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Size effect on peak axial strain and stress-strain behavior of concrete subjected to axial compression

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HIGHLIGHTS

- Study of size effect on peak axial stress, peak axial strain, and elastic modulus in test.
- Comparison of the current size effect formulas of peak axial stress.
- Analysis of the size effect law of peak axial strain.
- Proposal of size-dependent stress-strain curve model.

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ABSTRACT

Twenty-four cylinders with different diameters (150 mm $\le D \le$ 460 mm) and compressive strengths (C60, C45) were tested until failure to study the size effect behavior of concrete subjected to axial compression. The size effects on peak axial stress, peak axial strain, and elastic modulus were studied. Experimental results showed that peak axial stress and peak axial strain of the specimens tended to decrease with the increase in specimen diameter. The elastic modulus remained nearly constant when the specimen diameter increased, indicating that the size effect on the elastic modulus was insignificant. In addition, the size effects of peak axial stress and peak axial strain were analyzed based on existing theories and test data in the literature. A size-dependent stress–strain model of a concrete material subjected to axial compression was then proposed.

1. Introduction

In general, the compressive strength of concrete is accepted to decrease with the increasing concrete specimen size. This property is referred to as the size effect of concrete. Based on the research of Blanks and Sakino [1,2], the compressive strength of a concrete specimen decreases by 18.3% when the specimen diameter increases from 150 mm to 900 mm. Thus far, a number of experimental and theoretical investigations have been conducted to study the size effect of concrete. Gonnerman [3] first studied the size effect of concrete in 1925. Blanks [1] then conducted a test to investigate the influence of aggregate size and column diameter on the concrete compressive strength. The size effect of concrete has attracted considerable attention since then. The applications of mass concrete and high-strength concrete are growing with the continuous increase in building height and bridge span length. Thus, research on the size effect of concrete is also expanding. Experimental studies [4–12] were conducted to investigate the influence of section size on the axial compression strength of concrete, which demonstrates the size effect of concrete. The column diameter in the test conducted by Burtscher and Kollegger [10] and Muciaccia et al [12] reached 800 mm, and the size effect behavior was much more pronounced. The effects of the height-diameter ratio and cross-sectional shape on the size effect of concrete have been investigated by researchers [12–16]. The size effects of a cube and a prism were found to be more significant than those of a cylinder, while the variation in the nominal compressive strength was more related to the increase in the absolute size of the compressed sections rather than to the increase in the slenderness ratio when H/D was larger than 2 [12]. In addition,

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researchers [15,17] tested the size effect of concrete with different water–cement ratios (compressive strength); however, the results indicated that the influence of the water–cement ratio (compressive strength) is not evident. The size effect of concrete subjected to dynamic load was also investigated in the literature [18,19]. The size effect in such cases was much more significant.

Apart from plain concrete, the size effect law of FRP-confined and reinforced concrete was also studied in the literatures. Researchers such as Owen [20] and Wang et al. [21] investigated the size effect of FRP-confined concrete, and their experimental results showed that the compressive strength of FRP-confined concrete is influenced by the column diameter. The effects of the volumetric ratio of stirrup and longitudinal bar, stirrup form, type of force, and cross-section shape on the size effect of reinforced concrete were studied by Jin et al. [22,23], Li et al. [24], Du et al [25], Du et al. [26,27], and Song et al. [28]. Their studies indicated the existence of the size effect in reinforced concrete subjected to axial compression; the size effect of compressive strength was influenced by the level of confinement.

Although many studies have already investigated the size effect of concrete, most of these studies focused on the peak axial stress (compressive strength). Few studies investigated the size effect of the peak axial strain. To the authors' knowledge, only the researchers such as Jin et al. [22], Du et al. [25], Du et al. [26,27], Song et al. [28] have tested the size effect of peak axial strain, which demonstrated the existence of size effect in peak axial strain. The specimens in these papers are reinforced concrete, which differs from the research object in this paper (plain concrete) due to the influence of confinement. The elastic modulus is the property of concrete in the elastic stage, and the micro-cracks propagate slowly in this stage, while the size effect is related to the concrete fracture, thus the size effect of elastic modulus should not exist in theory. The specialized study on size effect of elastic modulus is quite limited. According to the tests conducted in the literatures [23–27], the stress-strain curves of concrete specimens with different sizes almost coincided with each other in the elastic stage, which demonstrated the inexistence of size effect of elastic modulus.

The behaviors of lateral dilation and stress–strain curves are influenced by the specimen size because they are all connected with the peak axial strain. Moreover, in the expected failure model of reinforced concrete, the longitudinal steel bars start yielding when the concrete approaches its strain limit. Nevertheless, the failure of concrete occurs earlier because of the influence of the size effect on the peak axial strain; thus, the full capacity of the steel bars cannot be realized, especially in the case of bars with a high yield strength. For FRP-confined concrete or concrete-filled steel tube, the dilation of concrete core and the confinement effect are affected by the size effect of the peak axial strain. Therefore, the size effect of the peak axial strain is critical and requires further investigation.

In this study, 24 specimens with different diameters ($150\text{ mm} \leq D \leq 460\text{ mm}$) were tested until failure to determine the size effect law of concrete material. The influence of the diameter on the peak axial stress, peak axial strain, and elastic modulus was analyzed. A modified stress–strain relationship model for concrete material was then proposed based on the size effect of the peak axial stress and the peak axial strain by considering the influence of the cross-section size.

2. Experimental procedure

2.1. Specimen design

Twenty-four cylinder specimens were experimentally studied until failure to investigate the size effect behavior of concrete columns. The key parameters were compressive strength f_c and column diameter D. Two grades of concrete were used in the test: C60 and C45. The column diameters in the C60 batch were 150, 224, 273, 374, and 460 mm, while those in the C45 batch were 178, 260, and 339 mm. Each specimen group included three identical specimens to reduce the effect of data scatter. Table 1 summarizes the design details, where D and H denote the column diameter and height of the specimens, respectively; E_c denotes the elastic modulus of the cross-section; and f_{co} and ε_{co} denote the peak axial stress and the peak axial strain of the specimens, respectively.

Two grades of concrete were used in the test, in which the height-diameter ratio of C60 is 2, and that of C45 is 3. This is

Table 1
Test design and results.

Concrete grade	Group	Label	D (mm)	H (mm)	E_c (GPa)		f_{co} (MPa)		ε_{co} (με)	
					Test	Mean	Test	Mean	Test	Mean
C60	1	A-1	150	300	38.7	38.8	70.1	70.8	1985	2103
		A-2	150	300	38.3		68.2		2091	
		A-3	150	300	39.4		74.0		2234	
	2	B-1	224	448	39.5	39.0	65.0	68.2	1798	1903
		B-2	224	448	38.2		67.3		1831	
		B-3	224	448	39.3		72.2		2082	
	3	C-1	273	546	38.8	39.0	64.8	65.1	1761	1838
		C-2	273	546	38.9		70.1		2058	
		C-3	273	546	39.3		60.3		1695	
	4	D-1	374	748	40.4	40.0	59.5	60.0	1789	1787
		D-2	374	748	40.5		62.2		1895	
		D-3	374	748	39.1		58.4		1677	
	5	E-1	460	920	39.4	39.4	63.2	61.7	1832	1740
		E-2	460	920	40.3		63.6		1775	
		E-3	460	920	38.4		58.2		1612	
C45	6	F-1	178	535	33.3	34.3	53.9	52.2	2174	2141
		F-2	178	535	34.0		46.0		–	
		F-3	178	535	35.5		56.6		2109	
	7	G-1	260	780	31.9	33.1	47.0	48.8	1855	1834
		G-2	260	780	34.2		48.2		1742	
		G-3	260	780	33.3		51.3		1905	
	8	H-1	339	1016	31.3	32.7	44.1	43.8	1706	1743
		H-2	339	1016	33.7		36.6		–	
		H-3	339	1016	33		43.5		1781	