Effect of Steel Fibers on Flexural Behavior of Normal and High Strength Concrete

K. M. Aldossari, W. A. Elsaigh, M. J. Shannag

***Abstract*—**An experimental study was conducted to investigate the effect of hooked-end steel fibers on the flexural behavior of normal and high strength concrete matrices. The fibers content appropriate for the concrete matrices investigated was also determined based on flexural tests on standard prisms. Parameters investigated include: matrix compressive strength ranging from 45 MPa to 70 MPa, corresponding to normal and high strength concrete matrices respectively; fibers volume fraction including 0, 0.5%, 0.76% and 1%, equivalent to 0, 40, 60, and 80 kg/m^3 of hooked-end steel fibers respectively. Test results indicated that flexural strength and toughness of normal and high strength concrete matrices were significantly improved with the increase in the fibers content added; whereas a slight improvement in compressive strength was observed for the same matrices. Furthermore, the test results indicated that the effect of increasing the fibers content was more pronounced on increasing the flexural strength of high strength concrete than that of normal concrete.

***Keywords*—**Concrete, flexural strength, toughness, steel fibers.

I. Introduction

STEEL FIBERS REINFORCED CONCRETE (SFRC) is a composite material consisting of a concrete matrix containing a random dispersion of steel fibers [1]. Plain concrete is a brittle material, with relatively low tensile strength and low tensile strain capacity. The role of randomly discontinuous fibers is to bridge across the cracks that develop and provide some post-cracking strength as shown in Fig. 1. The amount of fibers added to a concrete mixture is measured as a percentage of the total volume of the composite (concrete and fibers) termed, V_f. For various structural applications, typical volume fraction of steel fibers used ranges from 0.25 to 2.0 percent. The V_f in excess of 2.0 percent was found to reduce workability and may cause fibers clumping [2].

In general, a comparison between SFRC and plain concrete shows that SFRC exhibits superior mechanical properties, such as increase in total energy absorption prior to complete separation [3], improved fatigue resistance [4], larger impact strength [5], and higher shear strength [6], [7]. The improvement of the mechanical properties of SFRC can be attributed to the localized reinforcing effect of steel fibers, enhanced by either, (1) resistance to crack extension provided near a crack tip because steel fibers possess much higher strength than their surrounding concrete [8] or (2) after cracking, crack bridging effect attributed to steel fibers transmitting stresses across the crack [9]. Consequently, the localized reinforcing capability of steel fibers is greatly dependent on fiber-matrix interaction and steel fiber properties (i.e. texture, strength, and end shape), content, and orientation with respect to the direction of crack propagation. These properties would favor the use of the material for ground slab applications [10].

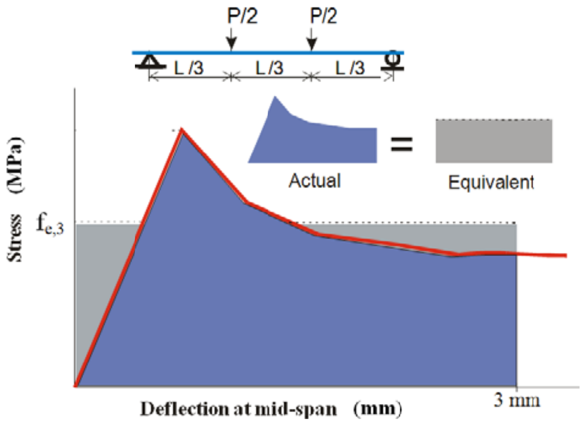

Fig. 1 Load-deflection curve for a prism loaded at third-points

Khaloo and Kim studied that the effect of concrete compressive strength on the mechanical properties of concrete reinforced with randomly distributed hooked-end steel fibers [11]. The concrete strengths investigated include 25 MPa for normal strength concrete, 50 MPa for medium strength concrete, and 69 MPa representing high strength concrete. The study have shown that increasing the steel fibers content from 0 to 1.5% increases the compressive strength by about 36.9, 11.3, and 16.7% for NSC, MSC, and HSC, respectively. The maximum increase of flexural strength results at 1.5, 1, and 1 % fibers contents was 85.2, 13.0, and 15.8% of plain concrete strength respectively for NSC, MSC, and HSC. Thomas and Ramaswamy studied that influence of addition of steel fibers on mechanical properties of concrete [12]. The concrete grade strengths investigated normal strength (35 MPa), moderately high strength (65 MPa), and high strength concrete (85 MPa). The study have shown that the increase in cube compressive strength due to the addition of steel fibers (V_f= 1.5%) was found to be minimal (3.65% in normal strength concrete, 2.65% in moderately high strength concrete, and 2.59% in high strength concrete). The increase in flexural strength due to the addition of steel fibers (V_f =1.5%) was

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found to be 46.2% in normal-strength concrete, 38.8% in moderately high-strength concrete and 40.0% in high-strength concrete.

The objectives of this investigation are to:

- Investigate the effect of steel fibers volume fractions on a flexural behavior of normal and high strength concrete.
- Determine the optimum steel fibers volume fraction appropriate for the concrete matrices investigated.
- Study the effect of steel fibers volume fractions on compressive strength of normal and high strength concrete.

The investigation was conducted by testing two prisms of (150×150×600 mm) and three cubes of (150×150×150 mm) for each mixture. Steel fibers volume fractions of 0%, 0.5%, 0.76%, and 1.0% were used with two different matrix grades. This study is a part of a broad research program on behavior of high strength steel fibers reinforced concrete ground slabs.

II. Experimental Program

Ordinary Portland cement (Type I) was used. 20mm maximum size crushed limestone with a specific gravity of 2.65 and 10mm maximum size crushed limestone with a specific gravity of 2.7 from the same local source were used as coarse aggregates. Red sand with fineness modulus of 2.55 and wash sand with fineness modulus of 2.6 were used as fine aggregates. Table I presents the concrete mixture proportions used in this investigation.

The steel fibers used were hooked-end wires with a length of 60mm, a diameter of 0.75mm, an aspect ratio (length/diameter) of 80 and a minimum tensile strength of 1050 MPa. The fibers are manufactured in water-soluble glued bundles to ensure their good dispersion in the concrete during mixing.

TABLE I
Mixture Proportions Per Cubic Meter

Materials	Compressive strength (f_{cu})	
	f_{cu} = 45 (MPa)	f_{cu} = 70 (MPa)
Cement(kg)	370	500
Water(L)	170	142
Coarse aggregates (kg)	1150	1100
Fine aggregates (kg)	673	674
Retarder & mid-range water reducing (L)	2	1.5
Superplasticizer (L)	-	2.5

f_{cu} = Compressive strength of cube after 28 days,

Quantities of each constituent for the concrete mixture were prepared. A laboratory tilting drum mixer with a maximum capacity of 0.1m^3 was used. The sequence of mixing can be summarized as follows: coarse and fine aggregates were mixed first along with one-thirds of total required water for approximately one minute, to allow for absorption of water and to attain uniform mixture. In the second step, the cement and silica fume if any, with the one-third of water and the chemical admixture were added. In the third step, the remaining third of water was added. For the mixture with steel fibers, the fibers were added in small amounts to wet mixture gradually, while the mixer was rotating, to avoid clumping and to achieve a uniform distribution. Finally, the mixer was left to rotate for approximately three minutes before the mixture is poured into molds. Slump tests were performed for all mixtures in accordance with the ASTM C 143 procedure [13].

The molds, including prisms and cubes, were lightly coated with mineral oil before use, in order to provide easy removal of hardened specimens. Concrete casting was carried out in three layers, each layer was approximately 50 mm thick. The Vibrating Table was used to compact the specimen for 15 to 30 second until no air bubbles emerged from the surface of the concrete. The concrete is leveled off smoothly using trowllers to the top of the molds. Then all specimens were kept covered with plastic sheets for 24 hours to prevent moisture evaporation. The specimens were demolded the next day and marked properly. Concrete cubes were subjected to full water curing in a tank while the prisms were cured by covering with wet burlap sheets until tested at 28 days.

The compressive strength test was carried out on three cube specimens (150×150×150mm) for each mixture, and tested after 28 days in accordance with BS 1881: part 116 procedure [14]. Two prism specimens (150x150x600mm) for each mixture were tested after 28 days to determine their flexural strength in accordance with ASTM C78 [15] as well as toughness and equivalent flexural strength in accordance with JSCE-SF4 [16]. Toughness (T) is defined as the total energy absorbed prior to complete separation of the specimen [1]. It was calculated as the area under the load-deflection curve up to a deflection of 1/150 times the span, which is equivalent to 3 mm for the prism specimen tested here. The equivalent flexural strength ($f_{e,3}$), shown in Fig. 1, is proportional to the area under the load-deflection curve up to a mid-span prism deflection of 3 mm. A Closed-Loop Material Testing System (MTS) was used in displacement control to apply the load, measure the applied load and record mid-span deflection. Mid-span deflection was measured by taking the average of two Linear Voltage Displacement Transducers (LVDTs) located at the mid span bottom part, at both sides of the prism as shown in Fig. 2.

Fig. 2 Flexural strength testing machine

III. Results And Discussions

A. Compressive Strength

The results for the average (i.e. average of three cubes) compressive strength test are summarized in Table II.

TABLE II
AVERAGE COMPRESSIVE STRENGTH RESULTS

f_{cu} (MPa)	Fibers volume fractions, V_f			
	0%	0.5%	0.76%	1%
45	45.3	47.7	52.1	52
70	72	76.3	76.2	77.9

The results presented in Table II indicate that the addition of steel fiber shave a minor effect on improving the compressive strength. However, observations indicated that the brittle mode of failure associated with plain concrete was transformed into a more ductile one with the increased addition of fibers. For normal strength concrete, the addition of fibers up to 0.76% was found to improve compressive strength. Beyond 0.76%, compressive strength was slightly reduced. For high strength concrete, the compressive strength showed a maximum value at 1% volume fraction. The increase in cube compressive strength due to the addition of steel fibers V_f = 1% was found to be 14.8% in normal strength concrete (45 MPa) and 8.2% in high strength concrete (70 MPa) compared to the control specimens. It can be observed from the compressive strength results that the steel fibers content has greater effect for lower compressive strength. In other words effect of V_f is more profound at relatively lower compressive strength.

B. Flexural Characteristics

The calculated average flexural strengths, toughness and equivalent flexural strengths are shown in Tables III and IV.

From the results obtained in Table III, up to fibers content of 0.76%, flexural strengths were found to increase with the increase in the volume fraction of fibers in the concrete mixture. It can be concluded that the most significant increase in the flexural strength is obtained at addition of 0.76% steel fibers volume fraction for both tested strength (45 and 70 MPa). The increase in flexural strength (f_f) due to the addition 0.76% of steel fibers was found 40.85% in normal strength concrete (45 MPa) and 68.35% in high strength concrete (70 MPa), compared to control specimens. It is obvious that the addition of fibers is more influential on flexural strength of HSC than that of NSC. It was observed that the control prisms (plain concrete) had a brittle failure and the prisms were completely separated into two segments immediately after cracking. The failure characteristics were, however, completely changed as a result of the addition of steel fibers. After the occurrence of initial cracking, the prism did not fail suddenly. The randomly oriented fibers crossing the cracked section resisted the propagation of cracks. This caused an increase in absorbed energy of concrete beyond the first cracking.

TABLE III
FLEXURAL STRENGTH RESULTS

f_{cu}(MPa)	Load (kN)*				Flexural strength, f_f (MPa)**			
	0%	0.5%	0.76%	1%	0%	0.5%	0.76%	1%
45	26.1	29.4	37	36.5	3.5	3.92	4.93	4.86
70	45.2	50.5	76	67.2	6	6.7	10.1	9

* Load is considered as the first peak on the load-deflection curve.

$**f_f = \frac{P.L}{b.h^2}$; P = Load in kN, L = The supported span (450mm), b and h = The width and depth of prism specimen (b = h = 150mm).

In addition, Table III and Fig. 3 showed that increasing the compressive strength from 45 to 70 MPa increased the flexural strength by 71, 71, 104 and 85.3% at fibers volume fractions of 0, 0.5, 0.76 and 1%, respectively. The maximum increase in flexural strength was at 0.76% of steel fibers volume fraction. Table IV indicated that increasing the compressive strength from 45 to 70 MPa increased equivalent flexural strength by 77.3, 55.7 and 52.8 at volume fractions of steel fibers 0.5, 0.76 and 1%, respectively. The maximum increase in flexural strength was at 0.5% of steel fibers volume fraction.

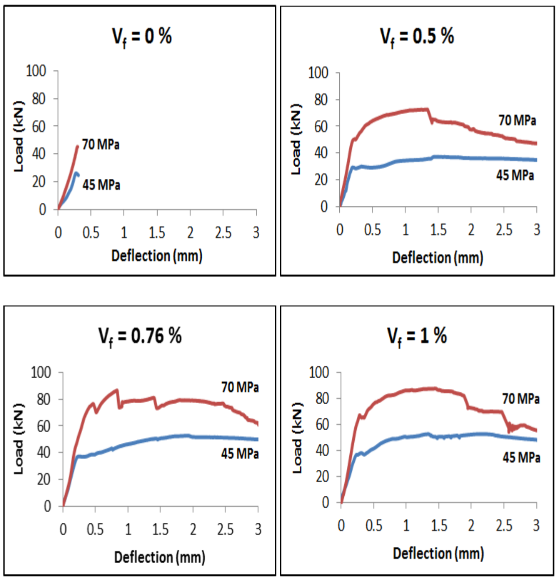

Fig. 3 Effect of compressive strengths on flexural behavior of SFRC

TABLE IV
TOUGHNESS AND EQUIVALENT FLEXURAL STRENGTH RESULTS

f_{cu} (MPa)	Area under curve – Toughness (N.m)				Equivalent flexural strength, $f_{e,3}$ (MPa)**			
	0%	0.5%	0.76%	1%	0%	0.5%	0.76%	1%
45	3.92	99.75	137.81	140.72	-*	4.4	6.1	6.25
70	6.14	174.66	214.6	214.65	-*	7.8	9.5	9.55

* Do not reach the deflection value required by JSCE-SF4 [16].

$**f_{e,3} = \frac{T}{3} \times \frac{L}{b.h^2}$; T = Toughness in N.m, L= The supported span (450 mm), b and h = The width and depth of prism specimen (b = h = 150 mm).

The load-deflection curves of control concrete and SFRC with fibers volume fractions of 0.5, 0.76 and 1% are shown in Figs. 4 and 5.

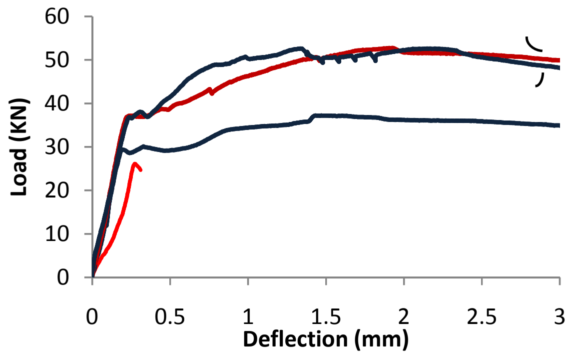

Fig. 4 Load-deflection curves of normal strength concrete (f_{cu}= 45MPa)

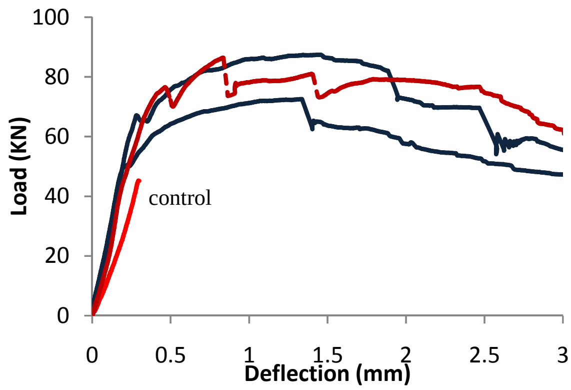

Fig. 5 Load-deflection curves of high strength concrete (f_{cu}= 70 MPa)

Figs. 4, 5 and Table IV show that the toughness (T) and equivalent flexural strength ($f_{e,3}$) increased with increasing fibers volume fractions in the concrete mix for both tested concrete (45 and 70 MPa). All fibers volume fractions improved T and $f_{e,3}$ compared to the control specimens (plain concrete), but the degree of improvement varied significantly. Fibers volume fraction of 0.5 % was found to have relatively small effect at various concrete grades compared to fibers volume fractions of 0.76% and 1%. Moreover, a minor difference in T and $f_{e,3}$ with respect to fibers volume fractions of 0.76% and 1% for various concrete grades was observed. Based on these findings, fibers volume fraction of 0.76% was prescribed for the full-scale ground slabs investigation. Such a plan will allow avoiding the wastage of steel fibers, if fibers volume fraction of 1% was to be used. On the other hand, the use of fibers volume fraction of 0.5% would result in a smaller increase in flexural characteristics of both normal and high strength concrete. Accordingly, 0.76% by volume (equivalent to 60 kg/m^3) of hooked-end steel fibers 80/60 is chosen and prescribed for the future investigation to be carried out for the ground slab study.

IV. Conclusion

- The addition of steel fibers has a minor effect on the improvement of the compressive strength values. Compressive strength of NSC is more sensitive to addition of fibers than that of HSC.
- As far as flexural strength is considered, the increase in compressive strength was found to be more significant at fibers volume fraction equal to 0.76%. Beyond this fibers volume fraction the effect of compressive strength starts to reduce. For the equivalent flexural strength, the results were not conclusive.
- At a particular concrete matrix compressive strength, both flexural strength (f_f) and equivalent flexural strength ($f_{e,3}$) increase with increasing fibers volume fraction. However, the increase is significant up to a certain fibers volume fraction and marginal at higher volumes.
- A hooked-end steel fibers (length/diameter = 80/60) volume fraction of 0.76% (60 kg/m^3) is found to be appropriate (chosen as optimum fibers content) for a concrete with compressive strengths of 45 and 70 MPa.

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