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Compressive and tensile behaviors of steel fiber reinforced concrete

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ABSTRACT

Steel fiber reinforced concrete (SFRC) is a concrete mixture containing discontinuous, discrete steel fibers that are randomly dispersed and uniformly distributed. The quality and quantity of steel fibers influence the mechanical properties of concrete. It is in general accepted that the addition of steel fibers significantly increases tensile toughness and ductility, also slightly enhances the compressive strength. The benefits of using steel fibers become apparent after concrete cracking because the tensile stress is then redistributed to fibers. The objective of this study is to investigate the compressive and tensile behavior of steel fibers in reinforced concrete by conducting an experimental program consisting of load testing on various specimens made from conventional concrete (CC) and steel fiber reinforced concrete (SFRC). Test series consisted of cylindrical compression (100×200 and 150×300 mm) and prismatic modulus of rupture (150×150×600 mm) specimens. Tensile tests on reinforcing bars surrounded by prismatic concrete specimens were also performed. The variables used in these tests were lengths (500, 1000, and 1500 mm) and cross-sectional dimensions (60×60, 100×100,150×150, 200×200 mm) of the prismatic concrete specimens around the reinforcing bar.

Keywords— *Steel Fiber Reinforced Concrete (SFRC), Compressive and tensile behavior*

1. INTRODUCTION

During the last four decades, fiber reinforced concrete has been increasingly used in civil engineering structures, often in combination with reinforced concrete, and many types of research have been undertaken to more fully understand its mechanical properties (Fanella and Naaman (1985) [1]. Steel fiber reinforced concrete (SFRC) is a concrete mixture containing discontinuous, discrete steel fibers that are randomly dispersed and uniformly distributed. The quality and quantity of steel fibers influence the mechanical properties of concrete. It is in general accepted that the addition of steel fibers significantly increases tensile toughness and ductility, also slightly enhances the compressive strength. The benefits of using steel fibers become apparent after concrete cracking because the tensile stress is then redistributed to fibers. Researches in the early of 1960's by Ramouldi and Baston (1963) and Ramouldi and Mandel (1964) on closely spaced random fibers, mainly steel fibers, started the era of using the fiber composite concretes that we have today[2].

Steel and synthetic fibers have been used to enhance the properties of concrete in practice for many years. However, commercial use of fibers in concrete begun in 1970's particularly in Europe, Japan, and the USA. In addition, Shah and Rangan (1971), Swamy (1975), and several other researchers in the United States, Japan, United Kingdom, and Russia performed extensive researches on the use of other types of fibers in addition to steel [3]. Other developments using bundled fiberglass as the main reinforcement in concrete members were introduced by Navy et al. (1971) and Navy and Neuwerth (1977) Nowadays, a wide range of engineering materials including ceramics, plastics, cement, and gypsum, are being used to improve composite properties of concrete [4], [5].

1.1 Motivation

It is widely known that concrete is brittle in tension and strong in compression. In the construction sector, this deficiency can be overcome by providing steel bars to carry the tensile forces to improve tension reinforcement in concrete. The reinforcement can also be in form of pre-stressed so that the concrete will be entirely in compression under load. The purpose of such reinforcements is to ensure that the capacity of the plain concrete does not go above the load capacity of the concrete sections (Cement and Concrete Association of New Zealand (2009). [6]. When steel fibers are used, the behavior of concrete changes. This change affects not only its strength but also its behavior under tension and compression. These changes affect the overall performance of the members made of SFRC. The flexural behavior of SFRC structural members can be estimated if behaviors under tension and compression of SFRC are known, shown in figure 1.

Fig. 1: Typical shape for hooked end steel fiber
(www.imerstore.it/product/4424/Kerabuild-HW-Steel-Fiber-Dramix-RC-80-30-BP-Conf.-da-20-kg.html)

1.2 Properties of Steel Fibers

The steel fibers have a length, if, usually ranging from 6 to 70 mm and an equivalent diameter, df, ranging from 0.15 to 1.20 mm. Steel fibers are short, have discrete lengths having an aspect ratio (ratio of length to diameter) about 20 to 100. They are manufactured in several different cross sections and are sufficiently small to be randomly dispersed in an unhardened concrete mixture using the usual concrete mixing procedure. Steel fibers are produced by various processes, in various shapes, and geometries. Most of the steel fibers, however, are round in cross-section with an equivalent diameter ranging between 0.15 and 2 mm and lengths ranging between 7 and 75 mm. The fibers used in the early times were round and smooth and obtained by cutting or chopping wires to the required lengths. Nowadays, steel fibers have either rough surfaces, can be crimped, hooked at their ends, or deformed along their length.

1.2.1 Fiber Content: In terms of fiber proportion within a concrete mixture, most literature refers to the percentage of fibers by volume expressed by the symbol Vf. The use of 78 kg/m3 of fibers results in 1% of fibers per volume of concrete. Typical fiber contents range from 0.25 to 1.5%, with non-structural applications typically requiring fiber contents of 0.5% or less, while quantities greater than 0.5% are typically required for most structural applications (Aoude, 2007). It should be noted that increasing fiber content beyond certain limits in traditional concrete (typically above 1%) can cause problems during mixing and placement.

1.2.2 Fiber Length: According to the National Research Council (CNR-204/2006), the length of steel fibers, lf, usually ranges from 6 to 70 mm. In the ACI 544.4R, steel fibers have lengths ranging between 25 and 60 mm. The definitions for length and the diameter of the fiber are shown in figure 2.

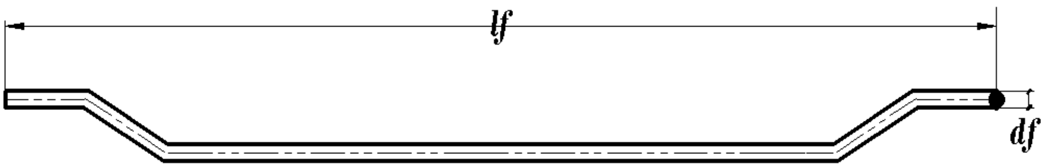

Fig. 1: Typical length and diameter for hooked end steel fiber

1.2.3 Fiber Equivalent Diameter: For fibers that are not circular in cross-section, the equivalent diameter is the diameter of a circle having the same area as that of the average cross-sectional area of the fiber.

1.2.4 Fiber Aspect Ratio: The fiber aspect ratio is the major characteristics of the slenderness of an individual fiber. It is defined as fiber (of) length divided by the equivalent fiber diameter (df) for a particular type of fiber. The aspect ratio is also a measure of fiber stiffness and bond characteristics. The fiber aspect ratio may be calculated as follows:

$$\text{Fiber aspect ratio} = \mathrm{l_f} / \mathrm{d_f} \tag{1}$$

1.2.5 Fiber Reinforcement Index (RI): Fiber reinforcement index is defined as the weight (Wf) or volume fraction of fiber multiplied by the fiber aspect ratio as shown:

$$RI = W_f \, \mathrm{x} l_f / d_f \tag{2}$$

2. EXPERIMENTAL PROGRAM

In this chapter, the test program performed at Structural Mechanics Laboratory at Civil Engineering Department at Atilim University is described. The concrete mixture proportions of test specimens, mixing and casting sequences, the test set-up, and test procedure are discussed in detail. Photos have taken during preparation, casting, and testing of specimens are also are included.

2.1 Test Specimens

Total of four batches (two SFRC and two conventional concrete) were cast to evaluate the effectiveness of SFRC compared to conventional concrete (CC). Three cylinders having 100×200 mm and three cylinders having 150×300 mm dimensions, three prismatic flexural (modulus of rupture) beams having 150×150×600 mm dimensions, and a number of square prismatic tension specimens having various cross-sections and lengths with single 12 mm diameter reinforcing bar at the center of the cross-section were cast per each batch. Five prismatic SFRC tension specimens having 100×100×500, 100×100×1000, 100×100×1500, 150×150×1000, and 200×200×1000 mm dimensions were cast in the first batch. For the second batch six prismatic CC tension specimens having 100×100×500, 100×100×1000, 100×100×1500, 150×150×1000, 200×200×1000, and 60×60×1000 mm dimensions were prepared. Six prismatic CC tension specimens having three 60×60×500 mm and three 100×100×500 mm were cast for the third batch. For the last batch, six prismatic SFRC specimens having three 60×60×500 mm and three 100×100×500 mm were prepared. The main parameters in the testing program were the type of concrete (CC or SFRC), specimen size for compression cylinders, cross-section size and length for the square prismatic tension specimens with reinforcing bar. Details of the prismatic tension specimens with single 12 mm diameter reinforcing bar are shown in Table 1. General views of the tension specimens are shown in figure 3and figure 4.

Table 1: Details of prismatic tension specimens with single 12 mm diameter reinforcing bar

Batch Number	Specimen Designation	Concrete Type	Cross Section (mm)	Length (mm)
First Batch	SFRC 100×100×500-01	SFRC	100×100	500
	SFRC 100×100×1000-01	SFRC	100×100	1000
	SFRC 100×100×1500-01	SFRC	100×100	1500
	SFRC 150×150×1000-01	SFRC	150×150	1000
	SFRC 200×200×1000-01	SFRC	200×200	1000
Second Batch	CC 100×100×500-01	CC	100×100	500
	CC 100×100×1000-01	CC	100×100	1000
	CC 100×100×1500-01	CC	100×100	1500
	CC 150×150×1000-01	CC	150×150	1000
	CC 200×200×1000-01	CC	200×200	1000
	CC 60×60×1000-01	CC	60×60	1000
Third Batch	CC 100×100×500-02	CC	100×100	500
	CC 100×100×500-03	CC	100×100	500
	CC 100×100×500-04	CC	100×100	500
	CC 60×60×500-01	CC	60×60	500
	CC 60×60×500-02	CC	60×60	500
	CC 60×60×500-03	CC	60×60	500
Fourth Batch	SFRC 100×100×500-02	SFRC	100×100	500
	SFRC 100×100×500-03	SFRC	100×100	500
	SFRC 100×100×500-04	SFRC	100×100	500
	SFRC 60×60×500-01	SFRC	60×60	500
	SFRC 60×60×500-02	SFRC	60×60	500
	SFRC 60×60×500-03	SFRC	60×60	500

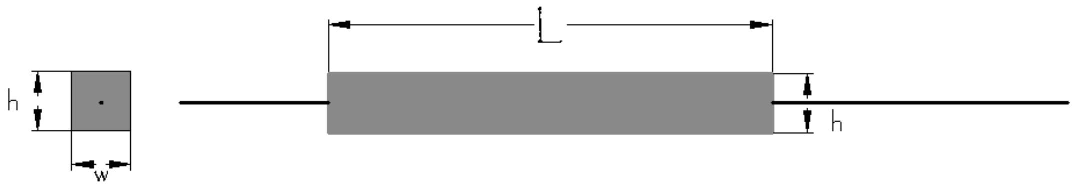

Fig. 3: Schematic view of prismatic tension specimens with reinforcing bar

Fig. 4: General view of prismatic tension specimens with reinforcing bar

2.2 Materials

2.2.1 Steel Fibers: Dramix ZP 305 type steel fibers were used in the concrete mix for the SFRC specimens. The manufacturer specified mechanical properties of the steel fibers are shown in table 2. A photograph of the fibers is shown in figure 5.

Table 2: Properties of steel fibers

Effective Length (mm)	Equivalent Diameter (mm)	Aspect Ratio	Young's Modulus (MPa)	Tensile Strength (MPa)	Density (kg/m3)
30	0.55	55	210000	1345	7850

Fig. 5: Dramix ZP 305 steel fiber used in the research

2.2.2 Reinforcement: Deformed reinforcing steel bars having 12 mm diameter and nominal yield strength of 420 MPa were used for the prismatic tension specimen with reinforcing bar. The stress-strain relationships of the reinforcement bars for various lengths obtained from tension tests in the laboratory is shown in figure 6.

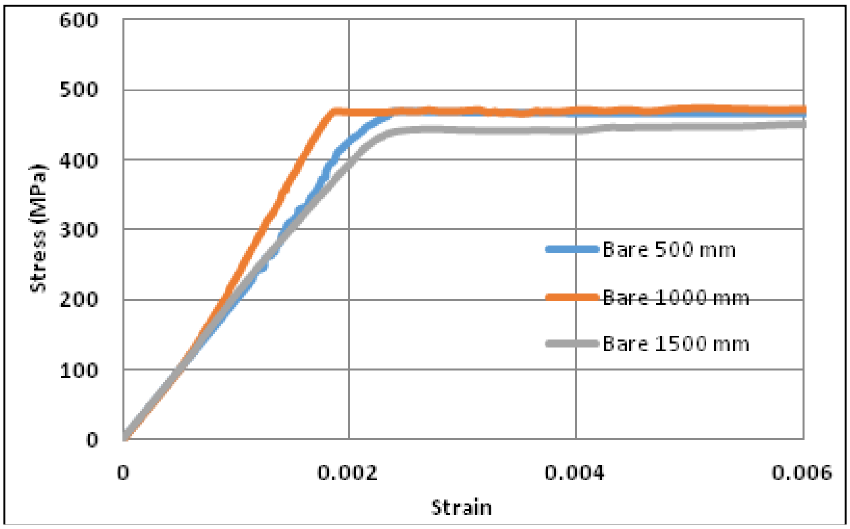

Fig. 6: Measured stress-strain relationships of 12 reinforcing bars

2.3 Specimen Preparation

1- Steel bar with 12 mm diameter
2- Chuck
3- Grip
4- Specimen
5- Steel girder
6- Hydraulic jack
7- Load cell with 10 ton capacity

Fig. 7: Schematic view of the test set-up for prismatic tension specimens with bar

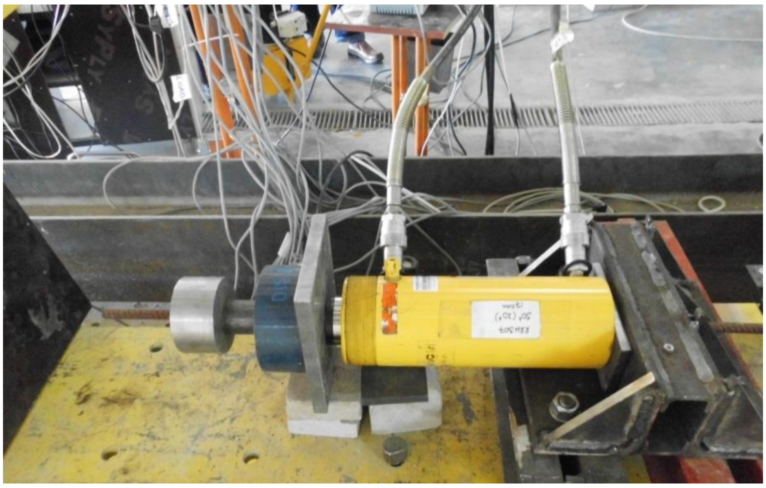

Fig. 8: Test set-up for prismatic tension specimens with bar- end 1 (hydraulic jack, load cell, and chuck)

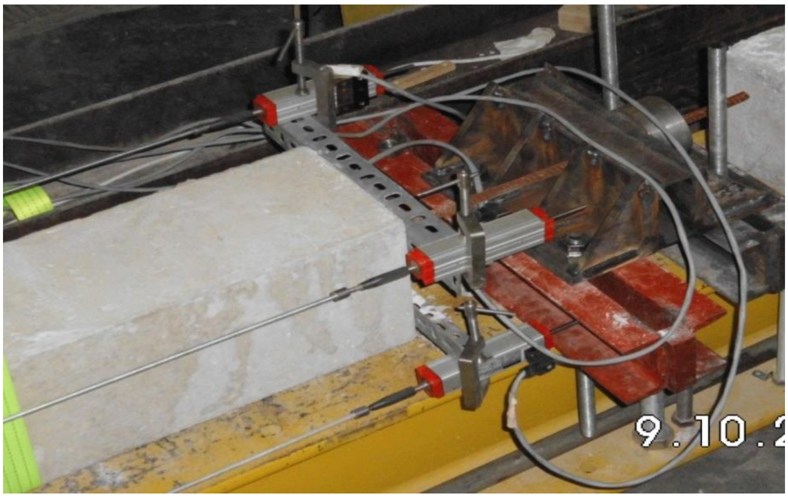

Fig. 9: Test set-up for prismatic tension specimens with bar - end 2 (displacement transducers)

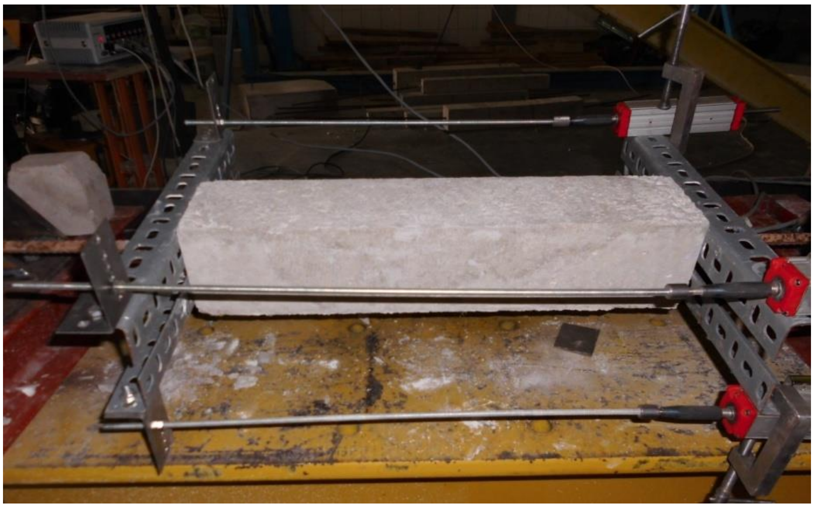

Fig. 10: Test set-up for prismatic tension specimens with bar

During testing, the longitudinal displacements of specimens throughout the length (from one end to the other) were measured and recorded continuously using four 50 mm displacement transducers. Two of these displacement transducers were attached at the top surface of the specimen whereas the other two were attached at the bottom face of the beam as shown in figure 9 and figure 10. The readings of the load cell and the displacement transducers were recorded continuously throughout the test using a data acquisition system.

This test set-up was used in a horizontal position for the tests of the first two batches. In the analysis of the test data, it was observed that the bending of the specimen due to its own weight affected the readings obtained from the displacement transducers. Although this effect can be eliminated based on some calculations in the analysis stage of the test data, the research group agreed on changing the position of the test setup from horizontal to vertical. The last two batches were tested in horizontal test set-up as shown in figure 11.

Fig. 11: Test set-up for prismatic tension specimens with bar (vertical direction)

3. TEST RESULT AND DISCUSSIONS

In this chapter, test results obtained from 100×200 and 150×300 mm cylinders under compression, 150×150×600 mm prismatic beams under flexure, and square prismatic tension specimens having various cross-sections and lengths with single 12 mm diameter reinforcing bar at the center of the cross-section are presented in tabular and graphical forms. Comments were made based on visual observations during the test periods and comparisons were performed based on the collected test data throughout the tests. Although all specimens were prepared using the same two mixture designs (CC and SFRC), the test results obtained from the same mixture but different time casts were slightly different.

3.1 Compression Test Results

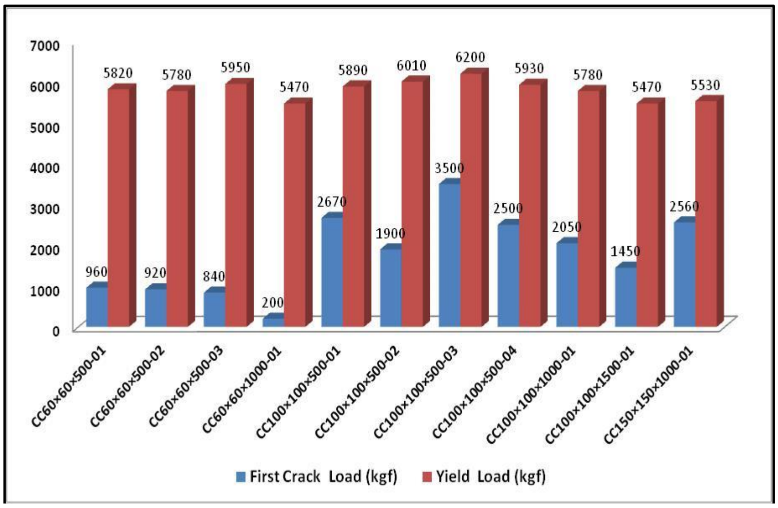

Fig. 12: Graphical presentation of initial crack and yield load of CC specimen

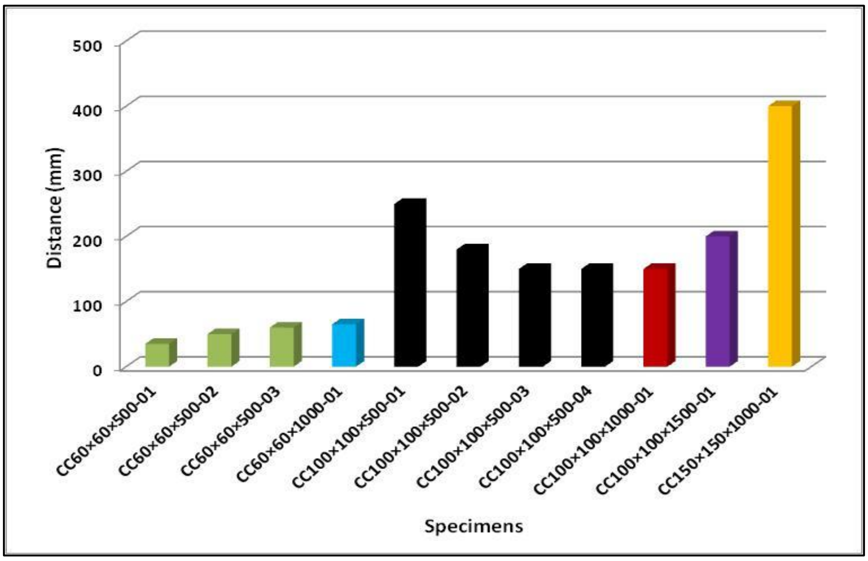

Fig. 13: Graphical presentation of the crack spacing of CC specimens

The initial crack load, yield load, and crack spacing of the SFRC specimens are tabulated in table 3. The graphical presentations of this table are shown in figure 14 and figure 15. The average initial crack and yield load were 967 and 6017 kgf for 60×60 specimens, 2417 and 6199 kgf for 100×100 specimens, and 5210 and 6090 kgf for 150×150 specimen. The results show that as the cross-section of the specimens increase, the initial crack load increases. However, the cross-sectional dimensions do not have any significant effects on the yield load of SFRC specimens. Also, the change in the length of the specimens does not have any significant effects on the initial crack and yield loads of the SFRC specimens. The average crack spacing were 200 mm for 60×60 specimens, 229 mm for 100×100 specimens, and 400 mm for 150×150 specimen. The results show that as the cross-section of the specimen's increase, the crack spacing increases. The change in the length of the specimens also does not have any significant effect on the crack spacing of the SFRC specimens.

Table 3: Comparison of SFRC tension specimens

Specimen	First Crack Load (kgf)	Yield Load (kgf)	Crack Spacing (mm)
SFRC60×60×500-01	1000	6000	250
SFRC60×60×500-02	900	6050	230
SFRC60×60×500-03	1000	6000	120
SFRC100×100×500-01	3500	6580	255
SFRC100×100×500-02	2350	6000	250
SFRC100×100×500-03	2500	5960	250
SFRC100×100×500-04	2100	6200	250
SFRC100×100×1500-01	1633	6254	140
SFRC150×150×1000-01	5210	6090	400

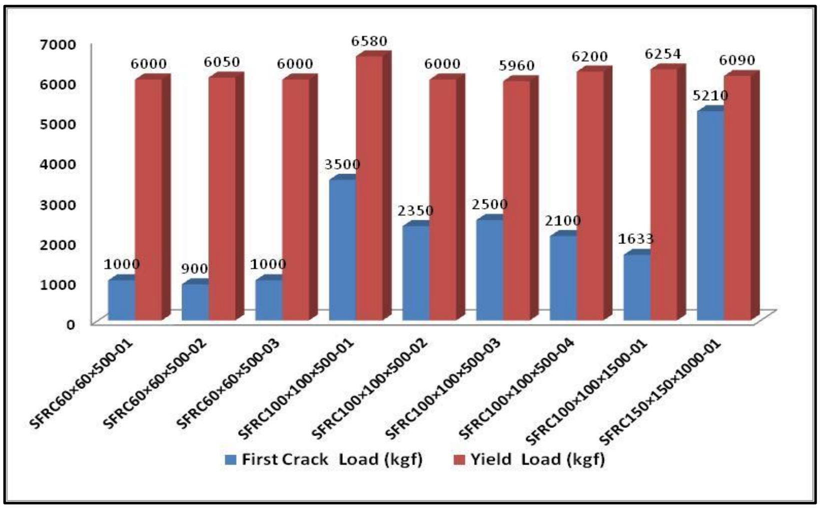

Fig. 14: Graphical presentation of initial crack and yield load of SFRC specimens

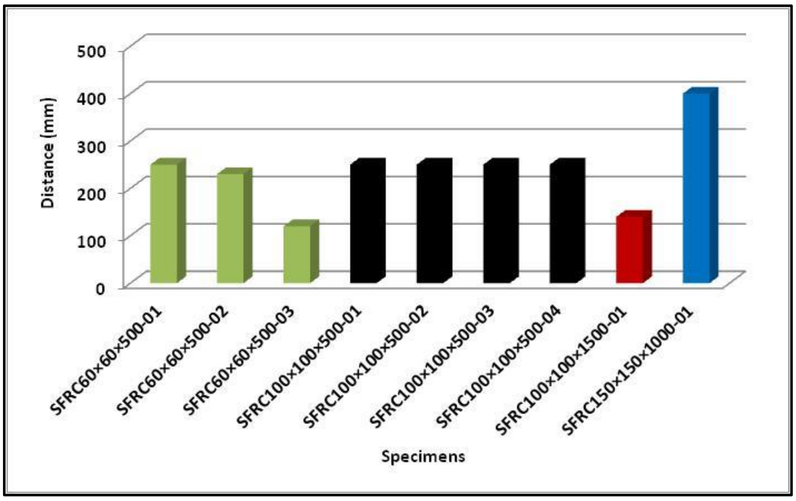

Fig. 15: Graphical presentation of the crack spacing of SFRC specimens

The CC and SFRC specimens having 60×60 mm cross-sections were compared in Fig and Fig7. The average initial crack loads were 730 and 967 kgf and the average yield load loads were 5755 and 6017 kgf for CC and SFRC specimens, respectively. It can be concluded that SFRC specimens having 60×60 mm cross-sections had greater initial crack and yield loads than that of CC specimens. The average crack spacing were 52.5 and 200 mm for CC and SFRC specimens, respectively. The results indicate that the spacing of cracks for SFRC specimens is greater than that of CC specimens having 60×60 mm cross-sections.

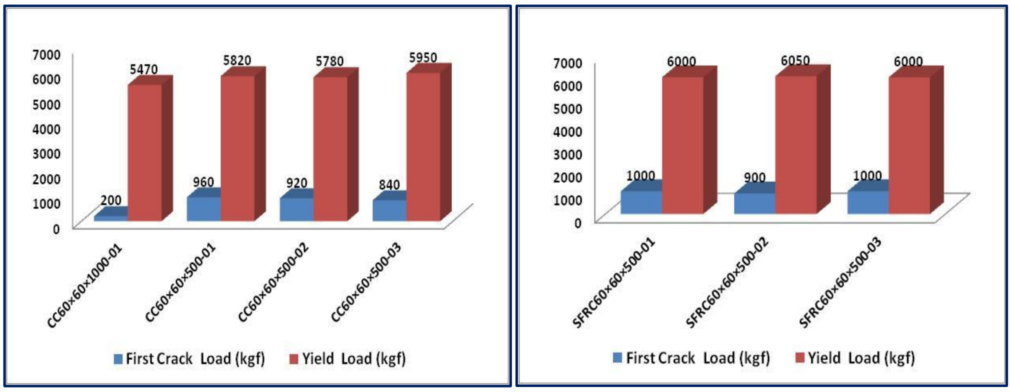

Fig. 16: Comparison of initial crack and yield load of CC and SFRC specimens having 60×60 mm cross-section

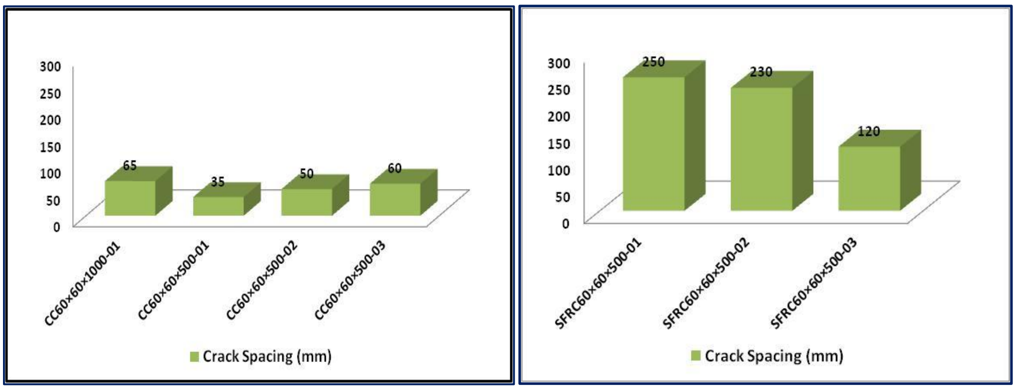

Fig. 17: Comparison of the crack spacing of CC and SFRC specimens having 60×60 mm cross-section

The CC and SFRC specimens having 100×100 mm cross-sections were compared in Fig18 and Fig19. The average initial crack loads were 2345 and 2417 kgf and the average yield load loads were 5880 and 6199 kgf for CC and SFRC specimens, respectively. It can be concluded that SFRC specimens having 100×100 mm cross-sections had greater initial crack and yield loads than that of CC specimens. The average crack spacing were 180 and 229 mm for CC and SFRC specimens, respectively. The results indicate that the spacing of cracks for SFRC specimens is greater than that of CC specimens having 100×100 mm cross-sections.

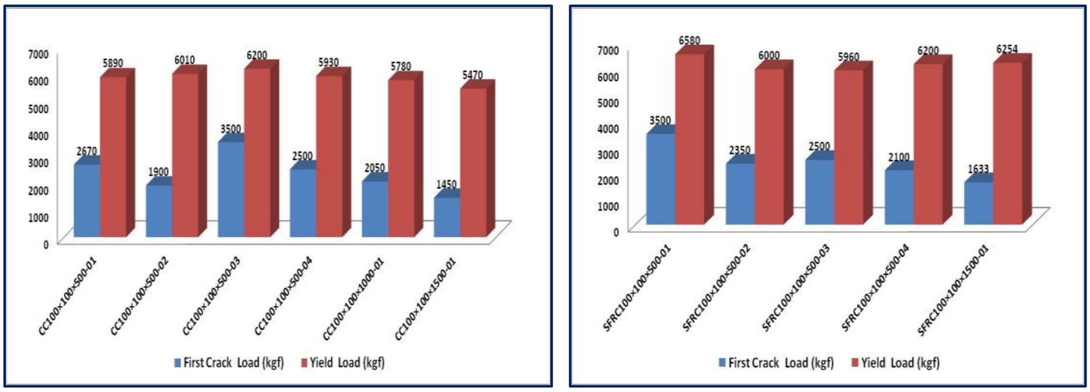

Fig. 18: Comparison of initial crack and yield load of CC and SFRC specimens having 100×100 mm cross-section

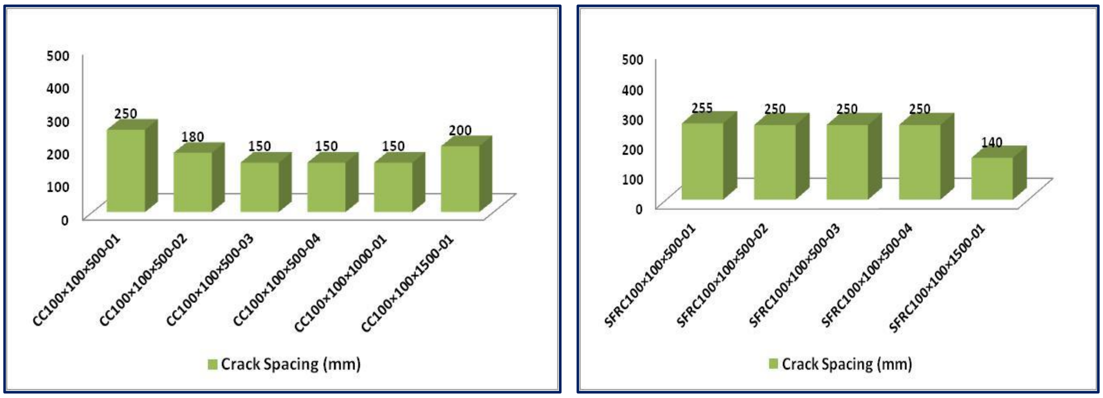

Fig. 19: Comparison of the crack spacing of CC and SFRC specimens having 100×100 mm cross-section

4. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

4.1 Summary

Compressive and tensile behaviors of steel fiber reinforced concrete have been investigated in this research. Test series consisted of 20 singly reinforced specimens. The main parameters in the testing program were the type of concrete, cross-section, and length. Two sizes of cylinders were tested, four batches of concrete were cast, two batches using CC and another two using SFRC. Behaviors of tested specimens were obtained and evaluated in terms of ultimate load, initial stiffness, and post-peak slope. Experimental load-deflection relationships obtained in this research were compared to the load-deflection curves obtained using the written Excel program. The stress-strain relationships available in the literature for SFRC in tension and compression were utilized in the numerical analyses. The proposed stress-strain relationships in the literature were compared and evaluated based on how accurately they predict the test data obtained in this research.

4.2 Conclusions

Compressive and tensile behaviors of steel fiber concrete have been obtained in this research. The observation and conclusions are as follows:

- The increase in the ultimate load capacity of the compression specimens with the addition of steel fibers was not significant compared to that of CC, however; the compressive strength of SFRC specimens was always greater than that of CC specimens.
- When the stress-strain relationships of CC and SFRC specimens are compared, although there was no significant difference in the ascending branches, the descending branches of SFRC specimens showed a more ductile behavior.
- Based on the comparisons of these stress-strain relationships of CC and SFRC specimens, no significant difference was observed between 100×200 and 150×300 mm cylinders.
- It was noted that the initial stiffness of SFRC increased when the cross-section increased, this was valid also for CC specimens.
- After cracking, the load carrying capacity dropped dramatically to zero for CC beams under flexure, however, the load carrying capacity of the SFRC beams increased to a maximum value after cracking then dropped gradually.
- Tensile SFRC specimens had a greater initial crack load, yield load, and crack spacing than those of tensile CC specimens for all types of cross-sections.
- For tension specimens, as the cross-section of CC and SFRC specimens increased, the initial crack load increased. However, the cross-sectional dimensions did not have any significant effects on the yield load of CC and SFRC specimens.
- For tension specimens, as the cross-section of CC and SFRC specimens increased, the crack spacing increased. The change in the length of the specimens also does not have any significant effect on the crack spacing of the CC and SFRC specimens.
- Based on the analytical study performed to estimate the load-deflection behavior of SFRC specimens, SFRC compression models presented by Wang (2006) resulted in the best estimate of test data in the scope of this research.
- Based on the analytical study to estimate the load-deflection behavior of SFRC specimens, Soranakom and Mobasher (2009) SFRC tension model with a □□value equal to 0.75 and ultimate tension strain = 0.010 mm can be used to estimate the tension behavior of SFRC members with a reasonable accuracy.
- It is noted that for compression, Wang (2006)'s model results in the best estimate for our research.

4.3 Recommendations

For future work, the following recommendations are made:

- For tension specimens with reinforcing bars, the test set-up oriented in a vertical direction shall be selected which produces no bending deformations due to the self-weight of the specimens.
- For tension specimens with reinforcing bars, selecting the length of the concrete prisms as a variable does not affect the behavior. Therefore, this variable may be eliminated.

5. REFERENCES

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