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Experimental study on the dynamic compressive mechanical properties of concrete at elevated temperature

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ABSTRACT

Strain rate effect and temperature effect are two important factors affecting the mechanical behavior of concrete. Each of them has been studied for several years. However, the two factors usually work together in the engineering practice. It is necessary to understand the mechanical responses of concrete under high strain rate and elevated temperature. A self-designed high temperature SHPB apparatus was used to study the dynamic compressive mechanical properties of concrete at elevated temperature. The results show that the dynamic compressive strength and specific energy absorption of concrete increase with strain rate at all temperatures. The elastic modulus decreases obviously with strain rate at room temperature and stabilizes at a level with slightly decrease at elevated temperature. The dynamic compressive strength of concrete at 400 °C increases by nearly 14% compared to the room temperature. However, it decreases at 200 °C, 600 °C and 800 °C with the decrease ratio of 20%, 16% and 48%, respectively. The dynamic elastic modulus decreases largely subjected to elevated temperature. The specific energy absorption at 200 °C, 400 °C and 600 °C is higher than room temperature and decreases to be lower than room temperature at 800 °C. Formulas are established under the consideration of mutual effect of strain rate and temperature.

1. Introduction

Concrete [1–3] is one of the most widely used civil engineering materials. Its mechanical properties aroused much concern from researchers. Strain rate effect and temperature effect, as two important factors affecting the mechanical performance of concrete, have been extensively studied during the past several years. Xu [4] performed drop-weight splitting tests to study the dynamic tensile properties of fiber reinforced concrete materials with different steel fibers. The results showed that the concrete with the two fiber types showed better performance than plain concrete material under both static and dynamic splitting tests in terms of tensile strength, fracture energy, post-peak energy, DIF, maximum measurable strain capacity, rate sensitivity and crack growing velocity. Giner [5] studied the influence of the steel fiber and carbon fiber additions on the mechanical properties of concrete containing silica fume, which showed that the dynamic elastic properties of concrete presented higher values than their static counterparts. Both carbon fiber and steel fiber additions leaded to slight decreases of the compressive strength of concrete. Wang [6] investigated the static and dynamic mechanical properties of steel fiber reinforced lightweight aggregate concrete, which showed that the compressive strength of high-strength, lightweight concrete was only slightly improved with the addition of steel fiber. However, splitting tensile strength and flexural strength were largely improved. When referring to the temperature effect, many researches focus on the mechanical properties of concrete after exposure of elevated temperature. However, the studies about its mechanical response at elevated temperature, which is of great importance for engineering safety and structure design, are relatively few and mostly with regard to the quasi-static properties. Evariste Ouedraogo et al. [7] studied the two andalusite- and bauxite-based refractory concretes through various uniaxial compression mechanical tests, from room temperature up to 1200 °C and the concrete exhibited quasi-brittle behavior with increasing strength from room temperature to 800 °C, and viscous behavior with decreasing strength from 900 to 1200 °C. Petkovski [8] reported on an experimental study of the effects of different heat-load regimes on the stress–strain behavior of partially sealed concrete under multiaxial compression at elevated temperature. The results suggested that the presence of stress during first heating produces a specific damage, which could be the cause for a major component of the load induced thermal strain in concrete. Gyu-Yong KIM [9] studied the effect of elevated temperatures ranging from 20 °C to 700 °C on the material mechanical properties of high-strength concrete of 40, 60 and 80 MPa grade. The results showed that the rel-

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ative values of compressive strength and elastic modulus decreased with increasing compressive strength grade of specimen. In recent years, fire and terrorist attack occurred frequently, which made the concrete structure not only suffered from impact loads, but also subjected to fire attack. Consequently, it is necessary to study the mechanical properties of concrete considering the mutual effect of strain rate and high temperature.

In the present paper, a self-designed high temperature SHPB apparatus was used to study the dynamic compressive mechanical properties of concrete at elevated temperature. The strain rate effect and temperature effect on concrete were analyzed and the formulas were established under the consideration of mutual effect of strain rate and temperature.

2. Experimental procedure

2.1. Materials

The following materials are used in the fabrication of concrete specimens: P.O 42.5R Cement, fly ash, silica fume (average grain diameter: 0.1–0.15 μm, SiO_2: 92%), limestone rubble (5–10 mm: 15%, 10–20 mm: 85%), river sand (river sand/limestone rubble = 0.67) with a fineness modulus of 2.8, high efficiency water-reducing admixture FDN and tap water. Table 1 presents the mix proportions of concrete.

2.2. Mixing and casting

The mixing processes for concrete can be described as follows: partial mixture of water and FDN and total sand (30 s), limestone rubble (30 s), cement, fly ash and silica fume (30 s), residual mixture of water and FDN (60 s). After the mixing procedure, cylindrical specimens of 49 ± 0.5 mm thickness and 98 ± 0.5 mm diameter were casted for dynamic properties tests. Thereafter, the specimens were left in their moulds for 24 h, and finally cured in the standard conditions of 20 ± 2 °C and > 95% relative humidity for 28 days until tested.

2.3. High temperature SHPB test

The dynamic compressive mechanical properties of concrete at elevated temperature were tested using a self designed high temperature SHPB system, which consists of Φ100 mm SHPB apparatus, box heating furnace and tubular heating furnace, as shown in Figs. 1 and 2. The box heating furnace and tubular heating furnace, with the maximum test temperature of 1200 °C, were specially designed to suit with the Φ100 mm SHPB apparatus. The specimens were first heated in the box heating furnace to the temperatures of 200, 400, 600 and 800 °C, respectively, at a heating rate of 10 °C/min. Then the target temperatures were maintained for 2 h to achieve the thermal steady state. Thereafter, they were transferred to the tubular heating furnace one by one within 6–7 s for impact tests. There is enough space in the box heating furnace for heating dozens of specimens simultaneously, thus making the tests more efficient. The tubular furnace can move in three directions, which makes the axle wires of specimens, bars and the tubular furnace in a straight line. To make up the temperature loss during the transportation, the specimens were kept in the tubular furnace at the same target temperatures for 10 min before impact tests.

Fig. 1. Box heating furnace.

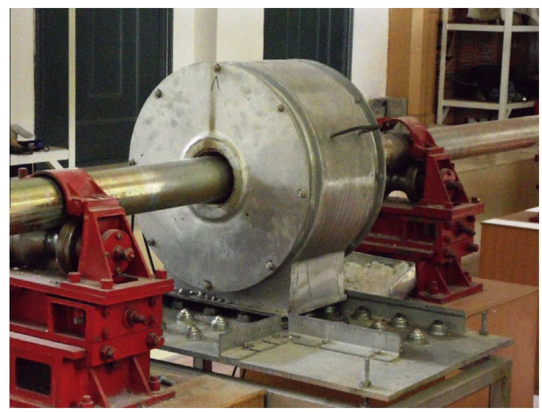

Fig. 2. Tubular heating furnace.

According to three-wave method, the stress, strain rate and strain histories of specimen can be expressed, respectively, as

$$\left.\begin{aligned} \sigma_s(t) &= \frac{E[\varepsilon_i(t)+\varepsilon_r(t+\tau_1)+\varepsilon_t(t+\tau_2)]A}{2A_s} \\ \dot{\varepsilon}_s(t) &= \frac{[\varepsilon_i(t)-\varepsilon_r(t+\tau_1)-\varepsilon_t(t+\tau_2)]c}{l_s} \\ \varepsilon_s(t) &= \int_0^t \dot{\varepsilon}_s(\tau)d\tau. \end{aligned}\right\} \quad (1)$$

where E is Young's modulus of bars, c is wave velocity in bars, A and As 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; τ_1 and τ_2 are time delays of reflected and transmitted pulses, respectively.

3. Results and discussion

The results of high temperature SHPB tests are shown in the Table 2.

Table 1
Mix proportions of concrete (kg/m^3).

Cement	Tap water	River sand	Limestone rubble	FDN	Fly ash	Silica fume
371	180	672	1008	5	99	25