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Direct tensile strength of lightweight concrete with different specimen depths and aggregate sizes

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HIGHLIGHTS

- This study examines the size effect in tensile strength of lightweight concrete.
- The reference tensile strength for size effect model is established.
- A stronger size effect with the decrease in concrete density is confirmed.
- This study finds a stronger size effect in direct tension than in compression.
- This study finds that the effect of aggregate size on tensile strength is negligible.

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ABSTRACT

To examine the size effect in direct tension, 8 ready-mixed concrete batches classified into all-lightweight concrete (ALWC) and sand-lightweight concrete (SLWC) groups were prepared. In each group, the maximum aggregate size varied between 4 mm and 19 mm, and then the lateral depth of specimen with rectangular section ranged from 100 mm to 500 mm in each concrete batch. The size effect curves based on the basic formulas proposed by Bažant (1984) [1], Kim and Eo (1990) [2], and Yang and Sim (2011) [3] were also determined using a total of 28 lightweight concrete (LWC) data of current tests and 114 normal-weight concrete (NWC) data compiled from the available literature (Carpinteri and Ferro, 1994; Hu, 2011) [4,5], though specimens with lateral depth beside 100 mm is very insufficient even in NWC. The present experimental observations and verifications by prediction models clearly showed that the size effect is more notable with the decrease of the unit weight of concrete and it is stronger in direct tension than in compression. The validity of Bažant's model (Bažant, 1984) [1] is significantly dependent on the maximum aggregate size, while the models proposed by Kim and Eo (1990) [2] and Yang and Sim (2011) [3] closely predict the size effect trend observed from test data, confirming that the influence of the maximum aggregate size on the concrete tensile strength and the size effect is negligible, especially for LWC.

1. Introduction

The tensile strength of concrete is a critical property that requires further research. Although the tensile strength of concrete is frequently neglected when evaluating the ultimate load-bearing capacity of reinforced concrete elements, it significantly affects the deflections, cracking, and shear and bonding behaviors in such elements. In particular, an accurate evaluation of the concrete tensile strength helps enhance the appearance, serviceability, and durability of concrete structural members by controlling cracks. The tensile strength of concrete has primarily been examined using splitting tension test methods because of their convenience, despite the common knowledge that a direct tension test provides more rational and reliable results [6]. As a result, the direct tensile strength of concrete has been given relatively little attention.

The tensile strength of concrete is significantly affected by the strength, surface texture, and size of the aggregates used in the

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Table 1
Details of ready-mixed concrete batches.

Concrete mix[a]	W/C (%)	d_a (mm)	Unit volume weight (kg/m^3)					Slump (mm)	f'_c (MPa)	ρ_c (kg/m^3)
			W	C	F_L	F_S	G_L			
A4	30	4	200	667	725	–	–	80	47.3	1650
A8		8		667	240		455	100	48.3	1620
A13		12		667	264		418	135	44.9	1607
A19		19		667	255		437	145	42.2	1617
S4	35	4		571	–	1423	–	90	37.6	2234
S8		8		571		520	455	150	44.3	1786
S13		13		571		566	418	188	38.5	1794
S19		19		571		549	437	175	39.1	1797

Note: W/C = water-to-cement ratio by weight, F_L = lightweight fine aggregate, F_S = natural normal-weight sand, G_L = lightweight coarse aggregates, f'_c = concrete compressive strength measured from a cylinder with 150 mm diameter and 300 mm height, and ρ_c = unit weight of hardened concrete.

[a] In the concrete mix notation, the first and second parts indicate the type of concrete and the maximum aggregates size, respectively. For example, A8 indicates an all-lightweight ready-mixed concrete with the maximum aggregates size of 8 mm.

concrete, because the tensile response of concrete is primarily governed by the aggregate interlock capacity and the cohesive cross-linking action between aggregate particles and pastes along micro- and macro-cracks [7,8]. Majeed [9] and Hong [10] confirmed that the size effect is one of the most important parameters to be considered in determining the nominal tensile strength of concrete. However, experimental investigations to examine the size effect in direct tension have been quite limited, even for NWC, despite the fact that it has occasionally been pointed out [10] that the size effect is greater in direct tension tests than in splitting tension tests. As a result, the experimental constants in the preferred basic models [1–3] used to determine the size effect curve have still not been determined for the direct tensile strength of concrete.

Artificial lightweight aggregates commonly have less strength and smoother surfaces than natural normal-weight aggregates. These differences result in a lower tensile strength, lower cohesion between aggregate particles and pastes, and a faster drop after the peak stress in LWC compared to NWC of the same compressive strength. Consequently, most of the code provisions [11,12] specify modification factors derived from limited splitting tension test data to account for the reduced tensile capacity of LWC. However, it is still controversial how to reasonably evaluate the relationship of concrete compressive strength and direct tensile strength, and what the difference in the size effects is between compression and tension. The available information on these characteristics is especially incomplete for LWC, although a stronger size effect would be expected in the direct tensile strength of such concrete because of the more severe brittleness fracture properties and weaker cohesion between the aggregates and pastes.

The present study tested eight ready-mixed concrete batches classified into ALWC and SLWC groups to evaluate the size effect in direct tension. In each concrete group, the maximum aggregate size (d_a) was selected as the main parameter, and the lateral depths (d) of the specimens were varied in each concrete batch. The measured tensile size effect in the present LWC specimens was compared with that obtained from the NWC data compiled from the available literature [4,5] and the compressive size effect of LWC [3]. In addition, the experimental constants in the preferred basic formula [1–3] used for predicting the size effect were refitted in direct tension using the existing data [4–6,9,10,13–18] and present test results to confirm the influence of the concrete unit weight (ρ_c) and d_a on the tensile size effect.

2. Experimental program

2.1. Specimen details

Table 1 presents the details of the eight ready-mixed LWC batches designed with the same targeted compressive strength of 35 MPa. The concrete batches tested were classified into two groups (ALWC and SLWC), and d_a values of 4, 8, 13, and 19 mm were used for each concrete group. It should be noted that the concrete specimen with a d_a of 4 mm indicates mortar without coarse aggregate. The mixing design procedure for the LWC followed the ACI 213 guideline [19]. Several laboratorial mixes were first examined to determine the mixing proportions for the ready-mixed concrete batches. The geometrical characteristics of the specimens for the direct tension tests were designed by referring to the RILEM recommendation [20]. All the tensile specimens had a rectangular cross-section. The lateral depths (d) of the specimens were 100, 200, 300, and 500 mm in each concrete batch, whereas their widths were kept constant at 100 mm. The total lengths of the specimens ranged between 267 and 1335 mm to maintain a constant proportion of 2.67 d. Notches with a depth of 0.167 d and width of 3 mm were also made at the mid-height on both sides of specimens.

2.2. Materials

Ordinary Portland cement (CEM I 32.5 N) without supplementary cementitious materials was used as the binder in all the mixtures. The physical properties of the aggregates used are given in Table 2. Artificially expanded clay granules were used for the lightweight aggregates. Locally available natural sand was also mixed in as a normal-weight fine aggregate in the SLWC batches. The lightweight aggregates, which is commercially available [21], were spherical and had a closed surface with a slightly smooth texture and porous structure. The water absorption of the lightweight aggregates was excessively high, and their specific gravity was 1.6 times less than that of natural sand. The specific gravity was approximately 1.2 for lightweight coarse aggregates, 1.65 for lightweight fine aggregates, and 2.6 for natural sand. The water absorption was approximately 18% for lightweight coarse aggregates, 13.68% for lightweight fine aggregates, and 1.85% for natural sand. The modulus of fineness measured from the lightweight fine aggregates was higher than that of the natural sand because of the relative poverty of particles under 1.2 mm, as shown in Fig. 1. The modulus of fineness of lightweight aggregates tended to decrease as d_a decreases.

Table 2
Physical properties of aggregates used.

Type		Maximum size (mm)	Unit volume weight (kg/m^3)	Specific gravity	Water absorption (%)	Modulus of fineness
Expanded lightweight clay granule	Coarse aggregate	19	729	1.21	18.96	6.56
		13	697	1.18	18.00	6.31
		8	759	1.22	18.77	5.86
	Fine aggregate	4	832	1.65	13.68	4.34
Natural normal-weight sand		5	1750	2.6	1.85	2.51