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Specimen shape and size effects on the concrete compressive strength under static and dynamic tests

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HIGHLIGHTS

- The compressive strength relations of cubic and cylindrical specimens are proposed.
- Empirical relations are obtained to correlate the strength of various size samples.
- The crack patterns of cubic and various cylindrical specimens are analyzed.

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ABSTRACT

Cylinder and cube are two common specimen shapes used in compressive tests to determine concrete strength. Many studies have proposed empirical relations to convert the static strengths of concrete obtained from specimens of these two shapes. There is, however, no study of the relations to convert the dynamic strengths of cylindrical and cubic concrete specimens obtained from impact tests. In this study, cubic and cylindrical concrete specimens of different sizes were prepared and tested under static and impact loads to investigate the shape and size effects on the concrete compressive strength under different loading rates. To investigate the influences of strength on these relations, concrete specimens of two characteristic strengths were made and tested. Cubes of dimension 50 mm and cylinders of diameter 50 mm with various length-to-diameter ratios were cast and tested. Empirical relations that correlate the static and dynamic compressive strengths of concrete obtained from specimens of different shapes and sizes were proposed. The crack patterns of different samples in both static and dynamic tests and their influences on the obtained compressive strengths were also analyzed. The results clearly demonstrate the influences of the specimen shape and size on the obtained compressive strength under static and dynamic tests.

1. Introduction

Compressive strength is one of the most important properties of concrete and is the basic mechanical parameter needed in design of concrete structures. The accurate evaluation of concrete compressive strength therefore is of high engineering and research significance. Concrete compressive strength is usually obtained from testing concrete specimens of either cubic or cylindrical shapes with different sizes as suggested by different codes and standards. It has been found that the testing conditions such as the specimen shape, size and boundary conditions significantly affect the testing results [1–4]. Bazant and Planas [3] studied the size and shape effects of the specimens on the nominal strength of concrete samples by changing the size and shape of the specimens in the static tests. No systematic study of specimen shape effect on dynamic strength of concrete material can be found in literature yet, although some studies of specimen size effects have been reported [5,6].

1.1. Previous studies on static compressive strength of concrete

In early years, researchers focused on the size effect of specimens [5–10]. Most of them found that the strength decreased with the increase of the specimen size [9–11]. Based on the modified size effect law (MSEL), a relation was proposed to quantify the size effect on the static compressive strengths obtained from specimens with different dimensions [11]. Apart from size effects, it

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was also noted that the compressive strength of concrete is also significantly affected by the geometry of the specimens. Therefore considerable efforts were also made to study the relation between the static strength of cubic specimens and that of cylindrical specimens. Some empirical relations have been developed, with a minimum conversion factor of about 0.76 for converting the static cube strength to static cylinder strength [12]. Comite Euro-International du Beton (CEB) defines that the conversion factor ranging from 0.7778 to 0.8696 could be used to convert the compressive strength of 150 mm cubes to that of Φ150 × 300 mm cylinders, depending on the concrete strength [13].

As the static compressive strength of concrete is dependent on both the dimension and shape of the tested specimens, the shape and size effects should be taken into consideration for derivation of the empirical relation for the conversion factors. Neville [14] considered the conversion factor of concrete compressive strength as a function of the volume V, lateral dimension d, height h, and the aspect ratio h/d (height to lateral dimension) and proposed Eq. (1) to correlate the compressive strength f_c of specimens with various shapes and sizes to f_{cu15}, the strength of 150 mm cubic specimen.

$$f_c/f_{cu15} = 0.56 + 0.697[d/(V/6h + h)] \quad (1)$$

where for cubic specimens, the height h is equal to the lateral dimension d.

It should be noted that the regression analysis carried out by Neville was based on testing results from different investigators with concretes cured in different conditions and tested at different ages, and these factors were not taken into consideration in the proposed relation. Further from Neville's analysis, Zhu and Yang [15] suggested a different relation to convert the static compressive strength of concrete specimens with various sizes and shapes based on careful linear, power, and exponential regression analysis on the experimental data as,

$$f_c/f_{cu15} = 1.317 - 0.1694(V/b_{15}hd + h/d) \quad (2)$$

where b represents the length of cubic specimens, and subscript 15 refers to 150 mm cube, as the standard specimen. Although the specimens used in [15] included cubes and cylinders, the ranges of the considered dimension and strength were quite limited. For example, the minimum lateral dimension of the specimens was 150 mm and only low-grade concrete with strength of 20 MPa was considered in the study.

From the above review, it is clear that the static compressive strength obtained in lab tests depends on the specimen size, shape, and strength level. There is no universal correlation law yet to convert the compressive strengths of concrete with various shapes and sizes, especially for specimens of relatively small sizes and different strengths.

1.2. Previous studies on dynamic compressive strength of concrete

The dynamic compressive strength of concrete is usually measured in the following three types of tests: servo-hydraulic loading tests, drop-weight tests [16,17] and split Hopkinson pressure bar (SHPB) tests [18]. Among them, SHPB technique has become the most commonly used set-up with cylindrical specimens. Therefore it is also used in the present study to test the dynamic compressive strengths of concrete specimens with different shapes and sizes.

A great number of tests have proved that the dynamic compressive strength of concrete is higher than its corresponding static strength [19–25]. CEB found that there exist a sudden change of slope at the strain rate of 30 s^{-1} in the curve of dynamic increase factor (DIF, the ratio of the dynamic strength to the static strength in uniaxial compression) and logarithmic strain rate ($\lg \dot{\varepsilon}$) [13]. Most SHPB experiments suggested that the dynamic strength enhancement of concrete became obvious at high strain rates ranging from 10^1 s^{-1} to 10^3 s^{-1} [24–26]. According to several results by various researchers, Bischoff and Perry gave a comprehensive review about the DIF with respect to the strain rate and showed that DIF increased 50% in average when strain rates increased from 10^{-5} s^{-1} to 10^1 s^{-1} [24]. Li and Meng [26] demonstrated that this apparent dynamic strength enhancement was wrongly interpreted as strain rate effect, which may lead to over-prediction on the dynamic strength of concrete-like materials. It was suggested that the obvious dynamic strength enhancement of concrete was caused by the lateral confinement, which was induced from the contact surface restriction and the lateral inertia during the rapid compression.

As a consequence, besides the strain rate effect, the effects of lateral inertia confinement and end friction confinement on the dynamic concrete compressive strength have been studied intensively [27–41]. Forrestal and Wright [42] indicated that the inertia effects became particularly important in the range of small strains for brittle materials like concrete. Li and Meng [26] discussed the end friction confinement effect and tried to find the optimal aspect ratio of the cylindrical specimens. Hao and Hao [36,41,43,44] indicated that the dynamic compressive strength was sensitive to the lateral dimension d and the aspect ratio. They stated that the value of DIF increased with the decrease of the aspect ratio which indicated a more significant end friction confinement effect, but this influence of end friction became less significant when the aspect ratio of specimen was larger than 1.0 [36]. Hao and Hao [36,41] also concluded that the friction coefficient strongly affected the strength of concrete. Based on the previous studies, it is obvious that in dynamic compressive tests the lateral inertia confinement and end friction confinement effects in dynamic tests are dependent on strain rate and specimen size. All the above studies are based on cylindrical specimens. No study that used cubic specimens on dynamic strength of concrete has been reported yet.

The above reviews indicate that concrete compressive strength varies if specimens of different sizes and different geometries are used in laboratory tests under static or dynamic loading. Although some empirical relations and conversion factors have been proposed to convert the concrete static compressive strength obtained from specimens of different sizes and shapes, there is no study yet focusing on the conversion of dynamic concrete strength obtained from specimens of different shapes. This is because the dynamic strength of concrete is usually obtained by performing SHPB tests on cylindrical specimens to minimize wave dispersion and to well maintain the one-dimensional wave propagation in the tested specimen. Such test is sufficient to obtain the uniaxial strength of the specimen at high strain rates. To more accurately and comprehensively understand the dynamic material properties under complex stress state, bi-axial and tri-axial impact tests are needed. Apparatus for such tests were not available before. Usually the dynamic properties of concrete specimens under multi-axial stress states were obtained by confined uniaxial tests [45–47]. Recently tri-axial dynamic testing facilities have been developed for direct testing of material properties under multi-axial stress states. For such tests, cubic specimens have to be used. In impact tests, a stress wave is generated and propagates inside the specimen. Because of the geometrical nature, very complex stress waves might be induced in the cubic specimen owing to wave dispersion and reflection. The conversion factors for static strength of concrete may not be applicable to converting the dynamic strength of concrete obtained from impact tests. Unfortunately, there is no study yet to correlate the dynamic material properties obtained from cylindrical specimens with those from cubic ones yet.

This study performed static and SHPB tests on cylindrical and cubic concrete specimens to investigate the influences of strain rate, specimen size and specimen shape on the dynamic