Fresh and hardened properties of steel fiber reinforced concrete produced with fibers of different lengths and diameters

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ABSTRACT

Concrete is a brittle material which has a low tensile strength and a low tensile strain capacity. These weak points of concrete can be resolved by including fibers made of different materials with high technical specifications. This special type of concrete is known as Steel Fiber Reinforced Concrete (SFRC) and exhibits superior properties in terms of ductility, fracture energy, toughness, strength and durability due to the addition of steel fibers when compared to conventional concrete. SFRC has a varied application area. In practice, steel fibers which have different lengths, diameters, and aspect ratios are used. These variable characteristics of steel fibers have highly influence on the performance of SFRC. The goal of this study is aimed at creating a standard foresight in determining the fiber types by comparing the steel fiber types which have the same tensile strengths and different lengths, diameters, and aspect ratios. For this purpose, the series of SFRC specimens which have the same concrete mixing ratios were produced by using steel fibers which have the same tensile strengths and different lengths, diameters, and aspect ratios. The fresh properties of the produced SFRC specimens were determined by the Slump test. The hardened properties were determined by compressive and flexural strength tests. It was shown that the fresh and hardened properties of the SFRC specimens were changed by steel fibers that had the same shapes, tensile strengths and different lengths, diameters, and aspect ratios. The optimum steel fiber types were determined according to the targeted fresh and hardened properties of SFRC.

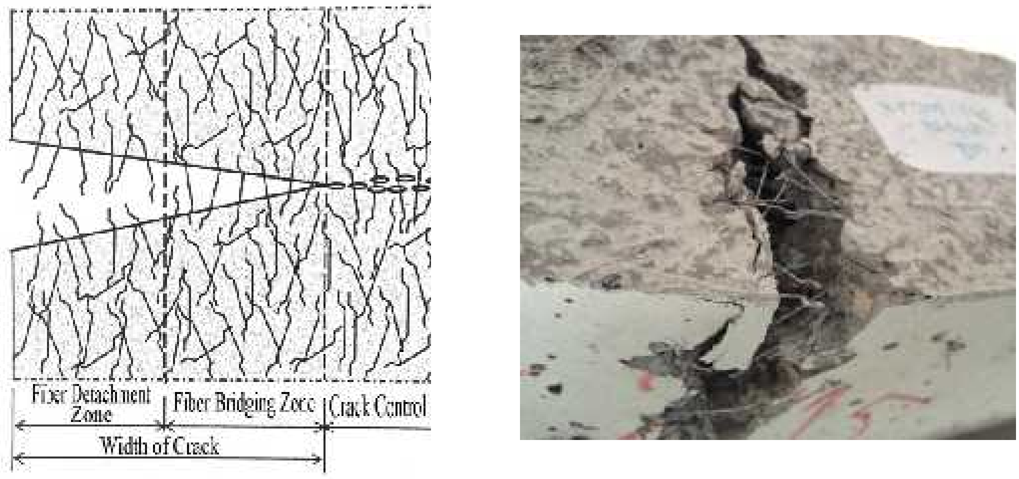
Keywords: *Fiber Reinforced Concrete, Steel Fiber, Fresh Properties, Flexural Strength, Toughness.*

INTRODUCTION

Concrete containing hydraulic cement, water, aggregate, and discontinuous discrete fibers is called Fiber Reinforced Concrete (FRC). Fibers of various shapes and sizes produced from steel, plastic, glass, and natural materials are being used. For most structural and nonstructural purposes, steel fiber is the most commonly used of all the fibers [1].

The use of fibers in building materials is not a new concept. Since ancient times, fibers have been used to reinforce brittle materials. Straw was used to reinforce sun-baked bricks, and horse hair was used to reinforce masonry mortar and plaster. In modern times, a wide range of engineering materials (including ceramics, plastics, cement, and gypsum products) incorporate fibers to enhance composite properties. The enhanced properties include tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance [2].

As a brittle material, concrete contains numerous micro cracks. It is the rapid propagation of microcracks under applied stress that is responsible for the low tensile strength of the material. Originally, it was assumed that tensile as well as flexural strengths of concrete can be substantially increased by introducing closely spaced fibers that would obstruct the propagation of microcracks, therefore delaying the onset of tension cracks, increasing the tensile strength of the material and improve the post-cracking behavior (Figure 1) [1].



(a) (b)

Figure 1 (a) Crack control and bridging effect of steel fibers in FRC, (b) steel fibers in FRC

Generally, in structural applications the use of steel fibers increases the ductility of the concrete, so that the addition of fibers increases fracture energy, tensile strength, flexural strength, ductility, toughness, impact resistance, abrasion resistance of concrete by means of crack bridge. Moreover, because of fibers providing crack resistance and crack control, capillarity of FRC are decreased. So that durability properties are enhanced in structural members.

In practice, various types of steel fibers have been produced. These steel fiber types can have different length, size, shape, and geometry. Thus, many of experimental studies showed that sizes and volumes of steel fibers have different influences on fresh and hardened properties of SFRC. For instance, Nili and Afroughsabet (2010) investigated the effect of silica fume on impact resistance and mechanical properties of SFRC mixes that has different fiber ratios and mix proportions [3]. Baran et al. (2012) performed pull-out tests on SFRC with two different fiber lengths and five different fiber contents. It is observed that steel fibers improved pull-out resistance of strands by controlling the crack size [4]. Olivito and Zuccarello (2010) performed an experimental study to classify mechanical behavior of SFRC with respect to fibers content and mix-design variations. Based on the experimental results, an analytical model, reported by Grimaldi and Luciano (2000) and used for the theoretical determination of direct tensile strength, was applied with the aim of making a comparison with experimental results [5-6]. In addition, Nguyen-Minh et al. (2011) investigated behavior and capacity of SFRC flat slabs under punching shear force. According to experimental results, steel fibers caused a significant increase of the punching shear capacity and considerable improvement of cracking behavior [7]. The study of Eren and Marar (2009) researched effects of crushed limestone powder content in aggregate and steel fibers on concrete and determined relations such as compressive strength/splitting tensile strength/water penetration depth/flexural toughness energy/impact energy/dust replacement level-fiber reinforcement [8]. Atis and Karahan (2009) studied shrinkage and freeze-thaw effect addition to the mechanical properties of SFRC that has different fiber and fly ash content [9]. Sahin and Koksal (2011) observed the effects of both steel fiber and matrix strengths on fracture energy of high strength concrete experimentally [10]. Bayramov et al. (2004) optimized the fracture parameters of SFRC with three type of steel fibers and different fiber content by means of a statistical method [11]. Considering the fact that the addition of steel fiber decreases the workability of concrete, Uygunglu (2011) investigated the fresh properties of a series of SFRC with two type fiber aspect ratios and five different fibers content by means of different mixing times. According to the results, it is reported that as the fiber content increases, the workability of SFRC mixtures decreases [12]. Yalcin (2009) proposed performance classes for SFRC according to both Serviceability Limit State (SLS) and Ultimate Limit State (ULS). For this purpose, for same water/cement ratio different type and content of steel fibers used. It is reported that as fiber volume fraction increases, flexural strength increases for both SLS and ULS significantly for a certain fiber aspect ratio [13].

In this study, SFRC mixtures that has the same mixture proportions were produced, then fresh and hardened state properties were investigated experimentally. All the SFRC mixtures contained four different fiber types and four different fiber volume fractions varied from 0 to 1.5%. The purpose of study is comparing the fiber types and observing how to change engineering properties of SFRC.

EXPERIMENTAL STUDY

Experimental study proceeds in two stages. Firstly, for the purpose of determining the fresh properties, slump tests were performed for each SFRC mixtures. Secondly, hardened properties were determined. The compressive strength test and four point bending test were performed at 28 days. Eventually, toughness and first crack load of specimens were obtained as well as compressive and flexural strengths.

Materials

For all SFRC mixtures, CEM IV B(P) 32.5 R cement was used (Table 1). In addition, crushed limestone aggregate was used with maximum size of 16 mm. The relative density of fine aggregate is 2,52 gr/cm^3 and water absorption rate is 2,10%. The relative density of coarse aggregate is 2,56 gr/cm^3 and water absorption rate is 1,50%. Figure 2 shows gradation of 50% fine+50% coarse limestone aggregate and A16 and B16, reference gradation curves of TS 802 [14].

Table 1 Properties of Cement

Property	CEM IV B(P) 32,5 R
SO3 (%)	2,8
MgO (%)	1,8
Cl (%)	0,01
Initial setting time (min)	180
Final setting time (min)	280
Total volume exp. (mm)	0,2
Specific surface (cm^2/g)	3771
Specific gravity (g/cm^3)	2,85
Compressive strength 2 days (MPa)	19,3
Compressive strength 7 days (MPa)	30,3
Compressive strength 28 days (MPa)	39,9

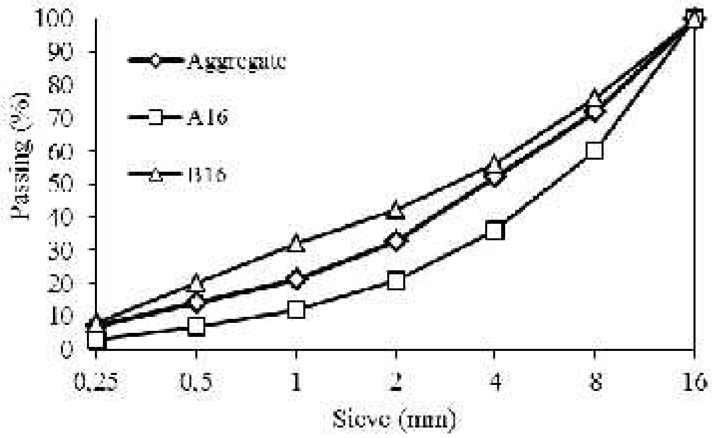


Figure 2 Gradation of limestone aggregate

Steel fibers, included in concrete, were used in four different types. Table 2 gives the properties of steel fibers. All fibers were hooked end and the volume fractions (V_f) of steel fibers were 0% (reference), 0.5%, 1% and 1.5%. As can be seen from Table 2, each fiber type has a code made of two digits. First digit gives aspect ratio of steel fiber which is fiber length divided by fiber diameter and second digit gives length of steel fiber.

Table 2 Properties of Hooked-end Steel Fibers

	Steel Fiber Type	Length (mm)	Diameter (mm)	Density (gr/cm^3)	Tensile Strength (N/mm^2)
Long fibers	80/60	60	0,75	7,85	1225
	65/60	60	0,90	7,85	1160
Short fibers	55/30	30	0,55	7,85	1345
	40/30	30	0,75	7,85	1225

Mixture Proportions and Fresh Properties

Assuming saturated-dry surface conditions for the aggregate, mix proportions of reference mixture is given in Table 3. Experimental studies were conducted on SFRC mixtures that had constant mix proportion and by changing the steel fiber types and volume fractions (V_f=0.5%, 1%, 1.5%), 12 different SFRC mixtures were produced. Besides for comparison, one mixture, named Reference, was produced with 0% steel fibers.

Table 3 Mix Proportions of Reference Mixture

Cement (kg/m^3)	Water/Cement (kg/m^3)	Aggregate (kg/m^3)	V_f (%)
320	0,65	1739	0

For the purpose of observing change of the fresh properties with steel fibers, Slump test were performed. Figure 3 shows the results of slump test.

As shown in Figure 3, Reference mixture has 15 cm slump value. Then, the more fiber was included in concrete, the less slump value of fresh mixtures got.

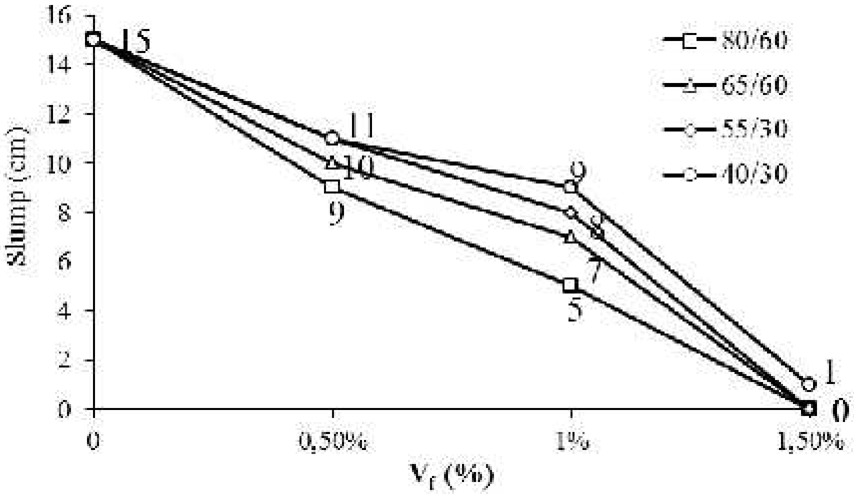


Figure 3 Slump test results

Especially, long fibers (80/60 and 65/60) caused to decrease in slump values more than the other fiber types. The reason is that SFRC tends to hang together and compared to short ones, long fibers supports this behavior more. According to results of slump test, compactability was linearly related with the aspect ratio and volume fractures of the fibers. As the aspect ratio and fiber volume fraction increased, the slump values of mixtures decreased. Because as volume fraction increased, stiff steel fibers pushed the aggregates apart, insomuch that most mixtures which had 1.5% volume fraction of fibers reached 0 slump values. So, it can be said that steel fibers affects the workability and sudden decrease of workability occurs for a certain volume fraction.

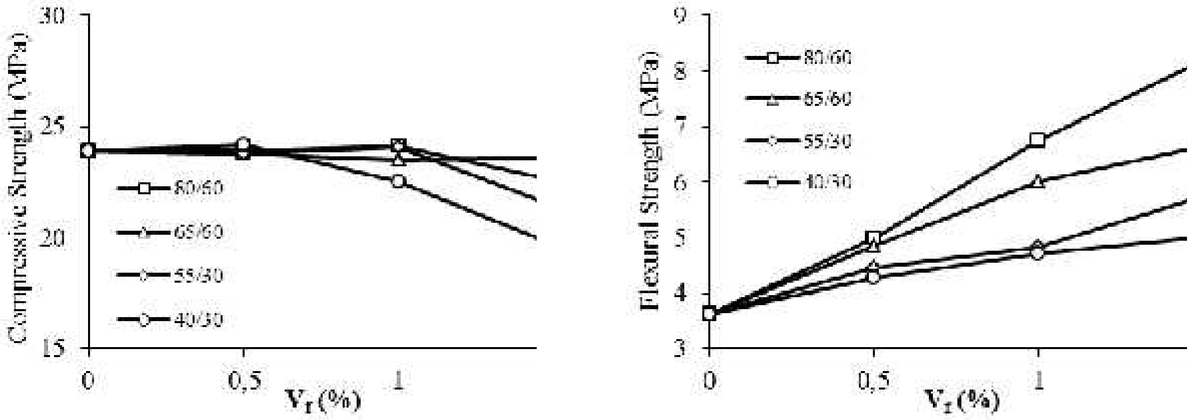
Figure 4 shows one of cube specimens that contained 80/60 type of steel fibers with 1.5% fiber volume fraction. It had a consolidation problem.

Figure 4 A cube specimen produced with 80/60 fiber type and 1.5% fiber volume fractions contains spaces

Mechanical Properties

In this study, 150x150x150 mm cube specimens and 100x100x500 mm beam specimens were produced for each SFRC mixtures. Then, at 28 days, compressive and four point bending tests were performed. While testing flexural strength of specimens, as recommended by ASTM C1080-97 [15], load and deflection values were obtained as well. So that, it was possible to be calculated the toughness parameters of specimens and be determined the first cracking load.

In general, it is known that steel fibers have not a significant effect on compressive strength compared to flexural strength.



(a) (b)

Figure 5 28 days compressive strength (a) and flexural strength (b) values of SFRC

As shown in Figure 5(a), compressive strength did not show a major change by steel fibers. Only, 1.5% volume fractions of fibers slightly reduced the compressive strength, because of spaces that specimens contained. Since workability of SFRC included 1.5% fiber volume fraction was low, the specimens had bigger volume of space.

When it comes to the flexural strength (Figure 5(b)), as fiber volume fraction increased, flexural strength of SFRC specimens were improved. All specimens contained steel fiber had larger flexural strength value than reference specimen. Especially, increasing the aspect ratio of steel fiber improved the flexural strength behavior. Thus, it can be said that long fibers are more effective than short fibers on flexural strength.

(a) (b)

Figure 6 At the end of bending tests, deflection of SFRC specimens with long (a) fibers and short (b) fibers

Besides, each beam specimens were loaded until failure detection value reached 85%. At the end of the tests, deflections of SFRC specimens with long fibers (deflection=40,25 mm) were larger than SFRC specimens with short fibers (deflection=13,48 mm) (Figure 6).

Load-Deflection Curves

Four point bending test was performed as recommended by ASTM C1080-97 [15]. The load-deflection curves of specimens were obtained. Thus, toughness and first cracking load values of SFRC specimens were calculated, owing to the load-deflection curves.

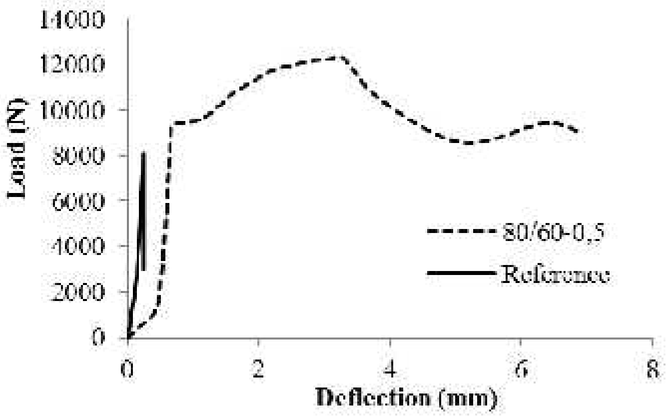


Figure 7 A typical Load-deflection curve belonged to Reference specimen and the specimen having 80/60 type 0.5% fiber volume fraction

Figure 7 shows load-deflection curve of a SFRC specimen and Reference specimen. Thanks to the ability of crack bridge, SFRC could continue to carry load after cracking.

First Cracking Load

First cracking load is defined as the first point, linearity of the load-deflection curve is lost. Identifying the point which the curvature first increases sharply and the slope of the curve exhibits a definite change [15]. Until the first cracking load, effect of steel fibers on behavior is limited. After onset of cracking of concrete matrix, steel fibers bridge the crack and limit the crack opening. Thus, first cracking load depends on concrete matrix performance.

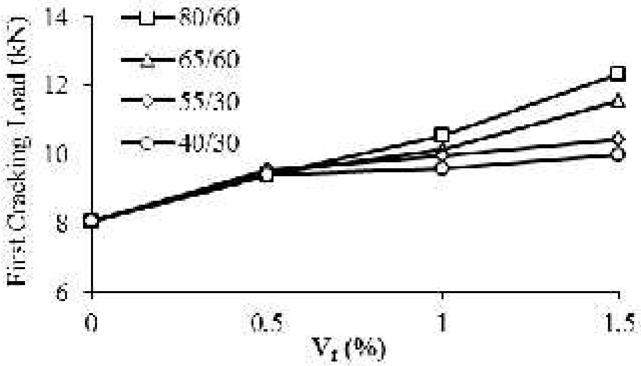


Figure 8 First cracking loads of SFRC

Figure 8 shows the first cracking loads of the SFRC specimens. According to graphic, as fiber volume fraction increased, first cracking load increased. Especially, 80/60 steel fiber type had the biggest first cracking load. As can be seen from the graphic, it is said that aspect ratio of the fiber has a positive effect on fist cracking load as flexural strength. Nevertheless, this effect was limited, because strength of concrete matrix was low.

Toughness of SFRC

Toughness is described as energy absorption capacity of SFRC which is very important for the behavior after onset of cracking. Toughness of SFRC is the area which is under the load-deflection curve.

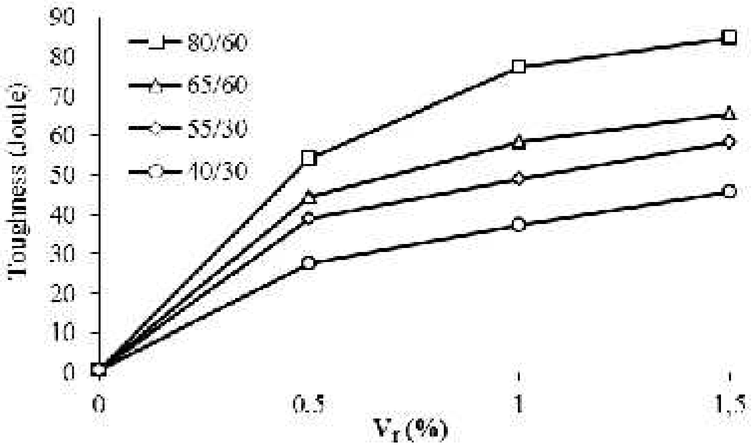


Figure 9 Change in toughness values of SFRC

As shown in Figure 9, fiber volume fraction and aspect ratio of fibers increased, toughness of specimens significantly increased as well. Toughness of Reference was 0,59 Joule. Even 0.5% fiber volume fraction had more toughness value than Reference and the largest toughness value belonged to 80/60 type fiber. Although 80/60 and 65/60 had the same fiber length, the fiber with larger aspect ratio improved toughness more. Here, it can be said that long fibers is more effective on the toughness than short fibers and aspect ratio is very important to enhance the toughness of SFRC.

CONCLUSIONS

In this study, it was investigated the effect of steel fibers on engineering properties of 12 type of SFRC with different fiber type and fiber volume fraction. Four types of steel fibers, had different length and aspect ratio, were used with three different fiber volume fraction. Steel fibers are known for improving flexural strength, first cracking load and strength, toughness, and the ability of plastic deformation of concrete. In this study, these features of steel fibers were proved and different types of hooked-end steel fibers were compared successfully.

As a result of this experimental study, it has been observed that fiber aspect ratio and fiber length have been very effective on engineering properties of SFRC. Firstly, addition of steel fiber has reduced the workability of SFRC, moreover long fibers have reduced the workability more than short fibers. When it comes to mechanical properties, although steel fibers have not improved the compressive strength, steel fibers have had a significant effect of enhancing flexural strength, first cracking load and toughness of SFRC. Besides, long length fibers and fibers with larger aspect ratio have improved these mechanical properties more than the short ones. Thus, it is recommended that if mechanical properties of structure are important, steel fibers with long length and large aspect ratio should be chosen.

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