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Effect of strain rate on compressive behaviour of high-strength concrete after exposure to elevated temperatures

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ABSTRACT

The effect of strain rate on the compressive behaviour of high-strength concrete (HSC) after exposure to elevated temperatures was experimentally investigated. 45 HSC prisms were heated up to 20, 200, 400, 600 and 800 °C. The pre-heated prisms were then axially loaded at a quasi-static strain rate of $10^{-5}\ \mathrm{s}^{-1}$ as well as two aftershock dynamic strain rates of 10^{-3} and $0.067\ \mathrm{s}^{-1}$, respectively. The test results indicate that the higher the temperature and strain rate are, the larger the number of cracks and fragments will be. Both the residual compressive strength and elastic modulus of HSC decrease with the increase of elevated temperatures, whereas they increase as the strain rate increases. Moreover, the peak strain is enhanced by the elevated temperature but hardly influenced by the strain rate. Finally, the stress–strain relationship and dynamic increase factor (*DIF*) of HSC after exposure to elevated temperatures are proposed.

1. Introduction

In recent years, high-strength concrete (HSC) has been widely applied as an excellent material for civil and infrastructure engineering. Although HSC has significant advantages in strength and durability, it shows an inferior performance under elevated temperatures as compared to normal strength concrete (NSC) [1]. Many studies have indicated that the elevated temperature deteriorates the compressive strength, tensile strength, elastic modulus and even durability of HSC [2–4]. It is necessary to point out that investigations on HSC after exposure to elevated temperatures focus mostly on static loading conditions in the past many years.

As a strain rate sensitive material, the compressive strength, strain at the peak stress (peak strain) and elastic modulus of concrete under the dynamic loading may change remarkably compared to those under static loading [5]. During the service lifetime, concrete may be subjected to dynamic loadings such as earthquake, impact, explosion, *etc*. Thus the investigation on mechanical properties of concrete at a higher strain rate is of great significance to designing and modelling concrete structures accurately. Since Abrams [6] reported the strain rate sensitivity of concrete during the compression test in 1917, many investigators have studied the concrete compressive behaviour at different strain rates mostly at room temperature. Most investigators [7–10] have indicated that the compressive strength of concrete will increase with the increase of strain rate. A literature review indicates that the influence of strain rates on the peak strain of concrete is still unclear. Previous studies have suggested that the peak strain of concrete would increase [5,11] or reduce [12,13] or remain constant [14,15] with the increasing strain rate. The increasing strain rate was also found, in general, to enhance the elastic modulus of concrete [5,16,17].

Up to now, there is no consensus on the mechanism of strain rate sensitivity of concrete. The plausible explanations can be roughly classified into four types:

1) The lateral inertia leads to the nonuniformity of the stress in the specimen under dynamic loading, which generates a considerable confining pressure. It seems that the uniaxial stress state in concrete becomes a multiaxial one as the strain rate increases. Therefore, the initiation and growth of cracks are restricted, and the compressive strength of concrete increases with the increasing strain rate [18,19];

2) Under static loading, for NSC, the cracks tend to go around rather than propagate through aggregate particles. Nevertheless, the cracks will propagate through aggregate particles under dynamic loading, and a greater load is needed to damage aggregate particles. As compared to the cracks in NSC, the ones in HSC can propagate through aggregate particles even if the compressive loading is static. Hence, the concrete with the higher compressive strength presents the lower strain rate sensitivity [10,20];

3) The higher strain rate could cause more cracks and fragments, which will consume more energy. Consequently, the compressive

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strength of concrete increases with the increasing strain rate [20];

4) The moisture in pores of concrete enhances the material viscosity at a high strain rate. Hence, concrete appears to be more sensitive to the strain rate if the moisture of content is higher [21,22].

Besides the compressive strength and the moisture presented, some other factors also can influence the strain rate sensitivity of concrete. Based on the test data, Sparks et al. [23] concluded that the strength improvement was greater for concrete with relative weak and soft aggregates compared to concrete with stiff aggregates with increasing strain rate. Also, very limited studies have showed that the strain rate sensitivity of concrete may be influenced by the curing condition, shape and size of aggregates [24].

As described above, the elevated temperature can result in a deterioration of the compressive strength of HSC. In addition, the moisture content and aggregate stiffness of HSC could vary with the exposed temperatures [25]. Therefore, it is assumed that the strain rate sensitivity of HSC may change when the exposure temperature increases. Weidner et al. [26] studied the dynamic compressive behaviour of concrete at and after 204 °C by drop hammer tests with the drop hammer mass of 62 kg released at height of 4.88 m. The results showed that the dynamic compressive strength of concrete after 204 °C was 80% higher than that at 204 °C, but was still 27% less than that at room temperature. In this study, a moderate temperature was employed, and further study is needed for the dynamic compressive behaviour of HSC after being exposed at higher temperatures.

Multi-hazard environments have increasingly posed a threat to civil engineering structures in recent years [27]. The compressive behaviour of HSC after exposure to elevated temperatures at different stain rates is an important indicator for HSC structures to resist the dual-hazard induced by both fire and dynamic loadings. For example, a warehouse in Tianjin of China exploded at about 23:30 on August 12, 2015. The explosion fireballs caused many building fires within the diameter range of 1 km. The naked fires had been put out at about 18:00 on August 14. But the explosions occurred again at the fire scene on August 15. In this accident, the HSC had to withstand a fire and an explosion dynamic loading successively. In fact, the similar scenario often occurs in an aftershock or explosion. The Japan Great Earthquake caused 371 fires on March 11, 2011. More significantly, there were more than 10,000 aftershocks in 3 years after the great earthquake. In addition, on July 6, 1988, a fire occurred in the Piper Alpha oil platform at North Sea in Britain, and the fire caused the gas explosion.

After a HSC structure suffers a fire, it might be put back into service with little retrofit or repair and could then be subjected to an aftershock dynamic loading. Therefore, the losses in residual static and dynamic strength of HSC due to fire must be properly addressed. However, limited published literature has been focused on the effect of strain rates on HSC after exposure to elevated temperatures. In this paper, an experimental investigation was conducted to study the strain rate sensitivity of HSC under compression after exposure to elevated temperatures and to attempt to reveal the underlying mechanism of it. Three strain rates of 10^{-5}, 10^{-3} and 0.067 s^{-1} were chosen to consider both the static and aftershock dynamic loadings [5]. Data from such an experimental study can contribute to the basic understanding of the response of the HSC structure after a fire under a dynamic loading.

2. Experimental programme

2.1. Materials and specimen preparation

In this study, PO52.5 Portland cement, slag powder and silica fume were selected. The minimum/maximum aggregate size of the siliceous crushed stone with continuous grading was 5/20 mm. The fine aggregate was river sand with a fineness modulus of 2.70. In order to improve the workability, superplasticizer was added to the HSC mixture. The mixture proportions of HSC are given in Table 1.

Forty-five $100 \times 100 \times 300$ mm^3 prisms were cast according to the mixture proportions as described in Table 1. After 24 h, all prisms were demolded and moved to a standard curing room with a temperature of 20 ± 2 °C and a relative humidity of more than 90%.

2.2. Elevated temperature test programme

After 28 days of curing, the prisms were removed from the curing room. To prevent the spalling of HSC during the heating process, the prisms were dried at 105 °C for 48 h in the pre-drying oven shown in Fig. 1. They were then heated in an electrical furnace with $650 \times 650 \times 1050$ mm^3 volume and 36 kW maximum power. The prisms were put in a special steel bar cage, as shown in Fig. 2, to avoid damaging the furnace walls by fragments due to potential spalling of HSC. A K-type thermocouple was installed in the electrical furnace to record and monitor the temperature variation.

There were five temperature series of 20, 200, 400, 600 and 800 °C in this experimental study, and each series consisted of nine prisms. The prisms were heated at a rate of 2.5 °C/min up to the target temperature (200, 400, 600 and 800 °C). It is noted that the heating rate is slower than that recommended in ISO-834; nevertheless, the residual mechanical behaviour of concrete after exposure to elevated temperatures will not be influenced [2]. Then the temperature was maintained at 200 °C for 3 h, 400 °C for 2.5 h, 600 and 800 °C for 2 h, respectively, following the work of Mohamedbhai [28]. At last, the vent hole at the top of the electrical furnace was opened to release the heat and the temperature will continue to be recorded until it was below 100 °C.

2.3. Dynamic compression test programme

The compression tests were conducted using an MTS servo-hydraulic concrete test system with a capacity of 3000 kN. Each temperature series of prisms was subdivided into three strain rate groups of 10^{-5}, 10^{-3} and 0.067 s^{-1}, and each group consisted of 3 prisms. In total, there were 15 groups (45 pieces) of prisms. The lowest strain rate of 10^{-5} s^{-1} was referenced as the static test *S*, and the other two higher strain rates of 10^{-3} and 0.067 s^{-1} were named as dynamic tests *D*1 and *D*2, respectively. For convenience, each prism was designated by the strain rate group followed by the temperature series and a number. For example, *S* (*D*1 and *D*2)-200-1 indicated the first prism with the exposed temperature of 200 °C, which was axially loaded at a strain rate of 10^{-5} (10^{-3} and 0.067) s^{-1}.

Prior to the compression tests, the end surfaces of the prism were lapped. The prism was placed on the MTS testing machine in the vertical direction, and two polytetrafluoroethene (PTFE) films were placed on each loading end to reduce the surface friction. The prism was preloaded to 10 kN within 10 s, then unloaded to 0 kN within 10 s. The preloading was repeated three times to ensure that the loading arrangement was properly aligned and the loading was in the axial direction. The axial strain of the prism increased at a pre-specified strain rate until the prism failed or crushed. To record the complete test data, the computerized data acquisition system must respond to the load and displacement in a very short time, and the highest frequency of recording could

Table 1
Mixture proportions of HSC (kg/m^3).

Cement	Slag powder	Silica fume	Crushed stone	Sand	Water	Superplasticizer
406	116	58	1115	655	136	14.5