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Effect of size on the response of cylindrical concrete samples under cyclic loading

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HIGHLIGHTS

- Effect of size on the cyclic response of cylindrical concrete samples is considered.
- Samples of different diameter and aspect ratio are tested under cyclic loading.
- Cyclic parameters are shown to be influenced by the diameter and aspect ratio.
- At smaller diameters, the post-peak response is less affected by the aspect ratio.
- Different cyclic-damage indices are used to describe the cyclic parameters.

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ABSTRACT

An experimental program is carried out to investigate the relation between size and the cyclic response of cylindrical concrete samples. For this purpose, normal strength concrete samples are cast in 9 different sizes and tested under strain-controlled cyclic loads. With the 9 sizes forming an array of samples with different diameters and aspect ratios, the effect of size on peak stress and peak strain is determined. Normalized cyclic stress–strain curves are then used to evaluate the variation of cyclic parameters in terms of the diameter and aspect ratio of the sample. The results of this study show that the diameter and the aspect ratio of the sample have the most influence on the reloading strength and reloading tangent of the cyclic response. Moreover, a key feature deduced from the results is that as the diameter of a sample becomes smaller, the effect of aspect ratio on the post-peak response diminishes. Finally, cyclic parameters are plotted against three different definitions of the damage index. With these definitions being based on strain, strength and dissipated energy, the results imply that the degradation of different cyclic properties might be originating from different damage mechanics.

1. Introduction

Having a deep understanding of the cyclic characteristics of structural materials is a key step in creating models which reliably predict the response of structural systems under cyclic loading. With the widespread use of concrete as a construction material, any study that increases the understanding of its response under cyclic loading is beneficial to a wide range of engineering structures. This not only refers to the design of new structures, but also to the performance evaluation of current ones.

One of the earlier works dealing with the fundamental characteristics of the cyclic response of plain concrete is the work carried out by Bahn and Hsu [1]. An important observation made in their work is the fact that the monotonic stress–strain response of concrete envelopes the cyclic curves. Although this correlation between the monotonic and cyclic behavior of concrete had also been reported in previous studies, a prominent feature that distinguishes the work of Bahn and Hsu [1] is the emphasis on random-amplitude cycles. With the intention of developing a cyclic model suitable for any general loading history, they not only took constant-amplitude cyclic loading into account, but also considered random-amplitude cycles in their experiments. Further work in this area has been carried out by other researchers [2–11]. The more recent study by Osorio et al. [9] aims at establishing a fundamental understanding of the behavior of confined concrete under cyclic loading by examining lateral and longitudinal strains during the load cycles. The experiments conducted by Lam et al. [7], involve monotonic and cyclic loading tests at elevated temperatures. A key observation made in their experiments is that,

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even at high temperatures, the monotonic stress–strain curve of concrete envelopes the cyclic response.

On the other hand, it has been well established that in concrete testing, the observed response depends on the size, the shape and the boundary conditions of the specimen being tested. While such dependencies have been widely investigated with the main focus on strength (f'_c) [12–16], few studies have considered the effect of size on peak strain (ϵ'_c) or other parameters that depend on strain, such as the tangent modulus (E_o). Through their experiments, Choi et al. [17] investigated the relation between the peak strain (ϵ'_c) and the aspect ratio (height-to-diameter ratio, $R = H/D$) of the sample, reporting an inverse relation between the two. It can also be concluded from their experimental data that this correlation becomes less pronounced as the aspect ratio becomes larger, especially for $R > 2$. Chin et al. [18] evaluated the effect of sample size on strength, initial tangent modulus and peak strain. Their experiments involved prismatic specimens with lateral dimensions down to 75 mm, whereby they concluded that the size of the specimen does not have a significant effect on the initial tangent or the peak strain. However, with lateral dimensions ranging from 400 mm to as small as 50 mm, the results reported by Sim et al. [19] indicate a clear increase in the peak strain (ϵ'_c) as the size of the sample decreases.

From another perspective, the use of smaller concrete samples can be advantageous when it comes to material testing. This is mainly due to the fact that their casting becomes more feasible, they require less storage space during curing, and that they can be tested using loading machines with less capacity. Note that ASTM provisions ([20]) allow cylindrical samples with diameters as small as 50 mm and an aspect ratio of $R = 2$ to be used for the determination of compressive strength and elastic modulus. Consequently, when it comes to the effect of size on basic mechanical parameters (f'_c, ϵ'_c and E_0), this lower range of sample dimensions has been covered in the literature. However, the effect of size on the observed cyclic characteristics of concrete is yet to be determined. Therefore, with the focus on small samples ($38 \leqslant D \leqslant 63$mm), the present work aims to determine the relationship between sample size and cyclic behavior. Through the experimental program of this work, the effect of size on strength (f'_c) and strain-related parameters (ϵ'_c and E_o) is first determined. Cyclic stress–strain curves are then normalized by f'_c and ϵ'_c, whereby the effect of size on cyclic parameters is studied.

The results obtained from this program lay out the foundation for future experimental and numerical studies of concrete under cyclic loading. An example is the effect of temperature on cyclically-damaged concrete, currently being carried out at Monash University. It is worth mentioning that these studies fall under a broader research program to determine the response of structures under post-earthquake fire conditions [21–23].

2. Experimental program

Cylindrical samples of normal strength concrete were cast, cured and tested in this program. These samples consisted of nine different sizes varying in diameter (D) and aspect ratio ($R = H/D$). With diameters of 38, 50 and 63 mm and aspect ratios of 1.0, 1.5 and 2.0, an array of samples depicted in Fig. 1 were prepared. Also given in this figure is the naming convention of the samples. This is in the form of $D\square R\square$, where the blank boxes (□) next to the letters D and R are respectively filled in by the diameter and the aspect ratio of the sample. For example, the sample with a 50-mm diameter and an aspect ratio of 1.5 is hereby denoted by D50R1.5.

2.1. Material

All specimens were made using the same concrete mix with a 28-day target strength of 35 MPa. With a maximum diameter of $d_a = 8$ mm, the coarse aggregates used in this study were small enough to avoid the wall effect [20,24]. The specific gravity of coarse aggregates was equal to 2.69 at a saturated surface-dry condition whilst 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, while the water-to-cement ration was selected as 0.55. Table 1 provides the material proportions of the concrete mixture used in this study.

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. All samples were tested on day-28, except for the samples that were used to monitor the development of strength over time. Note that not all samples that were tested in this program were made from the same concrete batch. Therefore, in order to ensure consistency between different batches, sample D50R1.5 was taken as the control sample and six samples of this size were always cast from each individual batch of concrete. The mechanical properties obtained from testing these control samples not only served as a reference to evaluate the consistency between different batches, but they were also used to normalize the results of other sample sizes within each individual batch (Section 3.1).

2.3. Testing scheme

The machine used for testing was a Shimadzu AG-X with a load capacity of 300 kN. Samples were loaded at a constant displacement rate of 0.1 mm/min which results in strain rates lower than $\dot{\epsilon} = 10^{-4}$ s^{-1} for all sample sizes. Displacements were recorded using a non-contact MTS laser extensometer (model LX1500) with a resolution of 1 μm. Fig. 2 illustrates the schematics and the actual laboratory view of the test setup used in this program. The relative displacement of the two hardened-steel platens was used to determine the overall longitudinal strain of the sample. This was achieved by targeting the laser extensometer towards the two retro-reflective tapes that were attached to the front of the platens (Fig. 2). It is generally understood that strains are not necessarily uniform along the sample height and that near the boundaries, strains are affected by the stiffness of the platens as well as the friction between the platens and the concrete surface. However, attaining reasonable strain values within the post-peak region was only possible when strains were calculated from the overall sample deformation [1,7,9]. Therefore, relative platen displacement was used to capture strains throughout the entire response. However, it should be mentioned that true strains may still be obtained by using a correction technique such as the one described by Mansur et al. [25].

The load history applied to the concrete samples involved multiple cycles of controlled straining up to specific values, followed by full unloading to near-zero stresses. Stress and strain values were constantly logged and monitored during the experiments, and load reversals were administered using real-time measurements. The maximum induced strain value was increased with each cycle, causing additional damage to the sample as the cycles progressed. Cyclic loading was continued until the reloading strength (f_r in Fig. 4) of the sample had reduced to half of the peak stress ($f_r < 0.5f'_c$). However, for samples where the reloading strength reduced rapidly, load cycles were continued until the unloading strain (ϵ_u in Fig. 4) was at least as twice as the peak strain ($\epsilon_u > 2\epsilon'_c$). Examples of stress–strain curves corresponding to this load history can be seen in Figs. 3 and 12. It is important to point out that Fig. 3b is produced by normalizing the plot in Fig. 3a with respect to f'_c and ϵ'_c. Note that in most of the following figures, stresses and strains have been normalized by the value of the peak stress f'_c and the value of the peak strain ϵ'_c, respectively. Each of the 9 individual sample sizes was cast and tested a minimum of 6 times in order to attain reliable statistical values. However, additional experiments were carried out when required.

3. Results and discussion

The variation of mechanical properties are derived and presented in this section. The properties considered in this paper are depicted in Fig. 4, and are referred to as either basic parameters or cyclic parameters in the following discussions. Basic parameters include the peak stress f'_c, peak strain ϵ'_c and initial tangent modulus E_0. On the other hand, cyclic parameters are the parameters related to the cyclic response of the material and are defined as the unloading strain ϵ_u, plastic strain ϵ_p, reloading strain ϵ_r, reloading stress f_r, and reloading tangent modulus E_r. These parameters are commonly used for the numerical simulation of concrete behavior under cyclic loading [1,26].

Fig. 5 shows the development of strength over time for sample D50R1.5 (sample with a 50-mm diameter and height to diameter ratio of 1.5). Also given in this figure, are the values of peak stress,