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Effect of pre-induced cyclic damage on the mechanical properties of concrete exposed to elevated temperatures

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HIGHLIGHTS

- Concrete samples are subjected to cyclic loading followed by elevated temperatures.
- Residual properties are attained for different levels of damage and temperature.
- Bezier curves are used to express residual properties against damage and temperature.
- The variation of residual properties is explained in terms of micromechanical changes.

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ABSTRACT

This research aims to investigate the effect of high temperature on concrete samples which have been previously damaged under cyclic loading. For this purpose, normal strength concrete samples are initially subjected to strain-controlled load cycles and then exposed to elevated temperatures. Residual mechanical properties of the samples are measured after allowing them to slowly cool down to room temperature. These properties are expressed in terms of two independent parameters, i.e. the level of damage induced by cyclic loading as well as the exposure temperature. It is shown that the variation of residual properties is simultaneously affected by both parameters, however, the influence of pre-induced damage diminishes as the exposure temperature increases. In addition, an effective approach is described for the numerical reproduction of stress–strain curves for any given level of damage and temperature.

1. Introduction

In view of the devastating outcomes of extreme events such as post-earthquake fires [1,2], the importance of having a model for the fire-resistant capacity of a seismically-damaged structure becomes evident. Creating such models requires research in the structural scale [3–6] as well as the material scale [7–9].

Due to its popularity as a construction material, the study of concrete is a vibrant topic and extensive research has been carried out on its behavior under cyclic loading [10–12] as well as high temperature [13–18]. However, there is a lack of experimental data when it comes to the changes that high temperature inflicts on a specimen that has already sustained cyclically-induced damage. At increasing temperatures, concrete undergoes changes in its chemical composition and physical structure. The chemical and mechanical changes that concrete experiences at high temperatures have been outlined by several researchers [13–15]. Exposure to high temperature affects the strength and durability of concrete members, and while some changes are instantaneous (e.g. stresses due to thermal incompatibility), others take place over time (e.g. dehydration of chemically bound water). Hence, the complex interaction of physical, chemical and mechanical changes becomes a time-dependent process.

Zhai et al. [19] investigated the properties of concrete samples after being exposed to high temperatures (up to 1200 °C). Their results show that the changes take place in both the cement paste and the aggregates. It also shows that these changes are of different nature at different levels of temperature. At the same time, the experiments conducted by Wu and Wu [17] imply that up to a temperature of 600 °C and over a duration of 1–6 h, the extent of strength degradation is almost independent of the duration of exposure.

Arioz [15] studied the effect of high temperature on the residual compressive strength of concrete specimens. Also included in this study, was the influence of aggregate type and water-cement ratio

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on the relative strength reduction. Attributed to the mineral structure, it was concluded that concrete made from river gravel experiences higher strength reductions when compared to crushed limestone. However, the results indicate that the water-cement ratio has negligible effect on the relative strength reduction.

Thermal incompatibility of the cement paste and aggregates is considered a main factor causing degradation at elevated temperatures [13,15,18]. Therefore, strength degradation of concrete is not only a result of the decomposition of cement hydration products, but is also influenced by the micro-cracks which develop due the difference between the thermal expansion of the paste and that of the aggregates.

Despite the importance of multi-phase load histories such as post-earthquake fire or post-impact fire, not much attention has been given to the understanding of such sequential load histories and their effect on construction material [7,20–22]. A recent investigation by Sinaie et al. [7] involved the behavior of cyclically-damaged mild steel at elevated temperatures. A similar problem is treated in the present paper for normal strength concrete. In other words, this research investigates the changes that material properties undergo when concrete samples are first subjected to cyclic loading and then exposed to elevated temperatures. The findings of this experimental program along with the results reported for mild steel [7] can be used as a framework to determine the post-earthquake fire resistant capacity of reinforced-concrete members. Please note that this study is part of a series of investigations currently being carried out at Monash University on extreme events and resilient structures [7,20–24].

2. Experimental program

When it comes to the effect of high temperature on concrete, three methods of testing are carried out by researchers [25]:

– Stressed tests at high temperature
– Unstressed tests at high temperature
– Residual tests after exposure to high temperature

Stressed tests at high temperature involve concurrent heating and loading on the sample. In these tests, samples are loaded up to a fraction of their nominal strength and then heated while the load is kept constant. Once the temperature reaches its target value, the existing load is increased until failure. *Unstressed tests at high temperature* are similar to stressed tests, but without the initial load. Stressed and unstressed tests are usually carried out in conjunction to one another [26]. While the existence of stress during heating leads to complex micro-mechanical interactions, results indicate that in general, stressed samples sustain less strength loss when compared to unstressed ones.

In contrast to stressed and unstressed tests at high temperature, for *residual tests after exposure to high temperature*, the sample is allowed to cool down to room temperature before being subjected to loading [17]. The relation between residual strength and high temperature strength varies depending on temperature. It has been reported that up to a temperature of 400 °C, residual strength is higher than strength at high temperature. However, as the exposure temperature rises beyond 400 °C, the residual strength is measured to be less than the strength at high temperature. This has been attributed to the decomposition of calcium hydroxide into calcium oxide and water which takes place at around 400 °C. While this decomposition causes strength loss at high temperature, it is reversible and as the calcium oxide absorbs water during cooling, the new calcium hydroxide crystals cause the existing cracks to open further and lead to additional strength loss [13].

This study aims to determine the *residual* mechanical properties of cyclically-damaged specimens after being exposed to elevated temperatures. For this purpose, the test program was divided into three separate phases:

– **Phase 1**. Induction of cyclic damaged.
– **Phase 2**. Exposure to elevated temperature.
– **Phase 3**. Determination of residual properties.

In the first phase, undamaged samples were taken and subjected to cyclic loading. This resulted in samples that were in a state of partial damage. In the second phase, the partially-damaged samples were exposed to different levels of temperature. After being cooled down to room temperature, samples were tested under compression in the third and final phase. A detailed description of each phase is given in Section 2.3.

2.1. Material

One major concern of this research was to induce a state of uniform damage throughout a single concrete sample. With the damage being of mechanical and thermal origin, the dimensions of the samples should be selected as to accompany uniform damage caused by both phenomena.

In regards to cyclic damage, the results reported by Sinaie et al. [12] were taken into consideration. On the other hand, to avoid size-related thermal damage, especially in the form of spalling, the findings of other researchers were taken into account [13,27,28]. This includes avoiding high moisture content of samples, which is known to be the main source of spalling, as well as rapid heating and asymmetric sample shapes. As a result, samples of 50-mm diameter and 100-mm height were used in this program (Fig. 1). This sample size has shown to produce reliable results in terms of reproducibility of data (less scatter within the test results) under monotonic as well as cyclic loading [12]. At the same time, with the cross section being of cylindrical shape and the diameter of the sample being 50 mm (smaller than the commonly used 100- or 150-mm diameter), the process of attaining uniform temperature is simplified.

The results of this study were intended to pertain to both new and existing structures. Therefore, with normal strength concrete being the most common class of concrete in both categories, the mix design used in this program was based on normal strength concrete with no special additives. All specimens were made using the same concrete mix with a 28-day target strength of 35 MPa. For this purpose, the water-cement ratio was set to 0.55 and the amount of water was selected such that the mix would have adequate workability. The specific gravity of coarse aggregates was equal to 2.69 at a saturated surface-dry condition and the fine aggregates were comprised of silica-based sand with a fineness modulus of 2.10. General purpose cement (type I Portland cement) was used as the only cementitious component of the concrete mix. Table 1 provides the material proportions of the concrete mixture used in this study.

As indicated in Table 1, the maximum diameter of coarse aggregates were limited to $d_a = 8$ mm in order to be small enough to avoid the wall effect. This aggregate size is smaller than the sizes commonly used in practice. However, the findings of this study are applicable to concretes made with larger aggregate sizes. Firstly, because the effect of aggregate size is shown to affect strength, not as an independent parameter, but in relation to sample size [29]. Secondly, the study performed by Arioz [30] indicates that sample size has no prominent effect on the percentage strength loss due to temperature exposure. It is important to note that the samples tested by Arioz [30] were made using the same maximum aggregate size. As a result, it can be deduced that maximum aggregate size does not influence the relative strength loss of concrete samples under high temperatures. In fact, although the experiments carried out by Kong and Sanjayan [31] on geopolymer concrete show that using smaller aggregates increases the risk of spalling, they also indicate that for samples that do not experience spalling, the percentage strength loss is not affected by aggregate size.

2.2. Sample preparation

Samples were cast into plastic molds. They were removed from their molds after 24 h and placed inside a curing tank where they would rest in lime-saturated water at a temperature of approximately 23 °C. On day-7, samples were removed from the tank and were allowed to cure further in free air at room temperature until testing day. On approximately day-10, the two ends of the samples were ground for a smooth and parallel finish. Note that not all samples tested in this program were made from the same batch. Therefore, in order to ensure consistency between different batches, three samples were taken as control samples from each individual batch of concrete and tested simultaneously with the rest of the batch.

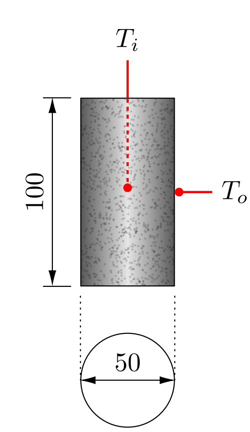

Fig. 1. Concrete sample geometry (in mm) and thermocouple placement.