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# Size and shape effects on compressive strength of lightweight concrete

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## HIGHLIGHTS

- ▶ This study examines the size and shape effects in compressive strength of lightweight concrete.
- ▶ We also provide comprehensive basic data for the influence of concrete unit weight on the compressive size and shape effects.
- ▶ We find that the size effect becomes stronger with the decrease of the concrete unit weight.
- ▶ We ascertain the accuracy of the existing equations and propose new generalized prediction models.

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## ABSTRACT

In this study, the size and aspect ratio effects on the compressive strength of lightweight concrete were examined using nine laboratorial concrete mixes and three ready-mixed concrete batches. At each concrete mix, the aspect ratios of specimens with circular or square sections were 1.0 and 2.0. The lateral dimension of specimens ranged between 50 and 150 mm at each laboratorial concrete mix, while it varied from 50 to 400 mm at each ready-mixed concrete batch. The present study also proposed generalized prediction models for the size effect based on the crack band theory of fracture mechanics, which can cover important influencing parameters such as the aspect ratio and lateral depth of the specimen and the unit weight of concrete. Test results showed that the crack band zone in lightweight concrete specimens was more localized with poor crack distribution than in normal-weight concrete specimens, regardless of the geometrical dimensions of the specimens. As a result, the size effect was stronger with the decrease of the concrete unit weight, and this trend was more notable in specimens with an aspect ratio of 2.0 than in those with an aspect ratio of 1.0. The compressive strength predictions of concrete obtained from the present models are in good agreement with the test results including a total of 1661 data. The trend of the size effect against different parameters as predicted by the present models has a consistent agreement with that observed from experimental results.



## 1. Introduction

The relevant standard and code requirements [1,2] to determine the concrete compressive strength allows different geometric dimensions for specimens. However, the compressive strength of concrete is significantly affected by the size and aspect ratio of specimens due to non-scaled aggregates, different frictions between concrete surfaces and loading platen, and variations of crack propagation and localized failure zone [3]. It has been generally known [4–9] that the concrete compressive strength decreases with the increase of the section size of the specimen, though the decreasing rate nearly remains constant beyond a certain size limit. In addition, the compressive strength measured from a cube is commonly higher than that recorded from a cylinder, while the effect of the section shape of the specimen on the size effect is somewhat controversial [5–7]. For these reasons, the ASTM standard provision [1] specifies a correction factor for concrete strengths of between 14 and 42 MPa to compensate for the reduced strength when the aspect ratio (height-to-diameter ratio) of specimen is less than 2.0, while the CEB-FIP provision [2] specifically mentions the ratio of $150 \times 300$ mm cylinder strength to 150 mm cube strength. However, both provision requirements do not specifically clarify the applicability and/or modification of the correction factors for the compressive strength to lightweight concrete (LWC).

The size and shape effects on concrete compressive strength are affected by the cohesion and void between pastes and aggregate particles together with the propagation of a number of cracks in the local failure zone [3,10]. The artificial lightweight aggregate generally produces a lower cohesion and a higher void in the

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interface with pastes, compared to natural normal-weight aggregates [9]. Furthermore, the cracks at the failure plane of concrete mainly passed through the lightweight aggregate particles [11]. Due to these different characteristics, the decreasing rate of the strength against the lateral dimension ($d$) of the specimen in LWC would be possibly distinct from that observed in normal-weight concrete (NWC). This means that the correction factors specified in the ASTM and CEB-FIP provisions and the experimental constants in empirical equations [3,12] to predict the size effect would need to be adjusted in LWC, because they are commonly determined from the statistical analysis of NWC test data. However, relevant literature on the size and shape effects of LWC in compression is very rare. There is also no available information on the safety and reliability of the correction factors of the ASTM and CEB-FIP provisions in predicting the nominal compressive strength of LWC measured from specimens with different sizes and/or shapes.

The objective of this study is to ascertain the size and shape effects on the compressive strength of LWC. With the variables of geometrical conditions of specimens such as lateral dimension, section shape and aspect ratio, two series of concrete mixes were tested; in the first series, nine LWC mixes were prepared using a pan mixer at the laboratory by varying the water-to-cement ratio and the replacement level of natural sand, whereas in the second series, three ready mixed concrete batches designed according to the type of concrete were used. The reliability of the correction factors specified in the ASTM and CEB-FIP provisions was then examined in LWC through the comparisons with the present test data. The present study also mathematically derived a basic formula following the concept of the crack band theory [3,10,12] of fracture mechanics in order to identify the effects of the aspect ratio of the specimen and the concrete unit weight on the size effect. The unknown coefficients in the proposed basic formula were determined by the least square method using a comprehensive data base, which includes the 1509 NWC specimens and 152 LWC specimens, compiled from available literature [4–6,13–18] and the present tests. The proposed equations were successively compared with the existing models proposed by Bažant [10] and Kim and Eo [12] based on non-linear fracture mechanics.

## 2. Experimental programme

### 2.1. Specimen details

The tests were conducted as two series considering a working environment, as given in Table 1. With reference to ACI 213R-03 [19], the present study classifies the type of concrete according to its unit weight ($\rho_c$) as follows: ALWC with $\rho_c < 1700$ kg/m$^3$; SLWC with $\rho_c < 2000$ kg/ m$^3$; and NWC with $2240 < \rho_c < 2480$ kg/m$^3$. In the first series, nine concrete mixes were prepared using a 0.3 m$^3$ capacity pan mixer in the laboratory. The mixing variables considered in the first series were the water-to-cement ratio by weight and the replacement level of natural sand to total fine aggregate by volume. In the second part, three ready-mixed concrete batches were prepared according to the type of concrete. The targeted compressive strength of all ready-mixed concrete batches was 35 MPa.

The size and shape of specimens tested in each series are listed in Table 2. In each concrete mix, circular and square section molds with the aspect ratios ($n_1 = h/d$) of 1.0 and 2.0 were used to measure 28-day compressive strength, where $h$ and $d$ are height and lateral dimension of the specimen, respectively. The circular section molds with the aspect ratios of 1.0 and 2.0 indicate a cylinder, while the square section molds with aspect ratio of 1.0 and 2.0 refer to a cube and a prism,

**Table 1**
Details of each concrete mix proportion.

| Series | Concrete mix[a] | $W/C$ (%) | $R_s$ (%) | Unit volume weight (kg/m$^3$) | | | | | | $f'_c$ (MPa) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $W$ | $C$ | $F_L$ | $F_S$ | $G_L$ | $G_C$ | | |
| 1 | A30-0 | 30 | 0 | 200 | 667 | 334 | – | 401 | – | 46.2 | 1691 |
| | S30-50 | | 50 | | | 167 | 311 | | | 43.7 | 1768 |
| | S30-100 | | 100 | | | | 622 | | | 40.4 | 1850 |
| | A35-0 | 35 | 0 | | 571 | 373 | – | | | 40.5 | 1578 |
| | A35-50 | | 50 | | | 187 | 348 | | | 37.3 | 1684 |
| | S35-100 | | 100 | | | | 695 | | | 34.2 | 1783 |
| | A40-0 | 40 | 0 | | 500 | 403 | – | | | 35.6 | 1552 |
| | A40-50 | | 50 | | | 201 | 375 | | | 33.5 | 1662 |
| | S40-100 | | 100 | | | | 750 | | | 30.4 | 1716 |
| 2 | A43-0 | 43 | 0 | | 465 | 417 | – | 401 | | 39.4 | 1661 |
| | S47-100 | 47 | 100 | | 426 | – | 866 | | | 37.8 | 1920 |
| | N55-100 | 55 | 100 | | 364 | – | 862 | – | 935 | 35.5 | 2314 |

*Note:* $W/C$ = water-to-cement ratio by weight, $R_s$ = replacement level of natural sand to total fine aggregate by volume, $F_L$ = lightweight fine aggregate, $F_S$ = natural sand, $G_L$ = lightweight coarse aggregates, $G_C$ = natural crushed gravel, $f'_c$ = concrete compressive strength measured from a cylinder with 150 mm diameter and 300 mm height and $\rho$ = unit weight of hardened concrete.

[a] In the concrete mix notation, the first part indicate the type of concrete, while the second and third parts give the water-to-cement ratio and replacement level of natural sand, respectively. For example, A30-0 indicates an all-lightweight concrete mix with water-to-cement ratio of 0.3 and without replacement of natural sand.

**Table 2**
Geometrical details of specimens used in each concrete mix.

| Series | Distribution of size and shape of specimen | | | |
|---|---|---|---|---|
| | Type | Shape | | Lateral dimension, $d$ (mm) |
| | | Section | Aspect ratio, ($h/d$) | |
| 1 | Cylinder | Circle | 1 | 100 and 150 |
| | | | 2 | |
| | Cube | Square | 1 | 50, 100 and 150 |
| | Prism | | 2 | |
| 2 | Cylinder | Circle | 1 | 50, 100, 150, 250, 300, 350 and 400 |
| | | | 2 | |
| | Cube | Square | 1 | |
| | Prism | | 2 | |