Effect of high temperature and confining pressure on the mechanical behavior of granite from Batang fault zone

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Abstract. The mechanical behavior of rocks under high temperature and confining pressure contributes to the design and stability analysis of deep-buried tunnels. In this study, a series of triaxial compression tests with high temperature and confining pressure was conducted on granite samples through a self-developed high temperature true triaxial test system. The granite samples were collected from the Batang fault zone located at the eastern of the Qinghai-Tibet Plateau. Based on the actual geological conditions, three temperatures (room temperature/70°C/110°C) and the confining pressure of 30 MPa were used. The stress–strain output, peak stress, and peak strain were summarized, and the relationship between the peak stress and temperature was obtained based on the experimental data. The results of the test show that high temperatures can weaken the mechanical properties of granite. The peak stress of the granite is decreased with the increase in temperature. A linear function can describe the strength behavior of the granite being studies at different temperatures. The experimental data obtained in this study can be used as basic parameters for the construction and stability evaluation of the deep-buried tunnels near the Batang fault zone.

Keywords: High temperature; High confining pressure; Triaxial compression; Granite; Mechanical properties

1. Introduction

In the next decade, Tens of deep-buried tunnels will be constructed in the Tibet Plateau of China. Due to the presence of large-scale thermal faults near the tunnel site, deep-buried tunnels in western China are exposed to high geo-temperature and -stress. The rock mechanical properties are sensitive to geo-temperature and -stress. Among the rock mechanics properties, strength and deformation contribute to the stability analysis of surrounding rocks of deep-buried tunnels. Therefore, it is necessary to investigate the effect of temperature and stress levels on the strength and deformation behavior of rocks.

Recently, some triaxial compression tests have been conducted to study the effect of temperature and confining pressure on the rock mechanical properties [1-8]. Based on the experimental results obtained, we found that the temperature magnitude, temperature gradient, and heat treatment method
affect the mechanical properties of rocks. The mechanical properties of rocks, after high temperature treatment, are different from those under high temperature [1, 3, 5, 8].

In previous studies, different confining pressures were used to simulate the different geo-stress levels. Two types of triaxial compression tests are used to investigate the thermal effect of rock mechanical behavior. The first triaxial compression test is conducted at high temperatures. The second triaxial compression test is conducted on the samples that have undergone high temperature treatment. The first triaxial compression test corresponds to the in situ conditions in the surrounding rocks of a deep-buried tunnel than the second triaxial compression test. The triaxial compression tests under high temperature and confining pressure are limited due to limited instruments [3]. The geo-temperature of a deep-buried tunnel is usually less than 150°C [7], whereas previous studies are conducted at a wider temperature range (up to 800°C).

The relationship between the mechanical behavior of the surrounding rocks and the geo-temperature, under a relatively small temperature gradient, is an open issue in deep-buried tunnel engineering. Thus, this paper presents experimental results of triaxial compression tests conducted on granite under different high temperatures and confining pressures.

2. Materials and Test method

2.1. Sample preparation

The granite cores used in this study were collected from the Batang fault zone in the eastern of the Qinghai-Tibet Plateau, China (30°00′N, 99°07′E). These cores are at a depth of about 460 m beneath the ground surface. Since homogeneous intact samples are required, complete granite cores with good homogeneity are chosen for specimen preparation. According to the International Society for Rock Mechanics (ISRM) recommendation [9], series of 100-mm length and 50-mm diameter cylindrical specimens were prepared for triaxial compression tests. Each specimen is cut using a diamond wire saw and polished at both ends. The tolerances for the end surface conditionality and perpendicularity are ±0.01 and ±0.02 mm, respectively.

Before the triaxial compression test, the densities and P-wave velocities of the granite samples are measured. To ensure the uniformity of the sample as much as possible, granite samples with a density in the range of 2.68–2.72 g/cm³ and a P-wave velocity in the range of 5000–6000 m/s were selected. The selected granite samples are shown in Figure 1.

![Granite samples](image)

**Figure 1.** Granite samples

2.2. Experimental equipment

The high temperature true triaxial compression test system (Figure 2) developed by Northeastern University (China) is used in this study to realize the conventional triaxial compression tests. The test system is composed of three main components: a three-dimensional stress-loading system, a high temperature control system, and a servo-control and data acquisition system.
The test system has a mixed loading mode, which is similar to the true triaxial test system designed by Mogi [10]. The three-dimensional stress-loading system consists of two rigid biaxial loading apparatus and a confining pressure cell. The three principal stresses are independently servo-controlled. As indicates in Figure 2, in true triaxial compression, major (σ1) and intermediate (σ2) principal stresses are applied using rigid biaxial loading apparatus, whereas the minor principal stress (σ3) is applied using confining pressure cell. In conventional triaxial compression (CTC), σ3 and σ2 are applied using confining pressure cells (σ2 = σ3), whereas σ1 is applied using rigid biaxial loading apparatus.

The maximum loading capacity of the rigid biaxial loading apparatus is 2000 kN, and the force precision is 0.1 KN. The maximum confining pressure is 70 MPa, and the stress precision is 0.1 MPa. In high temperature triaxial compression tests, the axial (ε1) and lateral strains (ε2) of granite samples are measured, respectively, using two axial-linear variable-differential transducers (LVDT) and a radial LVDT. The axial and radial LVDTs are placed parallel and perpendicular to the sample axis, respectively. In addition, the measurement range of these LVDTs is ±2.5 mm, and the precision is 1 um.

The high temperature control system consists of a heat source, a temperature servo-control module, and a cooling system. The maximum temperature provided by the heat source is 250℃; the temperature precision is 0.1℃. In this study, four electric heating plates with a total power of about 6000 W are used to apply the target temperature. Among them, two circular electric heating plates are placed at the bottom of the sample. The other two are rectangular and located in front of and behind the sample. In addition, four temperature sensors with a measurement range of 350℃ and an accuracy of 1℃ are used to monitor the temperature in real-time. The temperature servo-control module adjusts the temperature in real-time, according to the monitored temperature, thus, forming a stable temperature field around the tested sample.

![Figure 2. True triaxial compression system with high temperature and confining pressure](image)

1- Three-dimensional stress loading frame  
2- High temperature control system  
3- Servo control and data acquisition system

**Figure 2.** True triaxial compression system with high temperature and confining pressure

**2.3. Experimental program and procedure**

According to the field measurement in the deep boreholes in the Batang fault zone, the in situ stress at a depth of 1080 m is analyzed. We found that the major horizontal, minor horizontal, and vertical stresses are about 29.52, 20.38, and 28.62 MPa, respectively. Therefore, in this study, the confining
pressure of 30 MPa is chosen. In addition, the field measurement results indicate that the geothermal temperature in the Batang area varies within the range of [25, 85] °C, in which the temperature of 70°C is one of the representative temperatures. The machines used for engineering construction generate heat during operation. Therefore, the temperature of the surrounding rock may be higher than the geothermal. Considering the factors mentioned above, three different temperatures (room temperature/70°C/110°C) are selected to study the effect of temperature on the granite mechanical behavior.

Each high temperature triaxial compression test can be done in three loading stages: hydrostatic, thermal, and deviatoric stress loadings. In each loading stage, stress, strain, temperature, and confining pressure are recorded in real-time using a data acquisition system. Thus, we can judge whether the current test meets the requirements in real-time. The details of the three loading stages are as follows.

1. Hydrostatic stress-loading stage: Apply the confining pressure with a constant rate of 0.1 MPa/s up to 30 MPa and maintain it. Then, the required hydrostatic stress state ($\sigma_1 = \sigma_2 = \sigma_3 = 30$ MPa) is realized.

2. Thermal stress-loading stage: After the strain stabilization, under the hydrostatic stress state, apply the temperature at a rate of about 5°C/min up to the target value and maintain it at the value. The test sample expands due to thermal stress. The strains of the tested sample are changed with the increase in temperature. Therefore, to measure the strains caused by the deviatoric stress-loading, the strains must be stable before applying deviatoric stress. In this study, we found that two hours are needed for strain stabilization when the temperature is lower than 150 °C.

3. Deviatoric stress-loading stage: After the strain stabilization under the effect of target temperature, such as 110°C, the deviatoric stress is loaded with a constant displacement rate of 0.1 mm/min until the sample failure occurs.

3. Results and analysis

3.1. Stress–strain output

The stress–strain outputs are shown in Figure 3 for the triaxial compression tests at different temperatures under confining pressure of 30 MPa. In Figure 3, $\sigma_1 - \sigma_3$, $\epsilon_{\text{v}}$, and RT denote deviatoric stress, volumetric strain, and room temperature, respectively. Figure 3a shows the relationship between deviatoric stresses and strains (axial and lateral strain). Figure 3b presents the evolution of volumetric strains from the deviatoric stress.

Figure 3a shows that the deviatoric stress vs axial strain curves can be divided into four stages: an initial compaction stage, a linear elastic deformation stage, an elastoplastic deformation stage, and a post-peak stage. In the initial compaction stage, the granite samples show initial nonlinear deformation due to the closure of the microcracks. The nonlinear deformation is related to the temperature. For instance, the nonlinear deformation under 75°C is more evident than that under room temperature. This is because of more thermal cracks generated under high temperatures. In the post-peak stage, the deviatoric stress decreases with increasing axial strain, which demonstrates that the granite has a brittle failure.

As shown in Figure 3b, under the influence of high confining pressure and temperature, the volumetric strain experiences an initial increasing phase at a low deviatoric stress level. Then, a stable decreasing phase appears with the increase in deviatoric stress, which corresponds to the initiation and propagation of microcracks. The turning points of the volumetric strain correspond to the initial yield stress. These phenomena reveal that the compression–dilatation transition occurs in granite.

The peak stresses and peak strains changed with temperature in triaxial compression tests (Figure 3). The evolution of peak stresses and strains under the influence of temperature is further discussed in the next section.
3.2. Effect of high temperature on the strength

Figure 4 shows the evolution of the peak stress with temperature changes in triaxial compression. In Figure 4, $\sigma_P$ denotes the peak stress, and its value equals the maximum deviatoric stress.

As shown in Figure 4, the peak stresses obtained in the tests with temperatures of 70°C and 110°C are 374.3 and 359.4 MPa, respectively. We found that the peak stress decreases by 8.2% and 11.8% when the temperature is 70°C and 110°C than the 407.7-MPa peak stress obtained in the test at room temperature. Therefore, the increase in temperature degrades the peak stress of the granite in the triaxial compression tests. To quantify the degradation of the peak stress, the following relation is proposed to describe the evolution of peak stress with temperature:

$$\sigma_{P,T} = \sigma_{P,RT} - \eta T, \quad 25^\circ C \leq T \leq 110^\circ C$$

In this relation, $\sigma_{P,RT}$ and $\sigma_{P,T}$ are the peak stress at room temperature (RT) and temperature, $T$, respectively. $\eta$ is the parameter that depicts the thermal degradation effect of peak stress.

3.3. Effect of high temperature on the deformation behavior

Figure 5 presents the evolution of peak strains with temperatures. In Figure 5, the $\varepsilon_{1,\text{peak}}$, $\varepsilon_{3,\text{peak}}$, and $\varepsilon_v,\text{peak}$ are the axial, lateral, and volumetric strains corresponding to the peak stresses, respectively.
As shown in Figure 5, the axial peak strains are 0.89%, 0.87%, and 0.83%, for the real-time temperature of 25°C, 70°C, and 110°C. The corresponding lateral strains are 0.60%, 0.58%, and 0.55%, while the corresponding volumetric strains −0.31%, −0.25%, and −0.28%. These results indicate that the deformation of granite is insensitive to temperature changes when the temperature is in the range of 25°C to 110°C due to the constraint effect of high confining pressure (30 MPa). At failure, all the volumetric strains are negative. Thus, the granite has shear dilatancy behavior when it is subjected to high confining pressure and temperature. The failure of the granite is dominated by compression-induced dilation.

![Figure 5. Evolution of peak strains with real-time temperature under triaxial compression](image)

4. Conclusion
A series of high temperature triaxial compression tests with a confining pressure of 30 MPa have been conducted on granite samples. The effect of temperatures on strength and deformation behavior has been investigated. Based on the obtained experimental data, the following conclusions can be drawn:

(1) The peak stress of the granite decreases with increasing temperature. The linear relation provides the best fitting for the variation in the peak stress as a function of temperature change.

(2) When the temperature is in the range of 25°C to 110°C, the deformation of granite is insensitive to temperature changes due to the constraint effect of high confining pressure.

(3) Under the influence of high temperature and confining pressure, the compression–dilatation transition occurs in granite. In addition, the failure of granite is dominated by compression-induced dilation.

However, this study presents only the primary experimental results of the drilled granite due to the difficulty in obtaining deep borehole samples. More experiments will be conducted to verify the observations and findings of this study. Moreover, true triaxial tests under high temperature and pressure will be conducted on the samples in the next step.

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