Behavior of High-Performance Concrete Subjected to Biaxial Tension-Compression Stresses

by J. M. Calixto

Synopsis: The results of an experimental investigation on the behavior of high-performance concrete subjected to biaxial tension-compression stresses are presented. Short-term static tests were performed on 125 mm square by 12.5 mm thick plates. Strain controlled tests were executed in a biaxial testing machine constructed at the University of Texas. The primary studied variables were the discontinuity and the ultimate stress levels at each stress ratio. Results indicated that even small amounts of tensile stress reduced the ultimate compressive strength of the specimens substantially. The failure mode of the plate specimens fell basically into one category: tensile splitting in a plane or planes perpendicular to the direction of the principal tensile strain. The failure surface contained both fractures through coarse aggregate and mortar. These results suggest that the failure criteria for high-performance concrete, under biaxial tension-compression, is a limiting value for the tensile strain. The magnitude of the failure tensile strains is not constant, but increases with the degree of compression.

Keywords: behavior; biaxial tension-compression stresses; high-performance concrete; strength

José M. Calixto is an associate professor in the Structural Engineering Department at the Federal University of Minas Gerais, Belo Horizonte, Brazil. His research interests are in concrete materials and concrete structures.

INTRODUCTION

Concrete in normal conditions is a versatile, strong and durable construction material. However under several physical and chemical processes as well as certain environmental conditions it may deteriorate in a short period of time. This fact has led researchers in the last 30 years to develop the high-performance concrete. High-performance concrete (HPC) is a concrete which possess high workability, high strength and low permeability.

The production of a high-performance concrete can be achieved basically with a better selection of component materials, adequate mixture proportion, careful placement and proper curing. The required workability is normally attained with the use of superplasticizers. Since the manufacture of high-performance concrete does not involve the use of exotic materials and complicated procedures, its production is within the reach of most concrete producers.

In most structures, concrete is often subjected to biaxial states of stress, and the behavior of the material under these types of actions must be well understood. It is, therefore, not surprising that numerous investigations into the behavior and strength of conventional concrete under biaxial stress states have been conducted in the past 40 years (1,2,3). On the other hand, HPC differs from normal strength concrete (NSC) in several aspects and these differences are not yet totally understood. Thus more studies are necessary to better understand the behavior of this material and to facilitate the design and construction of more structures with HPC.

The aim of this paper is to gain further understanding on the behavior and failure mechanism of HPC when subjected to biaxial stresses. Short-term static tests were performed on 125 mm square by 12.5 mm thick plates subjected to biaxial tension-compression stresses at selected stress ratios (4). The strain controlled tests were executed in a biaxial testing machine constructed at the University of Texas. The primary variables studied were the discontinuity and the ultimate stress levels at each stress ratio. A comparative study with normal strength concrete is also presented.

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials

The proportioning of the components for HPC mixtures is more critical than for normal concrete since for HPC optimum performance is required from each component used. This means that quality materials in the mixture proportion and good quality control in the field are necessary. For the current investigation, the materials used included ASTM Type I cement (Brazilian Type CP I), crushed limestone, with a maximum size of 1.0 cm, as coarse aggregate and a river sand as fine aggregate. For the necessary slump the superplasticizer employed was Pozzolith 400–N manufactured by Master Builders of Cleveland, Ohio. The mixture proportion consisted of 575 kg of cement per cubic meter of concrete, a **W/C** (by mass) of 0.28, an aggregate/cement ratio of 2.88 and a coarse-to-fine aggregate ratio of 1.72. The superplasticizer/cement ratio (by mass) was 0.013.

A total of nine 100 mm x 200 mm cylinders and six 150 mm x 150 mm x 500 mm beams were cast using steel molds. A pencil vibrator was used for compaction of the concrete into the molds. The newly cast molds were covered with a wet burlap for 24 hours. The cylinders and beams were then removed from the molds and placed in a curing room at a temperature of 22 ± 2 °C and 95 to 100 percent relative humidity.

Specimen Preparation

The preparation of the plate specimens included the cutting of the 125 mm square by 12.5 mm thick plates from the beams. Cutting of the beams was initiated after at least 56 days of casting and was performed using a slow-feeding diamond blade lapidary saw. For the 12.5 mm dimension, the plates were sliced slightly larger than needed and ground down employing a vibrating lapidary table. After grinding, the specimens were washed with soap and water, rinsed and again stored in the curing room.

At least three days prior to testing, each specimen was removed from the curing room for preparation of the loading edges. The edges were sand-blasted with fine silica sand to roughen the surfaces, facilitating a good bond between the edges of the specimen and the epoxy adhesive.

For the transmission of the tensile forces, the edges of the specimen must be securely attached to the comb-platens and the binding material used must develop a sufficient strong bond with both the concrete and the aluminum to withstand the maximum tensile force expected. The exposed edges of the specimen were then coated with a thin layer of Adhesive Engineering Company 1411 Non Sag Paste Adhesive. The mating surfaces of the comb-platens and the specimen were then pressed together. The paste adhesive was allowed to cure at room temperature for at least 36 hours prior to testing.

Loading Apparatus and Testing Procedure

The loading apparatus used was a special biaxial testing machine built at The University of Texas. It consists of steel framing members, hydraulic rams and load cells as shown schematically in **Fig. 1**. The load was applied by hydraulic rams located in the vertical and horizontal directions. Each ram was controlled by an electronic hydraulic servo system. In order to prevent any significant confining stress, special steel brush-bearing platens were used for compressive loads (**Fig. 2**). They were of a design similar to those employed by Hilsdorf (5). For the tensile loads, a different set of platens (**Fig. 3**), made of a single aluminum plate and designed by Briggs (6), was used.

Instrumentation was necessary to measure and record loads and strains. Load cells were employed for measuring the loads, while strain gages were used for evaluation of the deformations. Two strain gages were glued on each face of the plate specimen parallel to the directions of the principal stresses. The rate of loading was conditioned to match the strain gage feedback signal by the electronic hydraulic servo system.

Three specimens were tested for each principal stress ratio. The principal stress-ratios used were $\sigma_2/\sigma_1 = 0$ (uniaxial compression); $\sigma_2/\sigma_1 = -$ 0,10, - 0.5 and – 1,0 for biaxial tension-compression; and $\sigma_2/\sigma_1 = \infty$ for uniaxial tension.

TEST RESULTS AND ANALYSIS

Concrete strength was evaluated using 100 mm x 200 mm cylinders tested at ages of 8, 56 and 172 days. The 56-day strength was of primary interest since the preparation of the plate specimens took place after the age of

56 days. The 172-day test was performed to compare the cylinder compressive strength with the uniaxial compressive strength of the plate specimens. The average cylinder compressive strengths were 52.7, 62.9 and 74.4 MPa at the ages of 8, 56 and 172 days respectively.

Typical stress-strain curves at the different principal stress ratio tested are shown in **Fig. 4**. It is interesting to note that only for the case of uniaxial compression, the stress-strain curve deviates significantly from linearity at high levels of straining. For all other cases tested, the stress-strain curves are almost linear up to failure.

The value of the modulus of elasticity for specimens tested in uniaxial tension (E_t = 46755 MPa) was only 3% greater than the average modulus of elasticity obtained in uniaxial compression (E_c = 45279 MPa). These values are larger than expected specially when compared to relation for determination of the modulus of elasticity proposed by ACI 363 (8). The value of Poisson's ratio was slightly higher in uniaxial compression (ν_{21} = 0,20) than in uniaxial tension (ν_{12} = 0,19). Similar differences were obtained by previous investigators (3, 7) for normal strength concrete.

The average stress and corresponding strain at failure for each principal stress ratio are presented in Table 1. The average uniaxial compressive strength determined using the plate specimens was 59.6 MPa, while the average cylinder compressive strength, tested at the same age, was 74.4 MPa. The difference between the two values can mainly be attributed to the effect of confinement, which practically does not exist in the case of the plate specimen.

The analysis of the results of Table 1 indicates also that the ultimate compressive strength of HPC under biaxial tension-compression is significantly less than the uniaxial compressive strength. Under uniaxial loading, the ultimate tensile strength of the HPC was 7 percent of the corresponding compressive strength. This relation is in good agreement with the equation proposed by ACI 363 (8) for tensile splitting strength if the plate compressive strength is employed in the equation.

With respect to the deformations, the results of Table 1 show that, in uniaxial compression, there is a significant increase in the tensile strains at failure in relation to the tensile strains at failure of all other ratios tested. As observed for normal strength concrete (3), high-performance concrete strength can also sustain a larger amount of indirect tensile strain, due to Poisson's effect, than direct tensile strains.

The biaxial tension-compression strength envelope is shown in **Fig. 5**. The strength envelope for normal strength concrete, obtained by Tasuji et al. (3), is also shown. The data presented in the plot are normalized with respect to the plate uniaxial compressive strength. The shape of the strength envelope for biaxial tension-compression of HPC is much more linear than that obtained for normal strength concrete under similar loading conditions. The comparison also indicates that the biaxial tension-compression strength is different for different strength concretes. Under biaxial tension-compression, the decrease in the compressive strength is lower for concretes with a normal uniaxial compressive strength (NSC), and is higher for concretes having a higher uniaxial compressive strength (HPC).

This difference in behavior has important implications on the design of HPC structures. An example would be in the shear design of reinforced concrete flexural elements. Since biaxial tension-compression stresses exist in the shear region of these elements, the stresses corresponding to the formation of the diagonal cracks should be more carefully determined when HPC is used.

The failure mode of all plate specimen tested fell into one category, tensile splitting in a plane or planes perpendicular to the direction of the principal tensile strain. The failure surface contained fractures through both mortar and coarse aggregate. These results suggest that the failure criterion for high-performance concrete under biaxial stresses is a limiting value for the tensile strain.

In the present study, the behavior of HPC at discontinuity was considered in addition to that at failure. According to Newman (9), discontinuity in NSC corresponds to the stage at which major microcracking of concrete is initiated. Carino and Slate (7) have indicated that the use of discontinuity as the basis for failure of NSC is more appropriate than the ultimate strength since it represents the end of quasi-elastic behavior and the beginning of extensive mortar cracking. Moreover, it has been shown by Rüsch (10) that the long term strength of NSC in compression corresponds to the stage at which extensive mortar cracking develops. Beyond discontinuity, NSC can no longer be considered a continuous material since any sustained load is expected to cause an eventual failure. This was the primary motivation for obtaining data at discontinuity.

Many procedures have been used to calculate the discontinuity point. In this study two procedures were employed. In uniaxial compression, discontinuity was defined as the point at which Poisson's ratio began to increase significantly. This method has been extensively employed by previous investigators (3,7) for NSC. In tests involving direct tension loading, discontinuity was defined as the point at which the stress versus the maximum tensile strain curve began to deviate significantly from a straight line. A 2% deviation was taken as a significant departure from linearity. Table 2 presents the average stresses and strains at discontinuity as well as the mean normal stresses for the various stress-ratios tested.

It can be seen from Table 2 that the principal tensile strain (ε_2) at discontinuity depends upon the state of stress, increasing with the degree of the compressive stress. A plot relating this principal tensile strain at discontinuity to the mean normal stress is presented in **Fig. 6**. A careful examination of the figure indicates that the data can be represented by a straight line whose corresponding equation is also shown. The correlation coefficient for the data used in obtaining the equation shown was 0.99. This finding suggests that there exists for HPC a linear relationship between the principal tensile strain and the mean normal stress at discontinuity for biaxial tension-compression stresses.

The principal tensile strain versus the mean normal stress for normal strength concrete (NSC), obtained by Tasuji et al. (3), is also presented in **Fig. 6.** A linear relationship also exists for NSC and the corresponding equation is indicated in the diagram. A comparison between the equations shows that the slope for NSC is 1.5 times the value corresponded to HPC. This fact implies that, under biaxial tension-compression, NSC can deform much more than HPC, confirming once more the more brittle behavior of HPC.

As for normal strength concrete, it is evident from the above results that a constant tensile strain failure criterion cannot fully describe the observed HPC behavior in biaxial tension-compression. A HPC failure criteria should take into account the fact that the limiting value of the tensile strain is dependent upon the applied state of stress.

CONCLUDING REMARKS

The results of an experimental investigation on the behavior of high-performance concrete under biaxial tension-compression stresses have been presented. Based on the analysis of the data, the following remarks can be drawn:

① The introduction of a principal tensile stress reduces HPC ultimate compressive strength under biaxial tension-compression stresses in relation to the uniaxial compressive strength.

② High-performance concrete, similar to normal strength concrete, can sustain higher indirect tensile strains, due to Poisson's effect, than direct tensile strains.

③ The failure mode of high-performance concrete plate specimen tested consisted of tensile splitting in a plane or planes perpendicular to the direction of the principal tensile strain.

④ The principal tensile strains at discontinuity were linear function of the mean normal stresses. This supports the idea that HPC failure criteria, under biaxial tension-compression, is a limiting value for the tensile strain. The magnitude of the failure tensile strains is not constant, but increases with the degree of compression.

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Table 1 – Average Stresses and Strains at Failure

Stress Ratio	σ_1 **(MPa)**	σ_2 **(MPa)**	ε_1 **(x 10^{-6})**	ε_2 **(x 10^{-6})**
Uniaxial Compression	59.58	0	1500	- 520
- 0,10	22.19	-2.22	480	- 152
- 0,50	6.85	- 3.43	135	- 95
- 1,0	3.81	- 3.81	63	- 95
Uniaxial Tension	0	- 4.20	18	- 98

Table 2 – Average Stresses and Strains at Discontinuity

Stress Ratio	σ_1 **(MPa)**	σ_2 **(MPa)**	ε_1 **(x 10^{-6})**	ε_2 **(x 10^{-6})**	σ_1 / f'_0	σ_m
Uniaxial Compr.	46.78	0	1050	- 315	0.79	15.59
- 0,10	14.74	- 1.47	308	- 108	0.25	4.42
- 0,50	4.81	- 2.41	113	- 68	0.08	0.80
- 1,0	2.17	- 2.17	50	- 50	0.04	0
Uniaxial Tension	0	- 2.06	9	- 45	0	-0.69

f'_0 – uniaxial compressive strength of the plate specimen = 59.58 MPa

σ_m – mean normal stress = $(\sigma_1 + \sigma_2) / 3$