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Experimental study and failure criterion analysis of plain concrete under combined compression-shear stress

Zhenpeng Yu [a], Qiao Huang [a,*], Xinghua Xie [b], Ning Xiao [a]

[a] School of Transportation, Southeast University, Nanjing 210096, China
[b] Nanjing Hydraulic Research Institute, Nanjing 210029, China

HIGHLIGHTS

- Plain concrete under combined compression-shear stress are tested.
- Failure modes of plain concrete under various compression-shear loading are examined.
- Mechanical characteristics of shear load-deflection curves at each stage are analyzed.
- Friction coefficient of plain concrete across shear failure plane is derived.
- Failure criterions of plain concrete under combined compression-shear stress are proposed.

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ABSTRACT

To study the mechanical properties of plain concrete (with a standard compressive strength of 30 MPa) under combined compression-shear stress, the concrete was tested using material compression-shear hydraulic servo machine under various axial compression conditions. In the experimental study, the shear failure modes and shear load-displacement curves of concrete are obtained. The peak shear strength and residual strength of concrete are then extracted from the load-displacement curves. A total of three development stages of shear load-displacement curves are identified and mechanical characteristics at each stage are analyzed. The results show that the shear failure behavior of concrete under different axial compression is quite different, and as the increase of axial compression ratio, the traces of friction on shear plane get more evident and the concrete failure slag also increases. Based on the experiment data and regression analysis, it is observed that both the peak shear strength and residual strength of concrete increase linearly as the increase of axial compression ratio. From the residual strength analysis, the shear failure plane of plain concrete has a relatively stable friction coefficient of 1.46. According to octahedral stress space analysis and unified strength theory, the failure criterion curves of concrete under compression-shear stress are obtained and the results fit the test data well. The proposed two types of failure criterion theories can effectively model the strength law of plain concrete under combined compression-shear stress.

1. Introduction

As one of the mostly used building materials, concrete has widely been adopted in buildings, bridges, dams and other structures due to the well-recognized advantages [1]. In engineering practice, concrete is not only subjected to the compression, tension and pure shear, but is more commonly affected by eccentric, multiaxial and combined compression-shear loadings [2,3].

Guo obtained the stress-strain curves of concrete subjected to eccentric compression and eccentric tension, along with the corresponding mechanical characteristics and failure behaviors [4]. By using the true triaxial test device, Song studied the mechanical properties of concrete under biaxial and triaxial load and the relevant failure modes and failure criterions were derived [5,6]. In practical engineering, concrete under compression-shear loading state cannot be neglected, such as the expressway under impact loading and complex bearing effects on the corbel and deep beams. However, there are few relevant studies of concrete subjected to compression-shear loading. On the other hand, unlike the compression or tension test of concrete material that has standard test

* Corresponding author.
E-mail address: 220173112@seu.edu.cn (N. Xiao).

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method and procedure, the test methods for concrete under compression-shear are quite difference and, to the best knowledge of the authors, there are no such standard test methods and procedures.

According to the direct shear tests on short beams and notched beams, Mattock and Iosipescu studied the mechanical characteristics of concrete under pure shear [7,8]. Ali R. Khaloo studied effect of stress path on mechanical behavior of concrete under compression-shear loading [9]. R.C.K. Wong quantitatively analyzed effect of mechanical bite force on the shear load between cement mortar and aggregate, the friction between contact surfaces, and the chemical adhesive force between cement mortar and aggregate through a shear test [10]. Zhang analyzed the test results and obtained the relation model between shear strength and tensile strength [11]. Recently, French R. and T.T. Bui studied the mechanical properties of concrete under direct shear and shear behaviors of concrete slabs under tension-compression loading [12,13]. Using wedged shear apparatus and dynamic triaxial apparatus, respectively, Wang and Song [15] conducted the test of concrete under combined compression-shear loading; however, different test methods can result in quite different relation models between shear strength and axial pressure ratio [14,15].

Concrete is similar to rock-soil type friction material that it not only has the cohesion but friction. The shear strength of such material are modelled using both the cohesion value and internal friction angle. For concrete, it is essential to study shear strength behavior; however, existing specifications fail to provide such shear strength values of c and φ, and to date, there is no standard test method for determining such shear strength values for concrete [16–20]. On the other hand, the shear failure behavior of concrete, failure mechanism underlying shear load-displacement curves, and the residual strength of concrete under different levels of axial force have not been well investigated. Furthermore, the strength criterions for concrete under compression-shear stress state also need to be developed.

In this paper, the plain concrete was tested by using pressure-shear hydraulic servo machine under different axial compression. Unlike other pure shear test methods, the servo machine devised can better meet the requirements of concrete under compression-shear load and can obtain accurate shear load and deformation results. The shear failure behavior and shear load-displacement curves of concrete are obtained through the experiments and the peak shear strength and residual strength of concrete are extracted from load-displacement curves. Meanwhile, the mechanical characteristics of concrete are identified in the shear load-deformation curves at each stage and the relationship between axial force ratio and peak shear strength or residual strength are established. Finally, according to the octahedral stress space analysis and unified strength theory, two failure criterions of plain concrete under compression-shear stress are proposed. The research work has prime significance on both technical design and engineering practice for application of plain concrete under compression-shear loading condition.

2. Experimental program

2.1. Cement mixture ratio

The compressive strength of plain concrete is 30 MPa with the plain Portland cement P.O42.5. The maximum particle size of coarse aggregate is 16 mm and the fine aggregate is made of natural river sand (medium sand) without additives. The cement mixture design is based on China national specification for mixture design of plain concrete JGJ 55-2011 [21] and the design is presented in Table 1.

Table 1
Cement mixture design of plain concrete.

Compressive strength of plain concrete	Density (unit: kg/m^3)			
	Cement	Water	Coarse aggregate	Fine aggregate
30 MPa (C30)	178	279	1034	780

2.2. Specimen fabrication

To determine the axial compression ratio, it is necessary to test the compressive strength of plain concrete prior to the compression-shear test. Consequently, the experimental design of this study considered a total of three test schemes: concrete under uniaxial compressive test, concrete splitting test and concrete under compression-shear test.

In concrete uniaxial compressive test and splitting test, the specimens are designed as cubes with dimension of 100 mm × 100 mm × 100 mm. A total of three specimens are separately tested in both the uniaxial compressive test and splitting test. Size of the specimen is designed as 205 mm × 205 mm × 150 mm and determination of the specimen size in the direct shear test is based on the following considerations: (1) Similar specimen size (200 mm × 200 mm) was used by Wong et al. (2007) [10] for the direct shear test of concrete; and (2) According to China national specification for standard test of mechanical behaviors of plain concrete GB/T50081-2002 [17], a total of three section dimensions are recommended, namely 100 mm × 100 mm, 150 mm × 150 mm and 200 mm × 200 mm. With different axial pressure ratio as a variable, there are totally eight loading schemes in compression-shear test and each case contains three specimens. The specimen identification and loading schemes are presented in Table 2.

According to the cement mixture design of Table 1, the coarse aggregate, fine aggregate and cement are weighted, respectively, and put into the mixer for a uniform mixing. The water is smoothly poured into the mixer to make it being fully blended. After that, the mixed concrete are placed into the formwork with a size of 100 mm × 100 mm × 100 mm and then moved onto the vibration table ensuring the concrete being vibrated densely. For specimens with size 205 mm × 205 mm × 150 mm, the vibrator was used in the process of concrete vibrating. After 24 h, all formworks are removed and all specimens are placed into the standard curing room with the temperature range of 20 ± 3 °C and the humidity being more than 95%. After 28 days curing time, the specimens are moved out of the curing room and cured again until the design strength developed.

2.3. Compression-shear testing system and procedures

The uniaxial compressive test and splitting test of plain concrete are performed using the hydraulic servo machine equipped with high-precision force and displacement sensors. In the uniaxial compressive strength test, a three-layer polyethylene film (with the interlayer of polyethylene film filled with machine oil) was placed on the loading surface to reduce friction. To eliminate the clearance between test device and concrete specimen, the force control method is firstly applied to preload the specimen, and then was repeated three times from 0 kN to 10 kN. After that, the specimen is subjected to displacement control with a velocity of 0.01 mm/s until the ultimate failure occurred, as shown in Fig. 1(a). The device used in concrete splitting test is presented in Fig. 1(b) and the same load and displacement control test procedure was used as such used in the uniaxial compressive test.