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Effects of strain rates on mechanical properties of limestone under high temperature

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ABSTRACT

The experimental tests for limestone specimens at 700 °C in uniaxial compression were carried out to investigate the mechanical effects of loading rates on limestone by using a MTS810 rock mechanics servo-controlled testing system considering the loading rate as a variable. The mechanical properties of limestone such as the stress–strain curve, variable characteristics of peak strength and the modulus of elasticity of limestone were studied under the strain rates ranging from 1.1×10^{-5} to 1.1×10^{-1} s^{-1}. (1) Sharp decreases were shown for the peak strength and elastic modulus of limestone from 1.1×10^{-5} to 1.1×10^{-4} s^{-1} at 700 °C as well as a downward trend was shown from 1.1×10^{-4} to 1.1×10^{-1} s^{-1} with the rise of the strain rate. (2) The peak strain increased from 1.1×10^{-5} to 1.1×10^{-4} s^{-1}, however, there was no obvious changes shown for the peak strain of limestone from 1.1×10^{-4} to 1.1×10^{-1} s^{-1}. These results can provide valuable references for the rock blasting effect and design of mine.

1. Introduction

Experimental study on the mechanical properties of loading rates on limestone under high temperature is one of the most important issues in rock mechanical engineering. There are lots of topics in rock mechanical engineering, such as developing geothermal resources, exploring the underground space of the metropolitan region and civil works, which are related to temperature, static load and stress wave. Through precise theorization and extensive experimentation, it has been proven that the constitutive relationship of a rock varies with its mechanical properties when the rock is bearing both dynamic and static loadings. At present, many studies on the rock failure under the normal temperature and static loading in rock mechanical research field have been conducted. However, few reports about the mechanical properties of loading 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, rock failure criterion as well as parameter optimization of the rock engineering [1].

In recent years, experts and scholars are greatly focusing on the study of the mechanical properties of loading rates on rocks. Some related experiments were done and it was shown that the rock's peak strength, the rock's strain and its elastic modulus increase with the strain rate, and the post-peak unloading of the stiffness under high strain rate is smaller than that under low strain rate for rocks [2–4]. Olsson used two different experimental equipments to study the uniaxial compression of the tuff with the stain rate of 10^{-6}–10^{3} s^{-1}, and the experimental results showed that the strength of the rock sample changed little along with the change of the strain rate (strain rate <$76^{-1}s^{-1}$, the compressive strength increased by 10% when the strain rate was increased from 10^{-6} to 10^{1} s^{-1}, and the strength of the rock sample increased sharply as the strength rate was increased (strain rate >$76^{-1}s^{-1}$) [5].

Zhao et al. concluded from the granite dynamic uniaxial compression experiment (Bukit Timah) that the granite compressive strength increased by 20% as the strain stress was increased from 10^{-5} to 10^{1} s^{-1} [6]. And at the same time, the strain rate had little influence on the granite elastic modulus and the granite poison ratio. Bieniawski and Peng studied the fine sandstone and tuff under different strain rates, respectively [7,8]. Chong and Borest studied the oil shale considering the strain rate from 10^{-4} to 10^{1} s^{-1} by using a servo-controlled rock mechanics testing machine [9]. Okubo et al. studied the second class rock whose strain became smaller after the process of peak stress under different strain rates, and a new empirical formula that the peak strength increases along with the strain rate was put forward [10].

Many studies about the rock mechanical property under different temperature levels have been done and results have shown that most of the rocks strength varied with the increasing temperature, but this decline was associated with the type of rock [11–14]. However, the effect of the strain rate on mechanical properties of rock under high temperature was rarely reported. In this paper, the experimental tests for limestone specimens at 700 °C under uniaxial compression were carried out to study the mechanical effects of loading rates on limestone by using a MTS810 rock mechanics

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servo-controlled testing system and an MTS652.02 high temperature furnace. During the experiment, the way of the load infliction was set to a controlled-displacement with the strain rate ranging from 1.1×10^{-5} to 1.1×10^{-1} s^{-1}, and the analysis of the stress–strain curve was used to reveal the mechanical properties of limestone at 700 °C under different strain rates.

2. Experimental

2.1. Specimens and preparation

Our specimens used were taken from a mine in Xuzhou, China. Generally, different dimensions and configurations exerted obvious effects on the measurement of rock mechanical parameters. Considering the limited space of the high temperature furnace used in our investigation, cylindrical rock specimens were chosen, about 45 mm in length and 20 mm in diameter, to meet the requirement of Test Rules of Physical and Mechanical Properties of Rocks DY-94 for Ministry of Geology and Mineral Resources of People's Republic of China [15]. The specimens were divided into five groups, of which the loading rates were set to 0.0005, 0.005, 0.05, 0.5 and 5 mm/s with 3–5 specimens to each group at 700 °C.

2.2. Equipments and process

The experiments were conducted using an MTS810 hydraulic servo system and an MTS653.02 high temperature furnace, as shown in Fig. 1. The entire experimental process was completed according to the requirements established beforehand by the Teststar II system, which has an optimum control of the test process. Using the menu of the main form, the system has functions for the distribution of sensors, definitions of the control model, setting boundaries, an automatic zero set of sensitive elements, selection output signals and setting some parameters as required. This system software includes GUI, a data interface, a software function generator, program designs, and system tools.

First of all, we set up the samples to ensure their ends fully touched the press load components, then, hitched the sensor on the carrying supporter, care was made to sure the clamping device of the axial displacement sensor had a complete touch with the sample. On this basis, we set the relevant experimental parameters in the following ways:

(1) The way of the experimentation was set as uniaxial compression through the computer terminal.

Fig. 1. MTS810 servo-controlled rock mechanics testing machine and MTS652.02 high temperature furnace.

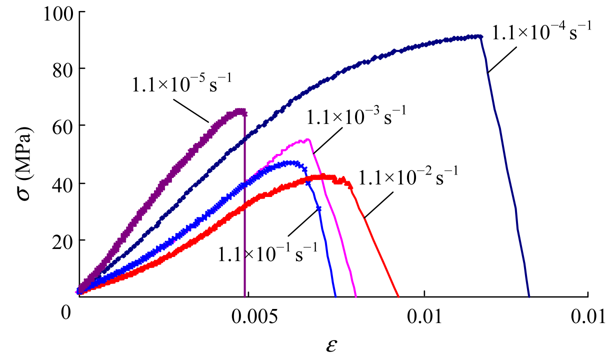

Fig. 2. Stress–strain curve with different strain rates of rock.

(2) The range control mode of the axial displacement sensor was set as an automatic mode, so as the experimental parameters could be input at every step. So the tests were done automatically.
(3) Chose the controlling ways as deformation modes.
(4) Set the limit displacement value, the limit load value and the load rate.

First, the specimens of each group were placed into a MTS653.02 high temperature furnace, where the specimens were heated to 700 °C at a rate of 2 °C/s. The temperature was kept constant for 2.0 h so that the specimens could be heated to the assigned value from the outside to the inside. The specimens were loaded by an electro-hydraulic loading servo system. The mechanical characteristics such as axial load, axial displacement, and axial stress and strain were obtained in the process of rock deformation and destruction by using the Teststar II control program.

3. Whole process stress–strain curves under different strain rates at high temperature

The stress–strain curves of limestone under the different strain rates at high temperatures are shown in Fig. 2. According to the axial load and displacement obtained from the uniaxial compression tests, peak strength and peak strain of the samples were obtained accordingly. The elastic modulus was calculated by using the approximate straight line section before the peak strength in the whole process stress–strain curve. The variations of peak strength, peak strain and elastic modulus of limestone specimens under the different strain rates at 700 °C are listed in Table 1.

The stress–strain curve under different strain rates at 700 °C are shown in Fig. 2. It can be seen that, the stress–strain curve goes through two stages when the strain rate of the rock was increased from 1.1×10^{-5} to 1.1×10^{-3} s^{-1}. That is: (1) The first sage is the process of approximate linear elastic deformation. Because the widths of the fissure and the fracture are different for different rocks, so the closed extend are different, therefore, the lengths of the linearity are dissimilar. (2) The second stage is a transitory phase from plastic deformation to failure. The curve shows a shape of concave, the ductility of the limestone had obviously been strengthened, and the value of the strain continued to increase slowly when the stress reached the peak value, while the final break point was a brittle failure.

When the strain rate was increased from 1.1×10^{-3} to 1.1×10^{-1} s^{-1}, the stress–strain curve separated into three parts which are compaction deformation, elastic deformation, and a transitory phase from plastic deformation to failure. At the initial loading stage, the shape of the curve is concave; the deformation develops fast along with the increasing stress. The primary reason