Cyclic Behaviour of Plain Concrete Subjected to Multidirectional Compression

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Abstract

The cyclic behaviour of plain cylindrical concrete subjected to multidirectional compression was investigated experimentally. A total of 42 cylindrical concrete specimens from three different concrete mixes were tested. This test program was particularly focused on the strength and deformation aspects of the concrete response and the process of damage build-up.

From this study, it was found that the most important response index for concrete subjected to cyclic loading was the history of damage accumulated in the microstructure which was measured in terms of volumetric strain. The degradation of the elastic stiffness due to cyclic loads was found to be primarily a function of geometrical change and insensitive to the type of concrete considered. The comparison with the monotonic response of concrete which was also investigated in this study suggests that the cyclic nature of the load promotes damage build-up at faster rates than the monotonic loading, and the path-dependence in the behaviour of concrete is primarily with respect to the deformations.

1 Introduction

In general, the behaviour of reinforced concrete structures or elements are either highly redundant or have pronounced three-dimensional characteristics. Examples can be found on the behaviour of connections in multibay frames, where the three dimensional stress-strain behaviour is induced by the restraining effect from adjacent members and also on the behaviour of reinforced concrete columns, where the three dimensional stress-strain behaviour is mobilized due to the presence of spiral or tie reinforcement. Because of their three-dimensional

\textsuperscript{1} Presented at the First International Conference on Computational Methods and Testing for Engineering Integrity, 19-21 March 1996, Kuala Lumpur, Malaysia
characteristics, understanding the behaviour of such structures requires the knowledge of response of concrete subjected to triaxial stress.

The response of concrete to triaxial stress is governed by several material, geometric, and load variables. This parametric complexity is the reason why it is not easy to adequately describe the mechanical problem in mathematical terms. The greatest challenge to constitutive modelling of concrete stems from the fact that the array of significant parameters has not yet been completely isolated, whereas the available database of tests which can be used as a point of reference for such developments has a number of limitations: (1) Very few complete experimental records of the deformation have been reported in the literature. (2) Many of the parameters considered in the studies were not entirely independent.

Recent research results have illustrated that damage in concrete due to microcracking is manifested by volumetric expansion of the material. The rate of volume change represents volumetric strain, which is also defined by the trace of the strain tensor. Partial or total restraint against expansion, which is usually imposed through boundary conditions, has a profound influence on the internal stress state of the material. It has been proposed that the residual stiffness and strength of concrete under arbitrary stress can be entirely quantified from the state of damage (described by strain measures) and from the kinematic restraints imposed by the boundary conditions. Implementation of this concept in constitutive modeling of concrete relies on the availability of an extensive database of test results supplemented by complete deformation records. It was already mentioned that such records are rare in the literature. One contributing factor for the scarcity of data has been the technical difficulty in obtaining a complete set of credible deformation measurements; usually, the standard triaxial test is conducted by encasing the specimen in a triaxial testing device, with practically no physical access to it but through the loading mechanism. To date, the most commonly used database which is complete with regards the deformation characteristics has been developed at the University of Colorado; the effect of the load path was the main parameter investigated in that study. However, the types of load paths considered in that study are still limited, especially those that are related to the cyclic load paths.

The experimental work presented in this paper was motivated by the limitations of the existing database of test results outlined in the preceding. A parametric experimental study consisting of a series of monotonic and cyclic tests was undertaken, aiming to explore and quantify the influence of a number of significant variables on the triaxial behaviour of concrete, for the benefit of improved understanding and modelling of the material. The experimental program and the results of the study are outlined in the following sections.

2 Experimental Program

The tests were done on cylindrical specimens using a triaxial cell that was originally designed for testing the mechanical properties of rock. The essential
features of the test apparatus are illustrated in Fig. 1. The cell and the jacket used were designed to withstand hydraulic pressures of up to 70 MPa, and accepted only N×-core sized specimens (i.e. specimens with diameter of 54 mm (2.125 in), and height of 108 mm (4.25 in)). While encased in the triaxial cell, the specimen was loaded axially under displacement control using an MTS servo-controlled loading frame.

**Specimen Preparation, Instrumentation and Experimental Variables**

The dimensions of the specimens used in the study were prescribed by the geometry of the available cell. In order to ensure statistical homogeneity of the specimens, larger concrete blocks were cast, from which cylindrical cores of 54 mm diameter were extracted. The cores were then cut to lengths of 115 mm (4.3 in) to remove irregularities and soft concrete from the top surfaces. Both end-faces of each core were ground (to within 0.001 in) so that they would be exactly orthogonal to the longitudinal axis of the cylinders.

Three different batches of concrete were cast, with w/c of 0.4, 0.55, and 0.75 respectively. The maximum aggregate size used was 10 mm. The specimens were moist-cured at 23±2°C, with 100% relative humidity. The 28-day compressive strengths of batches 1, 2 and 3 were 48.1, 38.3, and 19.9 MPa respectively, however, at the time of testing concrete was approximately 3.5 month-old and the corresponding uniaxial strength were increased to 64.7, 43.5, and 21.2 MPa, because of continuous moist-curing of the specimens.

Axial deformation was measured independently during the tests by a system of external LVDT’s. To evaluate the volumetric strain, ε_v, which was of primary interest in the study, the lateral strain ε_l of the cylinders was measured using 60 mm long high-strain capacity straingauges (with strain limit of 10-20%), which were glued directly on the surface of the cylinders at midheight, and were encased within the membrane of the triaxial cell during testing. Due to axisymmetry, ε_v was calculated from the algebraic sum ε_3 + 2ε_l (the convention used here is tension positive; ε_3 represents the strain in the axial direction of the cylinder).

Parametric dimensions of the study were w/c, intensity of load and load path. The range of values considered for the experimental variables were:

1. **W/c**: Three values for w/c were considered, i.e., 0.4, 0.55, and 0.75.
2. **Level of confining stress**: Seven levels of confining pressure, σ_l, were used in the study. These were, 0, 0.05, 0.1, 0.2, 0.4, 0.7 and 1.0 of f_c.
3. **Load path**: Two different load paths were considered, i.e. monotonic and cyclic load paths. These are given schematically in Fig. 2.

### 3 Discussion of the Test Results

**Characteristics of the Cyclic Response**

A total of 21 concrete specimens from three different concrete mixes were tested under cyclic triaxial test conditions in order to study the characteristics of
the cyclic compressive behaviour of concrete. In each test, unloading and reloading of axial load was carried out while maintaining the level of specified confining stress constant (Fig. 2b). Typical responses from the test series are plotted in Fig. 3 along with the corresponding monotonic test results. It can be observed from the stress-strain curve in that figure that the reloading path of the cyclic response always joins the monotonic stress envelope, almost at the level of previously attained maximum stress; this observation is also valid in cyclic tests of confined concrete. The similarity of monotonic and cyclic stress-strain envelopes indicates that the specimens subjected to unloading and reloading cycles experience very little or no strength degradation due to cycling, which suggests that the strength criteria for concrete are basically path independent.

However, the cyclic stress-strain curves exhibit hysteresis during unloading and reloading cycles especially past the peak-stress level of concrete. The magnitude of this hysteresis is a measure of the amount of energy dissipation due to crack formation during the loading cycles. Hysteretic behaviour is also observed in the plots of the corresponding volumetric strain response of the specimens; evidently, the average slope of the hysteretic loops (line connecting the turning points) has a horizontal trend, particularly so in the post-peak regime. Thus, it can be said that during the cycling process the volumetric strain is more or less constant. This implies that during unloading, the change of area-strain in the material is approximately equal to the decrease in axial strain. (Note that this result is consistent with observations reported by Van Mier (8), obtained from cyclically loaded concrete cubes under similar lateral stress conditions, i.e., $\sigma_1 = \sigma_2$.) In addition, the size of the hysteretic loops in the $e_v - e_1$ plots progressively increased with higher levels of applied confining stress. While decreasing the axial load, the applied confining stress was kept constant thereby squeezing the specimen. This resulted in a reduction of area-strain and promoted further reversal of the axial strain. Note that this additional reversal of axial strain is the reason why at high confining pressure the specimen experienced a decrease in volume during the initial stages of the reloading cycle, which represents compaction of the material in the axial direction. Thus, for the same level of axial strain at initiation of unloading, specimens subjected to higher confining stress experience greater reversal of strain in the axial direction, and hence, they undergo a larger volume contraction during the reloading stage, as illustrated by the larger size of hysteretic loops.

Furthermore, it appears that for the same level of axial deformation, specimens that were subjected to cyclic loading experienced more volumetric expansion than specimens subjected to monotonic loading. It is stated earlier that volumetric expansion is a reliable measure of internal damage. The results of this comparison suggest that the cyclic nature of the load promotes damage built-up at faster rates than monotonic loading, and hence, the path-dependence in the behaviour of concrete is primarily with respect to the deformations.
Degradation of the Elastic Modulus

The slope of the unloading loops in the stress-strain curve, which represents the residual elastic stiffness of concrete in the axial direction, decreases as the magnitude of induced axial deformation at which unloading begins is increased. This is attributed to the continuous growth of cracks within the concrete specimens with increasing level of imposed deformation. The crack formation caused an increase in the apparent porosity of the specimens (i.e. crack induced voids), which was orthotropically oriented and primarily affected the area normal to the compressive load. It has been established from early works that the larger the effective void ratio of concrete, the smaller its elastic modulus. It is for this reason why, cracking, as well as natural porosity, are considered to both have a parallel weakening influence on the elastic modulus of concrete.

To study the pattern of stiffness degradation in the axial direction, the average slope of the hysteretic loops in the axial stress-axial strain diagram (i.e., the line connecting the turning points at the ends of a loop), normalized with respect to the initial stiffness of undamaged concrete, was plotted for all tests in Fig. 4 against the area strain of the specimen cross-section carrying the axial load. It is evident from the figure that the area-strain variable organizes successfully the data for both confined and unconfined tests, thereby suggesting that degradation of the elastic stiffness is a manifestation and direct consequence of expansion due to cracking of the cross-section of the compressive strut. The experimental trend of Fig. 4 is described mathematically as follows:

\[
\frac{E}{E_0} = \frac{1}{1 + \frac{\varepsilon_A}{\alpha}}
\]

where \(\alpha\) is a normalizing constant; based on the available tests, the value of \(\alpha\) used in plotting the solid line in Fig. 4 was taken 0.05. From this correlation it can be concluded that the degradation of the elastic stiffness due to cyclic loads is primarily a function of geometrical change (in this case area-strain) and is insensitive to the type of concrete considered. Furthermore, using Eqn. 1 it is possible to evaluate the magnitude of axial strain, \(\varepsilon^R_3\), at which complete removal of axial stress is achieved (the point where the unloading loop intersects the axis of strains (Fig. 5)). Note that the stress at the point of initiation of unloading from the envelope, \(\sigma^E_3\), is given in terms of the accumulated area strain \(\varepsilon^E_{A3}\) and the corresponding axial strain \(\varepsilon^E_3\) (Fig. 5), by the following relationship:

\[
\sigma^E_3 = \frac{E_0 \varepsilon^E_3}{1 + \frac{\varepsilon^E_{A3}}{\beta}}
\]

where \(\beta\) is a material constant (it was shown in the reference paper that \(\beta = V_P^3 \nu_{cap} / 3\), where \(V_P\) is the volumetric fraction of paste in the concrete.
mix and \( n_{\text{cap}} \) is the capillary porosity of the paste; for the three concrete mixes considered in this study, the values of \( \beta \) were 0.006, 0.0035, and 0.002 for w/c of 0.4, 0.55, and 0.75, respectively). From Eqns. (1) and (2) the axial strain at complete removal of stress, \( \varepsilon_3^{R} \), is given as a fraction of the strain at the envelope \( \varepsilon_3^{E} \) (at the initiation of unloading) as follows (Fig. 5):

\[
\frac{\varepsilon_3^{R}}{\varepsilon_3^{E}} = \frac{\varepsilon_3^{E}}{1 + \frac{\varepsilon_3^{E}}{\beta}} \left[ 1 + \frac{1}{\beta} \right]
\]

Equation 3 is an empirical summary of the available cyclic test results, stating that the strain ratio \( \varepsilon_3^{R}/\varepsilon_3^{E} \) and hence the slope of the unloading loops decays with increasing amount of lateral expansion in the cross section of the compressive strut. Note that for the same level of envelope strain \( \varepsilon_3^{E} \), concrete specimens with higher confining pressures generally experienced lower amounts of expansion strain, \( \varepsilon_3^{A} \) and lower amounts of stiffness degradation during unloading. Hence, by linking the degree of stiffness degradation to the expansion strain variable (Eqn. 1), it is possible to describe this process for both confined and unconfined compressive cyclic stress states. The success of Eqn. 3 in capturing stiffness degradation in uniaxially loaded concrete is evidenced by the observed agreement with other more restricted empirical models of the same phenomenon; Fig. 5 compares the behaviour of Eqn. 3 with the well established model of Karsan and Jirsa (3) which summarizes the experimental data from a series of uniaxial cyclic tests conducted by the authors on cylinder specimens.

Conclusions

An extensive experimental program was undertaken in order to characterize the behaviour of concrete under cyclic multiaxial states of stress. Based on the experimental evidence it can be concluded that:

a) Under increasing lateral confinement, concrete experienced enhancement of strength and apparent ductility. This is due to the restraining action of the confining mechanism, which impeded and consequently slowed down the development of lateral expansion in the material.

b) The volumetric-axial strain history of specimens subjected to cyclic loading exhibited hysteretic loops, associated in shape and size with those commonly observed in cyclic stress-strain relationships. The size of these loops increased with increasing confining stress.

c) By comparing the results of the cyclic and monotonic tests it was found that the deformation behaviour of concrete was path dependent. On the other hand, the strength of concrete was observed to be basically path independent. It was also observed that concrete specimens subjected to cyclic loading experienced larger volumetric expansion than those subjected to monotonic loading. This indicates that the cyclic nature of the load promotes damage build-up at faster rates than the monotonic loading.
References


![Figure 1: Triaxial Testing Device](image1)

![Figure 2: Load Paths Used](image2)
Figure 3 : Sample Results of Cyclic Tests.

Figure 4
Degradation of Unloading Stiffness

Figure 5 : Residual Stress Values