Experimental evaluation of steel fiber effect on mechanical properties of steel fiber-reinforced cement matrix

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ABSTRACT. This paper investigates the possibility of combining steel fibers with different weight percentages along with their functions in increasing compressive strength, indirect tensile strength and bending strength. In this study, two types of steel fibers, hooked and crimped, have been employed in the preparation of samples. These fibers have a length to diameter ratio of 30 mm and 50 mm (L/D=30 and L/D=50). Further, the combination of these fibers caused a reduction in concrete flow and reduced its efficiency. The combination of these fibers caused considerable increase of concrete bending strength compared to fibreless and single-fiber type concretes. In this research, tensile strength and bending strength of samples with 1.5%, 2% and 2.5% fibers were investigated in which the tensile strength and bending strength of all samples increased. However, there were very considerable increases in tensile strength and bending strength of samples made with hybrid crimped fibers. The results indicated that steel fibers did not have much impact on concrete compressive strength.

KEYWORDS. Mechanical properties; Fiber concrete; Hybrid concrete; Steel fibers; Indirect tensile test.

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INTRODUCTION

Concrete, considering its structure, has advantages and disadvantages among which tensile strength and low bending strength versus its high compressive strength can be mentioned. This accounts for the brittleness of concrete and is considered a major cause for the sudden failure and destruction of concrete structures. Since mid-eighteenth century, steel round bars were used to improve the brittle behavior of concrete under tensile forces. However, in many cases, tensile forces could not precisely be spotted, and distribution of steel round bars all throughout the concrete is not possible. Therefore, nowadays, the use of various fibers is one of the solutions to improve concrete brittle behavior and reduce its permeability [1]. In 1960s, Baston and Ramualdi made the first attempt to reinforce concrete using steel fibers in the United States. Since then, countless researches and industrial applications have been carried out on steel fiber reinforced concrete [2]. Qureshi et al., investigated the properties of high strength concrete by adding steel fibers. Test results revealed adding steel fibers increases tensile strength in a linear manner, with the increase rate higher in the first 7 days [3]. Rodrigues et al., studied the behavior of concrete columns reinforced with fibers on fire. In this research, four columns, 0.25 m long, 0.25 m wide and 3 m high, strengthened with different longitudinal steel reinforcements were investigated. Columns 1 to 3 contained 38.8 kg, 27.24 kg and 16.56 kg steel fibers and 1.5 kg polypropylene fibers per cubic meter respectively, without any fibers in column 4. Tests indicated that steel and polypropylene fibers used in concrete improve the behavior of columns on fire. Polypropylene fibers can control concrete flaking. Moreover, steel round bars are needed in columns to resist against fires. Therefore, to replace steel bars by steel fibers is not a good option when concrete is on fire [4].Vandewalle, did some experiments on hybrid fiber-reinforced concrete. He used three types of fiber: very short fibers with a length of 6 mm, short fibers with a length of 13 mm and long hooked-end fibers with a length of 35 mm. Beams 550 mm to 600 mm long and 150 mm wide and high were used in the experiments. The amount of fibers used varied from 0 to 90 kg per cubic meters, added to the concrete mix separately as well as a combined with two or three types of fiber. The results of measuring changes of the openings in cracks show the 3 mm and 13 mm fibers are very effective at the openings of tiny cracks, while 35 mm fibers provide appropriate plasticity at big and wide cracks. Tiny cracks grow, come together and join big cracks. Long hooked end fibers become very active in joining these cracks [5]. Milind V mohod et al., in this experimental investigation for M30 grade of concrete to study the compressive strength and tensile strength of steel fibers reinforced concrete containing fibers varied by 0.25%, 0.50%, 0.75%, 1%, 1.5% and 2% by volume of cement cubes of size 150mm×150mm×150mm to check the compressive strength and beams of size 500mm×100mm×100mm for checking flexural strength were casted. All the specimens were cured for the period of 3, 7 and 28 days before crushing the result of fibers reinforced concrete 3 days, 7 days, and 28 days curing with varied percentage of fiber were studied and it has been found that there is significant strength improvement in steel fiber reinforced concrete. The optimum fiber content while studying the compressive strength of cube is found to be 10% and 0.75% for flexural strength of the beam [6]. Carneiro et al., conducted experimental investigations on the mechanical properties of construction and demolition waste concrete with hooked-end steel fibers. Recycled aggregate concrete with hooked-end steel fibers exhibited a better mechanical performance with a 0.75% volume fraction than natural aggregate concrete. Ahsana Fathima et al. [7], presented the experimental study on the effect of steel fibers and polypropylene fibers on the mechanical properties of concrete, experimental program consisted of compressive strength test, split tensile strength test and flexural strength test on steel fiber reinforced concrete polypropylene fiber reinforced concrete three types of fibers used of length 30mm crimped steel fibers of length 25mm and endure 600 polypropylene of length 50mm with aspect ratio 50. The main aim of this experiment is to study the strength properties of steel fibers and polypropylene. Fibers reinforced concrete of M30 grade with 0%, 0.25%, 0.5% and 0.75% by volume of concrete [8]. Graybeal, attributed the increase in the flexural behavior of UHPC to the particle packing and the addition of fibers which hold the cement matrix together after cracking has occurred. UHPC exhibits ductility because as the specimen begins to micro crack the small scale fibers reinforce the matrix causing smaller, less damaging cracks to form [9].

STEEL FIBER-REINFORCED CONCRETE

Fiber concrete (steel fibers) consists of a concrete body composed of cement, aggregates, water, and some percentage of short steel fibers scattered randomly and disorderly into the mix in various directions. The steel fibers improve concrete properties compared to its normal state. Steel fiber-reinforced concrete is cast and agglomerated like plain concrete. Mixture designs for steel fiber reinforced concrete are basically similar to those of plain concrete. However, measures should be adopted for the even distribution of fibers and preventing them from being separated and intertwined into balls, so as to produce an efficient mix to cast, agglomerate and smoothen [2].

EXPERIMENT DESIGN AND RESEARCH APPROACH

The present study, by doing experiments with various fiber weights in steel fiber-reinforced concrete, aims at investigating the impact of fiber content on strength parameters of this type of concrete. In this research, 381 of specimens have been examined. Numerically, 69, 189, 123 samples of these number have been employed based on compressive strength, splitting tensile test and bending test.

Indirect tensile test, known as the Brazilian test

To assess tensile strength, sample splitting test (Brazilian test) was carried out on cylindrical samples of steel fiber-reinforced concrete, and the results were evaluated against each other and fibreless samples. Tensile strength measurement test was accomplished at ages 3, 7, and 28 days as per ASTM C496 standard [12]. In this test 300 × 150 mm cylindrical samples were used. Three samples with 0%, 1.5%, 2% and 2.5% fibers are provided. The samples, as shown here, are placed in the trays of pressing machine. Once the press is turned on, the load gradually increases, and the sample fractures under the tension produced by the pressure in a direction perpendicular to the pressure axis. The load increases evenly with a rate of 7 to 14 kgf/cm^2 per minute till the sample fractures. At this time, the maximum load applied by the machine is read and recorded. Now, the fracture tension is calculated by the following equation:

$$\mathrm{FSP} = \mathrm{FCT} = \mathrm{T} = \frac{2 \times \mathrm{P} \times 1000}{\pi \times \mathrm{L} \times \mathrm{D}} \tag{1}$$

where," T" is fracture tension in MPa," P", maximum pressure applied by the machine in kN, "L", sample length in mm and "D", sample diameter in mm.

Figure 1: Cylindrical sample under sample splitting tensile test (Brazilian test).

Bending strength test

The bending test is carried out via four-point bending machine as per ASTM C78 standard (Fig. 2). As shown in the picture, four-point bending machine is used in this study to perform bending test [10]. The bending strengths of concrete cubic samples reinforced with steel fibers are compared to each other and the fibreless sample. The samples are 100×100×50 mm. Three samples from each mentioned range were made with 0%, 1.5%, 2% and 2.5% fibers. To investigate bending strength in this study, the samples were tested after 28 days. The tensile strength of concrete while bending is calculated using the following equation:

$$\mathrm{Fr} = \frac{\mathrm{p} \times \mathrm{L} \times 1000}{bh^2} \tag{2}$$

where "Fr" is the fracture module in MPa, "P", maximum pressure applied by the machine in kN, "L" length of the distance between the two bases of the sample in mm, "b" sample's base in mm, and "h" height of the sample in mm.

Compressive strength

As most properties of concrete such as tensile strength, modulus of elasticity, permeability and abrasion resistance are directly related to its compressive strength, thus, to calculate it becomes of utmost significance. The compressive strength is usually determined using 100 mm or 150 mm cubic samples. In this study, compressive strength is determined as per ASTM C39 standard [11]. The standard necessitates the loading rate to be fixed. For this purpose, cubic samples with dimensions of 150 × 150 × 150 mm were used. To determine compressive strength, a pressing machine with a maximum capacity of 300 tons was used. This is the most common test on the quality of concrete, concerning strength. In this experiment, there are three cubic samples with known dimensions, which are to be converted to the equivalents of cylindrical ones at the end. The experiment is done using pressure test equipment (pressing machine) applying even pressure on the sample through two heavy jaws. The machine applies enough pressure until the sample fractures, showing maximum pressure in kgf. This maximum pressure (force) is written down, and calculated in MPa with the help of compressive test graph.

Figure 2: Four-point bending machine.

Figure 3: Compressive strength machine.

Experiment method

Two sets of compressive samples are smoothened with the help of a grindstone. The samples are then placed and fixed between the pressing machine jaws. The compressive strength is calculated as: maximum load recorded by the machine divided by cross-sectional area of samples.

$$fc = \frac{p \times 1000}{b \times d} \tag{3}$$

Materials used

Quartz aggregates are used in this study, with particle sizes at most 5.0 mm and a specific gravity of 2.75 g/cm^3. The dimensions of the aggregates used in this research are given in Tab. 1.

The quality and requirements of the water used in steel fiber-reinforced concrete are similar to those used in plain concrete. The water used in this study is the drinking water of the city of Arak[1] which is of acceptable quality. Type 2 cement of Delijan[2] cement factory was used in making all samples. It is worth noting that, micro silica slurry and PCE super plasticizer (produced by Vandshimi Company) have been used in this research. Also, the fibers employed in the

[1] Center of Markazi province
[2] A city in Markazi province

research consist of two types of hooked steel fiber and one type of crimped steel fiber, the characteristics of which are shown in Tab. 2.

Aggregates
0.0 – 0.1 mm
0.1- 0.3 mm
0.3 - 1.0 mm
1.0 - 2.0 mm
2.0 – 3.0 mm
3.0 – 5.0 mm

Table 1: Dimensions of quartz aggregates used.

Fiber	Mechanical anchors	Diameter (mm)	Length (mm)	Specific Gravity (kg/m^3)	Tensile Strength (MPa)	Elasticity Modulus (GPa)	Fiber Coating
HE	Hooked-End Steel	1.0	50	7850	800	210	-
HE	Hooked-End Steel	1.0	30	7850	800	210	-
Crimped	Crimped	1.0	50	7850	850	212	copper

Table 2: Characteristics of fibers used in the research.

Figure 3: General scheme of fibers used in research.

Mixture design

Maximum amount of fibers used in the mixture was estimated to be 2.5%. The fibers were added at the end of mixing process. To control the efficiency of the mixture, the fibers were divided into 5 equal parts, i.e. each part contained 0.5% of the entire fibers. Each part was gradually added to the mixture. After adding all parts and ensuring even distribution of the fibers, the mixture is checked for efficiency. The process of mixing the material is shown in Fig 4. The mixing process starts with mixing the dry aggregates and micro silica for about 2 minutes. When this mixing process is done, cement will be added to them and all the dry materials will be completely mixed together for about 2 minutes. The super plasticizer will be mixed by 70 percent water. Using this method of distribution, makes it possible to have a better performance in having the same distribution in all areas and increasing the cement efficiency. After completing the process of mixing the dry materials, the mixing of super plasticizer and water will be added gradually over a period of 4 minutes. Finally, by adding 30 percent of the remaining water over a period of 4 minutes, the quality and efficiency needed for adding the fibers, will be reached. The final mixture design hence obtained is presented in Tabs. 4 and 5.

2 minutes	---------->	Aggregate
2 minutes	---------->	Cement
1 minutes	---------->	Micro silica
4 minutes	---------->	Super plasticizer + 70% Water
4 minutes	---------->	30% remaining water

Figure 4: Mixing process.

Cement matrix	Cement (kg)	Micro silica (kg)	Aggregate (kg)	Water (kg)	Super Plasticizer (L)
Weight ratio	1.0	0.1	1.58	0.35	0.006

Table 4: Cement matrix final mixture design.

Materials	Mass (kg)
cement	944.86
Aggregate (0.0- 0.1 mm)	111.96
Aggregate (0.1- 0.3 mm)	111.96
Aggregate (0.3- 1.0 mm)	320.96
Aggregate (1.0- 2.0 mm)	291.113
Aggregate (2.0- 3.0 mm)	238.855
Aggregate (3.0- 5.0 mm)	418.007
Micro silica	94.481
Super plasticizer	6.238
Water	330.702

Table 5: Final mixture design (kg/m^3).

EXPERIMENTAL RESULTS

In this research, three samples from each mentioned range were made with 0%, 1.5%, 2% and 2.5% fibers which were tested based on compressive strength, splitting tensile test, bending test and the results were evaluated against each other and fibreless samples. The tensile strength of cylindrical samples was determined using sample splitting test (Brazilian test) through applying diagonal force on cylindrical concrete samples placed horizontally between the two plates of testing machine. To test the tensile strength in this study, the constructed samples were tested at the ages of 3, 7 and and 28 days.

As shown in Fig. 5, the 28-day tensile strength of mixture design has to large extent changed. It is worth noting that application of steel fibers has increased long-term tensile strength of concrete in all cases. According to Fig. 5, the 28-day tensile strength of all samples has increased. Based on these results, the highest 28-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 7.11 MPa and 80% tensile strength increase.

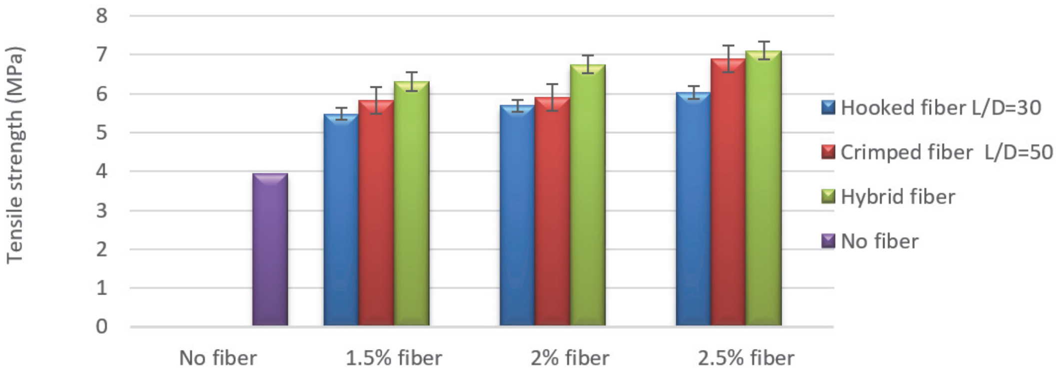


Figure 5: The impact of fiber content on the 28-day tensile strength of steel fiber-reinforced concrete.

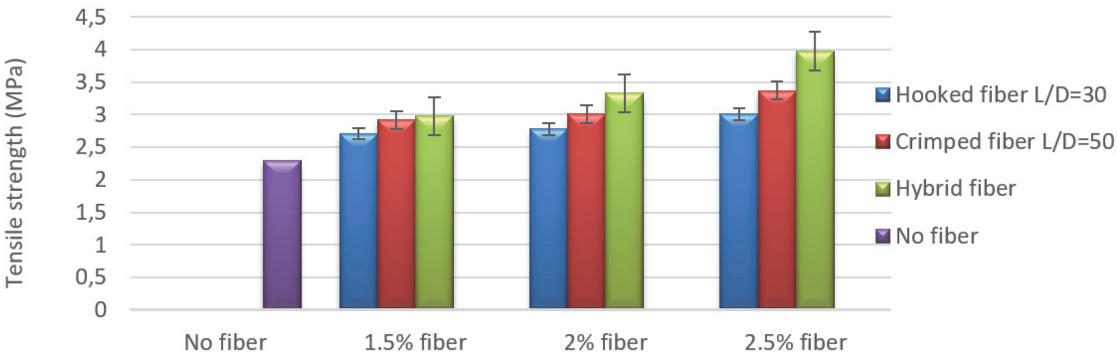


Figure 6: Impact of steel fiber content on 3-day tensile strength of steel fiber reinforced concrete.

Figure 7: Tensile toughness of cylindrical samples.

As shown in Fig. 6, application of steel fibers has increased short-term tensile strength of concrete in all cases**.** According to Fig. 6, the 3-day tensile strength of all samples has increased. Based on these results, the highest 3-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 3.98 MPa and 73.79% tensile strength increase according to Fig. 6. Pictures below show samples after splitting test. The tensile toughness of concrete has significantly increased and concrete behavior become softer.

As shown in Fig. 8, the 28-day tensile strength of mixture designs has remarkably changed. It is worth noting that the use of steel fibers has contributed to concrete long-term tensile strength increase in all cases. According to Fig. 8, the 28-day tensile strength of all samples has increased. Based on these results, the highest 28-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=50 and crimped steel fibers L/D=50) with 7.02 MPa and 77.72% tensile strength increase. However, according to Fig 8, the use of steel fibers has contributed to concrete tensile strength increase in all cases. Based on Fig. 9, the 7-day tensile strength of all samples has increased. Based on these results, the highest 7-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=50 and crimped steel fibers L/D=50) with 5.45 MPa and 82.27% tensile strength increase according to Fig. 9.

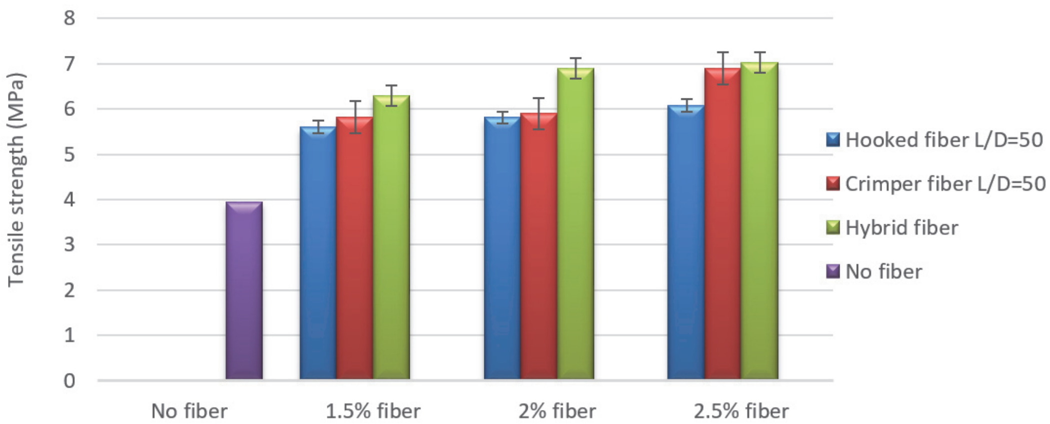


Figure 8: Impact of steel fiber content on 28-day tensile strength of steel fiber-reinforced concrete.

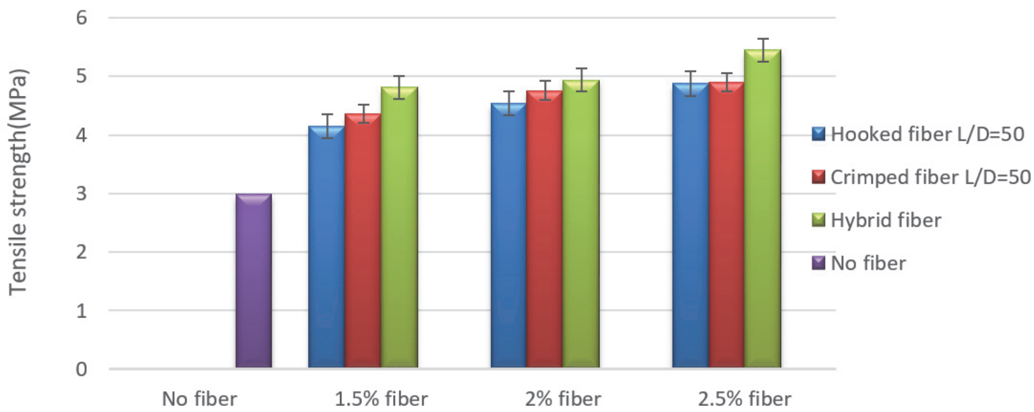


Figure 9: Impact of steel fiber content on 7-day compressive strength of steel fiber-reinforced concrete.

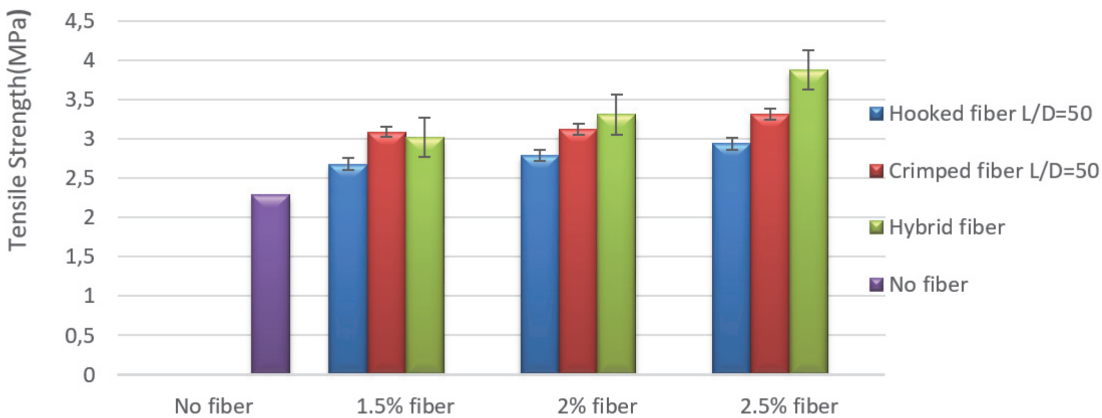


Figure 10: Impact of steel fiber content on 3-day compressive strength of steel fiber-reinforced concrete.

As shown in Fig. 10, the use of steel fibers has contributed to concrete short-term tensile strength increase in all cases. Based on Fig. 10, the 3-day tensile strength of all samples has increased. Based on these results, the highest 3-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=50 and crimped steel fibers L/D=50) with 3.88 MPa and 69.43% tensile strength increase according to Fig. 10.
As shown in Fig. 11, the 28-day bending strength of mixture designs has remarkably changed. It is worth noting that the use of steel fibers has contributed to concrete long-term bending strength increase in all cases. According to Fig. 11, the

28-day bending strength of all samples has increased. Based on these results, the highest 28-day bending strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 12.96 MPa and 329% bending strength increase.

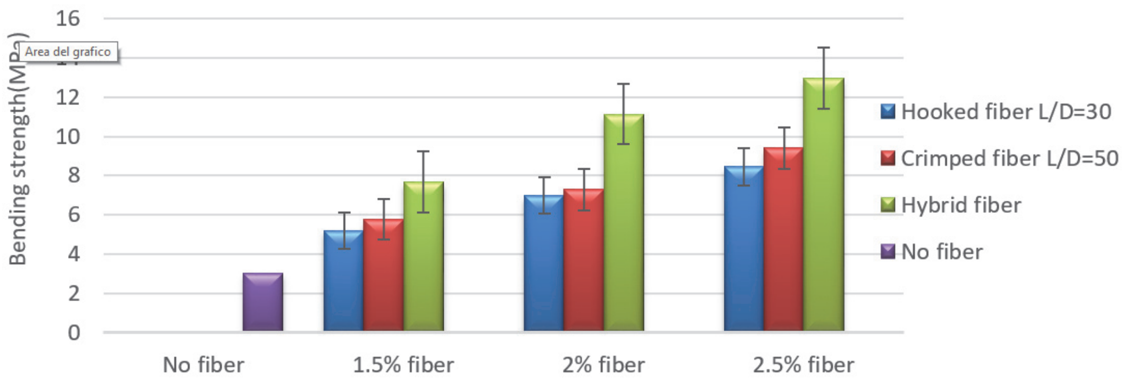


Figure 11: Impact of steel fiber content on 28-day bending strength of steel fiber-reinforced concrete.

Based on Fig. 12 the lowest bending strength increase exists in samples reinforced with 1.5% steel fibers L/D=50 with 5.16 MPa and 70.86 bending strength increase.

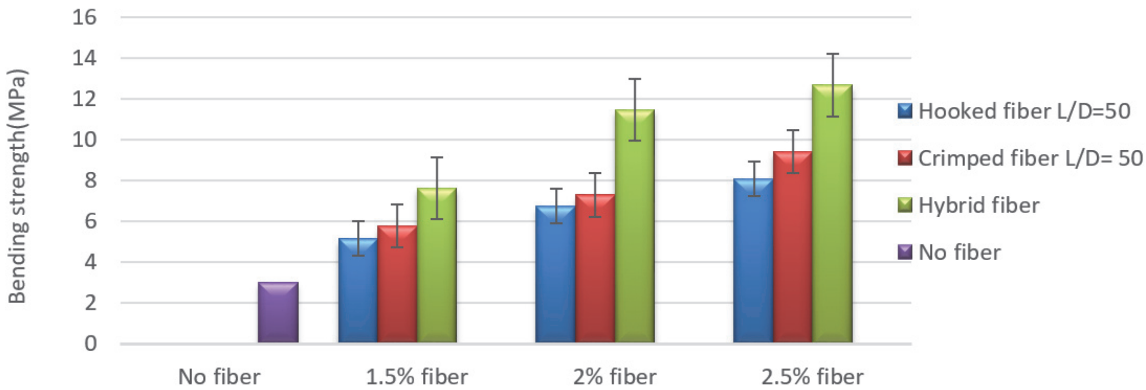


Figure 12: Impact of steel fiber content on 28-day bending strength of steel fiber-reinforced concrete.

Addition of steel fibers in bending test contributes to increased toughness and energy absorption which play an important role in the type of concrete fracture. The use of fibers causes an increase in concrete tensile toughness and softer behavior.

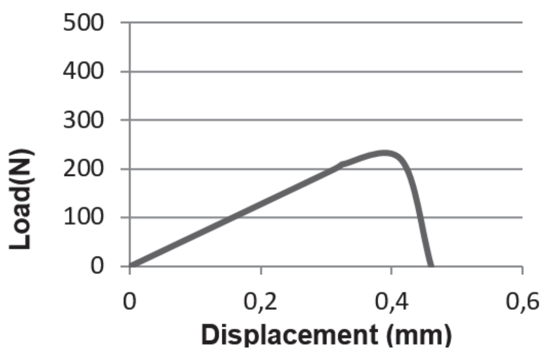
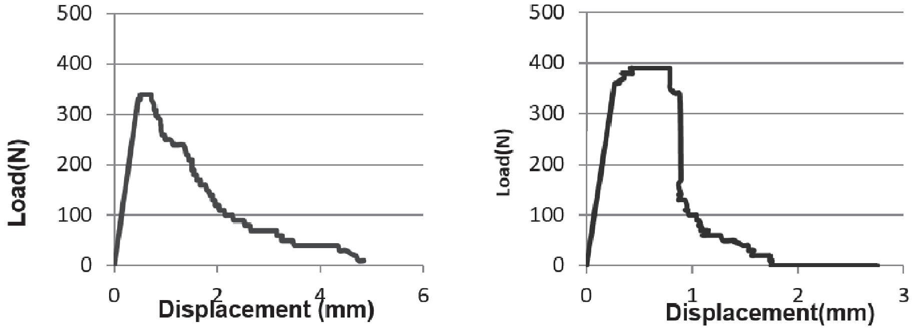
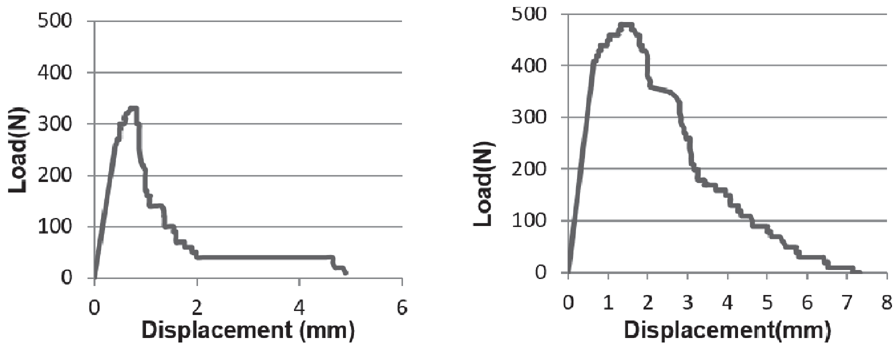


Figure 13: Load-displacement graph for fibreless sample on 28-day.



a) Hooked fiber (L/D=30) b) Hooked fiber (L/D=50)

Figure 14: Load- displacement graph - samples reinforced with 1.5% steel fibers on 28-day.



a) Crimped fiber (L/D=30) b) Hybrid fiber (L/D=50)

Figure 15: Load- displacement graph - samples reinforced with 1.5% steel fibers on 28-day.

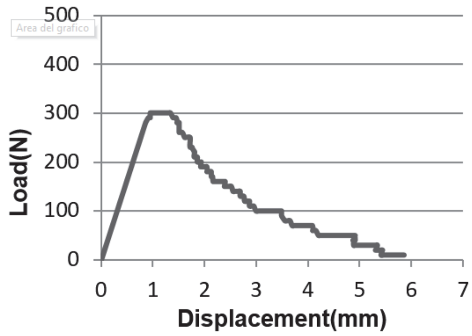
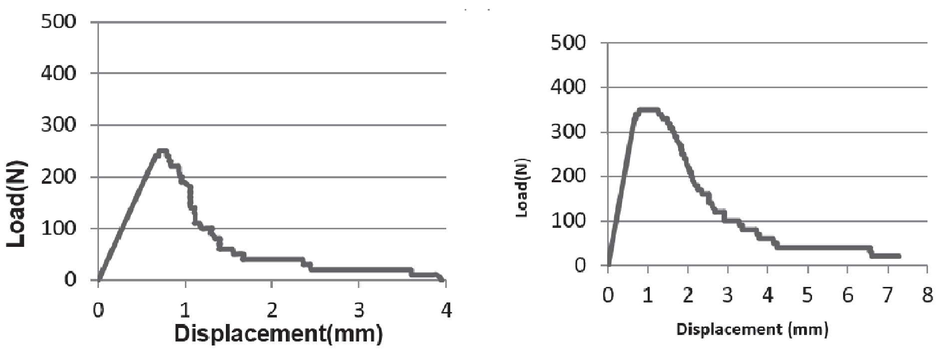
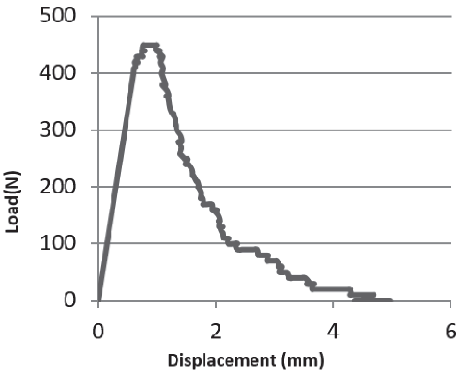


Figure 16: Load- displacement graph - samples reinforced with 1.5% hybrid steel fibers (L/D=50, L/D=50) on 28-day

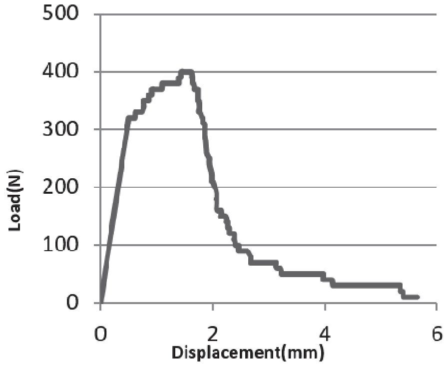


a) Hooked fiber (L/D=30) b) Hooked fiber (L/D=50)

Figure 17: Load- displacement graph - samples reinforced with 2% steel fibers on 28-day.



a) Crimped fiber (L/D=30)



b) Hybrid fiber (L/D=50)

Figure 18: Load-displacement graph - samples reinforced with 2% steel fibers on 28-day.

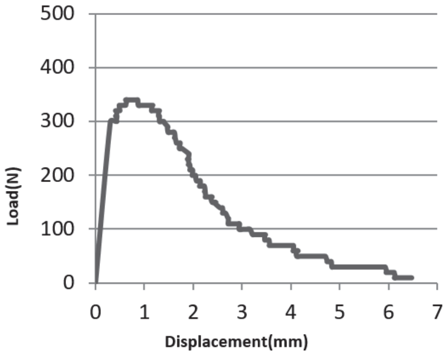
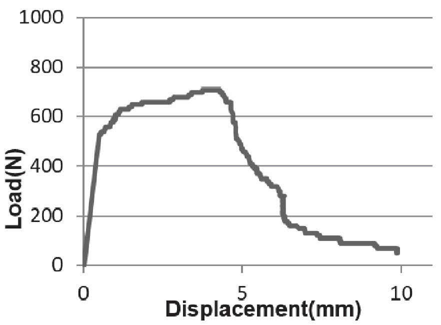
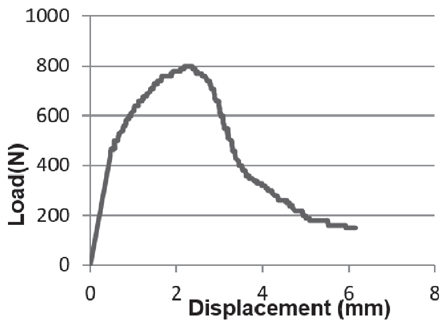


Figure 19: Load- displacement graph - samples reinforced with 2% hybrid steel fibers (L/D=50, L/D=50) on 28-day.

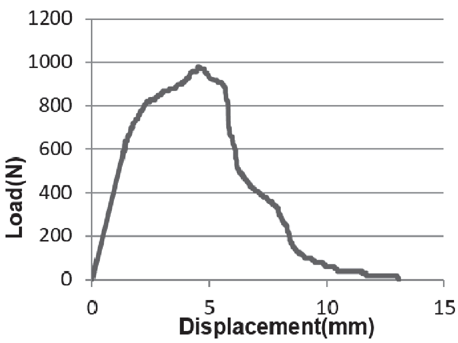


a) Hooked fiber (L/D=30)

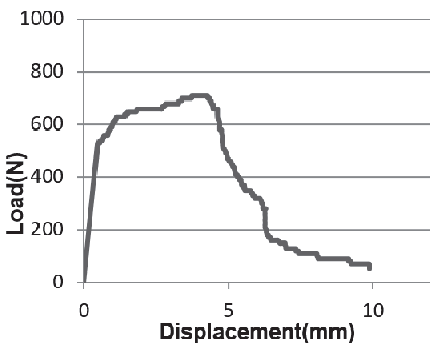


b) Hooked fiber (L/D=50)

Figure 20: Load-displacement graph - samples reinforced with 2.5% steel fibers on 28-day.



a) Crimped fiber (L/D=30)



b) Hybrid fiber (L/D=50)

Figure 21: Load- displacement graph - samples reinforced with 2.5% steel fibers on 28-day.

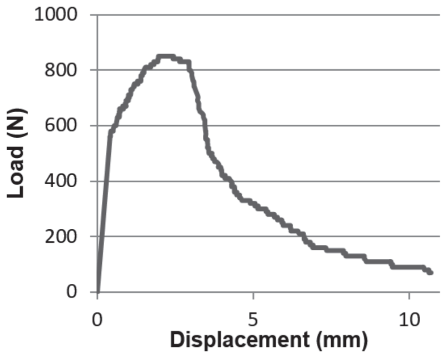


Figure 22: Load-displacement graph - samples reinforced with 2.5% hybrid steel fibers (L/D=50, L/D=50) on 28-day.

Compressive strength results

The samples in this research were brought under compressive strength test 28 days after they were constructed. To investigate the impact of the application of steel fibers on the compressive strength of fiber-reinforced concrete, the graph below shows changes in compressive strength for samples reinforced with 1.5%, 2 % and 2.5 % fibers after 28 days.

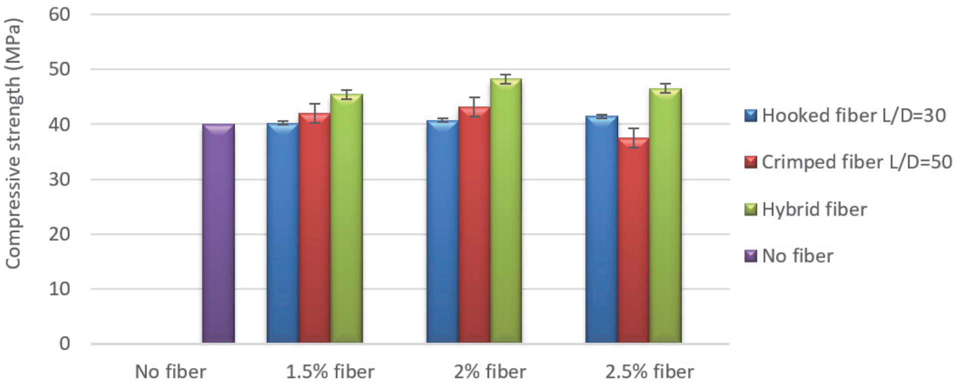


Figure 23: The impact of steel fiber content on 28-day compressive strength of concrete reinforced with steel fibers.

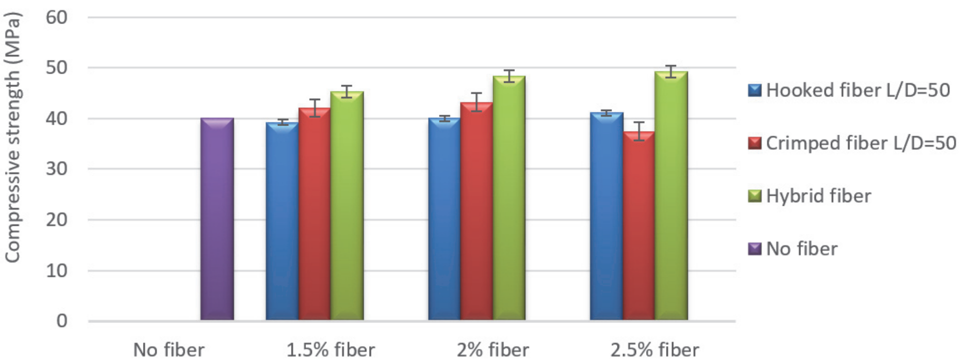


Figure 24: The impact of steel fiber content on 28-day compressive strength of concrete reinforced with steel fibers

Based on Figs. 23 and 24 the compressive strength of mixture designs are to some extent similar to each other. It is worth noting that the use of steel fibers has contributed to concrete long-term compressive strength decrease in some cases. Except the 2.5% crimped steel fibers designs (L/D=50), and 1.5% and 2% hooked steel fibers (L/D=50), the 28-day compressive strength of all samples have increased. Based on these results, the highest 28-day compressive strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=50 and crimped steel fibers L/D=50) with 22.84 compressive strength increase. Further, the highest amount of compressive strength decrease with 6.39% exists in crimped steel fibers (L/D=50).

CONCLUSION

Concrete tensile strength

1. Reinforcing samples with steel fibers, results in considerable increase in tensile strength. The more fibers used in concrete, the more its tensile strength increases
2. The results show that with the use of steel fibers after 3 days, 7 days and then 28 days, the concrete tensile strength increases in all cases. The tensile strength is higher in concrete containing hybrid steel fibers
3. By Reinforcing samples with steel fibers, the behavior of the concrete under tensile strength takes on more plasticity than samples with no steel fibers. Based on these results, the fracture of samples without steel fibers has been brittle, whereas those of the samples reinforced with steel fibers have been gradual and soft. Therefore, after samples crack, no fractures occur and the fibers join aggregates to each other.
4. The highest 28-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 7.11 MPa and 80% tensile strength increase.
5. The highest 7-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 5.48 MPa and 83.27% tensile strength increase
6. The highest 3-day tensile strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 3.98 MPa and 73.79% tensile strength increase
7. The lowest tensile strength increase occurred in samples containing 1.5% hooked steel fibers (L/D=30) with 18.34%, 37.79% and 38% in the ages of 3, 7 and 28 day respectively.
8. The lowest tensile strength increase occurred in samples containing 1.5% hooked steel fibers (L/D=50) with 17.03%, 38.79% and 41.77% in the ages of 3, 7 and 28 day respectively.

Concrete bending strength

1. The results acquired from the study show that after 28 days, there is a significant rise in bending strength, and the 28-day bending strength of all samples has increased.
2. The use of fibers considerably increases bending strength which is noticeably related to fiber type and content. Fiber increase with higher percentages had greater effect.
3. The lowest bending strength increase occurred in samples containing 1.5% steel fibers (L/D=50) with 5.16% MPa and 70.86% bending strength increase
4. The highest 28-day bending strength exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=30 and crimped steel fibers L/D=50) with 12.96 MPa and 329% bending strength increase.
5., Another important impact of adding steel fibers to concrete in bending test, as in indirect tensile test, is increased toughness and energy absorption which play an important role in the type of concrete fracture. The use of fibers causes a considerable increase in concrete tensile toughness and softer behavior.

Compressive strength

The results of compressive strength test of samples reinforced with 1.5%, 2% and 2.5% steel fibers are as follows:
1. Using steel fibers in this study decreased the efficiency of concrete. Based on these results, in cases where steel fibers are employed the compressive strength of some samples decreased.
The use of pozzolanic materials caused a significant increase in the compressive strength of fiber reinforced concrete. Based on these results, the highest 28-day compressive strength with 22.84 compressive strength increase exists in samples reinforced with 2.5% hybrid steel fibers (hooked steel fibers L/D=50 and crimped steel fibers L/D=50). Further, the highest amount of compressive strength decrease with 6.39% exists in crimped steel fibers (L/D=50).
2. One of the reasons for compressive strength increase of steel fiber-reinforced concrete is the application of micro silica with its filling and pozzolanic properties. The pozzolanic materials react to calcium hydroxide in the concrete and by producing more cement gel make the concrete denser which in turn increases the compressive strength.
3. The increase in compressive strength of concrete by adding fibers is not significant; however, adding fibers increases concrete compressive toughness and makes its behavior softer. Moreover, the increase in the weight percentage of fibers in hybrid samples increases their compressive strength and combining fibers has positive impact on the degree of compressive strength.

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