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Stress versus strain relationship of high strength concrete under high lateral confinement

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Abstract

A common application of high strength concrete (HSC) is in columns subjected to large compressive forces. However, a major problem is the insufficient ductility available in HSC columns. To determine the required lateral reinforcement to maintain sufficient ductility, a good understanding of the stress-strain behaviour of confined concrete needs to be established. This paper describes a testing program carried out to obtain experimental data of complete (ascending and descending) stress-strain relationships between axial stress, axial strain and lateral strain for HSC. Compressive strengths of concrete tested were 100 MPa and 60 MPa. The confining pressures used were 4 MPa, 8 MPa and 12 MPa. A total of 18 stress-strain curves are presented. The experimental results obtained seem to indicate that, for high confining pressures, the lateral strain at peak stress for 100 MPa concrete was 20% less than that of the 60 MPa concrete.

Keywords: Compressive strength; Mechanical properties; High performance concrete; Modeling; Stress-strain curve

1. Introduction

High strength concrete (HSC) with compressive strengths between 50 to 120 MPa can be produced using conventional production methods and are observed to have better durability and strength characteristics. One of the main applications of HSC is in lower-storey columns of tall buildings. The use of HSC allows a significant reduction of column sizes which increases the floor area for rental, leading to economic advantages. In bridge design, the use of HSC can reduce the required number of beams. Also, in prestressed concrete, for a given level of prestress, the loss of prestress due to creep is smaller than in a lower strength member [1]. The most significant disadvantage of using HSC is the reduction of ductility with increase in compressive strength. Therefore, when designing with HSC, care is required to avoid brittle failure.

When a reinforced concrete column is subjected to an increasing static load, initially, the confining steel does not have any effect on the load deformation behaviour of the column. With the increase in load, the Poisson's ratio effect of concrete will cause a lateral expansion of confined concrete which will be resisted by the confining steel. The confining pressure applied on the concrete core by the confining steel increases with the increase in axial load and depends on the relationship of axial strain and lateral strain of concrete. Lateral expansion of concrete under axial load has been observed to decrease with increasing compressive strength of concrete and may have serious implications on the amount of confining steel required for a particular level of ductility in a HSC column [2].

2. Previous work

The behaviour of concrete under lateral confinement can be investigated by testing cylindrical specimens under a lateral fluid pressure. The fluid is usually oil or water. The advantage of this method is that the observations can be directly related to a range of applications rather than being limited to hoop confined columns. The disadvantage is that the fluid pressure provides an active confinement on concrete rather than the passive one encountered in laterally confined columns. However, provided the stress-strain curve of the reinforcing steel and the volume dilation of concrete is known, the results can be related to the case of passive confinement.

In "active confinement" provided by fluids, the full lateral pressure is applied and held constant at the beginning of the test. In "passive confinement" provided by stirrups and ties, the confining effect is initiated by the lateral expansion of the concrete and the confining pressure gradually increases as the concrete continues to expand.

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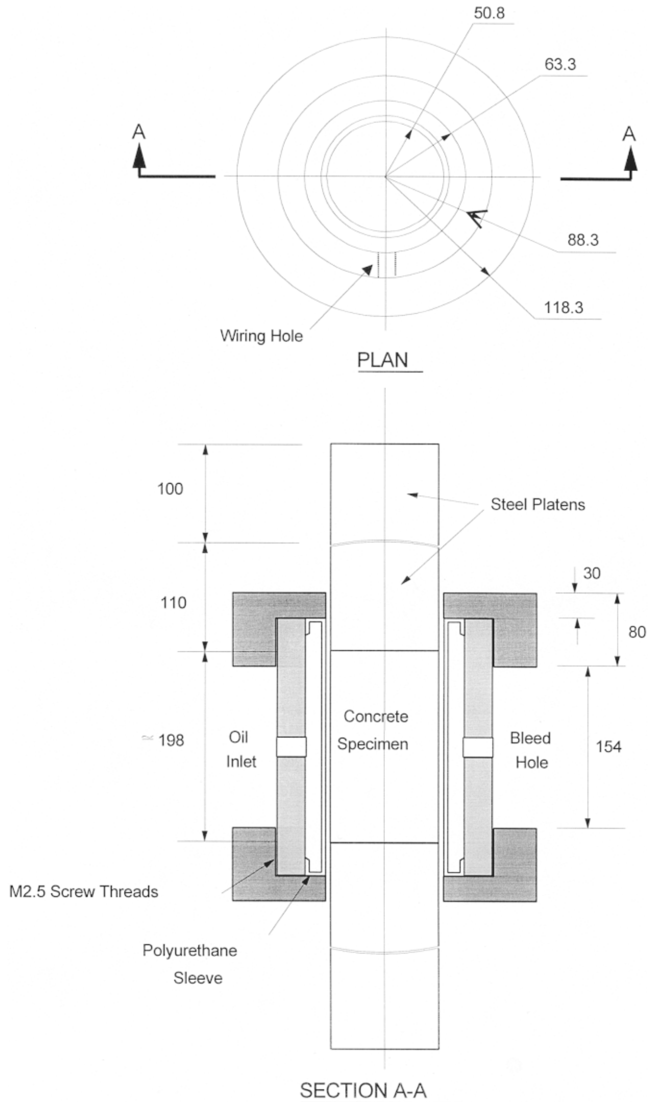

Fig. 1. Schematic diagram of the triaxial cell.

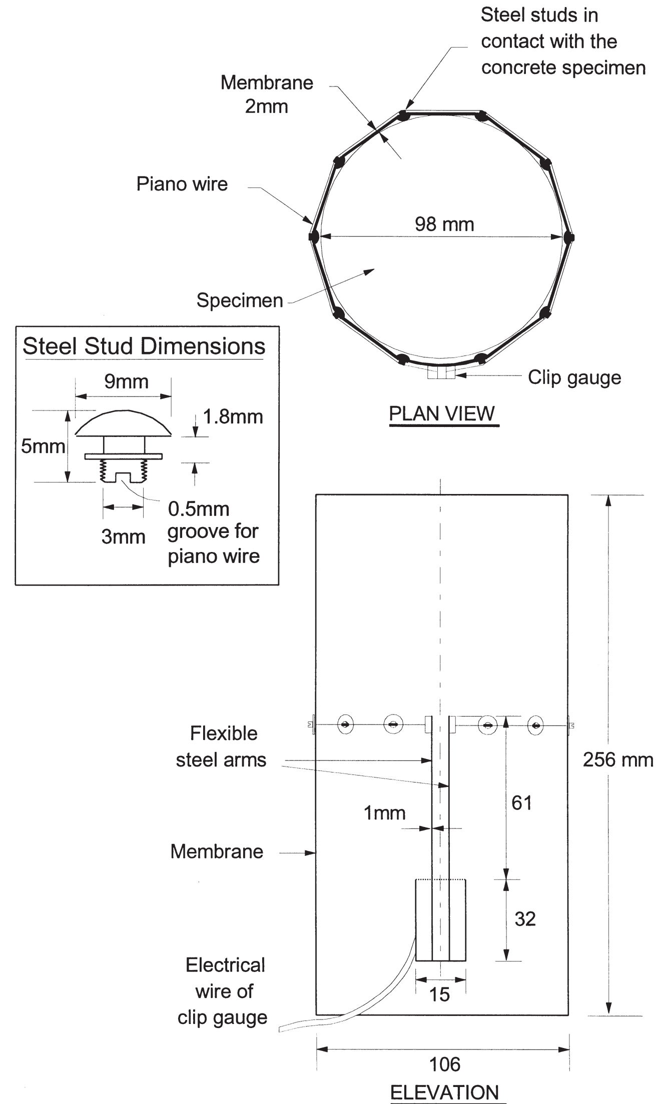

Fig. 2. Schematic diagram of the lateral expansion measuring system.

2.1. Effect of fluid pressure on strain gauges

In triaxial tests, the concrete specimen is under a fluid pressure. Therefore, if strain gauges are to be used in the triaxial tests, the effect of fluid pressure on the gauges needs to be known. Studies conducted by Dahl [3] indicated that normal foil type strain gauges are not sensitive to pressure on the face of the gauge.

2.2. Proportional loading versus normal loading

When applying the confining pressure on the test specimen, the two most commonly used load paths are normal loading and proportional loading. Normal loading is achieved by applying the full confining pressure at the beginning of the experiment and thereafter increasing the vertical stress until failure is reached. In proportional loading, the ratio of the two principal stresses (the axial stress and the confining pressure) are kept equal (i.e., the confining pressure is gradually increased with increasing vertical stress).

Most researchers believe that, regardless of the load path method chosen, there will be little or no difference to the ultimate strength, and it is better to use the normal load path method as this method is practically easier to apply than the proportional loading method.

3. Experimental program

3.1. Triaxial cell

The triaxial cell used in the experiments is shown in Fig. 1. The main component is a pressure cell which accommo-

Table 1
Uniaxial strengths at 28 days and at time of testing

	U60	U100
28 day strength (MPa)	49.7	86.4
Strength at testing (MPa)	60.6	103.3
Age at testing (days)	56	90

Table 2
Mix proportions used for U60 and U100

Material	U60	U100
Cement (kg)	360	550
Water (kg)	180	165
Coarse Agg (kg)	1130	1340
Fine Agg (kg)	830	520
Superplasticiser (kg)	-	8.7
Water / Cement Ratio	0.5	0.3
Target Slump (mm)	100	150

dates a 100 × 200 mm cylindrical specimen. The required confining pressure was applied using oil through a flexible polyurethane membrane. As shown in Fig. 1, a bleed hole and an oil inlet was provided in the middle of the cell body. The compressive load was applied to the specimen using two spherically seated cylindrical loading blocks which were designed to fit either end of the cell with a clearance of 1.3 mm.

The specimen to be tested was enclosed in a membrane which had the confining pressure applied to it. The membrane was made out of flexible polyurethane and had a thickness of 2 mm. The required confining pressure was applied using an Enerpac hydraulic hand pump. Also, a pressure gauge was connected in series in order to measure the pressure being applied. The pressure gauge used was a PDCR 610 made by Druck Ltd, Leicester, England, and it required a 10-volt exciter.

3.2. Measurement of axial displacement

Displacement transducers (LVDTs) were used to measure the longitudinal or axial deformation. However, adopting this method required accounting for the flexibility of the loading components. A calibration was done using an aluminium cylinder which had a yield stress higher than the compressive stresses encountered in the testing of concrete.

Although LVDTs were adopted to measure the axial strain, each sample tested was fitted with at least one axial strain gauge (most had two diagonally opposite axial strain gauges). This was to verify the LVDT readings until the peak stress was achieved.

3.3. Measurement of lateral displacement

Special concrete strain gauges of length 70 mm were used to measure the radial or lateral strain. However, preliminary tests showed that the strain gauges malfunctioned during the descending portion of the stress-strain curve due to the large magnitude of the post-peak lateral strains and cracking of the concrete sample. Therefore, a dual measuring system was incorporated to measure the lateral deformation. The strain gauges were used to measure the ascending portion of the stress-strain curve and a special device was built to measure the large lateral strains along the descending portion of the curves. The lateral strain measuring device developed at Monash University is shown in Fig. 2. To ensure that the flexible membrane surrounding the concrete sample did not influence lateral strain measurements, “direct contact” with the specimen was achieved by drilling 10 holes half way up the membrane and fitting the holes with studs. A sealant was used to ensure that no fluid reached the specimen. A groove was cut on the outside of the studs and a thin wire (piano wire) was placed in these grooves with the ends connected to the two arms of the clip gauge as shown in Fig. 2. The arms of the clip gauge were fitted with 4 strain gauges forming a Wheatstone bridge and hence any movement of the arms were recorded into a data-logger.

The accuracy of the lateral strain measurements obtained by the new device was verified using strain gauges (until the strain gauges failed, which was usually around the peak strength). Except at small strains, which the device needed

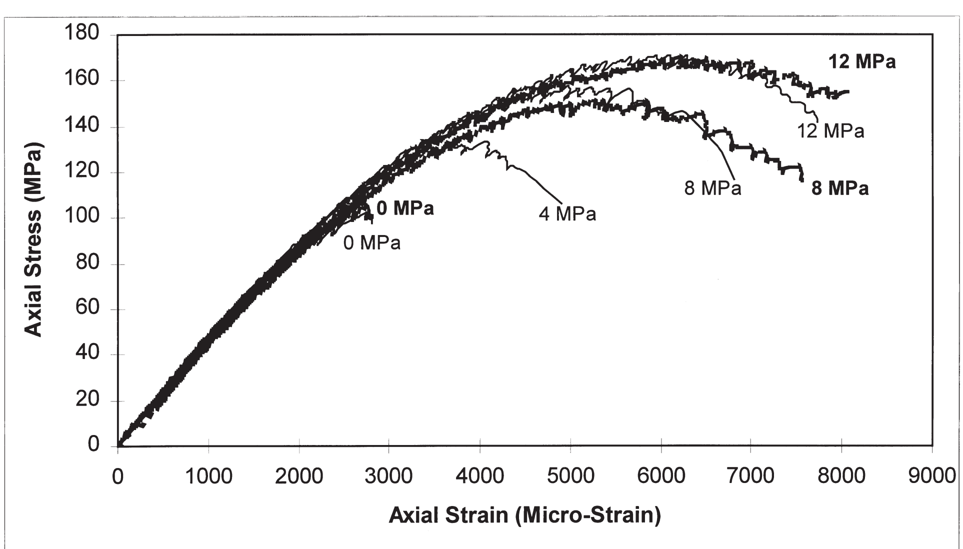

Fig. 3. Axial stress-axial strain curves for the U100 specimens at 0, 4, 8 and 12 MPa confining pressures.

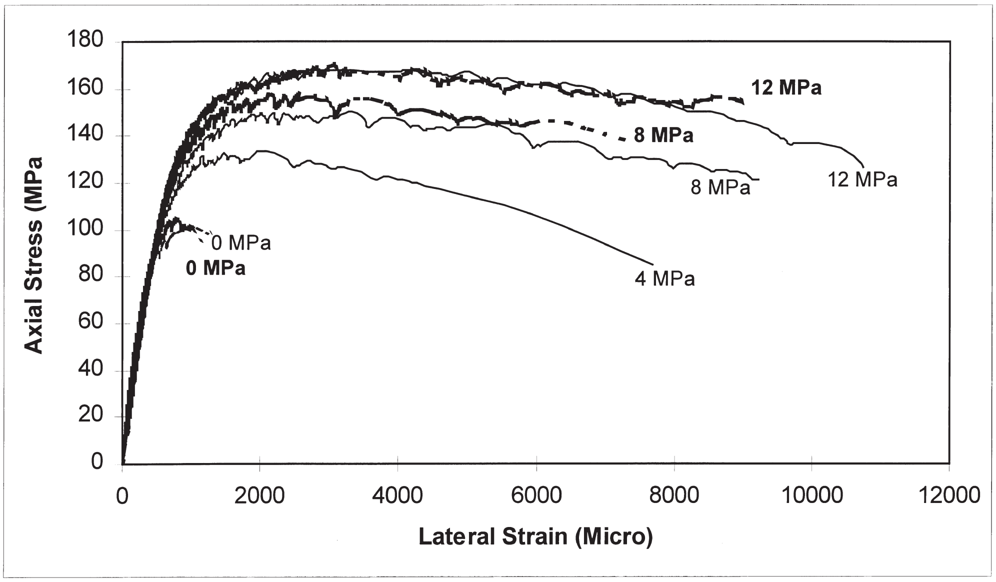

Fig. 4. Axial stress-lateral strain curves for the U100 specimens at 0, 4, 8 and 12 MPa confining pressures.

to overcome friction between the studs and the piano wire, there was agreement between the strain gauge readings and the readings of the new apparatus.

Some previous attempts by researchers to obtain lateral strain measurements gave inconsistent results [4]. Therefore, the repeatability of the device was checked by carrying out two tests at a given confining pressure and the device was found to give repeatable measurements.

3.4. Details of concrete mixes

The target strengths were 60 MPa and 100 Map. The 60 MPa and 100 MPa strengths basically represent the lower and upper ends of the high strength concrete spectrum, respectively. Although the 28 days strength of the mixes were lower than the target strengths, the target strengths were achieved at the time of triaxial tests. Table 1 shows the 28 day strengths and the strength and age at the time of triaxial testing. The mix proportions used are given in Table 2. The concrete batches were denoted U60 and U100, "U" representing uniaxial and 60, 100 representing the target test strengths. The type of coarse aggregate used was basalt with a maximum size aggregate of 14 mm. The type of superplasticiser used was RHEOBUILD 1000, which was supplied by MBT PYT LTD (Australia).

3.5. Specimen preparation

The size of the specimens were 98 $\times$ 200 mm (98-mm diameter specimens were used rather than the standard 100

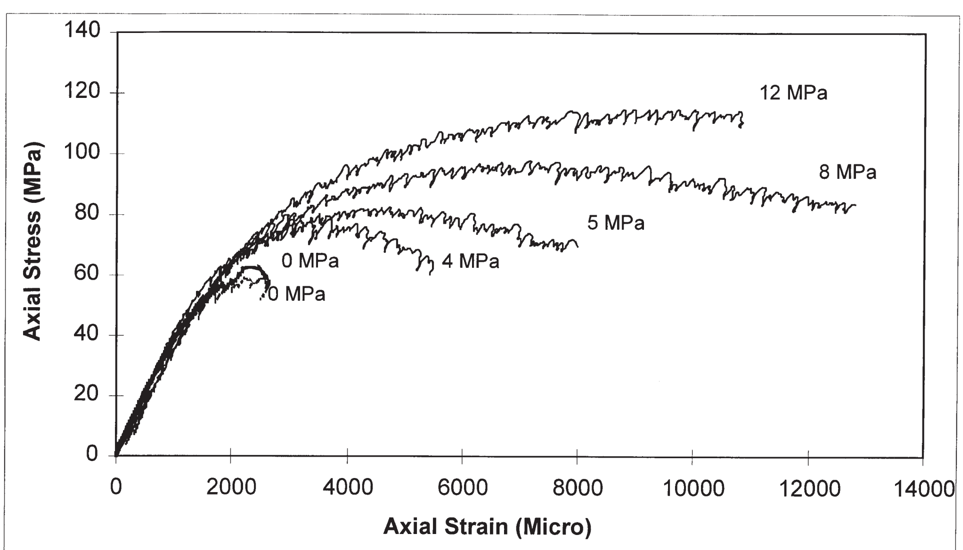

Fig. 5. Axial stress-axial strain curves for the U60 specimens at 0, 4, 5, 8 and 12 MPa confining pressures.

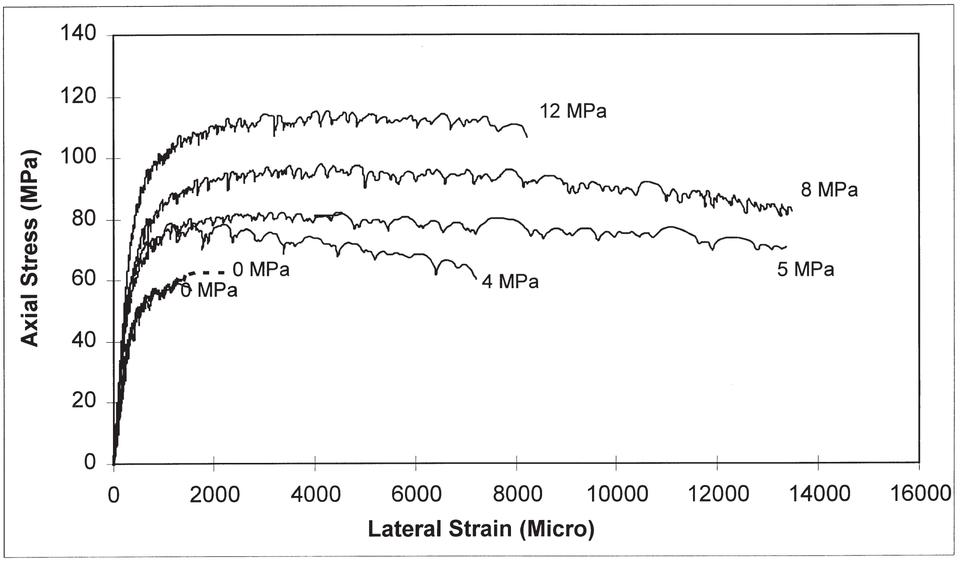

Fig. 6. Axial stress-lateral strain curves for the U60 specimens at 0, 4, 5, 8 and 12 MPa confining pressures.

mm to enable ease of removal of tested samples). In order to achieve a diameter of 98 mm, a 1-mm thick sheet of plastic sleeve was inserted in the mould. The specimens were demoulded 24 hours after casting, and were bath cured at 23°C. The cylinders were taken out at 28 days and ground at both ends before testing. To prevent membrane damage, the specimen pores were filled with casting plaster.

3.6. Testing procedure

The confining pressures used were 4, 8 and 12 MPa. Two samples were tested at each confining pressure for each strength. Of the 12 tests conducted, two were unsuccessful due to the piano wire of the clip gauge breaking and one due to an electronic failure of the data logging equipment. Hence, a total of nine triaxial tests were successfully completed. After the specimens were ground and prepared, two lateral strain gauges and two longitudinal gauges were attached on the middle third of the specimen. The longitudinal gauges were placed diametrically opposite each other as were the lateral gauges.

Once the Hoek cell was in place in the testing machine (Amsler), a small vertical load was applied, to ensure that the cell was secure, before applying the confining pressure. The testing machine was then set to compressive displacement control at the rate of 2.5 mm vertical displacement every 10 minutes. The tests were continued until the post-peak behaviour of the axial stress-axial strain curves were well defined, thus giving an indication of the ductility of the specimen. In the testing of specimens subjected to large confining pres-

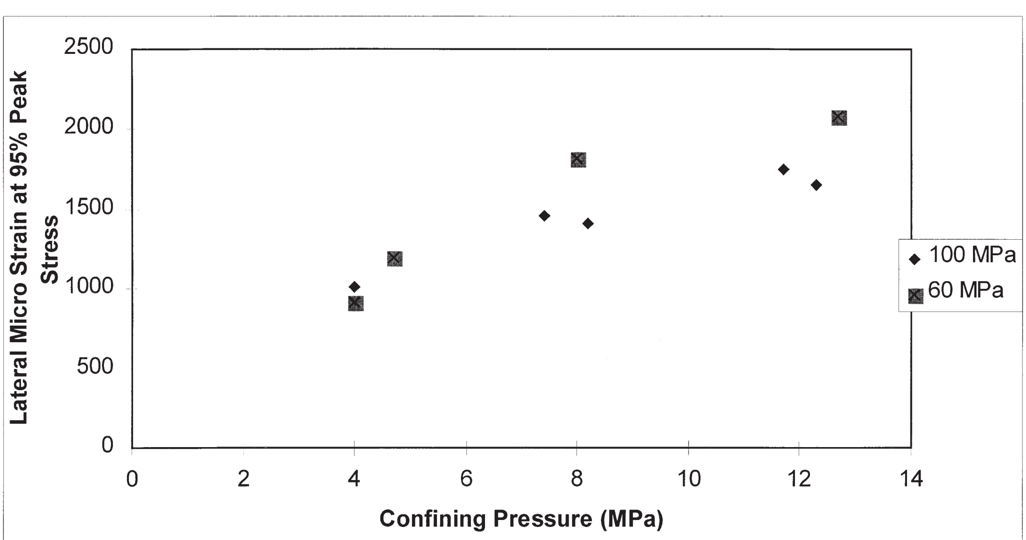

Fig. 7. Relationsip between lateral strain at peak strength and confining pressure.

Table 3
Lateral strain at 95% peak stress comparison for U100 and U60

Confining pressure (MPa)	U100ε_{95}/U60ε_{95}
4	1.12
8	0.78
12	0.8

sures, axial strain at the peak stress was as high as 7000 microstrains. In these tests, axial strain values of up to 12000 microstrains were recorded before termination of the tests.

4. Results

The results obtained for the U100 concrete specimens are shown in Figs. 3 and 4. The confining pressure at which each curve was obtained is indicated on the figures. The results obtained for the U60 concrete specimens are shown in Figs. 5 and 6.

5. Discussion

Many of the existing models for the behaviour of confined concrete are based on the results of column tests. These models are dependent on the level of confinement estimated and assumed effective area of the column core. Confinement models based on triaxial tests do not incorporate these assumptions. The main difference between confinement by spirals, ties, steel tubes or other materials such as carbon fibre in a column and fluid pressure in a triaxial cell is that lateral reinforcement provides a passive confinement. Passive confinement is dependent on the lateral dilation of the concrete under axial load and the stress-strain relationship of the confining material. In order to model the behaviour of a confined column, accurate information about the lateral expansion of confined concrete is required.

Measurement of lateral strain in a specimen under triaxial compression is difficult primarily because the concrete specimen is fully enclosed within the triaxial cell. In addition the concrete specimen needs to be fairly large and measurement of an average lateral strain is preferred to a localised measurement. The apparatus described in this paper has successfully overcome such difficulties.

The results indicated that the increase in the strength of concrete due to confining pressure can be predicted using a conventional relationship such as:

$$f_{cc} = f_c + Af_r$$

for both HSC and NSC, where f_{cc} is the strength of confined concrete, f_c is the uniaxial compressive strength, f_r is the confining pressure and A is a constant.

Fig. 7 shows that the lateral strain corresponding to the peak stress, ϵ_l, increases with the confining pressure. It also shows that at 4 MPa confining pressure, U100 and U60 concretes have a similar lateral strain at 95% of peak stress (ϵ_{95}). However, the results appear to indicate that the higher strength concrete has significantly less ϵ_{95} at higher confining pressures. Table 3 shows that U100 had 20% less ϵ_{95} than U60 at 8 MPa and 12 MPa confining pressures.

In a passive situation, a higher value of lateral strain would indicate a higher confining pressure while the material which confines concrete is still in the elastic stage. Early researchers Ahmad and Shah [2] have expressed concern about the reduction of lateral expansion of concrete under axial load with increase in compressive strength of concrete, which will reduce the effective confining pressure of a passively confined HSC member. Results reported here support their predictions to a certain extent although more results are required to draw firm conclusions.

6. Conclusions

The paper described an experimental testing program conducted by the authors at Monash University to obtain axial stress-axial strain and axial stress-lateral strain curves for high strength concrete under triaxial conditions. Stress-strain curves were obtained for concretes with uniaxial strengths of 60.6 MPa and 103.3 MPa. The confining pressures used were 4 MPa, 8 MPa and 12 MPa.

A simple but effective apparatus to measure lateral strains of concrete enclosed in membranes is described. The “direct contact” measuring system provided accurate and repeatable post-peak lateral strain measurements.

The experimental results indicate that the lateral strain at peak stress is similar for 60 MPa and 100 MPa concrete at low confinements. However, at high confinements, the lateral strains at peak for 100 MPa concrete is only 80% of the corresponding lateral strain for 60 MPa. This implies that the effective confinement offered by lateral reinforcements will be less for high strength concrete under high confinement.

Due to the technical difficulties encountered when attempting to measure lateral strains of high strength concrete under triaxial confinement, there exists a lack of such data in current literature. Therefore, the results presented in this paper would be valuable particularly to those simulating the behaviour of laterally confined high strength concrete.

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