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Mechanical behavior of different types of concrete under multiaxial tension–compression

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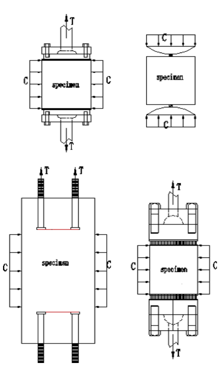
HIGHLIGHTS

- The mechanical behavior of normal air-entrained concrete under multiaxial T–C was studied.
- The results of different types of concrete conducted in same testing machine was compared and analyzed.
- The failure criterion of various types of concrete under multiaxial T–C was proposed.

GRAPHICAL ABSTRACT



Loading method of concrete specimen for biaxial T-C and triaxial T-C-C test

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ABSTRACT

The strength of concrete under multiaxial tension–compression (biaxial tension–compression (T–C) and triaxial tension–compression–compression (T–C–C)) in the direction of tensile stress and compressive stress was lower than the uniaxial tensile strength and uniaxial compressive strength, respectively. This reduction is affected by many factors. Among these factors, type of concrete, method of friction-reducing in the direction of compressive load, stiffness of testing machine and loading rate etc. are the main factors. The mechanical behavior of normal air-entrained concrete subjected to biaxial T–C, triaxial T–C–C was studied in this paper. The experimental results of normal air-entrained concrete under multiaxial tension–compression and mechanical behavior of other types of concrete under multiaxial tension–compression conducted in the same testing machine was compared and analyzed. The failure criterion of various types of concrete under biaxial T–C and triaxial T–C–C was proposed. It provides the experimental and theory foundations for strength analysis of various concrete structures.

1. Introduction

Concrete is currently one of the most widely used man-made products and second only to water as the most utilized substance in the world [21,29]. On average, for each person in the world, more than one ton of concrete is produced each year, and about six billion tons are produced per year. As a reliable material, concrete is applied throughout the infrastructure of a nation's industry, defense, utility, transportation and residential sectors. With more and more concrete structures are being built in various environments, different types of concrete are needed to meet different engineering environment [8,19,23,25]. And with the development

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of science and technology, many recent innovations in advanced concrete materials technology have made it possible to produce concrete with exceptional performance characteristics. Now, various types of concrete, such as light weight aggregate concrete [1,7], wet-screened concrete [3,5], dam concrete [12,30], high performance concrete [20,26] and normal air-entrained concrete etc. has been applied in practical engineering.

In practical engineering structures, concrete is inevitable to subject to biaxial tension–compression and triaxial tension–compression–compression stress states [15]. The decrease of ultimate strength will be caused because of the action of tensile stress. As brittle material with lower tensile strength, the cracks will be caused due to the decrease of strength, then cause steel corrosion and even reduce service life. On the other hand, with the application of finite element method in the analysis of the concrete structure [6,27], the behavior of the different types of concrete material under multiaxial tension–compression should be well understood.

It can be known that experimental studies of mechanical behavior of various types of concrete under biaxial tension–compression and triaxial tension–compression–compression has been carried out by researchers through consulting the relevant documents and materials. And comparative analysis of experimental results of different types of concrete under multiaxial tension–compression was made. According to comparison and analysis on the experimental results got by different researchers, it can be found: even for the same type of concrete, the decreasing degree of strength under biaxial tension–compression and triaxial tension–compression–compression over uniaxial compressive (tensile) strength is quite different. Through comparison and analysis, the conclusion that the mechanical behavior of concrete under multiaxial tension–compression was affected by many factors: the testing apparatus, the measuring and testing technique (such as the applied mode of tensile load, the method to reduce the friction between the pressure surface of concrete specimen and the loading steel platen of the testing apparatus) and type of concrete. was got. Based on this, the experimental studies of normal air-entrained concrete under multiaxial tension–compression were conducted in a triaxial testing apparatus. Then the experimental studies of other types of concrete (normal concrete [24], high-performance concrete [32,31], two-graded aggregate concrete [9], light weight aggregate concrete [14], wet-screened concrete [9], wet-screened two-graded aggregate concrete [2] and dam concrete [13]) under multiaxial tension–compression with the same triaxial testing apparatus were introduced. And the analysis and comparison of the experimental results were given out.

2. Experiment

2.1. Materials and mix proportions

Dalian Local material was first selected in the production of all types of concrete. Table 1 shows the mixing proportion by weight of normal air-entrained concrete and other types of concrete.

Normal air-entrained concrete (NAEC): Portland cement: 42.5#, fine aggregate: natural river sand with fineness modulus of 2.60, coarse aggregate: crushed stone with diameter ranging from 5 mm–10 mm. 1.03 kg air-entraining agents was added in per meter concrete.

Normal concrete (NC) [24]: Portland cement: 32.5#, fine aggregate and coarse aggregate used was consistent with normal air-entrained concrete.

High-performance concrete (H-P-C) [32,31]: Portland cement: 52.5#, fine aggregate: natural river sand with fineness modulus of 2.70, coarse aggregate: crushed stone with diameter ranging from 5 mm–10 mm. Fly ash was used to replace part of cement. 94.52 kg fly ash and 6.77 kg superplasticizer were added in per meter concrete.

Two-graded aggregate concrete (T-G-C) [9]: Portland cement: 32.5#, fine aggregate used was consistent with normal air-entrained concrete, coarse aggregate was a crushed stone with diameter ranging from 5 mm–80 mm (coarse aggregate are divided into three categories according to the particle size: 5 mm–20 mm, 20 mm–40 mm, 40 mm–80 mm. the proportion of three categories by weight was: 1.00:1.00:1.33). Fly ash was used to replace part of cement. 0.43 kg superplasticizer and 35.8 kg fly ash were added in per meter concrete.

Light weight aggregate concrete (L-A-C) [14]: Portland cement: 42.5#, fine aggregate was natural river sand with fineness modulus of 2.71, coarse aggregate was fly ash aggregate with maximum diameter 20 mm. And 10.80 kg superplasticizer was added in per meter concrete.

Wet-screened concrete (W-S-C) [9]: Portland cement: 42.5#, fine aggregate used was consistent with normal air-entrained concrete, coarse aggregate was a crushed basalt stone with diameter ranging from 5 mm-150 mm (the classification standard of coarse aggregate are consistent with two-graded aggregate concrete). 0.43 kg superplasticizer and 0.89 kg air-entraining agents were added in per meter concrete.

Wet-screened two-graded aggregate concrete (W-S-T-G-A-C) [2] *and Dam concrete (D-C)* ([13]: Portland cement: 42.5#, fine aggregate and coarse aggregate used was consistent with wet-screened concrete [9]. Coarse aggregate are divided into four categories according to the particle size: 5 mm–20 mm, 20 mm–40 mm, 40 mm–80 mm, 80 mm–150 mm, the proportion of above coarse aggregate by weight was: 1.00:1.00:1.25:1.75. Superplasticizer and air-entraining agents were added in per meter concrete.

2.2. Samples and testing programs

The order of normal air-entrained concrete mixing are as follows: (1) cementitious materials ingredients, coarse aggregates and fine aggregates were added into a mixer and mixed for about 1 min, (2) water was added in 1 min, and ingredients were mixed for about 2–3 min. After concrete specimens (100 mm cubes) were cast in steel molds, a vibrating table was used to compacted and decrease the amount of air bubbles. Specimens were demoulded after 24 h from steel molds and then cured in a curing room with condition of 20 ± 3 °C and 95% relative humidity for 27 days according to "Standard for test methods of long-term performance and durability of ordinary concrete" (GB/T50082-2009) (National Standard of the People's Republic of China [18]).

For normal concrete [24], high-performance concrete [32,31], light weight aggregate concrete [14], wet-screened concrete [9], wet-screened two-graded aggregate concrete [2] and dam concrete (Jun [13], the size of concrete specimen is 100 mm (length)–100 mm (width)–100 mm (height). For two-graded aggregate concrete [9], The size of concrete specimen is 150 mm (length)–150 mm (width)–300 mm (height).

The biaxial tension–compression and triaxial tension–compression–compression tests were conducted in a special triaxial testing apparatus [16] that is capable of developing three independent tensile or compressive forces. The testing of the specimens was carried out through strain-controlled. The loading speed was 0.0002 mm per second in the direction of principal tensile stress for uniaxial tension, biaxial T–C and triaxial T–C–C. The three load directions can be controlled together and each axis for itself. So it is possible to follow any strain path until the failure of the specimen was reached.

The experimental study of different types of concrete under biaxial T–C (stress ratio expressed as $\alpha_1 = \sigma_1{:}\sigma_3$) and triaxial T–C–C (stress ratio expressed as $\alpha = \sigma_1{:}\sigma_2{:}\sigma_3$) were performed. The relationship of principal stresses can be expressed as $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$ (tension denoted as negative and compression denoted

Table 1
Mix proportions and major parameters of different types of concrete.

Type of concrete	w/c	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)
N-A-E-C	0.40	413	587	1186	164	25.64	−2.666
N-C [24]	0.50	383	663	1154	193	34.20	−3.140
H-P-C [32,31]	0.31	470	616	1095	175	60.16	−5.080
T-G-C [9]	0.60	179	699	1357	129	23.31	−2.260
L-W-C [14]	0.37	450	719	507	257	21.40	−2.706
W-S-C [28]	0.43	252	526	1498	130	28.88	−2.566
W-S-T-G-A-C [2] and D-C [13]	0.41	130	511	1843	82	32.43	−3.140