Jordan Journal of Civil Engineering, Volume **15**, No. **4, 2021**

Flexural Strength of RC Beams with Partial Replacement of Concrete with Hooked-steel Fiber-reinforced Concrete

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ABSTRACT

This paper investigates the potential improvement in the flexural strength of reinforced concrete beams when plain concrete is partially replaced by Hooked-Steel Fiber Concrete (HSFC). The main parameters considered in the experimental work were the height (h_f) of the HSFC layer and the volume fraction (V_f) of the steel fiber used to create the HSFC layer. The volume fractions (V_f) of steel fiber used ranged from 0.5% to 1.5% with a 0.5% increment. For each steel fiber fraction, the height of the HSFC layer was varied as 20, 40, 60 and 100% of the overall depth of the section. In addition to the control reinforced concrete beam (h_f = 0.0h and V_f = 0.0%), twelve hybrid beams were cast and tested using a fourth-point bending mode. Three distinct loading states were considered in this study: cracking, yielding and ultimate loads. Additionally, the effect of the material's hybridization on ductility, cracking stiffness, toughness and cracking behavior is discussed. The test results showed that partial replacement of plain concrete with HSFC of h_f = 0.6h has approximately the same effect on the load-carrying capacity of the tested beams as compared to the full replacement (h_f = 1.0h). In addition, the fiber content of 1.5% showed better results as compared to the lower contents of 0.5% and 1.0%..

KEYWORDS: RC beams, Flexural strength, SFRC, Steel fiber, Partial replacement, Fiber content, Volume fraction.

INTRODUCTION

Fiber-reinforced concrete is a composite material consisting of discrete low-aspect ratio fibers that are randomly distributed within the concrete mix to act as crack-controlling devices. The high tensile strength of almost all types of fibers and their ability to absorb external force energy are the most favorable key factors that make fibers an ideal option for concrete strengthening. According to many international standards, such as ACI Committee 544 (2018), fibers can improve the performance of concrete members by resisting tensile stresses or by controlling crack limits, which improves the durability of concrete. In addition, fibers can considerably enhance the structural strength of RC members without increasing the amount of steel reinforcement required and improve the ductility and durability of structural elements.

During the last few decades, the possibility of enhancing the properties of concrete by employing fibrous materials, such as steel and synthetic fibers, in concrete mixes has been extensively investigated. Many research articles have studied the effect of fibers on concrete performance by using various types of fibers. This section, therefore, briefly reviews the most recent studies related to the use of fibers in reinforced concrete applications for the period 2007-2020.

Altun et al. (2007) studied the effects of the addition of steel fiber on the mechanical properties of RC beams. RC beams with compressive strengths of 20 and 30 MPa were fabricated with the addition of steel fiber at dosages of 30 and 60 kg/m^3 for each compressive strength. All beams were tested under a third-point bending scheme. The study concluded that doubling the mass of steel fiber from 30 to 60 kg/m^3 resulted in a tenuous enhance in both ultimate load and toughness. Therefore, the study stated that a steel fiber dosage of 30

Received on 20/6/2021.
Accepted for Publication on 19/8/2021.

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kg/m^3 is economically better than higher dosage options.

Thomas and Ramaswamy (2007) investigated the mechanical properties of steel fiber-reinforced concrete with grades of 35, 65 and 85 MPa, with variable volume fractions of steel fiber of 0.0, 0.5, 1.0 and 1.5%. The results obtained showed that the maximum increase in the splitting tensile strength was about 40% as compared to the traditional concrete. However, the compressive strength only increased by 10% in almost all concrete grades studied. In addition, fiber dosage had to be increased to 1.5%, about 120 kg/m^3, to obtain a sufficient improvement in the toughness.

Soulioti et al. (2011) investigated the effects of geometry (waved and hooked-end fiber) and volume fraction of steel fiber on the flexural behavior of SFRC. The study applied four volume fractions of steel fiber ranging from 0.0 to 1.5% with a 0.5% interval. Generally, the experimental results indicated that fiber plays an important role in enhancing the mechanical properties of concrete, especially when there is a high fiber content. However, it was stated that as the fiber quantity increased in the concrete mix, the workability decreases significantly and therefore, the FRC consolidation process would be very difficult and can result in increased air content in the mixture. In addition, analysis of compressive strength results indicated that fiber had a slight effect on the compressive strength of the concrete. The same experimental work and results were also reported by Sasikala and Vimala (2013).

Rizzuti and Bencardino (2014), on the other hand, analyzed the effects of steel fiber on the compressive and flexural behaviors of RC beams with fiber volume fractions of 1.0, 1.6, 3.0 and 5.0%. The results indicated that fiber does not affect compressive strength, as it only appeared to improve the flexural strength of the tested elements. It was also stated in that study that higher steel fiber content considerably enhanced the fracture strength and toughness.

Sinha and Verma (2017, 2018) investigated the effects of steel fiber with varying volume fractions of 0.0, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0% on the strength- and workability-related properties of high–strength (M60 grade) concrete, from which the authors concluded that the optimum percentage of steel fiber is 1% by volume fraction; adding more than this percentage decreased the compressive and tensile strengths of concrete because of the balling effect that can result in improper bonding between fibers and the constituents of the concrete mixture. It is worth noting here that the flexural strength was found to increase as the volume fraction of steel fiber increased, since these fibers can act as bridging devices across the cracks during the loading state, as discussed earlier.

Gumus and Arslan (2019) investigated the effects of fiber on the flexural behavior of high-strength RC beams with a low reinforcement ratio. Steel fiber was incorporated into the concrete at different volume fractions of 0.33, 0.66 and 0.99%, from which it was found that the yield load increased with increasing steel fiber content, an improvement that was attributed to the better bonding between the fiber and concrete after the cracking stage.

Al-Taan et al. (2020) investigated the effects of steel fiber content on the workability of high-strength concrete through performing slump tests, finding that increasing the fiber content from 0.0 to 3.6% resulted in a sharp decrease in the slump characteristics of the tested concrete from 120 to 20mm.

In light of the brief review above, it can be seen that previous efforts have mainly focused on important parameters, such as volume fraction, geometry of the fiber and concrete grade. In most of these studies, the common conclusion reached was that fiber can only enhance the tensile strength and has no, or tenuous, effect on the compressive strength of concrete. Since there is a generally strong agreement that fibrous materials can only improve the tensile characteristics of RC elements, one might reasonably ask why such materials would then be added to the parts of the structural member subjected to compressive stresses when their influence can apparently be omitted. This question is important, since incorporating such fibrous materials into the concrete-strengthening process is expensive and reduces workability, therefore rendering the production of such concrete a more expensive and time- and labor-intensive process.

The present study aims to investigate the flexural strength response when concrete in the tension zone of the beams' cross-section is partially replaced by Hooked-Steel Fiber Concrete (HSFC) of varying layer heights. If partial HSFC replacement at specific layer height(s) results in a similar flexural strength as the full HSFC, then the recommendation could be made to consider partial replacement in concrete strengthening. Such a recommendation may considerably reduce the budget and time required to complete projects that utilize steel fiber concrete. In this research, steel fiber was applied with the most practical volume fractions of 0.0, 0.5, 1.0 and 1.5%, as this range of steel fraction has previously been widely considered in the literature. On the other hand, the height of the HSFC layer was varied from 0% to 100%, as will be discussed in the next section.

EXPERIMENTAL PROGRAM

Materials and Mixing Proportions

The experimental program for this research involves testing twelve RC beams, fabricated using steel fiber at varying levels of beam height. The concrete mix was designed to attain a compression strength of 35 MPa for all beam samples. Before casting the beam samples, six concrete cubes were poured using the designed concrete mix (400 kg/m^3 of cement, 1010 kg/m^3 of coarse aggregate, 640 kg/m^3 of fine aggregate and 0.4 of w/c ratio). These cubes were then tested at ages of 7 and 28 days; with each test repeated in triplicate. The average compressive strength of each group was determined, as reported in Table 1.

Table 1. Summary of compressive strength tests

Cube ID	Age	Compressive Strength (MPa)	Average (MPa)
C1	7 days	30.30	30.10
C2		31.40	
C3		28.70	
C4	28 days	35.41	35.41
C5		35.77	
C6		35.05	

Once the designed compressive strength was confirmed, beam samples were then cast to investigate the effects of partial replacement of plain concrete by steel fiber concrete on the flexural behavior of the tested beams.

Ordinary Portland Cement (OPC) and a low ratio of water (160 liters/m^3) were utilized in the mix design. Locally available coarse and fine aggregates were tested and used throughout the experimental work. Polycarboxylic-based superplasticizer (MegaFlow110) was added to the mix to recover the decreasing workability due to the use of hooked-end steel fibers, the relatively low water content and the high environmental temperature at the time of concrete pouring (around 35ºC). The dosage of the superplasticizer was 0.5% by weight of cementitious material.

Hooked-end steel fibers, as shown in Figure 1, were added into the mixes at different volume fractions (V_f = 0.5, 1.0 and 1.5% by volume) to assess the extent to which the addition of fiber would affect the flexural behavior of the tested beams.

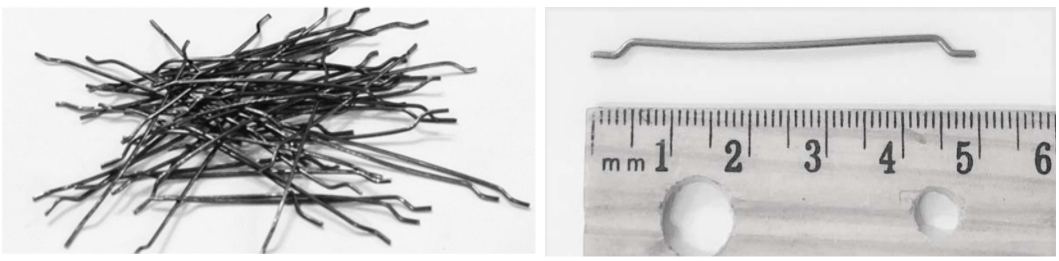


Figure (1): Hooked-end steel fiber used

For each of the volume fractions above, steel fiber was added to form a layer of HSFC with heights (h_f)

equivalent to 0.2h, 0.4h, 0.6h and 1.0h, as shown in Figure 2. The geometrical and mechanical properties of the steel fibers were provided by the manufacturer and are summarized in Table 2. Quantities of all materials used in the mix are illustrated in Table 3.

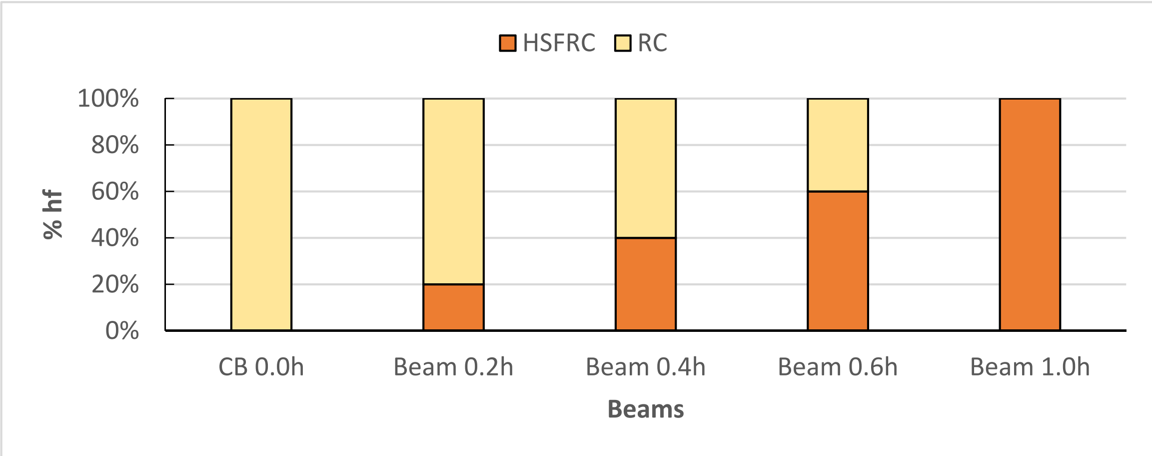


Figure (2): Heights of HSFRC in the tested beams according to h_f

Table 2. Properties of steel fiber

Fiber Type	Length (mm)	Cross-section	Diameter (mm)	Aspect Ratio	Tensile Strength (MPa)
Steel	50	Round	1	50	1050

Table 3. Mix proportions (per one cubic meter of concrete)

Mix No.	Mix ID	*V_f (%)	DF (kg/m^3)	Cement (kg/m^3)	W/C	FA (kg/m^3)	CA (kg/m^3)	MF (Liter/m^3)
1	CB	-	-	400	0.4	640	1010	2
2	SF1	0.5	39.3					
3	SF2	1.0	78.6					
4	SF3	1.5	117.9					

* where; "Vf" is the volume fraction of fiber, "DF" is the density of fiber, "W/C" is the water-to-cement ratio, "FA" is the fine aggregate, "CA" is the coarse aggregate, "MF" is the superplasticizer (MegaFlow110) and "CB" and "SF" represent the control beam and the fiber beam mixes, respectively.

RC Beam Specimens

All beam samples had the same rectangular cross-section of 120 x 200 mm (W x H). The beams were tested by applying the standard test method of flexural strength of concrete by using simply supporting the beam with fourth-point loading. The span of the beams was 1000 mm, as shown in Figure 3.

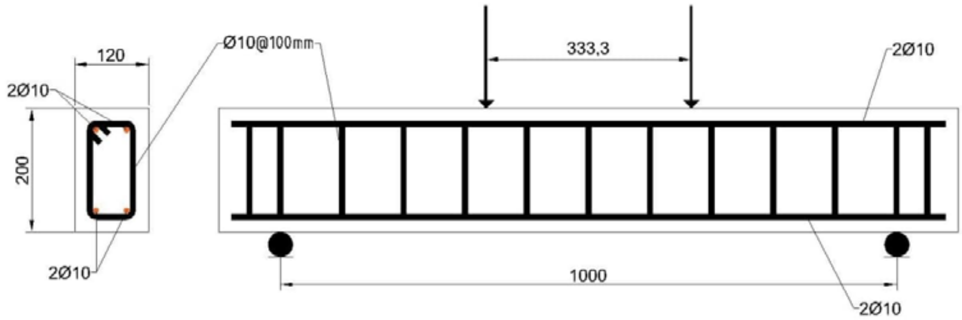


Figure (3): Schematic representation of the tested beams (*all dimensions are in mm*)

The beams were longitudinally reinforced by using tested and approved steel reinforcement of a nominal diameter of 10 mm (yield stress 550 MPa). The ultimate stress of the steel used was 640 MPa with corresponding elongation of 10%. The concrete cover of the longitudinal reinforcement steel was 25 mm.

In order to allow the beam specimens to be "tension-controlled beams"; i.e., flexural failure occurs by yielding of steel before the concrete reaches its maximum strain of 0.003, the steel reinforcement must be larger than the minimum allowed steel (0.0028) and smaller than the balanced steel (0.02), as recommended by ACI 318 Code. Therefore, two - Φ10 mm steel bars (ρ_s = 0.0065) were provided in the tension zone of the section. The upper two - Φ10 mm steel bars in the compression zone of the section were only utilized as hangers for shear reinforcement.

Shear reinforcement (i.e., stirrups) of Ø10 @ 100 mm were added to ensure pure flexural failure. Details of RC beam samples are summarized in Table 4.

Table 4. Details of the tested beams

Beam ID	V_f %	h_f %	*HSL (mm)
S0.5-0.2h	0.5%	20%	40
S0.5-0.4h		40%	80
S0.5-0.6h		60%	120
S0.5-1.0h		100%	200
S1.0-0.2h	1.0%	20%	40
S1.0-0.4h		40%	80
S1.0-0.6h		60%	120
S1.0-1.0h		100%	200
S1.5-0.2h	1.5%	20%	40
S1.5-0.4h		40%	80
S1.5-0.6h		60%	120
S1.5-1.0h		100%	200

* where; "HSL" is the height of HSFC layer.

Test Procedure and Instrumentation

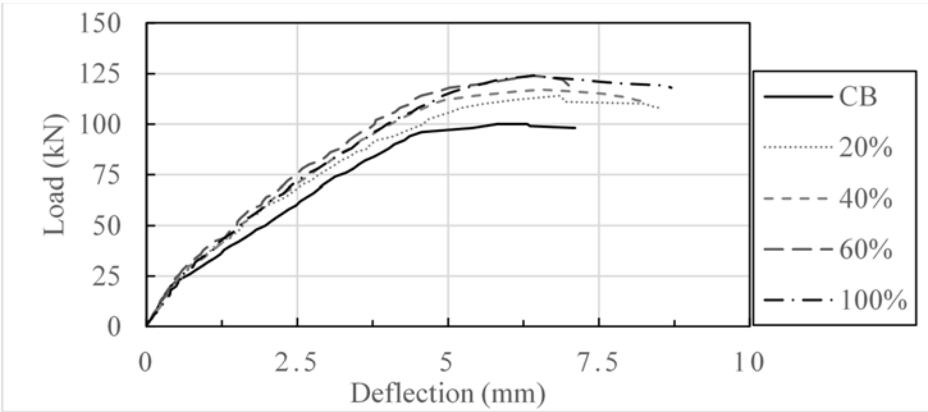
A flexural testing machine of 200 kN capacity was used throughout the experimental work to obtain the flexural strength of the tested beams. A steel load spreader beam was placed at the top of the tested beams to spread the machine load into two equal point loads. The maximum deflection at the mid-span of the tested beams was determined by using a digital dial gauge of 14 mm travel and 0.01 mm accuracy. Rubber shims were used to eliminate any gap that may exist between the specimen and the loading or supporting apparatus. The load was automatically applied at a constant rate of 0.5 kN/s until the failure of the tested specimens. All tested beams had been painted with white color before testing to facilitate the visual detection of cracks and to easily monitor their propagation during the test.

EXPERIMENTAL RESULTS AND DISCUSSION

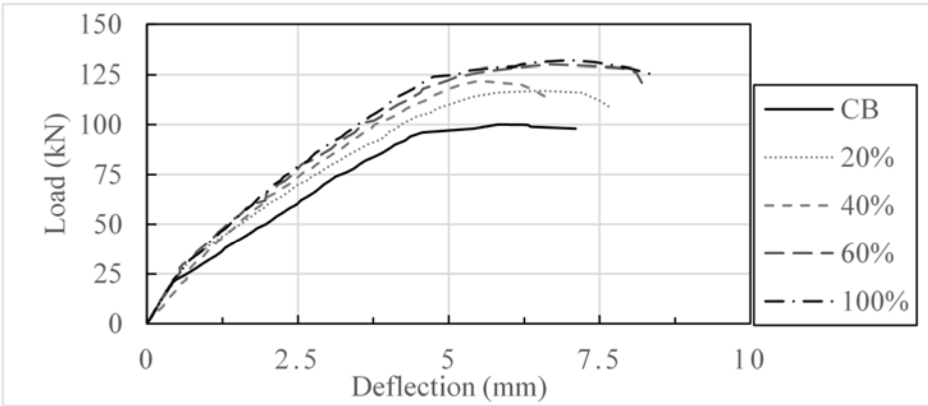
Load Capacity

In this section, load-mid span deflection relationships will be reported and discussed considering cracking, yielding and ultimate loading states. During the test, both sides of the specimen were monitored closely and the load at which the first crack appeared on either side was recorded as the "cracking load." At this point, the deflection was also recorded directly by reading the dial gauge. The determination of yielding load point directly from the load-deflection curves was difficult, because almost no test curve has a well-defined yield point. To estimate the yield point, the method proposed by Pam, Kwan and Ho (2002), which utilizes the elastoplastic behavior of the loaded beam, was used in this research. Here, the yield load (P_y) was defined as 0.75 times the ultimate load (P_u) and displacement (δ_y) was taken as 1.33 of the displacement corresponding to the defined yield load. The load-deflection curves of the

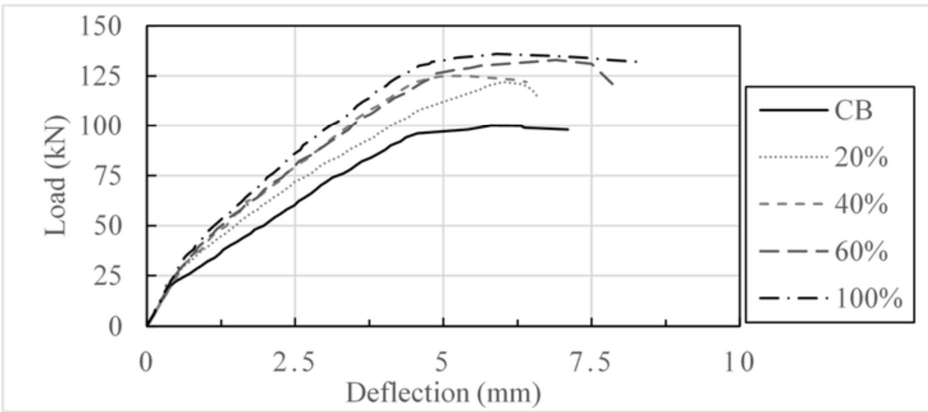
RC beam are comparatively plotted in Figure 4, grouped by the ratio of beam height and volume fraction.



(a) $V_f = 0.5\%$



(b) $V_f = 1.0\%$



(a) $V_f = 1.5\%$

Figure (4): Load-deflection response of beams with respect to fiber height: (a) $V_f = 0.5\%$; (b) $V_f = 1.0\%$ and (c) $V_f = 1.5\%$

As can be observed from Figure 4, all beams generally showed linear load-deflection behavior until the cracking state at loads of around 20 and 30 kN for the CB and SF beams, respectively. Then, as the applied load was increased, the corresponding deflection was also found to increase due to the rapid spreading of cracks until the failure loading of the loaded beam was reached. The curves shown in Figure 4 display other significant results, such as comparing the load-deflection responses of beams with V_f = 0.5 (a), V_f = 1.0 (b) and V_f = 1.5% (c). In each of the three fiber content groups, results of partial replacement of plain concrete by HSFC at heights of 20, 40, 60 and 100% are shown as well.

Table 5, on the other hand, summarizes the load values of the three loading states discussed previously. In addition, this table also lists the percentage increase of the ultimate load at each height of the HSFC layer as compared to both CB and SF beams.

Table 5. Experimental and calculated load-deflection criteria of tested beams

*Beam	P_{cr} (kN)	P_y (kN)	P_u (kN)	% P_u	δ_{max} (mm)	μ	K_{cr} (kN/mm)	Toughness (kN.mm)
CB	20	91.9	100	0	7.10	1.83	18.59	502.98
S0.5-0.2h	30	99.9	114	58	8.50	1.85	18.12	709.91
S0.5-0.4h	30	106.5	117	71	8.25	1.84	20.24	709.62
S0.5-0.6h	31	113.9	124	100	7.12	1.57	21.63	611.80
S0.5-1.0h	32	112.8	124	100	8.70	1.80	20.05	784.91
S1.0-0.2h	34	105.7	117	53	7.87	1.65	18.59	641.84
S1.0-0.4h	36	110.0	122	69	7.70	1.49	21.17	546.82
S1.0-0.6h	35	119.0	130	94	8.20	1.78	22.03	775.28
S1.0-1.0h	36	121.5	132	100	8.40	1.83	23.05	812.80
S1.5-0.2h	35	110.1	122	61	6.60	1.37	18.85	527.98
S1.5-0.4h	36	115.4	125	69	6.40	1.53	23.54	553.17
S1.5-0.6h	38	120.4	133	92	7.85	1.71	21.86	750.47
S1.5-1.0h	38	124.3	136	100	8.30	1.93	24.56	850.68

* where; "P_{cr}, P_y and P_u" are the cracking, yielding and ultimate loads, respectively, "%P_u" is the percentage increase in ultimate load, "δ_{max}" is the maximum deflection, "μ" is the ductility and "K_{cr}" is the post-cracking stiffness.

This percentage increase was calculated using Eq. 1 below:

$$\%P_{u\,increase} = \frac{P_{u\,\%h} - P_{u_{CB}}}{P_{u\,100\%h} - P_{u_{CB}}} \qquad \text{Eq. 1}$$

The aim of reporting the percentage increase in the ultimate load at each level of HSFC layer, as compared to the control beam and the full fiber beams, is to determine the extent to which, or height, partial replacement can be effective and whether designers might consider partial replacement as an alternative to full replacement. For example, beams "S0.5-0.2h" (i.e., V_f = 0.5% and h_f = 0.2h) showed a percentage increase in the ultimate load capacity of only 58% applying Eq. 1 above. Increasing the thickness of the HSFC layer from 0.2h to 0.6h, as in beams "S0.5-0.6h", showed a larger percentage increase that was equivalent to 100% of the full HSFC beams. The same calculations were performed for all other beams with higher fiber content.

Careful examination of Table 5 reveals that increasing the thickness of the HSFC within the tensile part of the beam (i.e., tension fiber that is below the neural axis in the case of a simply supported beam) can result in an increase in the load-carrying capacity of SF beams. This improvement in load-carrying capacity is more pronounced in beams with higher fiber content (i.e., V_f = 1.5%). However, when the thickness of the HSFC layer exceeds the neutral axis of the section, no improvement in the load-carrying capacity was achieved in almost all the loading states discussed above. This conclusion confirms that replacing the plain concrete of the tension fiber in the RC section with HSFC is effective as a full replacement of the section. In general, partial or full replacement of the plain concrete with

HSCF with different fiber contents increased the cracking, yielding and ultimate load capacities, with the effect being more pronounced at higher fiber contents.

Ductility (μ), post-cracking stiffness (K_{cr}) and the toughness of the tested beams have also been calculated and listed in Table 5 to determine the effect of steel fiber on their behavior. These indices were calculated using Eq. 2, Eq. 3 and Eq. 4 suggested in the literature (Abdul, Ali and Sultan, 2021; Ashour, 2000; Pam et al., 2002; Yang, Joh and Kim, 2018).

$$\mu = \frac{\delta_{max}}{\delta_y} \quad \text{Eq. 2}$$

$$K_{cr} = \frac{P_y - P_{cr}}{\delta_y - \delta_{cr}} \quad \text{Eq. 3}$$

Toughness = Area under "load-deflection curve" Eq.4

It is also apparent from Table 5 that when plain concrete was replaced with HSFC, the ductility of the tested beams dropped slightly. In contrast, both cracking stiffness and toughness indices were slightly increased, especially when an increased fiber content was utilized. These results can be explained by the fact that both cracking stiffness and toughness incorporate loading states in their equations, whereas the ductility index only considers deflection output, which was changed slightly due to the replacement of plain concrete with HSCF.

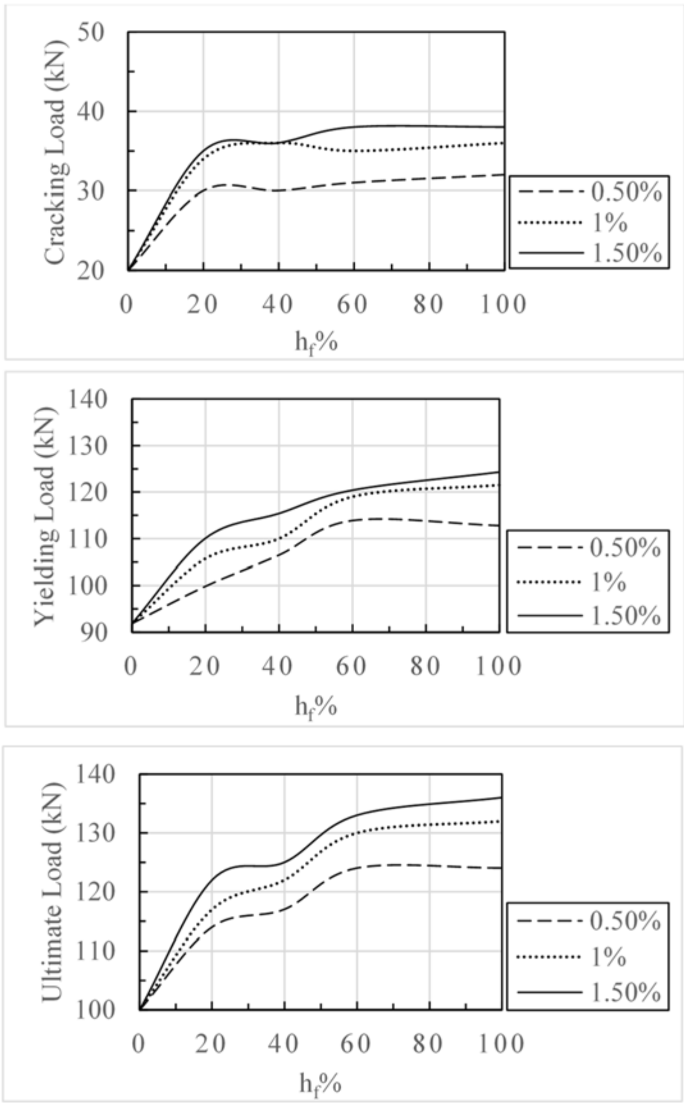


Figure (5): Cracking, yielding and ultimate loads as functions of fiber layers with different fiber contents

In Figure 5, values for the cracking, yielding and ultimate loads at each thickness of the HSCF layer are represented by curves for comparative purposes. It can be seen from Figure 5, for example, that the cracking loads of the beams containing steel fiber were considerably affected by increasing the thickness of the HSCF layer (h_f), regardless of the thickness of the layer itself. In other words, the differences in the cracking load between the control beams and beams with HSCF layers of 0.5, 1.0 and 1.5% fiber content were, on average, 11, 15 and 17 kN, regardless of the actual thickness of the HSCF layer. These results are anticipated because cracking normally begins at the bottom fiber of the tested member in the case of simply supported beams and therefore the thickness of the HSFC layer is not a factor in such cases.

In contrast, increasing the thickness of the HSCF was found to improve the yielding and the ultimate load capacity and this improvement was more pronounced in beams with higher fiber content, as discussed previously. For example, increasing h_f from 0.2h to 1.0h in beams with a V_f of 0.5% increased the ultimate load capacity by 14 and 24k N, respectively, whereas increasing h_f from 0.2h to 1.0h in beams with a V_f of 1.5% increased the ultimate load capacity by 22 and 36 kN, respectively, as compared to the control beams. This can be attributed to the mechanical interlocking properties of the steel fiber (Gumus and Arslan, 2019).

Crack Arrangement

Figure 6 shows the number and the distribution of the cracks that formed due to the loading of the beams. As depicted in this figure, the cracks that formed can be classified as either flexural, shear-flexural, or shear cracks. Shear and shear-flexural cracks are inevitable as P_y and P_u in almost all the tested beams exceeded 100 kN (more than 50 kN in each support) and the concrete shear strength for the tested beams is about 21 kN, as determined from Equation 11-3 of ACI 318-11 Code as shown below (Eq. 5). Therefore, such cracks formed at some point of loading.

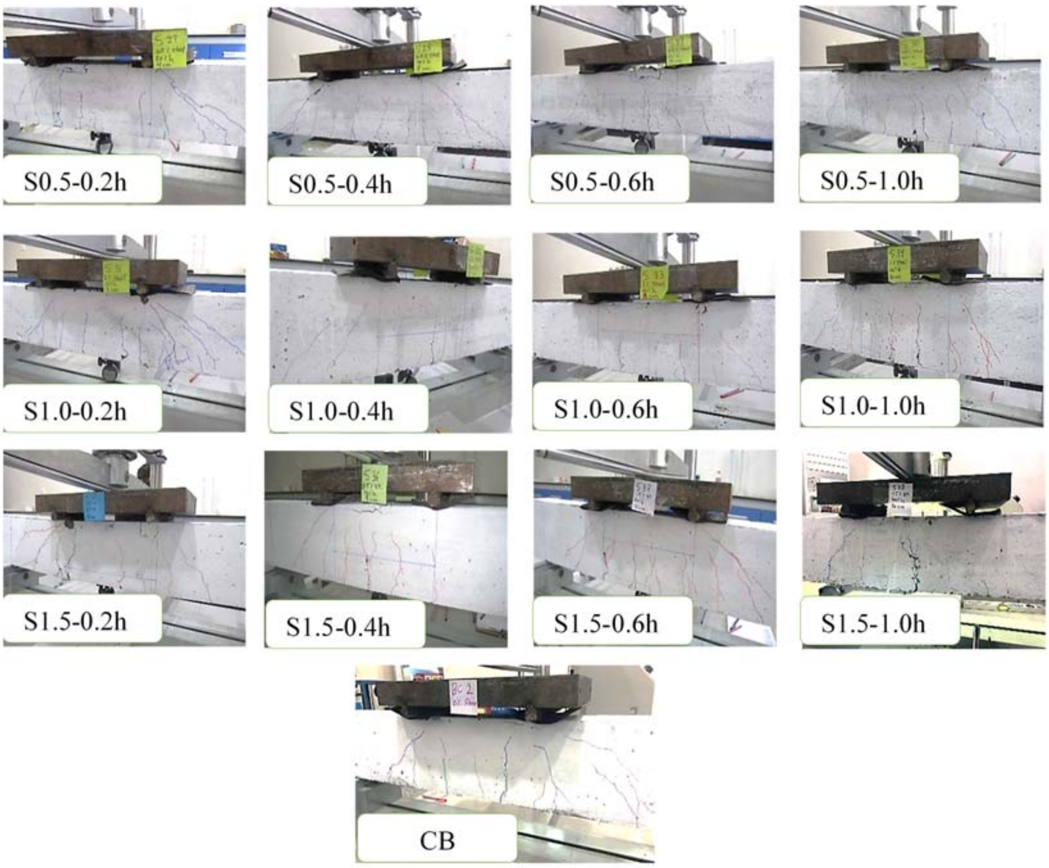


Figure (6): Cracking patterns of the tested beams

$$V_c = 0.17\lambda\sqrt{f'_c}b_w d \qquad \text{Eq. 5}$$

Providing a shear reinforcement of Φ10 @ 100mm c/c provided for an additional shear strength of about 151 kN, as determined by Equation 11-15 of ACI 318-11 Code and shown below (Eq. 6), resulted in the flexural failure mode being predominant in all tested beams.

$$V_s = \frac{A_v f_{yt} d}{S} \qquad \text{Eq. 6}$$

It is interesting to note that, in all tested beams, as the fiber content and the thickness of the HSFC increased, the number and distribution of the flexural cracks that formed decreased; however, their width and path towards the upper side of the section became more severe. This can be attributed to the "bridge action" that steel fiber can provide in RC members.

SUMMARY AND CONCLUSION

The aim of this research was to investigate the effects of the partial replacement of plain concrete with hooked-steel fiber concrete (HSFC) with different fiber thicknesses (h_f) and contents (V_f) on the flexural strength of RC beams. The experimental results determined suggest the following conclusions:

- Partial replacement of plain concrete with HSFC increases the load-carrying capacity in all loading states; i.e., cracking, yielding and ultimate load capacity. The positive effect is more explicit with higher fiber content.
- On average, the cracking load was increased by 55, 75 and 85% when plain concrete was replaced by HSFC with a fiber content of 0.5, 1.0 and 1.5%, respectively, regardless of the thickness of the HSFC layer.
- On average, the yielding load was increased by 18, 24 and 28% when plain concrete was replaced by HSFC with a fiber content of 0.5, 1.0 and 1.5%, respectively, regardless of the thickness of the HSFC layer.
- On average, the ultimate load was increased by 19, 25 and 29% when plain concrete was replaced by HSFC with a fiber content of 0.5, 1.0 and 1.5%, respectively, regardless of the thickness of the HSFC layer.
- In all fiber content groups, it was noticed that increasing the thickness of the HSFC layer from 20% to 60% of the depth of the RC section slightly improved the load-carrying capacity of all loading states. After this point, no significant improvement was observed between h_f = 60% and full replacement. This means that providing steel fiber in the compression fiber of the section (i.e., above the neutral axis) resulted in no apparent effects on the flexural strengths of the tested beams.
- The ductility of the tested beams was slightly degraded when plain concrete was replaced by HSFC; this degradation was more pronounced in higher fiber content beams.
- The cracking stiffness index of the tested beams was improved on average by 7, 14 and 20% due to the replacement of plain concrete by HSFC with a fiber-content of 0.5, 1.0 and 1.5%, respectively, regardless of the thickness of the HSFC layer.
- The toughness index of the tested beams was improved on average by 40, 38 and 33% due to the replacement of plain concrete by HSFC with a fiber content of 0.5, 1.0 and 1.5%, respectively, regardless of the thickness of the HSFC layer.
- The conclusions above all confirm that adding steel fiber can positively affect the tensile behavior of RC elements and has no noticeable effect on compressive behavior; this is in full agreement with all previous studies reviewed in the course of this research.

Wrapping all conclusions above, it can be said that replacing plain concrete of a thickness equivalent to 60% of the cross-sectional depth (i.e., h_f = 60%) by HSFC at any desired fiber content is equivalent to full replacement. Indeed, this would save the cost, time and effort required to finish any project that employs steel fiber in its design.

Acknowledgments

The authors would like to acknowledge the contribution of the Construction Laboratory at Thi-Qar Oil Company (South of Iraq) for allowing the research team to perform the necessary tests for this research.

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