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EXPERIMENTAL STUDY ON MECHANICAL BEHAVIORS OF PSEUDO-DUCTILE CEMENTITIOUS COMPOSITES AND NORMAL CONCRETE UNDER BIAXIAL COMPRESSION

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Abstract: Experimental investigations were conducted to characterize the responses of Pseudo-Ductile Cementitious Composites (PDCC) and normal concrete when subjected to uniaxial and biaxial compression. Two different strength grades of PDCCs and one kind of concrete were examined. The specimens were loaded with a servo-hydraulic jack at different stress ratios. The principle stresses and strains were recorded, and the failure modes with various stress states were examined. The test results indicated that the ultimate strength of PDCC increased because of the lateral confining stresses, and the maximum increase of ultimate strength occurred at the stress ratio 0.25, which was very different with concrete. For PDCC specimens, the biaxial strength may be even lower than the uniaxial strength when subjected to equal biaxial compression, and the failure mode showed a shear-type failure because of bridging effect of fibers. The test results provide a valuable reference for obtaining multi-axial constitutive law of PDCC.

1 INTRODUCTION

Pseudo-Ductile Cementitious Composites (PDCC) are a class of fiber reinforced cementitious composites that display post-cracking strain hardening behavior with multiple cracks when subjected to uniaxial tension. The ultimate tension strain of PDCC could reach to 2%-6%, which is approximately 200-600 times above that of conventional concrete [1]. Up to now, a series of experimental and theoretical studies have been carried out on the performance of PDCC by the team of V.C. Li in the past twenty years. The studies covered the field of component design [2,3], mechanical properties [4-6], the performance of structural member [7,8], and so on.

The high ductility and high energy absorption capacity have promoted more and more application of PDCC in civil engineering, such as seismic structure, bridge structure, engineering repairing, and so on. For many components of these structures, the materials are subjected to multi-axial stress. So the mechanical behavior of PDCC and concrete under multi-axial stress state are necessary to be investigated.

However, up to now, very limited study on the behaviors of PDCC under multi-axial stress state could be found. Kittinun S. [9] studied the behavior of six kinds of high performance fiber reinforced cementitious composites (HPFRCC) under biaxial compression with two stress ratios, i.e., 0 and 1, and triaxial compression with equivalent confining pressure. It was found that the compressive strength under biaxial compression was much higher than the compressive strength under uniaxial compression. Under the triaxial compression, the Young's modulus was not influenced significantly by the loading condition, but the strength and ductility were improved as the level of external confining pressure increased. Li [10] studied the behavior of PDCC under triaxial compression with the equivalent confining pressure and found that the ultimate strength and peak strain were significantly improved with increasing confining pressure. Willie Swanepoel [11] studied the behavior of one kind of the Strain Hardening Cementitious Composites (SHCCs) under the entire range of stress combinations from biaxial compression to biaxial tension. However, the tests only studied the behaviors of one kind of PDCC under biaxial loading. The experimental data were so limited that more experiments are needed to be carried out to understand the behavior for different types of PDCC under biaxial loading.

In this paper, a series of specimens were used to study the biaxial compressive behaviors of two kinds of PDCCs and one kind of concrete with the size of 100mm×100mm×100mm. The principle stresses and strains of the specimens were recorded, and the failure modes with various stress states were examined. With the experimental data, a failure envelope of PDCC under biaxial stress state is proposed.

2 EXPERIMENTAL PROGRAM

2.1 Mix proportions

Two kinds of PDCCs and one kind of concrete were used in this test.

The basic materials used in the experiment for PDCCs including Type I Portland cement, fine silica sand, mineral admixtures (Fly ash and silica fume), PVA fiber and superplasticizer. The water/binder ratios were 0.28 and 0.22. And the volume fraction of PVA fiber was 2%. The dimensional information and mechanical properties of PVA fibers are listed in Table 3 [12].

The concrete test specimens were made of Type I Portland cement. The water/cement ratio was 0.53. The coarse aggregate consisted of crushed limestone with the maximum size 20 mm, the minimum size 5mm, and the fineness modulus of the sand was 2.6.

Table 3 Properties of PVA fiber

Fiber type	PVA
Tensile strength/MPa	1620
Fiber diameter/μm	39
Fiber length/mm	12
Young's modulus/GPa	42.8
Elongation/%	6.0
Density/(g/mm^3)	1.3

The specimens used in biaxial tests were cubes with the dimensions of 100mm×100mm×100mm. In addition, for each mix proportion, three cylinder specimens were cast with the size of 100mm×200mm (D×H) in order to obtain the uniaxial compressive strength f_c. All specimens were cast in steel moulds, and cured in a curing room with the humidity exceeded 95%, temperature 20±2°C for 28 days.

2.2 Test setup

The tests were carried out in a triaxial apparatus, as shown in Figure1, with a loading capacity of 1,800 kN in compressive in each direction.

The control schemes for the tests were composed of one closed control loop and one open control loop. The master-slave control mode was adopted. The vertical direction was master and the horizontal direction was slave. Loading system in the vertical direction was closed-loop and displacement controlled with the loading rate 0.002mm/sec. However, the horizontal direction was force controlled by the pressurization valve manually. When the feedback signal of major direction was given to the servo system, the output from the load cell was used as a command signal for manually controlling the hydraulic jack in horizontal direction. Then the proportional loading was achieved.

In both the vertical and horizontal directions of the specimens, two LVDTs were set up along the whole length of the specimen to measure the deformations as well as global strains. Besides, strain gauges were used to measure the local strains of the investigated specimens.

Figure 1: The triaxial apparatus

To minimize the friction effect between the specimen and the loading platens under compression, three slices of polyethylene pads were placed between the specimens and steel platens. The thickness of each polyethylene pad is 0.05 mm.

Six stress ratios were designed for PDCC specimens in the test (0, 0.1, 0.25, 0.5, 0.75, 1.0) and five for concrete specimens (0, 0.1, 0.25, 0.5, 0.75). Because of the brittleness of concrete, it was very dangerous for the test when the stress ratio was 1.0, especially for the manual control system, so the test on this stress ratio was not conducted.

3 TEST RESULTS

3.1 Ultimate strength

All the test resuls are shown in Table 2. Based on the data results, the strength envelope between the normalized principal stresses, σ_1/f_c' and $\sigma_2/\ f_c'$, are drawn in Figure 2.

Table 2: Summary of biaxial experimental results

		PDCC_I	PDCC_II	Con.
f_c'(Mpa)		39.41	48.87	47.76
0	$\sigma_1/\ f_c$	1	1	1
	$\sigma_2/\ f_c$	0	0	0
0.1	$\sigma_1/\ f_c$	1.112	1.096	1.269
	$\sigma_2/\ f_c$	0.114	0.110	0.127
0.25	$\sigma_1/\ f_c$	1.140	1.14	1.322
	$\sigma_2/\ f_c$	0.283	0.287	0.334

0.5	σ_1/f_c	1.132	1.102	1.407
	σ_2/f_c	0.567	0.55	0.704
0.75	σ_1/f_c	1.112	1.075	1.299
	σ_2/f_c	0.834	0.807	0.974
1.0	σ_1/f_c	0.938	0.995	-
	σ_2/f_c	0.934	0.993	-

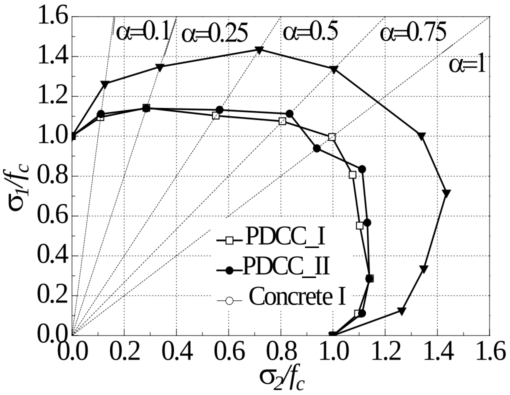


Figure 2: The failure envelope obtained by the tests

From Table 2 and Figure 2, it is indicated that confinement stress in the minor axis (σ_2) has a pronounced effect on the strength of PDCC and concrete.

The maximum increases occurred at a biaxial stress ratio of 0.25 for the two kinds of PDCC. At this stress ratio, a strength increase of about 14% was observed. At the stress ratio 0.1, the strength increased most rapidly, 11% for PDCC_I specimens and 9.6% for PDCC_II mixtures. After it reached maximum strength, the relative strength increase became smaller as the stress ratio increasing. At the stress ratio of 1.0, the strength obtained was even smaller than the uniaxial strength.

In general, the ultimate strength of concrete under biaxial compression is higher than that under uniaxial compression [13-15]. For the concrete specimens investigated, the maximum biaxial strength occurred at a biaxial stress ratio of 0.5 for the concrete specimens tested. At this stress ratio, a strength increase of about 44% for the specimens was observed. At the stress ratio of 0.75, the relative strength increase was smaller than that at the stress ratio of 0.5. The strength increase was 29.9% compared to the uniaxial compressive strength.

From the results, it could be found that when the uniaxial compression strength of PDCC is the same with that of concrete, the biaxial strength of PDCC shows a different trend from concrete under biaxial compression. The increase of the biaxial strength is not very pronounced as concrete. For PDCC specimens, the maximum biaxial strength occurred at the biaxial stress ratio of 0.25 for the two kinds of PDCC specimens. However, the concrete specimens obtained its maximum biaxial strength at 0.5 for concrete. For PDCC specimens, the relative increase of biaxial strength was much smaller than concrete as the stress ratio increased. Especially at the stress ratio was 1.0, the biaxial compressive strength of PDCC was even smaller than the uniaxial compressive strength, which showed opposite trend with concrete obtained by other researchers [13-15].

3.2 Failure mode

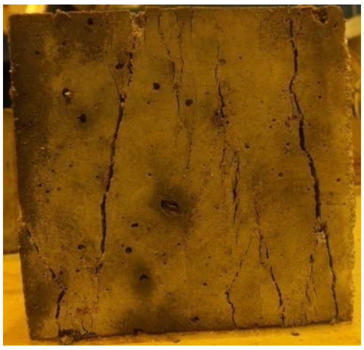
The crack patterns and failure modes for all specimens were observed in this test.

From Fig.3 (1), it could be seen that under uniaxial compression, a series of column-type fragments occurred for concrete specimens because of the formation of the micro-cracks which were basically parallel to the applied load. The failure surface passed through parts of the aggregates and parts of mortar. PDCC specimens (Fig. 4(1)) showed different crack patterns with plain concrete specimens. Because of the confinement provided by PVA fibers, the cracks were unsystematic and discontinuous, although they were basically parallel to the applied load. And also, the bridge effect of fibers made the specimens still an entirety during the tests.

Fig.3 (2-5) shows the crack patterns for concrete specimens under biaxial compression. As the introduction of the minor principal stress, a series of plate-type fragments occurred by the formation of the micro-cracks. When the stress ratio were smaller than 0.5, the major cracks were inclined at an angle of 10-25 degrees to the free surface of the specimens. The inclined angle of the major cracks decreased with the stress ratio increasing. When the stress ratio was 0.75, the major cracks were basically parallel to the free surface of the specimens and perpendicular to the loading surface.

Fig. 4 (2-6) shows the crack patterns for PDCC specimens under biaxial compression. When the stress ratio was 0.1, the failure mode was similar with that under uniaxial compression, which indicated that the confinement provided by the lateral stress was not large enough to change the failure mode obviously. As the stress ratio increased, the failure mode changed into shear failure mode, which could be seen from Fig. 4 (3-6). In shear failure mode, a series of major cracks formed at an inclined shear plane which was inclined at the angle of 15-30 degrees to the free surface of the specimens. The inclined angle and the number of the major cracks were independent on the stress ratio.

1) α=0



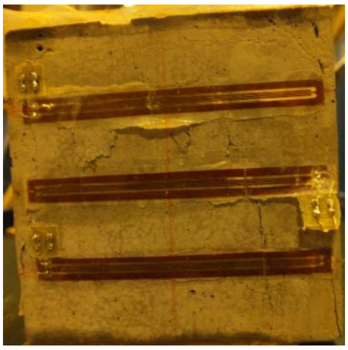
2) α=0.1

3) α=0.25

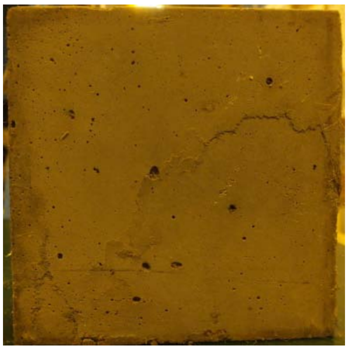
4) α=0.5

5) α=0.75

Figure 3: Failure mode of Concrete under biaxial compression tests

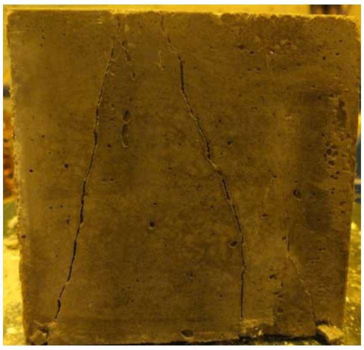


1) α=0



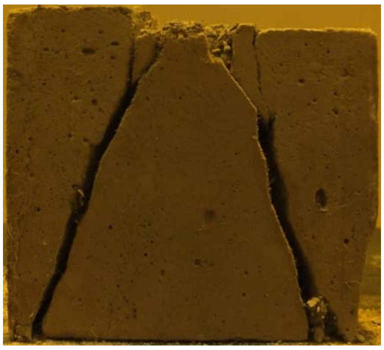
2) α=0.1

3) α=0.25



4) α=0.5

5) α=0.75



6) α=1.0

Figure 4: Failure mode of PDCC under biaxial compression tests

3.3 Stress and strain relationship

The loads and deformations in two principal directions were measured for all specimens using strain gages, and the LVDT for the free plane directions. In stress-strain curve, the vertical axis represents the normalized stress, and the abscissa shows the actual strain.

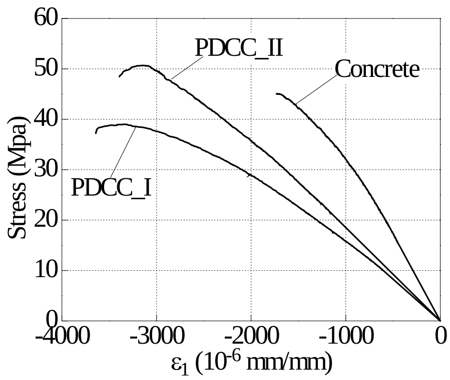


Figure 5: The stress-strain curve in uniaxial compression test for Concrete and PDCCs and concrete I

Fig. 5 shows the stress–strain relationship under uniaxial compression for the investigated PDCCs and

Concrete. In uniaxial compression, the stress-strain curve of PDCCs and Concrete showed the similar trends, linear in initial stage and nonlinear when the stress reached to a certain value for all specimens. The elastic modulus of the three cementitious composites were 1.6×10^4Mpa, 1.85×10^4Mpa and 3.45×10^4Mpa for PDCC_I, PDCC_II and the concrete investigated. The strains corresponding to the ultimate strength were 3200με, 3000με and 1800με for PDCC_I, PDCC_II and the concrete investigated, respectively. It was indicated that the ductility of PDCC decreased with the uniaxial strength increasing by the value of elastic modulus and the strain corresponding to the ultimate strength. And also, when the uniaxial strength was same, concrete showed much stiffer than PDCCs.

Figure 7-9 shows the normalized stress and actual strain relationship under uniaxial and biaxial compression for the investigated Concrete and PDCCs. Under biaxial compression, the normalized stress-strain curves showed the same trends with the uniaxial compression. As the stress ratio increasing, the stiffness of σ_1/f_c-ε_1 increased which could be explained by the increasing of elastic modulus. This is because the lateral stress σ_2 prevented the development of the internal microcracks, which resulted in a more rigid characteristic in the major principal direction σ_1. From the σ_1/f_c-ε_2 curve of biaxial compression, it could be seen that when the stress ratio was less than 0.5, tensile strain could be obtained. It was demonstrated that when lateral compressive stress was small, the lateral strain caused by Poisson effect of σ_1 was the dominant. As the stress ratio increased, the Poisson effect of σ_1 was gradually weakened and ε_2 changed from tensile strain into compression strain. In the direction of free surface, ε_3 were tensile strain because of Poisson effect. The strain corresponding to the peak stress ε_3 could reach to 3000-5000 με, which was much larger than that under uniaxial tension [16].

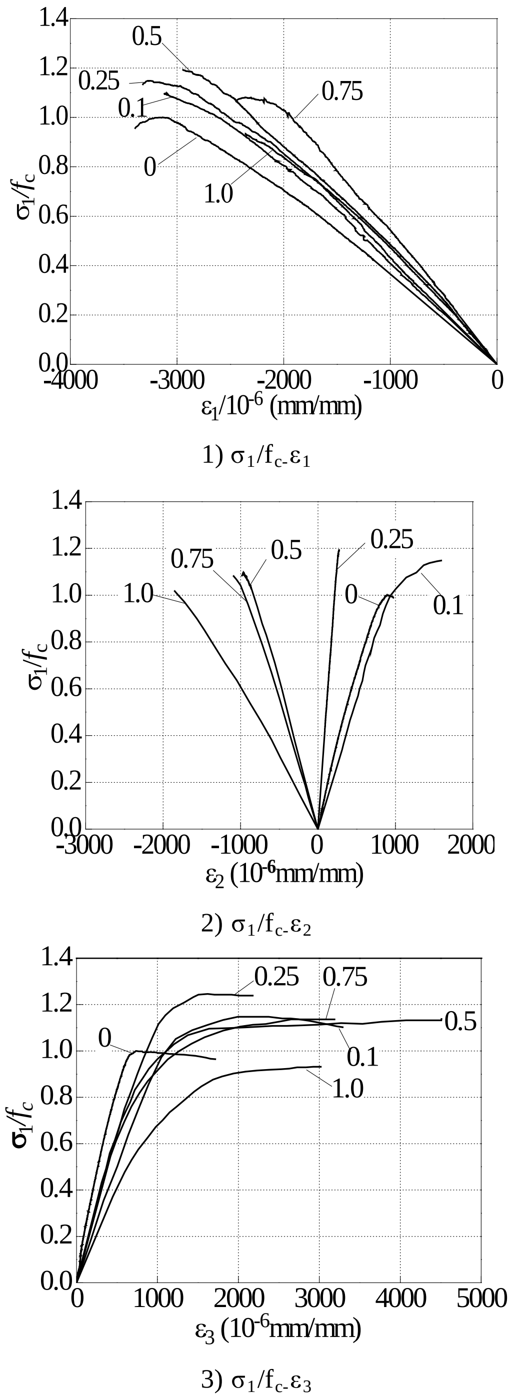
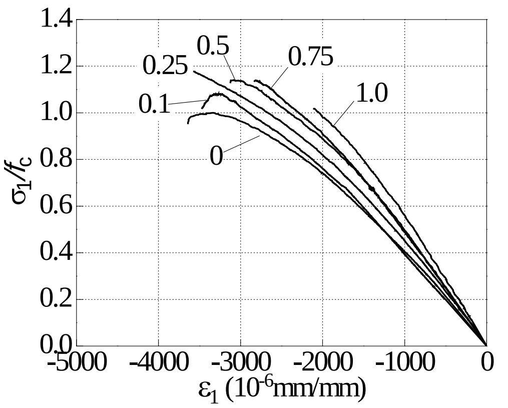
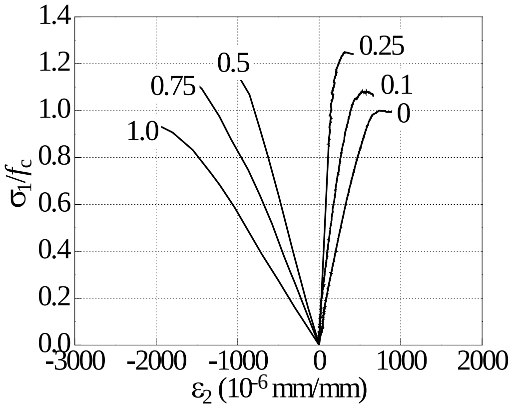


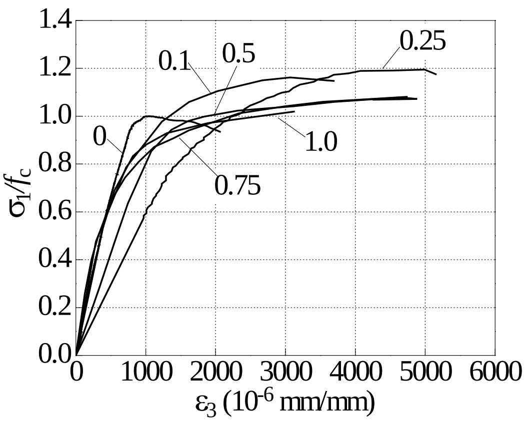
Figure 6: The stress-strain curve in biaxial compression test for PDCC I



1) σ_1/f_c-ε_1

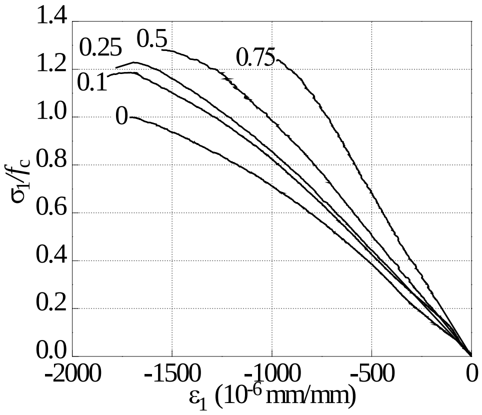


2) σ_1/f_c-ε_2

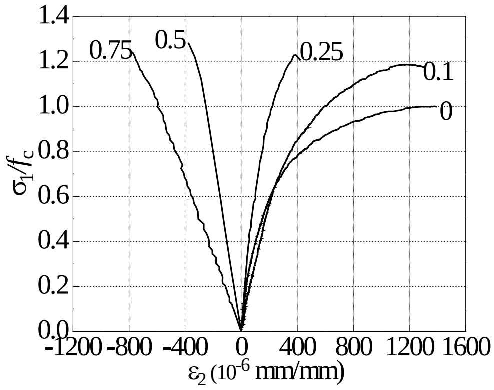


3) σ_1/f_c-ε_3

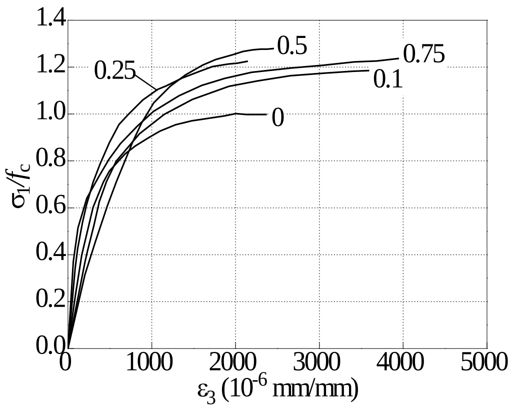
Figure 7: The stress-strain curve in biaxial compression test for PDCC II



1) σ_1/f_c-ε_1



2) σ_1/f_c-ε_2



3) σ_1/f_c-ε_3

Figure 8: The stress-strain curve in biaxial compression test for Concrete

4 CONCLUSIONS

In this paper, the biaxial mechanical characteristics of three kinds of cementitious composites were investigated. Based on the test resuts, the following conclusions can be drawn:

1) The biaxial compressive strength of the two kinds of PDCC investigated is higher than the uniaxial compressive strength. The maximum biaxial strength

occurred at a biaxial stress ratio of 0.25 for all specimens tested with a strength increase of 14% for the specimens. And the normalized strength increased most rapidly when the stress ratio was 0.1. When the biaxial stress ratio reached to 1.0, the strength obtained was even smaller than the uniaxial strength. As the increasing of the uniaxial strength, the relative increasing decreased compared with the uniaxial strength;

2) Compared to PDCC, the behavior of the investigated concrete showed a different trend under biaxial compression. The ultimate strength of the concrete under biaxial compression is higher than under uniaxial compression. The maximum biaxial strength occurred at a biaxial stress ratio of 0.5 for all specimens tested with a strength increase of 44% for the specimens. And also, the normalized strength of PDCC increased more slowly than that of concrete at the same stress ratio.

3) Splitting tensile failure mode could be obversed in uniaxial compression for the two kinds of PDCC. As the stress ratio increasing, the failure mode changed from Splitting tensile mode into shear failure mode. On the other hand, concrete showed a different failure mode under biaxial compression compared to PDCC. Slitting tensile failure mode could be obversed in uniaxial and biaxial compression tests of concrete, and the lateral stress in minor direction σ_2 changed the inclined angle of the major cracks decreased with the stress ratio increasing.

4) The stress-strain curves showed that under different stress ratio introducing a lateral stress could significantly affect the elastic modulus of all specimens in the direction of the first principal stress σ_1. But it indicated that PDCC were more ductile than concrete from the value of elastic modulus and the strain corresponding to the ultimate stress.

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