear strength, and longitudinal wave velocity begin to decrease rapidly with the increasing temperature [10-12]. Although experimental investigations yielded consistent conclusions at high temperatures, these tests were mainly conducted at isothermal conditions. The behaviors of hard rock after subjected to thermal cycles were not fully investigated.

In this study, effects of thermal cycles on mechanical properties of a moderately weathered granite were investigated. Uniaxial compression tests were conducted to determine the uniaxial compressive strength and elastic modulus of granite specimens subjected to various thermal treatments. The effect of thermal treatment, including the temperature and numbers of thermal cycle, were analyzed based on the test results.

2. Methods

2.1. Material and sample preparation

The material used in this study was a moderately weathered granite collected from the Mawan tunneling project in Shenzhen, Guangdong, China. Cylindrical specimens with dimensions of 50mm × 100mm (diameter × height) were prepared from the core samples (see figure 1). The specimens were subsequently dried at 100°C for 24h to generate consistent initial moist conditions. Note that no artificial cracks formed during sample preparation.

![Figure 1. Granite specimens for uniaxial compression test](image)

2.2. Test equipments

The equipment for uniaxial compression tests is a universal testing machine which has a loading capacity of 200t (see figure 2a). A muffle furnace was employed for heating the specimens and the maximum operating temperature is 1200°C (see figure 2b). An ultrasonic tester (RSM-SY5T) was used for measuring the longitudinal wave velocity of the specimens.
2.3. Test procedure
To group the specimens, their longitudinal wave velocity was measured using the RSM-SY5T ultrasonic tester. A sensor coated with Vaseline was attached to both ends of the specimen. The duration that the shear wave transmits along the axis of the specimen was recorded. A longitudinal wave velocity of 3800–4200m/s was determined based on the testing results of 66 specimens.
All the specimens were divided into six groups, with a comparable longitudinal wave velocity in each group. One of the six groups (six specimens) was used for uniaxial compression tests at room temperature. Five of the six groups, with 12 specimens in each group, were subjected to thermal treatment prior to uniaxial compression tests; the specimens in each one of the five groups were further divided into four small groups, with three specimens in each small group (for a purpose of reliability of the test results). As for the thermal treatment, the initial dried specimen was heated to a scheduled temperature (i.e., 100°C, 200°C, 300°C, 400°C, and 500°C); the heating rate is 10°C/min in all the cases. After the target temperature attained, the specimen was immersed into water (with a temperature of 20°C); then, this specimen was heated to the same temperature and cooled down in the air. It is emphasized that the specimen underwent a heating-cooling cycle and a wetting-drying cycle in one thermal treatment. After a given times of thermal treatments (i.e., 3, 6, 9, and 12 times), uniaxial compression tests were conducted on the air-dried specimens using the universal testing machine. A loading rate of 0.5MPa/s was employed, and each test was ended after failure of the specimen. The average values of the uniaxial compressive strength and elastic modulus were determined for the three specimens underwent the same thermal treatment.

3. Results and analysis
3.1. Stress-strain relationship
The uniaxial compression curves (i.e., axial stress–axial strain relationship) of the specimens after various thermal treatments are shown in figure 3. All the specimens were observed to accomplish a brittle failure and the axial stress peaked at an axial strain of about 1–2%. In the case of the same times of thermal treatment, the axial stress at which the axial stress peaked increased with the increasing temperature and began to decrease after a boundary temperature.
This boundary temperature was observed to increase within the first six thermal treatments and begin to decrease as the numbers of thermal treatment further increases.

![Diagram](image1.png)

(a) After 3 thermal treatments  
(b) After 6 thermal treatments  
(c) After 9 thermal treatments  
(d) After 12 thermal treatments

**Figure 3.** Uniaxial compression curves of specimens after various thermal treatments

### 3.2. Uniaxial compressive strength

The peak stress was employed as the uniaxial compressive strength (UCS) of the specimen. UCS of the untreated specimen was determined to be 93.7MPa. UCS of the specimens after various thermal treatments is presented in figure 4. It is observed that, for the specimens treated below a temperature of 300°C, UCS presents an overall decrease with the increasing numbers of thermal treatment (figure 4a). For the specimen treated above a temperature of 400°C, UCS increased sequentially in the first six thermal treatments, and the tendencies reversed as the thermal treatment was further proceeded (figure 4a). On the other hand, UCS presented a non-monotonic relationship with the temperature (figure 4b). For a given numbers of thermal treatment, UCS was observed to increase with the increasing temperature and begin to decrease as the temperature reached beyond 200°C.
3.3. Elastic modulus

The slope of the stress-strain curve during elastic compression was deemed as elastic modulus of the specimen. The elastic modulus of untreated specimen was determined to be 10.2 GPa. The elastic modulus of the specimens after various thermal treatments is shown in figure 5. The experimental tendencies were similar to that of the uniaxial compressive strength. For the specimens treated at a temperature of lower than 300°C, elastic modulus decreased with the numbers of thermal treatment (figure 5a). For the specimens treated at a temperature of higher than 400°C, elastic modulus increased sequentially in the first six thermal treatments, and the tendencies reversed as the numbers of thermal treatment further increases (figure 5a). The elastic modulus also showed a non-monotonic relationship with the temperature (figure 5b).

In the case of the same times of thermal treatment, elastic modulus increased with the increasing temperature and began to decrease as the temperature exceeded 200°C.

It is observed that the temperature at which the UCS and elastic modulus peaked is identical; this indicates a consistent mechanism of the effects of thermal treatment on the mechanical properties of granite. The mineral crystals in granite specimen are expected to expand during heating. At a temperature of lower than 200°C, the initial voids in the specimens closed; as a consequence, UCS and elastic modulus increased because of a denser pore structure. As the temperature further increases, disintegration and phase change of the mineral crystals were considered to occur; consequently, the resistance of a looser pore structure to the external load was weakened.
4. Conclusions
Uniaxial compression tests were conducted on granite specimens after subjected to thermal treatment. UCS and elastic modulus were determined and effects of temperature and numbers of thermal treatment were analyzed. The following conclusions can be draw:
(1) For the specimens treated below 300°C, UCS and elastic modulus decreased with the increasing numbers of thermal cycle. As the temperature reached beyond 400°C, UCS and elastic modulus increased after the first six thermal treatments and the tendencies reversed as the thermal treatment was further proceeded.
(2) For a given numbers of thermal treatment, UCS and elastic modulus peaked at 200°C and began to decrease as the temperature further increases. This may be due to the expansion of the mineral crystals into initial voids at moderate temperatures and disintegration and phase change of the mineral crystals at very high temperatures.
(3) The abovementioned findings can be used for optimizing the rotation speed of the milling wheels during excavating granite bedrocks.

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