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Effect of strain rate on the dynamic compressive mechanical behaviors of rock material subjected to high temperatures

Shi Liu [a,*], Jinyu Xu [a,b]

[a] Aeronautics and Astronautics Engineering College, Air Force Engineering University, Xi'an 710038, China
[b] College of Mechanics and Civil Architecture, Northwest Polytechnic University, Xi'an 710072, China

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ABSTRACT

Strain rate is not only an important measure to characterize the deformation property, but also an important parameter to analyze the dynamic mechanical properties of rock materials. In this paper, by using the SHPB test system improved with high temperature device, the dynamic compressive tests of sandstone at seven temperatures in the range of room temperature to 1000 °C and five impact velocities in the range of 11.0–15.0 m/s were conducted. Investigations were carried out on the influences of strain rate on dynamic compressive mechanical behaviors of sandstone. The results of the study indicate that the enhancement effects of strain rates on dynamic compressive strength, peak strain, energy absorption ratio of sandstone under high temperatures still exist. However, the increase ratios of dynamic compressive strength, peak strain, and energy absorption ratio of rock under high temperature compared to room temperature have no obvious strain rate effects. The temperatures at which the strain rates affect dynamic compressive strength and peak strain most, are 800, and 1000 °C, respectively. The temperatures at which the strain rates affect dynamic compressive strength and peak strain weakest, are 1000 °C, and room temperature, respectively. At 200 and 800 °C, the strain rate effect on energy absorption ratio are most significant, while at 1000 °C, it is weakest. There are no obvious strain rate effects on elastic modulus and increase ratio of elastic modulus under high temperatures. According to test results, the relationship formula of strain rate with high temperature and impact load was derived by internalizing fitting parameters. Compared with the strain rate effect at room temperature condition, essential differences have occurred in the strain rate effect of rock material under the influence of high temperature.

1. Introduction

Information regarding dynamic mechanical properties of rock material represents a crucial issue for rock structural engineering (Zhang and Zhao, 2013), such as mining excavation, tunnel excavation, civil works and blasting engineering. In fact, the structural design and assessment of underground rocks engineering need to take into account particularly severe dynamic scenarios, which could occur on the structures during their lifetime (e.g. severe earthquakes and impact loads) (Asprone et al., 2014). Strain rate is not only an important measure to characterize the deformation property, but also an important parameter to analyze the dynamic mechanical properties of rock materials. Different rock materials exhibit different mechanical responses with the change of strain rate (Zhang and Zhao, 2014). So strain-rate effects on the compressive mechanical properties of various rock-like materials, e.g., concrete, rock etc, have become an

* Corresponding author. Tel.: +86 13572206216.
E-mail address: fzdyhtbdy@126.com (S. Liu).

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important consideration in protective structure engineering. Strain rate can be classified according to its amplitude: low strain rates (10^{-5}–10^{-2} s^{-1}), intermediate strain rates (10^{-2}–10^{2} s^{-1}), high strain rates (10^{2}–10^{4} s^{-1}) and ultra high strain rates (more than 10^{4} s^{-1}) (Blanton, 1981; Tarasov, 1990; Bischoff and Perry, 1991). The use of the split Hopkinson pressure bar (SHPB) apparatus (Kolsky, 1949) to obtain experimental dynamic material properties is a popular and acceptable procedure to measure the mechanical properties at high strain rates. Rock material behavior under dynamic loading depends on the strain rate such that with the increase of strain rate, rock peak strength, strain, and elastic modulus rise. This strain rate hardening effect is particularly pronounced with brittle materials such as rocks. A variety of researches had been conducted to investigate the strain rate effect on mechanical properties of rock-like brittle materials (Kumar, 1968; Brace and Jones, 1971; Ross et al., 1989; Bischoff and Perry, 1991; Gray, 2000; Grote et al., 2001; Li and Meng, 2003; Grantham et al., 2004; Zhou et al., 2007; Li et al., 2008; Wang et al., 2009; Dai et al., 2010; Liu et al., 2011;Hao et al., 2013).

There are also lots of topics in rock mechanical engineering, such as underground coal gasification, underground construction in case of fire, developing geothermal resources, which are related to temperature effect. At present, a great number of tests have been performed to the mechanical properties of rock under high temperature (Heuze, 1983; Shmonov et al., 1999; Funatsu et al., 2004; Paterson and Wong, 2005; Liang et al., 2006; Abdulagatova et al., 2009; Chen et al., 2012).

However, previous works were only limited to dynamic mechanical investigations at room temperature, or high temperature investigations at low or intermediate strain rates using the servo-controlled testing machines, both of which do not reveal the dynamic impulsions of rock materials under the high temperature subjected to high strain rate loads.

Strain rate effect on rock material, as mentioned in the previous paragraphs, is usually aimed at room temperature. However, as one of the dynamic mechanical parameters of rock material, strain rate is not only affected by impact load, but also directly affected by temperature. Currently, few reports about the mechanical properties of high strain rates on rock under high temperature have been published in the literature so far, even though it is the theoretical foundation for the study of rock explosion mechanism.

In this paper, we will aim to address the following two main questions:

(1) How does the strain rate affect dynamic properties of rock materials under high temperature environment subjected to impact load, and whether the strain rate hardening effects still exist?
(2) How do the impact load and temperature influence the strain rate?

Aiming above problems, based on SHPB test system improved with high temperature device, the dynamic compressive tests of rock under different impact loads and high temperatures were carried out. The influences of strain rate under different high temperatures on dynamic compressive mechanical behaviors of sandstone were studied in Section 3. According to test results, by internalizing fitting parameters, the changing rule of the strain rate with high temperature and impact load was derived and proposed in Section 4.

2. Experimental study

2.1. Material

All testing was carried out on sandstone specimens prepared from block samples which were taken from the Qinling Mountains, located at the Central China. The rock blocks were picked up just after the excavation and transported to the laboratory, where the samples (ϕ 100 × 50 mm) were cored ensured maximum specimen uniformity and repeatability in the testing results (ISRM, 1979). Later non-destructive ultrasonic P-wave velocity tests performed in samples indicated that the rock exhibits a clear isotropic behavior. It is a homogeneous medium-grained sandstone made of quartz (52%), calcite (27%), plagioclase (8%), k-feldspar (6%), illite (3%), chlorite (2%), montmorillonite (1%) and dolomite (1%) with longitudinal wave velocity (2060 m/s), density (2.65 g/cm^3) and static compressive strength (59.68 MPa).

2.2. Test set-up

To carry out dynamic compressive tests on rock material under high temperature with split Hopkinson pressure bar, the traditional ϕ 100 mm SHPB test device need to be improved. The self designed ϕ 100 high-temperature mm SHPB test device (Fig. 1) consists of the traditional ϕ 100 mm SHPB test device, box type resistance furnace and real-time temperature-control device (Liu and Xu, 2013).

The specimens were first heated in the box type resistance furnace to the temperatures of 100, 200, 400, 600, 800 and 1000 °C, respectively, at the heating rate of 10 °C/min. Then the target temperatures were maintained for 3 h to achieve the thermal steady state. Thereafter, they were transferred to the tube-type heating furnace one by one. The impact velocity was controlled to 11.0–15.0 m/s by adjusting the air pressure.

Based on the plane and stress equalizing assumption, and using the one-dimensional stress wave theory, the measurement data can be converted into strain rate, stress and strain, which can be expressed respectively as follows (Lindholm, 1964; Ravichandran and Subhash, 1994):

$$\left.\begin{aligned} \dot{\varepsilon}(t) &= \tfrac{c}{l_s}(\varepsilon_i - \varepsilon_r - \varepsilon_t) \\ \varepsilon(t) &= \tfrac{c}{l_s}\int_0^t(\varepsilon_i - \varepsilon_r - \varepsilon_t)dt \\ \sigma(t) &= \tfrac{A}{2A_s}E(\varepsilon_i + \varepsilon_r + \varepsilon_t) \end{aligned}\right\} \quad (1)$$

where E is Young's modulus of bars, c is wave velocity in bars, A and A_s are cross-sectional areas of bars and specimen, respectively; l_s is original length of specimen, ε_i, ε_r, ε_t are incident, reflected and transmitted strain, respectively.