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Mechanical performance of self-compacting concrete reinforced with steel fibers

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HIGHLIGHTS

- Workability of SCC decreases considerably by adding steel fibers.
- Compressive strength loss in HS-SCC class was lower than that of MS-SCC class.
- Flexural toughness enhances significantly when steel fibers were utilized.

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ABSTRACT

Self-compacting concrete (SCC) is a highly-workable concrete that without any vibration or impact and under its own weight fills the formwork, and it also passes easily through small spaces between rebars. In this paper, the effect of steel fibers on rheological properties, compressive strength, splitting tensile strength, flexural strength, and flexural toughness of SCC specimens, using four different steel fiber volume fractions (0.5%, 1%, 1.5%, and 2%), were investigated. Two mix designs with strengths of 40 MPa (medium strength) and 60 MPa (high strength) were considered. Rheological properties were determined through slump flow time and diameter, L-box, and V-funnel flow time tests. Mechanical characteristics were obtained through compressive strength and splitting tensile strength tests with standard cylindrical specimens of 150 × 300 mm, and flexural strength and flexural toughness tests were performed by using beams of 100 × 140 × 1200 mm.

The results revealed that the workability of medium and high strength SCC classes is reduced by increasing the steel fiber volume fraction, and using high percentages of fibers led to decrease of other rheological characteristics that have been specified by EFNARC and ACI 237R. On the contrary, splitting tensile strength, flexural strength, and flexural toughness are increased by increasing the percentage of fibers; however compressive strength is decreased by increasing the percentage of fibers.

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1. Introduction

In the recent two decades, Self-Compacting Concrete (SCC) has been identified as one of the important achievements in the concrete industry. Due to its high workability, SCC is compacted under its own weight without any vibration. To obtain the desired workability in SCC, more fine aggregates and superplasticizer admixture are to be used. Besides, in comparison to the conventional concrete, a smaller maximum size of aggregate should be utilized. When the superplasticizer is used, creep and shrinkage cracks increase, and it leads to more segregation. The use of filler and fly ash increases the mortar volume of SCC, which in turn, improves the workability [1–5].

Hardened SCC has similar mechanical properties compared to conventional concrete [6]. Before 1970s, a kind of concrete was used in Europe which needed less vibration; SCC, however, had not been developed until late 1980s. Initial ideas of SCC were generated in Japan, though Sweden was the first European country which built transportation structures with SCC in 1990s [6,7].

Plain concrete is brittle, thus it seems essential to use materials that can fix this problem. Using fibers in the concrete decreases brittle fracture of the concrete significantly, and under various loads, especially the compressive loads, tensile loads, and blast loads, the behavior of fiber-reinforced concrete will be ductile. By bridging between sides of cracks, fibers tend to preserve the integration of concrete until high deformation and therefore prevent brittle failure. Nowadays, fiber-reinforced concrete is utilized in various areas including road pavements, sidewalks, bridges, lining of tunnel segments, and slabs [8].

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There have been conducted a number of studies on the SCC. El-Dieb [9,10] studied mechanical and durability properties of ultra-high strength fiber-reinforced concrete (UHS-FRC) with self-compacting characteristics and the influence of fibers on rheological properties. Siddique [11] investigated the properties of SCC made with different amounts of fly ash. According to Fava et al. [12], in SCC with ground-granulated blast furnace slag (GGBFS), the strength can be increased. Flexural performances of reinforced, pre-stressed and composite self-compacting concrete beams were also studied by Cattaneo et al. [13]. Soutsos et al. [14] also scrutinized the flexural performance of fiber-reinforced concrete made with steel and synthetic fiber.

According to the above mentioned studies, the present research is aimed at investigating the influence of steel fibers on rheological and mechanical properties of SCC with different strength classes. To determine the rheological properties of SCC, slump flow time and diameter, V-funnel flow time, and L-box tests were used. In order to investigate the mechanical properties of the fiber-reinforced SCC, compressive strength, splitting tensile strength, flexural strength, and flexural toughness of SCC beams were obtained.

2. Experimental plan

2.1. Materials

The cement used was commercially available ASTM Type II Portland cement with a specific gravity of 3.12 and a fineness of 295 m^2/kg. In addition, silica fume was used as a reactive pozzolanic material in conjunction with lower W/B ratio to produce high strength SCC class. Table 1 summarizes the chemical composition of cement and silica fume. Silica fume particles size falls in the range of 0.05 to 0.2 μm. Steel fibers used had hooked shape. Fig. 1 illustrates the image of the steel fibers and the physical characteristics of the steel fibers are given in Table 2.

Superplasticizer was used for improving the workability of concrete mixtures is based on high performance poly-carboxylic, with the specific gravity of 1.1. Besides, a polysaccharide based viscosity modifying agent (VMA) was utilized with a specific gravity of 1.01 ± 0.01 VMA is used for retaining the integrity of the SCC composition and it also decreases the bleeding phenomenon.

It has to be noted that aggregates are of different parts, namely the coarse and fine aggregate as well as the filler. Coarse aggregate with a maximum size of 12.5 mm, a specific gravity of 2.65, and water absorption of 1.43% was used. The fine aggregate is natural river sand with a specific gravity of 2.61, absorption of 1.95%, and fineness modulus of 3.11. Both the coarse and fine aggregates met the requirements of ASTM C 33 [15]. Potable water was used for preparation of concrete mixtures.

Fig. 2 provides the gradation curves for the coarse aggregates, fine aggregates, and the filler, as obtained through sieve analysis. The coarse and fine aggregates used in this research were in the form of saturated surface dry (SSD).

2.2. Mixing and testing procedures

In the current study, various fiber volume fractions of 0.5%, 1%, 1.5%, and 2% were used. Also, it should be mentioned that the fiber volume fractions were based on the mortar volume of SCC. In addition, the two strength classes of SCC (40 MPa and 60 MPa) were investigated. The concrete mix designs are given in Table 3. Overall, 10 mix designs were made, two of which were plain and without any fibers while the others had fibers. MS-SCC-FX and HS-SCC-FX are the two kinds of specimens terms used for coding. MS-SCC-FX stands for medium-strength self-compacting concrete and *X* is the steel fiber volume fraction in percent. HS-SCC-FX stands for high-strength self-compacting concrete with the steel fiber volume fraction of *X* percent.

The process of making SCC with fibers is the same as that of fiber-free conventional concrete, with the fibers being added during the mixing process. The SCC mixture was made in 3 steps. First, the powder materials and aggregates were mixed in dry form for 1 min. Then half of the water containing the whole superplasticizer was poured and mixed for 3 min. Following that, a 1 min rest was allowed and finally the rest of the water containing VMA was added to the mixture and mixed for another 2 min.

Table 1
Chemical analysis of cement and silica fume (values are in percent).

Chemical analysis	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	SO_3	$Na_2O + K_2O$
Cement	20.4	3.9	63.0	4.9	1.7	2.0	0.9
Silica fume	93.2	1.5	0.4	0.7	0.3	0.1	1.4

Fig. 1. Steel fibers.

Table 2
Characteristics of used steel fibers.

Length (mm)	Width (mm)	Thickness (mm)	Aspect ratio
20.6	1.8	0.5	20

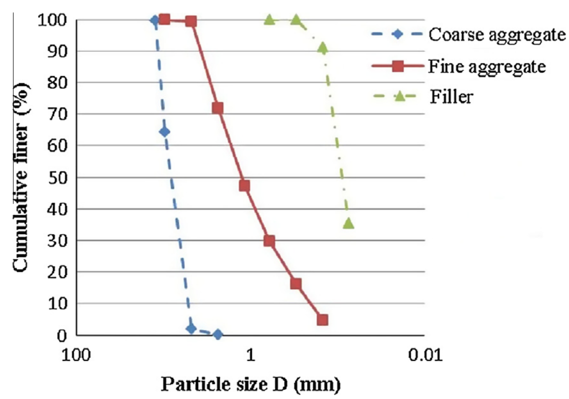

Fig. 2. Gradation curves of filler, fine and coarse aggregates.

After the materials were mixed, fresh concrete tests were performed to determine the rheological properties of the SCC. The flow rate of SCC depends on the viscosity of the concrete. SCC must have four main characteristics. First, it should be able to fill out the form with its weight. Besides, it should be of an acceptable level of resistance against segregation. Yet another important characteristic of SCC is its ability to pass through spaces between rebars, and finally, it needs to have a smooth surface after demoulding. In order to achieve these characteristics, there are some tests in EFNARC and ACI 237R such as slump flow time and diameter, V-funnel flow time, visual stability index, J-ring, and L-box [1,6].

According to Nagataki and Fujiwara's research [16], slump flow time and diameter tests are two common methods to determine the flow characteristics of unobstructed concrete in horizontal surface. In these tests, the fresh concrete is poured into a slump cone. When the cone is withdrawn upwards, the time it takes from the beginning of the upward movement to when the concrete has flowed to a diameter of 500 mm is measured, called the T_{50} time. The largest diameter of the flow spread of the concrete and the diameter of the spread at right angles to it are then measured and the mean is the slump-flow diameter.

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. There are two variations of the test, namely the two-bar test and the three-bar test. The three-bar test, which was also used for the purpose of the present study, simulates more congested reinforcement. Hence, the concrete is poured from the container into the filling hopper of the L-box. Then the gate is raised so that the concrete flows into the horizontal section of the box. When the movement is ceased, the vertical distances are measured, at the end of the horizontal section of the L-box, between the top layer of the concrete and the top of the horizontal section of the box, and at three positions equally spaced across the width of the box. Differing from the height of the horizontal section of the box, these three measurements are used to calculate the mean depth of concrete as H_2. The same procedure is followed to calculate the depth of concrete immediately behind the gate as H_1. The value of H_2/H_1 as blocking ratio is then reported.

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