Construction and Building Materials 126 (2016) 263–273

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study of equal biaxial-to-uniaxial compressive strength ratio of concrete at early ages

Wei Dong [a], Zhimin Wu [b,*], Xiangming Zhou [c,b], Hui Huang [b]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology & Ocean Engineering Joint Research Center of DUT-UWA, Dalian 116024, PR China
[b] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, PR China
[c] Department of Mechanical, Aerospace and Civil Engineering, Brunel University London, Uxbridge, Middlesex UB8 3PH, United Kingdom

HIGHLIGHTS

- A formula between β and early age is derived.
- β noticeably decreases from 3.5 to 1.2 within 7 days.
- There is less effect of concrete strength and maximum aggregate size on β.
- Columnar/flaking damages are observed under uniaxial/equal biaxial compression.

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 1 August 2016
Accepted 14 September 2016
Available online 20 September 2016

Keywords:
Equal biaxial-to-uniaxial
Compressive strength ratio
Biaxial compressive strength
Concrete
Early age

ABSTRACT

The ratio of equal biaxial to uniaxial compressive strength of concrete, denoted as β, is an important parameter in the determination of failure criterion for concrete, which has been widely adopted in finite element codes in simulation of fracture and failure of concrete. However, there is no experimental study on β conducted for concretes at early ages. In this study, an experimental study on the uniaxial and equal biaxial compressive strengths of concretes at early ages up to 28 days was carried out using an in-house electro-hydraulic servo-controlled triaxial test machine. Concrete specimens with different coarse aggregate sizes (10 mm, 20 mm, 30 mm) and strength grades (C30, C40, C50) were tested at various ages (6 h, 12 h, 1 d, 3 d, 7 d, 14 d, 28 d). The results showed that β decreases with the increase of concrete age. In comparison, there are less significant effects of concrete strength and maximum coarse aggregate size on β. By regression analyses of experimental results, an empirical equation was proposed for β by considering the effects of age on β for concrete at early ages.

1. Introduction

Numerical modelling of concrete and other cement-based materials is an efficient tool for the investigation of the static/dynamic behaviour of concrete elements/structures. In this context, the failure envelope plays a significant role in numerical analysis of concrete structures and has been widely studied through experimental and theoretical approaches in the last decades. There are several failure criteria for concrete proposed by researchers. Through calibrating elementary strength data of uniaxial compression, uniaxial tension, and equal biaxial compression from experiment, a three-parameter criterion was proposed by Menetrey and Willam [1]. Based on the fracture theory, a four-parameter criterion was proposed by Hsieh et al. [2] to determine material's behaviors from initial yielding to fracture failure. Meanwhile, a five-parameter failure criterion [3], which is dependent on three stress-tensor invariants, was proposed through the introduction of a new two-parameter function describing the deviatoric cross section of the failure surface. Recently, aiming at normal strength concrete and high strength concrete in compression-com pression-tension, compression-tension-tension, triaxial tension, and biaxial stress states, a unified strength criterion in the principal stress space has been proposed by Ding et al. [4]. Among these, the shape of failure surface in the deviatoric stress space is affected by the out-of-roundness eccentricity parameter, which was recommended as 0.5 for a triangular shape and 1.0 for a circular shape [1]. Meanwhile, the parameter of the out-of-roundness is affected by the curvature of the tensile meridian, so that it is usually calibrated under equal biaxial compression. Therefore, to use the aforementioned failure criterion in numerical analysis, it is

* Corresponding author.
E-mail addresses: dongwei@dlut.edu.cn (W. Dong), wuzhimin@dlut.edu.cn (Z. Wu), xiangming.zhou@brunel.ac.uk (X. Zhou), Hhuang@163.com (H. Huang).

http://dx.doi.org/10.1016/j.conbuildmat.2016.09.040
0950-0618/

necessary to obtain the equal biaxial-to-uniaxial compressive strength ratio, β, of concrete.

For mature normal-strength concrete, many experimental investigations [5–7] have been conducted to derive β with the value of 1.14 [1] widely adopted by the engineering and academic communities. However, with the increase of concrete strength from normal to high strength, it seems that β does not remain constant. According to the study on high-strength concrete by Hussein and Marzouk [8], β decreases with the increase of concrete strength. Further, based on the statistical data obtained from experimental results of concretes with various strengths, Papanikolaou and Kappos proposed a relationship between β and uniaxial concrete strength through a power-law regression curve fitting analysis [9]. According to their research, β decreases from 1.2 to 1.05 when concrete strength grade increases from C20 to C120. In addition to concrete strength, coarse aggregate size is another important factor affecting β. In general, the equal biaxial compressive strength f_{bc} is related to the uniaxial compressive strength f_c of concrete, so that the only variable is f_c in the function of f_{bc} [10,11]. It is understandable that f_c is strongly influenced by coarse aggregate size in fresh or hardened concrete [12]. However, it has not been verified by experiment or theoretical analysis that concrete, with the same f_c but different coarse aggregate sizes, exhibits similar f_{bc}. Chen et al. [11] conducted an experimental investigation on biaxial compressive strength for concrete with similar uniaxial compressive strength but different maximum coarse aggregate sizes. Their results indicated that biaxial compressive strength will increase with the increase of coarse aggregate size for concrete with similar uniaxial compressive strength. Meanwhile, aiming at concrete for dam, Wang and Song [13] investigated the normalized biaxial compressive strength of concrete with the maximum coarse aggregate sizes of 20 mm, 40 mm and 80 mm. Similar conclusions to those drawn by Chen and Leung [11] were reported by them for concrete used for the construction of dams and wet-screened components. However, the quantitative relationship between maximum coarse aggregate and β was not presented in the research of Chen and Song (2009), and Wang and Song (2009), although the variation trend of β was discussed.

It should be noted that the aforementioned research has focused on the behaviour of mature concrete under biaxial compression. Research on early-age concrete under biaxial compression is very limited and only Liu et al. [14] conducted such research but on creep of early-age concrete under biaxial compression. In reality, some massive concrete structures, such as nuclear power plants and docks, is under a multiaxial stress state during construction, i.e. at early ages. Therefore, it is significant to derive the failure criterion in early-age concrete for the purpose of safety evaluation of a concrete structure under construction. β, as a key parameter, affects the out-of-roundness which further determines the shape of failure surface of concrete under biaxial/triaxial loading. Therefore, it is essential to investigate β with respect to concrete age when adopting a failure criterion to assess the safety of a concrete structure during construction. However, for concrete at early ages, to the best of the authors' knowledge, no formula for biaxial compressive strength is reported. Particularly, in the case of early-age concrete with different strength, the study on the effect of maximum coarse aggregate size on β has not been carried out in previous research. Therefore, together with the characteristic of early-age concrete, it is significant to investigate the variation of β for concrete with various strength and coarse aggregate sizes.

In line with this, the objective of this paper is to focus on the variation of equal biaxial-to-uniaxial compressive strength ratio β for early-age concretes. Through measuring the equal biaxial and uniaxial compressive strength of concretes with various strength grades and coarse aggregate sizes, the relationship between equal biaxial-to-uniaxial compressive strength ratio β and concrete age within 28 days was obtained based on the experimental results. Further, the effect of concrete age and maximum aggregate size on β for early-age concretes was analysed, and the specimen failure characteristics under equal biaxial compression was discussed with respect to age for a series of concrete with various strength grades. It is expected that the experimental results presented here can lead to a better understanding of the mechanical properties and failure characteristics of early-age concrete so that the failure criteria can be used to assess the safety and durability of concrete in numerical analyses from the moment of final setting to in service.

2. Experimental program

2.1. Materials and specimens

Three grades of concretes, i.e. C30, C40 and C50, were prepared to measure their uniaxial and equal biaxial compressive strengths within 28 days. Coarse aggregates with maximum sizes of 10 mm, 20 mm and 30 mm, respectively, were used in preparing each grade of concretes. River sand was used as the fine aggregate. The grade C30 and C40 concretes were made with Grade R42.5 Portland cement (Chinese Standard of Common Portland Cement, GB175-2007 [15]), and the grade C50 concrete was made with Grade R52.5 Portland cement (Chinese standard of Common Portland Cement, GB175-2007 [15]). The mix proportions of the three grades of concretes and their uniaxial compressive strength at 28 days are listed in Table 1. It should be noted that the uniaxial compressive strength listed in Table 1 was obtained on 150 mm cubes conforming to Chinese code of Standard for Test Method of Mechanical Properties on Ordinary Concrete, GB/T 50081-2002 [16], without the friction reducing measure between the loading plate and the specimen surfaces prior to testing. Meanwhile, to obtain the equal biaxial-to-uniaxial compressive strength ratios at different ages, a series of tests on uniaxial and equal biaxial

Table 1
Concrete mix proportions for different strength grades.

Concrete	Maximum aggregate size (mm)	Water	Cement	Sand	Aggregate	Cement grade	f_c (MPa)
		(kg/m^3)					
C30	10	205	331	709	1110	R42.5	34.9
	20	205	331	691	1128	R42.5	37.5
	30	205	336	653	1161	R42.5	38.8
C40	10	220	500	501	1064	R42.5	52.7
	20	215	488	512	1140	R42.5	52.1
	30	210	477	530	1181	R42.5	51.5
C50	10	210	525	496	1054	R52.5	60.8
	20	205	513	507	1130	R52.5	64.5
	30	213	520	467	1200	R52.5	63.8