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EXPERIMENTAL STUDY ON MECHANICAL BEHAVIORS OF MECHANICAL BEHAVIOR OF SHCC UNDER TRIAXIAL COMPRESSIVE STRESS LOADING

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Abstract: Experimental investigation was conducted to characterize the responses of Strain-Hardening Cementitious Composites (SHCC) when subjected to triaxial and compression. The SHCC examined in this test is a class of fiber reinforced cementitious composites with ultra-high ductility by using a low volume fraction (2%) of Polyvinyl Alcohol (PVA) fiber. One kind of SHCC was examined with cubic specimen size of 100mm in the tests. The specimens were loaded with a servo-hydraulic jack at different stress ratios. The principle stresses and strains of the specimens were recorded, and the failure modes with various stress states were examined. The experimental results indicated that the stress states and stress ratios had significant influence on the strength and deformation of SHCC under triaxial compression. 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 SHCC.

1 INTRODUCTION

Strain-Hardening Cementitious Composites (SHCC) 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 SHCC could reach to 2%-6%, which was 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 SHCC 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 SHCC in civil engineering, such as seismic structure, bridge structure, engineering repairing, and so on. For many components of these structures, the materials were subjected to multi-axial stress. So the mechanical behavior of SHCC under multi-axial stress state are necessary to be investigated.

However, up to now, very limited study on the behaviors of SHCC under multi-axial stress state can be found until now. 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 SHCC 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 SHCC 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 SHCC under triaxial loading.

In this paper, a series of specimens were used to study the biaxial compressive behaviors of one kind of SHCC 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 SHCC under triaxial stress state is proposed.

2 EXPERIMENTAL PROGRAM

2.1 Mix proportions

The basic materials used in the experiment for SHCC include Type I Portland cement, fine silica sand, mineral admixtures (Fly ash and Silica fume), PVA fiber and superplasticizer. The water/binder ratio was 0.28. And the volume fraction of PVA fiber was 2%. The dimensional information and mechanical properties of PVA fibers are listed in Table 1.

Table 1 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 triaxial 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 triaxial testing machine with the load capacity of 3000 kN along three axial directions is used for the biaxial and triaxial compressive tests. This machine is a servo-controlled loading system with close-loop displacement control along the vertical axis and force control along the other two perpendicular axes. The test setup is shown in Figure 1. For the multiaxial compressive tests, a proportional loading path was adopted. The loading rate in the vertical direction was 0.002mm/s, while the forces along the horizontal axes were exerted by the automatic pressure valve in accordance to the output force of the vertical load cell.

In order to obtain the stress-strain curves, the gobal deformations of the specimens were measured by two external linear variable displacement transducers (LVDTs) in each direction of the specimen. Additionally, strain gauges were bonded on the free surface to measure the local strains of concrete specimen under biaxial compression. In the experiment, rigid steel loading platens were used to apply external load. Three layers of greased plastic membrane were used to reduce the friction between the specimen surfaces and loading platens. Fifteen were used for triaxial compressive tests, which are shown in Table 2. At least three specimens were tested for each stress ratio. In the tests, the three principal stresses are expressed as $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$.The loading configurations are shown in Figure 2.

Figure 1: The experimental setup

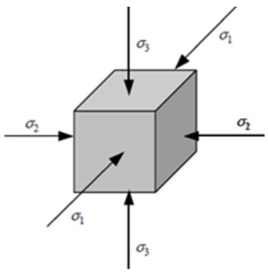


Figure 2: The loading directions in triaxial compression tests

3 TEST RESULTS

3.1 Ultimate strength

All the test results were shown in Table2. Based on the data results, the strength envelope between the normalized principal stresses were drawn in Figure 3.

Table2 Summary of triaxial experimental results

f_c	Stress ratio	σ_3/f_c
41.45	0.025:0.25:1.0	1.67
	0.025:0.5:1.0	1.84
	0.025:0.75:1.0	1.75
	0.025:1.0:1.0	1.62
	0.05:0.25:1.0	1.89
	0.05:0.5:1.0	2.09
	0.05:0.75:1.0	2.00
	0.05:1.0:1.0	1.81
	0.1:0.25:1.0	2.43
	0.1:0.5:1.0	2.59
	0.1:0.75:1.0	2.58
	0.1:1.0:1.0	2.30

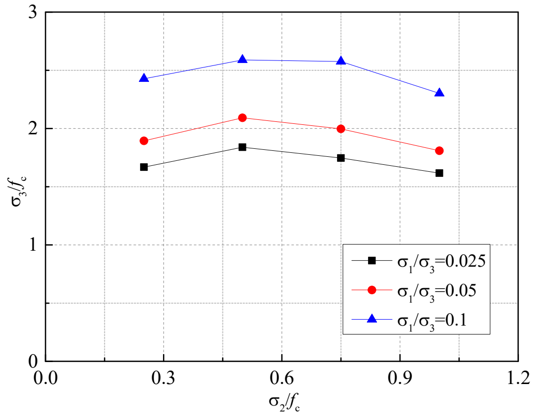


Figure 3: The failure envelope obtained by the tests

As shown in Table 2 and Figure 2, the triaxial ultimate strength is generally greater than the uniaxial compressive strength, and the increase of strength is dependent on the stress ratio.

If the ratio between the maximum principal stress and the minimum principal stress (σ_1/σ_3) is fixed, the maximum triaxial compressive strength was reached when σ_2/σ_3= 0.5. In current test program, only three sets of stress ratios between the first and third principal stresses (σ_1/σ_3=0.025, 0.05, 0.1) were designed due to the limitation of load capacity of the test machine. According to the test results, when SHCC was subjected to triaxial stress state, the maximum triaxial compressive strength were 2.589 times of the uniaxial compressive strength for tested SHCC. The maximum compressive strength was reached at the stress ratio of $\sigma_1/\sigma_2/\sigma_3$ = 0.1/0.5/1. Interestingly, the maximum increase occurred at a stress ratio of $\sigma_1/\sigma_2/\sigma_3$ = 0.1/0.25/1. At this stress ratio, an increase of 243% compared with uniaxial compressive strength was observed for the investigated SHCC. After the maximum strength is reached, the normalized strength decreased with increasing the second principal stress σ_2 when the other principal stress ratio (σ_1/σ_3) is fixed, which showed the same trends with the biaxial compressive tests[15].

3.2 Failure mode

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

Under triaxial compression, the stress σ_3 prevents the deformation along the directions of σ_2 and σ_1. Figure 3 shows the crack patterns for the SHCC specimens under triaxial compression. As σ_1/σ_3 increases, a pronounced shear cracks developed on the surface which the principal stress σ_2 was applied. There are two main cracks could be found along the surface σ_2, and inclined at an angle of 30 degrees to the direction of σ_1. There is no difference in the failure mode of the SHCC specimens under different stress combinations.

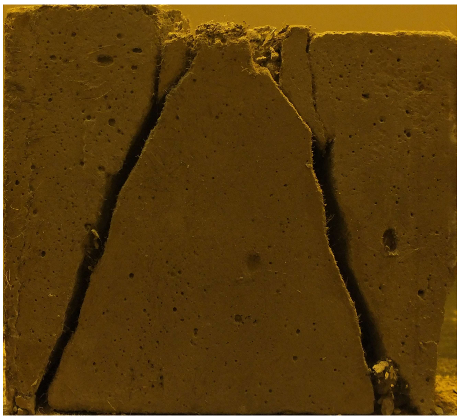
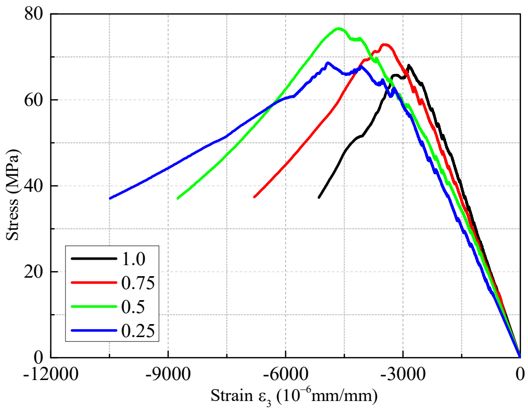


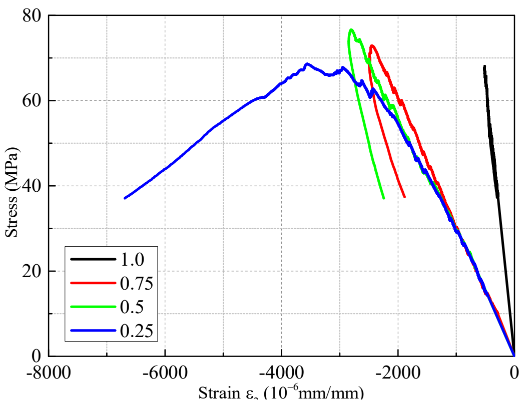
Figure 4: Failure mode of SHCC under triaxial compression tests

3.3 Stress and strain relationship

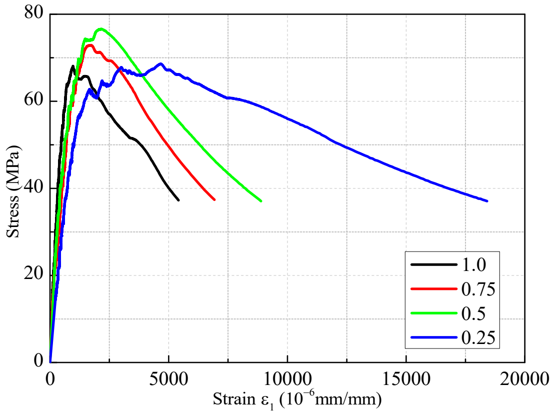
The loads and deformations in three principal directions were measured for all specimens using the LVDT. In stress-strain curve, the vertical axis represents the stress, and the abscissa shows the actual strain.



(1) σ_3-ε_3 curve



(2) σ_3-ε_2 curve



(3) σ_3-ε_1 curve

Figure 5: The stress-strain curve in triaxial compression test for SHCC (σ_1/σ_3= 0.025)

Fig. 5 showed the stress–strain relationship under triaxial compression for the investigated SHCC when stress ratio σ_1/σ_3 fixed at 0.025. In triaxial compression, the stress-strain curve of SHCC and concrete[14] showed the similar trends, linear in initial stage and nonlinear when the stress reached to a certain value for all specimens. As the stress ratio σ_2/σ_3 increasing, the stiffness of σ_3-ε_3 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_3. From the σ_3-ε_2 curve of triaxial compression, compressive strain could be obtained. As the stress ratio increased, the Poisson effect of σ_3 was gradually weakened and ε_2 increased. In the direction of σ_1, ε_1 were tensile strain because of Poisson effect. The strain corresponding to the peak stress ε_3 could reach to 2000-5000 με.

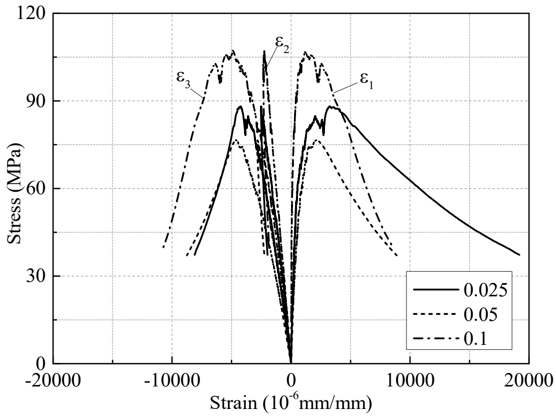


Figure 6 The stress-strain curve in triaxial compression test for SHCC (σ_2/σ_3= 0.5)

Figure 6 shows the stress-strain curves of the SHCC under triaxial compression (σ_2/σ_3=0.5). As shown in Figure 5, the slope of σ_3–ε_3 curves and the ultimate strain ε_3 increase significantly in triaxial compression when the stress ratio σ_1/σ_3 increased from 0.025 to 0.1. This indicates that application of the lateral stresses can effectively improve the stiffness and ductility of the specimens. From the σ_3-ε_2 curves, the strain ε_2 is compressive, which is induced by the lateral confinement of σ_1 . Besides, from the σ_3-ε_1 curve, the strain along the first principal direction ε_1 is tensile strain because of the Poisson's effect.

4 CONCLUSIONS

In this paper, the triaxial mechanical characteristics of one kinds of strain-hardening cementitious composites were investigated. Based on the test resuts, the following conclusions can be drawn:

(1) The ultimate triaxial compressive increases with the stress ratio between σ_3 and σ_1. For the specimens with fixed stress ratio between σ_1 and σ_3, the greatest increase of the strength for the HPC was reached at the stress ratio of σ_2/σ_3=0.5.

(2) Shear failure mode could be found for the SHCC specimens under triaxial compression. The failure mode shows no relationship with the stress ratio.

(3) The stress-strain curves showed that the lateral stress has significantly effect on the stiffness and ductility of SHCC in the direction of σ_3 under triaxial compressive loading.

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