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Experimental and modeling investigation on the dynamic response of granite after high-temperature treatment under different pressures

Hui Guo [a], Weiguo Guo [a,*], Yue Zhai [b,*], Yu Su [c]

[a] School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China
[b] School of Geology Engineering and Geomatics, Chang'an University, Xi'an 710072, China
[c] Department of Mechanics, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- Dynamic test is conducted under coupled effects of temperature and confined pressure.
- Variation laws of peak stress, peak strain and modulus with temperature are analyzed.
- Mechanical properties at unconfined and confined pressure are studied comparatively.
- The main failure modes of granite under uniaxial impact loading are discussed.
- A temperature and rate dependent damage constitutive model is proposed.

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ABSTRACT

In this work, the dynamic compressive mechanical properties of Beishan granite are investigated under the condition of uniaxial load and confined pressure, respectively. The purpose of this investigation is to study the effect of hydrostatic pressure and pre-heating temperature on the strength property and failure of such material. The investigation is carried out with the use of a large-diameter split-Hopkinson pressure bar (SHPB), which is equipped with an active confining device. The dynamic stress–strain behaviors of the granite samples under different confined conditions are obtained with a pre-heating temperature ranging from 25 to 800 °C. We analyzed the temperature-dependent variation of the peak stress, peak strain and elastic modulus of the material under selected values of confined pressure. It is observed that the uniaxial compressive behavior of Beishan granite under unconfined pressure is strongly dependent on the pre-heating temperature. The values of the peak stress and the elastic modulus both decrease as the pre-heating temperature increases, while the value of the peak strain increases with the rise of pre-heating temperature, indicating a characteristic change from elastic-brittle to elastic–plastic. Under confined pressure, the strength of the material can be greatly improved, and higher pre-heating temperature tends to bring down the value of the strength. With the confined configuration, the strengthening of the peak stress is not significantly associated with the value of the confined pressure; instead the dependence on the strain rate becomes more remarkable. For the temperature effect, the value of the peak stress can be linearly correlated with the temperature level through comparative analysis. Moreover, the elastic modulus of the material can be associated with the temperature by a functional form, known as the temperature shift factor. Finally, an elastoplastic-damage constitutive model is established to predict the dynamic mechanical behavior of the material after high-temperature treatment under different confined pressures.

1. Introduction

Granite with its high strength, good mechanical stability, low permeability, beautiful color and so on, is widely used in various industries, such as mining, civil construction, railway and highway tunnels, nuclear waste storage and other fields [1–3]. In recent years, with the increase in granite demand and decreasing of shallow resources, deep exploration is very necessary. With the increase of mining depth of granite, the in-situ stress and temperature of rock stratum rise to some extent, and the dynamic mechanical properties of deep rock mass differ from those of shallow rock mass. Furthermore, deep rock engineering in high

* Corresponding authors at: School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China (W. Guo). School of Geology Engineering and Geomatics, Chang'an University, Xi'an 710072, China (Y. Zhai).

E-mail addresses: weiguo@nwpu.edu.cn (W. Guo), zy@chd.edu.cn (Y. Zhai).

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temperature and high pressure environment is prone to rock burst, instability and other major engineering accidents. Therefore, the key to solve the practical engineering problems is to have a better understanding of the dynamic mechanical properties of granite under high temperature and high pressure.

With the increasing application of granite, research has been done on the mechanical properties of the material under dynamic loading condition. For example, Friedman et al. [4] conducted uniaxial compression tests on granite with the strain rate from 10^{-4} to 10^3 s^{-1}. It was found that the elastic modulus and failure strength of granite increase with the increase of strain rate. Janach et al. [5] investigated the uniaxial compressive mechanical behaviors of granite using a split Hopkinson pressure bar system. It was observed that the dynamic loading condition can lead to a much higher uniaxial compressive strength than the static loading condition. Subsequently, Li et al. [6] obtained the rate-dependent stress–strain behavior through the dynamic compression measurements of granite subjected to intermediate loading rate. Dai et al. [7] performed experimental study on flexural tensile strength anisotropy of Barre granite over a wide range of strain rates. They found strong flexural strength anisotropy in the material under quasi-static loading condition, while diminishing anisotropy was noticed under dynamic loading condition. In addition to the study of strain-rate effects, experimental investigations were carried out to study the thermodynamic properties of granite at varying temperatures. In earlier research, Atkinson et al. [8] studied the fracture toughness of granite at the temperature range of 20–500 °C, and observed the damage process of the material under high temperature by acoustic emission method. Alm et al. [9] studied the mechanical response of granite at different temperatures, and obtained a relation between the mechanical properties of granite and the density of cracks after high temperature. More recently, Chen et al. [10] reported the influence of temperature on the creep properties of granite. They concluded that the temperature variation exceeding 90 °C has great influences on the critical strain of creep failure of the material. Yang et al. [3] studied the thermal-damage response of granite after different temperatures, and obtained the evolution mechanism of micro-cracks of the material in different temperature ranges. In addition, the mechanical properties of granite are studied under the condition of multiaxial loading. Brace et al. [11] carried out dynamic triaxial compression tests on granite at the strain rate from 10^{-8} to 10^{-3}/s, and their results show that the failure strength of the material increases with the increase of strain rate under dry and water-saturated conditions. Li et al. [12] conducted triaxial compression tests on Bukit Timah granite under different strain rates and confined pressures, and found that the compressive strength of granite increases with the increases of strain rate and confined pressure, while its Poisson's ratio have not apparent changing rule. Subsequently, Lin et al. [13] investigated the triaxial compressive mechanical behavior of Inada granite with confined pressure of 50 MPa under different strain rates, and the results show that the compressive strength of granite increases linearly as the increase of logarithmic strain rate in range of intermediate strain rates. Hokka et al. [14] studied the influence of hydrostatic pressure on the strength and fracture behavior of Kuru granite. They observed that there is an increase in the material strength with the increase of confined pressure. Some scholars have also put forward some constitutive models suitable for granite materials through experimental research and theoretical analysis. For example, Maranini et al. [15] carried out the triaxial creep tests of granite at confining pressure varying from 0 to 40 MPa, and developed a non-associated viscoplastic constitutive model. Saksala et al. [16] developed a constitutive model suitable for the dynamic compressive behavior of Kuru granite under different confined pressures based on damage mechanics and viscoplastic theory. Chen et al. [17] also produced a damage-mechanism-based creep model suitable for granite at different temperatures according to the experimental data of temperature dependent creep behavior. To sum up, preliminary researches have been carried out to study the mechanical properties and failure characteristics of granite under various working conditions. Valuable experimental results are obtained on this topic. However, there remains questions regarding the mechanical properties and failure characteristics of granite under the coupled effect of high temperature, high pressure and dynamic loading condition. Specifically, how are high temperature and high pressure influencing the mechanical properties of granite? These are the questions that need to be answered while the mining depth is fast increasing during the recent years. Therefore, there is an urgent need to conduct a comprehensive study on the failure mechanism of granite with particular concentration on the coupled influence from strain rate, temperature as well as multiaxial loading.

As the main task of this paper is to examine the dynamic mechanical behavior of granite after high-temperature treatment under different confined pressures, a systematic experimental study for Beishan granite is carried out with selected values of confined pressure and pre-heating temperature. The dynamic mechanical test is done by using a large-diameter split-Hopkinson pressure bar with an active confining device. The selected value of the confined pressure is 10 and 20 MPa, respectively, and the pre-heating temperature ranges from 25 to 800 °C. The measured compressive stress–strain characteristics of the material are then compared under different loading conditions. Based on the experimental results, we established a damage model to describe the temperature dependent mechanical behavior of granite under different loading conditions. The applicability of the established model is finally confirmed by the experimental results.

2. Experimental methods

2.1. Material and specimens

The granite material in this paper is provided by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, China. This granite material is generally known as Beishan granite in the previous studies [18,19]. The main components of Beishan granite are alkali feldspar and quartz, its natural density is 2.8 g/cm^3. To assure a uniform stress state and minimize inertial effect and frictional effect in SHPB tests [20], the dimension of the specimens used in dynamic experiments is designed as Φ100 mm × 50 mm, as shown in Fig. 1. In order to meet the accuracy requirements of SHPB tests, the preparation of standard specimen has experienced the treatment processes of coring, cutting and grinding. The surface roughness of the treated specimens is less than 0.01 mm, and the nonparallelism of upper and lower end faces is less than 0.5×10^{-3} mm. Here, the surface roughness is the quantitative representation of the rugged phenomenon on the cylindrical surface of the specimen, while the nonparallelism refers to the maximum allowable error of the upper end face of cylindrical specimen which is not parallel to the lower end face. The machining precision of granite specimens is satisfied with the design requirements of SHPB experiments for brittle materials in the ASM Handbook [20], thus avoiding premature failure of the specimens.

2.2. High-temperature test technology

The high-temperature environmental test equipment consists of SX2-10-13 box-type resistance furnace and AI-518 intelligent temperature controller, which can be utilized to achieve a high temperature from 200 to 1000 °C. To ensure that resistance furnace has a dry environment before heating, the high-temperature furnace box is heated to 200 °C for 6 h, and then heated to 800 °C for 2 h, which ensure that the resistance furnace can meet the temperature conditions required for this test. If the heating rate is too fast during the heating process, a burst phenomenon would occur in the specimen because of the internal heat accumulation. Therefore, the slow heating is taken to ensure uniform heating of granite specimens during heating, and the temperature is maintained for 2 h after warming to the target temperature. After the specimen is heated, it is placed in a room temperature environment for natural cooling, and the natural cooling process lasts for two weeks before further experiments. It can be observed from Fig. 1 that granite specimens post high temperatures showed varying degrees of color change and damage. With the processing temperature rising, the color of granite specimens graded gradually from dust color to snuff color, and at the same time the damage crack increased gradually.