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Effects of cube size and placement direction on compressive strength of self-consolidating concrete

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HIGHLIGHTS

- Size effects of self-consolidating concrete (SCC) cube were investigated.
- A comprehensive experimental program has been conducted.
- Effects of placement and loading directions on the mechanical properties were considered.
- The Least-Square Method (LSM) was employed for the results.
- Parameters pertaining to modified size effect law for SCC were evaluated.

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ABSTRACT

An experimental program has been carried out to investigate the influences of cube size and placement direction on the compressive strength of self-consolidating concrete (SCC). Three types of SCC mixtures were designated and cast in cube molds with various sizes. Results of compressive strength test on cured specimens were used in regression analyses to obtain equations for prediction of compressive strength regarding the influences of size and placement direction. The strength ratio of standard cylindrical to cube specimen with normal placement and loading direction was lower than that with parallel placement and loading direction. Influence of placement direction is more significant than size effect for SCC specimens. The strength ratio of standard cylindrical to cube specimen for SCC is slightly lower than that of traditional concrete. Also, effect of placement and loading directions on the strengths in SCC specimen is more significant compared with traditional concrete specimen.

1. Introduction

In the classical material's failure criteria based on elastic allowable stress, plastic limit analysis and other stress–strain constitutive relations, the strengths of structures with similar shape and any given geometry are independent of the size of the structure. However experimental results on concrete structures and in general structures made of brittle materials demonstrated a deviation from these classical criteria due to variation in size of the structure. This phenomenon is called size effect and originates from the nonlinear fracture in concrete and other brittle materials [1,2].

The most important material property in design of concrete structures which is routinely specified and tested by control specimens is compressive strength of concrete. Different countries use various kinds of specimens in shape and size. Thus, compressive strength of concrete specimens with similar mixtures and different sizes and shapes are different. Most common shapes are cylindrical and cube specimens in which cylindrical specimen with height 30 cm and diameter of 15 cm is known as the standard specimen.

In order to solve this problem, many investigations were carried out. Early works in this field were reported by Gonnermann [3], Blanks and McNamara [4], Gyengo [5] and Neville [6]. They used different specimen geometries to investigate the size effects on concrete strength.

An important study in this area was carried out by Walsh [7] who studied the fracture of plain concrete. The experimental

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results revealed size effect for the nominal strength of notched concrete beams under three-point bending. Theoretical basis of size effect phenomenon has been investigated in papers [8,9] in order to provide sound representative models for prediction of size effect.

Bazant studied the various aspects of size effect in concrete and published several papers with different coauthors in this area. He has eventually collected his works in two books [1,2].

Bazant presented his well-known size effect law (SEL) for geometrically similar concrete members using a dimensional analysis based on energy balance at crack propagation in concrete [10]. The mentioned size effect law has been improved by Kim and Eo [11] to modified size effect law (MSEL) in which the influences of initial cracks and similar and dissimilar cracks were considered. This modified model was also proposed by Bazant and Xiang [12] using a different methodology. They presented a simple and intuitively clear explanation of the size effect phenomenon and then proposed the simplified model to determine size effect in compressive failure. A nonlinear fracture mechanics approach was employed by Kim et al. [13] to investigate the size effects on the compressive strength of cylindrical concrete specimens with and without spiral reinforcement. They also proposed modification for the modified size effect law (MSEL) to include the height to diameter ratio for concrete cylinders.

Effects of specimens' size and shape on the compressive strength of high strength concrete were investigated by Tokyay and Ozdemir [14]. They reported no significant effect for length-to-diameter ratio of cylinder specimens on the compressive strength of high strength concrete.

Specimen size effects on the compressive strength of concrete at the bearing area were studied by Ince and Arici [15]. They reported a good agreement between their experimental results and the specimen size effect law.

A comprehensive study on specimen size effects on compressive strength was carried out by Yi et al. [16]. They studied the characteristics of axial compressive failure of concrete based on the fracture mechanics and suggested equations for prediction of the compressive strengths considering the specimen size, shape, and placement direction.

Yazici and Sezer [17] investigated the relationship between the compressive strength of 150/300 mm and 100/200 mm cylindrical concrete specimens of eight different strength levels, which have water/cement (W/C) ratios ranging between 0.37 and 0.77. No significant difference was reported for specimens having compressive strength between 14 and 50 Mpa. There is also an expression given by Neville [18] for converting the cylindrical strength to cubic strength.

1.1. Research significance

It should be noted that most of the investigations about the size effects of specimens belong to traditional concrete specimens. However, this phenomenon exists in most of the cement-based composites which may have different structural constitutions. One of the most important and applicable cement-based composites is self-consolidating concrete. Self-compacting concrete (SCC) or self-consolidation concrete is a highly-fluid concrete which can be easily placed and consolidated by its own gravity in a formwork, without external consolidation by vibration. SCC has the advantages of fast construction, noise reduction, good formability, and energy effectiveness [19].

Due to the fact that the relative proportions of SCC mixtures are completely different from those of traditional concrete, different structural properties are expected for SCC hardened specimens.

Although, there are many published work on various mechanical properties of self-consolidating concrete, the size effects of SCC specimens has been rarely investigated.

In this study, based on the theoretical aspects of size effect reported in the literature, a comprehensive experimental program is conducted to investigate the size effects of cubic specimens for self-consolidating concrete. Placement and loading directions are considered as another important factor on the mechanical properties. Finally the Least-Square Method (LSM) is employed for the results of the experimental program to obtain the modified size effect law parameters for SCC.

2. Experimental program

2.1. Materials

In order to investigate mechanical properties of self-consolidating concrete, three kinds of mixture designs are used. Mixtures proportioning are provided in Table 1. Natural fine and natural coarse aggregates with maximum size of 12.5 mm (based on ASTM C136 [20]) are used in the mixtures. Bulk specific gravities of coarse and fine aggregates are 2.67 and 2.71 and their water absorptions are 1.3% and 1%, respectively. ASTM Type II general purpose cement, a high-efficiency polycarboxylate ether type super plasticizer (HRWR) and Limestone powder as an inert addition are also used in design of SCC specimens.

A laboratory concrete mixer is used for mixing the concrete mixtures for five minutes. Standard cylindrical ($\varphi 15 \times 30$ cm) SCC specimens as the control specimens and cube SCC specimens with various sizes (5, 7.5, 10, 12.5 and 15 cm) and different placement directions (parallel and normal to loading direction) are cast without any mechanical vibration. After casting, all the molded specimens are stored in the casting room for 24 h and then are demolded and transferred to the moisture curing room, and are maintained at room temperature and 100% relative humidity until testing time. Types of the specimens and their specifications are given in Table 2.

2.2. Test

The methods for evaluating the workability of conventional concrete in the fresh stage are not suitable for SCC due to its high fluidity. The slump flow tests (D-final & T-500) are conducted to assess the flowability and the flow rate of self-compacting concrete in the absence of obstructions based on the slump test described in EN 12350-2. The result is an indication of the filling ability of self-compacting concrete. The T-500 time is also a measure of the speed of flow and hence the viscosity of the self-compacting concrete [21].

The viscosity and filling ability of self-compacting concrete are measured by V-funnel test. In the V-funnel test, the period in which fresh SCC passes through a small space is used to as a measure of the flowability of SCC. A shorter V-funnel time means a higher flowability, while a longer V-funnel time means a lower flowability [19]. The L-box test is used to assess the passing ability of self-compacting concrete to flow through tight openings including spaces between reinforcing bars and other obstructions without segregation or blocking [21].

Among various kinds of proposed tests for SCC, Slump flow diameter and time (D-final & T-500), V-funnel and L-box tests are carried out on fresh concrete mixtures and the results are given in Table 3.

Table 1
Mix proportions and description of self-consolidating concrete mixtures.

Mix	Water (kg/m^3)	Cement (kg/m^3)	W/C (%)	Sand (kg/m^3)	Gravel[a] (kg/m^3)	HRWR[b] (kg/m^3)	Limestone powder (kg/m^3)	Average f'_c (MPa)
M1	140	400	35	858	802	9.2	240	45.6
M2	156	400	39	850	695	8.4	240	33.9
M3	172	400	43	841	688	7.6	240	24.0

[a] Maximum aggregate size of 12.5 mm.
[b] High-range water-reducing admixture (super plasticizer).