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Constitutive model and failure criterions for lightweight aggregate concrete: A true triaxial experimental test

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HIGHLIGHTS

- Lightweight aggregate concrete under multiaxial loading are tested.
- Failure modes of lightweight aggregate concrete under multiaxial loading are examined.
- Residual strength of lightweight aggregate concrete after triaxial test is analyzed.
- Failure criterions of lightweight concrete under local multiaxial loading are proposed.

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ABSTRACT

Lightweight aggregate concrete has the advantages of light weight and high strength so that it can effectively reduce the weight of concrete structure in practical engineering. In this paper, a multiaxial test has been conducted on the lightweight aggregate concrete along with the development of theoretical failure criterion. The lightweight aggregate concrete specimen is subjected to multiaxial and local multiaxial loading with various lateral pressure and stress-strain curves and physical material properties were derived. Some specimens are re-tested under uniaxial or local uniaxial loading after the triaxial or local triaxial load test to study the residual strength and initial damages of lightweight aggregate concrete by triaxial or local triaxial loading. The test results show that failure cracks on specimen under local compression mainly appear on the interface between the steel block and concrete, differing from the distribution patterns of cracks on the surface of specimen under full section compression. The peak stress increase coefficient under local compression is larger than that under full section compression and it is larger under multiaxial compression than that under uniaxial compression. The lightweight aggregate concrete has a certain residual bearing capacity after being damaged by triaxial compression and the residual capacity decreases as the increase of lateral pressure. Finally, failure criterion of lightweight aggregate concrete has been proposed based on the test results under multiaxial and local multiaxial loading. The proposed failure criterion, simple yet effective, provides a technical basis for design of lightweight aggregate concrete structure in practical engineering.

1. Introduction

Concrete is widely used in civil engineering structures such as fittings, bridges and buildings. The characteristic material properties of concrete, including the discreteness, randomness and nonlinearity, had been extensively studied [1]. Due to such intrinsic concrete characteristics and effects on the physical properties, it is of great essence in developing the multiaxial constitutive models for the concrete, especially for the tri-axial constitutive model since the application of concrete in engineering practice is mostly under triaxial stress state. Most of existing multiaxial tests are based on conventional triaxial test with equal lateral hydraulic confining pressure (i.e., $\sigma_X = \sigma_Y$); however, concrete material is usually under actual complex state with unequal confining pressure in tri-directions (i.e., $\sigma_X \neq \sigma_Y \neq \sigma_Z$). The true triaxial test can represent and model the realistic stress state of the concrete so that it is able to derive more accurate and realistic constitutive models for the concrete [2]. On the other hand, concrete is not only subjected to multiaxial loading but also local multiaxial loading, such as the stress state within the local anchorage zone of concrete specimen due to post-tensioned prestressing load [3]. Hence, studies on concrete material model under local loading is also valuable.

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Recently, lightweight aggregate concrete has been widely used because of its advantages of light weight, high strength, thermal insulation and fire resistance. A typical application of lightweight aggregate concrete was conducted by Shinkansen in Japan [4–8]. The existing study of lightweight aggregate concrete constitutive model is mainly based on the traditional triaxial test, rather than a test with true triaxial loading which is more consistent with the real stress state of concrete used in practice. Unlike the traditional triaxial test, the true triaxial test can independently control the stress levels in three directions, making it a useful technique to examine various loading paths with different hydrostatic pressure and loading angles. Therefore, the overall characteristics of failure surface in stress plane can be accurately captured and revealed.

Test of ordinary concrete subjected to multiaxial loading has been conducted extensively and various failure criterions have been proposed, such as the Willam-Warnke five-parameter model, Ottosen model, twin shear theory etc. [9–11]. However, such experiential studies for lightweight aggregate concrete under multiaxial loading are very limited, especially for the concrete material under local multiaxial loading. In addition, it is well known from ordinary concrete that peak stress of concrete under multiaxial compression is greater than those under uniaxial compression, damages of concrete is not obvious under the low lateral pressure, and the residual material strength remains after the triaxial compression test [12–14]. However, it is the best knowledge of the authors that there are no studies reported in modeling and revealing such material behaviors for the lightweight aggregate concrete.

In this paper, the lightweight aggregate concrete was tested under both multiaxial compression and local multiaxial compression through a true triaxial test. According to the stress-strain curves derived from the test, mechanical properties of lightweight aggregate concrete under various loading conditions were analyzed. In addition, to reveal failure modes and residual strength of the concrete, the lightweight aggregate concrete specimens were re-tested under uniaxial or local uniaxial compression after the triaxial or local triaxial loading tests. Finally, failure criterion of lightweight aggregate concrete under various loading conditions has been proposed based on the test data and the twin shear theory model to predict strength of lightweight aggregate concrete under true triaxial compression. The proposed simple but effective criterion provides a theoretical design basis for the application of lightweight aggregate concrete in engineering practice.

2. Experimental set-up and loading conditions

2.1. The concrete mixture ratio

According to the standard procedure for light aggregate concrete mixture [15], the mixture ratios of lightweight aggregate concrete are shown in Table 1, along with the physical properties used in the experiments in Table 2.

According to the state-of-art reference size of the test specimens and capacity of the test machine, the test specimens are designed as cubes with a dimension of 100 mm × 100 mm×100 mm. The lightweight aggregate concrete was made of ordinary Portland cement (P.O 32.5) with the largest particle size of 5 mm for river sand and 10 mm for lightweight aggregate [16–24].

2.2. Specimen fabrication

The steel formwork was used to construct the test specimens ensuring all the fabricated ones have equal design size. Before pouring the lightweight aggregate concrete for each specimen, the steel formwork have been cleaned and the release agent was brushed onto the inside surface of steel formwork.

The cement, fine aggregate and lightweight aggregate are weighted, respectively, and then transferred into the mixer for a homogeneous mixing of these materials. The weighted tap-water is added into the mixer and the mixer machine is stirred for about 5 min. After that, the lightweight aggregate concrete mixtures are filled into the steelwork and then moved onto the vibration table. The vibration table will not be turned off until the paste comes out of the mixture and the extra concrete is scraped in the end.

After a duration of 24 h, the steel formworks are removed and the lightweight aggregate concrete is placed into the curing room with a temperature of 20 ± 2 °C and the humidity more than 95%. After 28 days, the specimens are moved out of the curing room to be cured under the natural environment.

2.3. Triaxial testing system and procedures

In this test, the rock fracture seepage testing machine, equipped with force and displacement sensors, was used as the test device. Three vertical loading actuators, each with a tonnage of 100 t, are equipped in the machine. The force and displacement measurements are recorded with a deformation measurement accuracy controlled within 0.0005 mm. Before each test, the equipment will be equipped with a frame to adjust its own stiffness so that the descending branch of stress-strain curve can be obtained, as shown in Fig. 1(a). The axial stress of the test concrete cube is determined through the measured force from the force sensor and the loading area, and the strain is derived from deformation data from the displacement sensors, as shown in Fig. 1(a).

The local loading test is achieved by a steel block (with a size of 60 mm × 60 mm×30 mm) placed on top center of the specimen, as shown in Fig. 1(b). In addition, a steel plate with size of 100 mm × 100 mm×5mm is placed on top of the steel block to protect the testing machine, shown in Fig. 1(b).

In the multiaxial compression test, the antifriction measures were taken to achieve an accurate load input. A three-layer polyethylene film (with the interlayer of the film filled with machine oil) was installed on the lateral loading surfaces of the specimens to reduce the friction effect. The vertical (Z) direction of loading surface is brushed with a layer of machine oil and such antifriction effect is effective in satisfying the test requirements [12,25].

2.4. Loading scheme

As shown in Fig. 2, a total of nine loading conditions are used in the test. For test cases from Fig. 2(a)–(c), the lightweight aggregate concrete is under the uniaxial loading or local uniaxial compression. Meanwhile, the test cases from Fig. 2(d)–(g) are subjected to multiaxial loading or local multiaxial loading. The residual material strength of lightweight aggregate concrete can be derived by re-testing the specimens under uniaxial or local uniaxial compression after the triaxial or local triaxial loading tests. Through such test arrangement, damages of lightweight aggregate concrete

Table 1
Mixtures of lightweight aggregate concrete (unit: kg/m^3).

Material	Cement	Water	Fine aggregate	Lightweight aggregate
Lightweight aggregate concrete	460	200	650	670