Elevated Temperature Behavior of Impact-Induced Partially Damaged Concrete

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SUMMARY

Designing protective structures capable of withstanding the combined extreme actions of impact/blast and fire necessitates the accurate prediction of material properties under the coupled effects of high-strain-rate and subsequent elevated temperature loadings. An extensive experimental program was being carried out in the Civil Engineering Laboratories at Monash University to investigate the post-impact fire properties of plain self-compacting concrete (SCC) material and the results are presented in this paper. This will help in evaluating whether partially damaged concrete elements can further sustain additional stresses in case of a subsequent fire outbreak. Specimens have undergone interrupted high-strain-rate compressive loading, controlled locally at defined levels of axial displacement, to account for different deformation states. Results indicate that the mechanical behavior of concrete subject to post-impact fire scenarios is dependent on the rate of loading, the damage history and the fire temperature to which it is subsequently exposed.

INTRODUCTION

Protective concrete structures must be capable of enduring extreme loads such as impact or fire and their combined effects such as post-impact-fire situations. Concrete, as one of the most widely used construction materials, is both rate- and temperature-dependent. A large number of experimental results have been published on the behavior of plain concrete under impact loading [1, 2]. It has been identified that the load-carrying capacity of concrete increases substantially at higher strain rates, which may be due to an inertial effect and resistance to crack opening [1]. Furthermore, studies have shown that the compressive strength enhancement of concrete with strain rate are influenced by many uncertain factors, such as different testing techniques, specimen size effect, material properties (e.g. concrete static compressive strength), aggregate grade, curing and moisture condition, age, boundary effects and specimen

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lateral inertial effect. Recently, Mirmomeni et al. [3] investigated the effect of size, boundary, and curing conditions on the dynamic compressive strength (strain-rates under $5 \text{ s}^{-1}$) of self-compacting concrete (SCC), a high performance concrete developed in Japan in 1988 [4]. Based on experimental results, some typical empirical formulas such as the CEB Model [5] have been developed and used for predicting the dynamic increase factor of concrete material.

A significant amount of research work has been carried out to assess the fire resistance of concrete materials [6, 7]. The mechanical properties of concrete under elevated temperatures depend on the concrete mixtures and compositions. Under elevated temperatures, the behavior of concrete undergoes a detrimental effect and loses a substantial amount of its mechanical strength such as compressive stress. The concrete strength variation with the temperature has been accounted for using reduction factors and design curves in design codes [8].

However, the material tests performed on concrete in recent years do not address the influence of the combined sequential effect of high-strain-rate and temperature on the mechanical properties of concrete. This paper experimentally investigates the mechanical characteristics of high-strain-rate-induced partially damaged unconfined self-compacting concrete meso-scale specimens at elevated temperatures.

**EXPERIMENTAL PROGRAM**

**Test material and specimens**

Unconfined self-compacting concrete specimens with nominal dimensions of 40mm diameter and height/diameter ratio of 1, with a target strength grade of C37 (i.e. 37 MPa) have been utilized for the experiments. SCC is well known for its excellent deformability, segregation resistance and consequent vibration-free placing process. The mixture proportion of self-compacting concrete used by Mirmomeni et al. [3] was adopted here and is presented in Table I.

The SCC concrete samples were water-cured for 7 days and subsequently air-cured at room temperature for the remainder of the curing period until tested on the 28th day.

**TABLE I. THE MIXTURE PROPORTION OF SELF-COMPACTING CONCRETE.**

<table>
<thead>
<tr>
<th>Ordinary Portland cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Class F Fly ash (kg/m³)</th>
<th>Coarse aggregate (kg/m³)</th>
<th>Fine aggregate/Sand (kg/m³)</th>
<th>Superplasticizer (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>213.3</td>
<td>112.1</td>
<td>53.3</td>
<td>400.8</td>
<td>434.1</td>
<td>13</td>
</tr>
</tbody>
</table>

For each type test, at least 3 specimens were cast and tested. Where the consistency of the three was not proven to be satisfactory (a deviation of more than 5% from the average strength value of the samples), more tests were carried out till data consistency was achieved. Moreover, samples were chosen from different batches of cast concrete to ensure the accuracy of the results.
**Instrumentation, Test Set up and Procedure**

The effect of post-impact fire on the residual compressive strength of high-strain-rate partially damaged concrete at elevated temperatures up to 600°C is investigated in this study. The dual-phase experimental set-up simulating the impact and subsequent fire conditions adopted for the tests is presented in Figure 1.

**PHASE I: IMPACT SIMULATION**

Interrupted high-strain-rate compression tests were conducted at room temperature via an Instron 8802 servo-hydraulic testing machine with a load capacity of 250kN as shown in Figure 1(a). Tests were run in displacement-control mode. Load and position were determined using built-in transducers while direct measurement of strain was achieved using a MTS LX500 non-contact laser extensometer.

In order to reduce the effect of the friction between the machine interface and the specimen, a fine layer of high pressure grease was applied to the top and bottom surfaces. Two impact speeds of 150mm/sec and 75mm/sec were chosen to induce the initial partial deformation. The nominal rate of strain was calculated by the ratio of \( \frac{V}{L_0} \), where \( L_0 \) is the length of the specimen and \( V \) is the crosshead displacement rate. Hence, to achieve a specific nominal strain rate during a test, the machine was operated at a relevant constant crosshead velocity.

Uninterrupted uniaxial high strain rate (HSR) compression tests at aforementioned two different impact speeds were carried out and the obtained load-axial shortening curves were used to define damage levels for each strain rate. For each strain rate regime, two distinct damage levels are defined with respect to the displacement \( (D_u) \) corresponding to the ultimate compressive load \( (P_u) \) (Figure 2). In the lower damage level, namely 0.5 \( D_u \), high-strain-rate-induced micro-cracks are introduced into the material, however, it is still close to its linear elastic behavior. In the higher damage level, 0.8 \( D_u \), although the material is still fully intact, visible longitudinal micro-cracks appear on the surface of the specimen. Hence the following damage index,
defined as the ratio of dissipated energy per unit volume, is indicative of the level of
the induced pre-damage to the material:

\[
\text{Damage index} = \frac{\int_{D=0}^{D=D_i} PdD}{\int_{D=0}^{D=D_u} PdD}
\]  

(1)

where \( D_i \) is the value of axial shortening at the test interruption point and \( D_u \) is
displacement at which the material is completely damaged, i.e. at the point
corresponding to the ultimate compressive load \( (D_u) \).

During phase I tests, specimens underwent interrupted high-strain-rate
compressive loading, controlled locally at these defined levels of axial displacement to
account for different deformation states. Tests were abruptly terminated by the
operating software at the designated shortenings. Subsequently, specimens were taken
out of the machine ready for the second Phase.

PHASE II: FIRE SIMULATION

In the second phase, quasi-static compression tests at elevated temperature were
carried out on high-strain-rate-induced partially damaged specimens (from Phase I) to
understand the influence of elevated temperature on the residual mechanical properties
of damaged concrete. Specimens were tested to failure using an Instron environmental
chamber mounted onto an Instron 5982 testing machine with a load capacity of
100kN, as shown in Figure 1(b). The partially damaged specimens were tested under
target temperatures of ambient, 300°C, 450°C, and 600°C. The surface temperature of
the specimen was measured by means of three type \( K \) thermocouples positioned in
intimate contact with the surface of the specimen. A fine hole with the dimensions of
the tip of thermocouple have been designated in some of the samples to measure the
inside temperature gradient of the samples.
Each specimen was initially heated up to the specified temperature with a heating rate of 10 °C/min and maintained at that constant temperature until the temperature was stabilized, as shown in Figure 3. The data on this figure are based on the readings of the inside sample thermocouples. During the heating process, the load on the specimen was manually maintained at zero. On stabilization of the temperature (at the end point of Figure 3 curves), uniaxial compression load was applied at a displacement rate of 0.1 mm/min until failure.

RESULTS AND DISCUSSION

Figure 4 shows the results of the uninterrupted compressive tests at three loading rates which were performed primarily to indicate the rate dependency characteristics of the test material at room temperature. As anticipated, the behavior of SCC is rate-sensitive.

Figure 3. Temperature-time curve for the heat-up process of Phase II tests.
The strain-rate induced strength increase model recommended by CEB [5] is one of the most commonly used formulations for concrete in compression which is:

\[
DIF_C = \frac{f_{cd}}{f_{cs}} = \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_s} \right)^{1.026\alpha_s} \quad (\dot{\varepsilon} \leq 30\text{s}^{-1})
\]  

where, \(f_{cs}\) and \(f_{cd}\) are the static and dynamic strength of concrete respectively, in MPa, \(\dot{\varepsilon}\) is the dynamic strain rate, \(\dot{\varepsilon}_s = 30 \times 10^{-6} \text{s}^{-1}\) and the empirical parameters are taken as \(\alpha_s = (5 + 9\frac{f_{cs}}{f_0})^{-1}\), and \(f_0 = 10\text{MPa}\).

The actual measured strain rates for the high-strain-rate tests with impact velocity of 75 mm/s and 150 mm/s are 1.1 and 2.5 s\(^{-1}\), respectively. The dynamic increase factor (DIF) obtained, based on Figure 4 is approximately 1.18 for the lower strain rate and 1.28 for the higher strain rate. These DIF values calculated via the CEB model for the 75mm/s and 150mm/s loading rates are 1.24 and 1.26, respectively, which shows a small difference to those obtained via test results. This is likely caused by different test conditions between the experiments herein and those used for developing the model, as well as size effects [3]. However, the overall trend of the stress-displacement curve is in agreement with the CEB model, indicating an increase in the compressive stress of the material with an increase of strain rate.

The residual strength of high-strain-rate-induced partially damaged specimens tested in Phase II at different elevated temperatures is presented in Figure 5, for both loading rates.
The ultimate compressive strength (UCS) of the SCC has a slight increase up to 300°C, but decreases dramatically from 300°C onward. The maximum stress achieved decreases as the temperature increases, such that at 600°C there is more than 40% reduction in the compressive strength of the material. According to BS 8110 [8], the ratio of material strength at 600°C and 450°C to that at the ambient temperature is 0.5 and 0.8, respectively. As can be seen from Figure 5, the reduced strengths due to temperature-only effects (no induced pre-deformation) are slightly less than those predicted by the
aforementioned code for dense concrete, indicating that SC concrete maybe capable of maintaining its properties better than conventional concretes.

With an increase in damage level the material has an increased loss of capacity, hence the residual compressive strength is decreased. This decreasing trend is similar for all temperatures for the tests with the impact velocity of 75mm/s. However, for higher impact rate loading tests, at low temperatures (upto 300°C), the increased amount of micro-cracking introduced into the material and the resultant increase in the damage index enable partial restoration of the material strength. The rational of the strength restoration in higher strain rates is currently being investigated by the authors through X-ray tomography of induced micro-cracks. However, with an increase of temperature to 450°C, temperature is the dominant factor for strength reduction and there is no apparent strength restoration. For tests with pre-deformation at higher impact rate loading and tested at low fire temperatures, the material is capable of maintaining more than 90% of its no-damage strength. This resilience declines with the increase of temperature.

CONCLUSION

The residual elevated temperature compressive strength of self-compacting concrete material, which has been partially damaged under high-strain-rate loading conditions, has been experimentally investigated. The elevated temperature behavior of high-strain-rate-induced pre-damaged concrete was compared to that of each individual loading scenario and to experimental results available in the literature, for high-strain-rate loading and also elevated temperature effects. The stress-strain relationship of concrete under the individual effect of high temperatures was found to be consistent with what has been reported in the literature. The test results demonstrate that the combined effects are different from those in which the material is subject to either high strain rate or thermal loading individually. This is more apparent with an increase in the impact loading rate, where the material is capable of restoring its strength to some extent at low temperatures, whereas at elevated temperatures of 450°C and above, temperature is clearly the dominant factor. This study has thus found that the stress-strain behavior of concrete is dependent on the rate of loading, the damage history and the fire temperature to which it is subsequently exposed.

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