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HOOKED ENDS STEEL FIBERS EFFECTS ON ENERGY ABSORPTION CAPACITY OF CONCRETE

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ABSTRACT

The addition of fibers to concrete has been of great interest in the field of materials science. The toughness of concrete mixes is affected by the material, geometric, and amount of fiber used. Since different fibers produce different flexural behavior, it is necessary to conduct an experimental test to determine the effects of fibers on the mechanical properties of concrete. Therefore, the present study investigates the energy absorption capacity of hooked ends steel fiber reinforced concrete (0.3 and 0.9% volume fraction) against unreinforced concrete. Four different codes are used to evaluate the flexural toughness in all cases. The overall best results are obtained for the steel fiber–reinforced concrete with 0.90% volume fraction that depicted the largest toughness in comparison with the lower fiber proportion concrete mix (0.3% of vol.). In this concrete mix, the first-crack deflection was 0.06 mm, flexural toughness based on ASTM C1018 method starting from 5.1 up 32.2, and, flexural toughness values of 3.1, 1.06, and 71.6 for JSCE, Banthia and Trottier, and ACI 544 methods, respectively. Experimental results also illustrated the beneficial effects of the steel fiber used to delaying the flexural strength peak in the strain hardening region.

Keywords: steel fiber, fiber-reinforced concrete, toughness.

INTRODUCTION

In plain concrete is well-known that for its intrinsic weakness associated with a low tensile strength capacity, it is easy to produce first crack formation under a lower amount of tensile force [1]. Incorporating fiber on concrete mixes improves its tensile capacity and several related properties as plastic shrinkage cracking, toughness or ductility, and impact resistance that improves performance (e.g. to resist material disintegration) and reduce section thickness [2].

Steel fibers enhance post-cracking performance, prevented crack development, and increase ductile and ultimate strength cause by the consumed energy prior to reach the failure [3]. Also, steel fiber improves contact energy dissipation in the initial state to beams subject to flexural actions [4]. Although the additional among of fiber above a certain threshold does not increase the peak flexural strength, this augments the energy absorbing capacity of concrete [5]. In this direction, the behavior of high-performance steel fiber-reinforced short concrete columns with 0.50 and 0.75 of its volume fractions has been investigated in [6]. It was found that the deformability after concrete cracking increases as the amount of the fibers is augmented and extends beyond the peak load for the highest dosage of steel fiber. A study [7] concluded that an optimum volume fraction of steel fiber of 1.5% is recommended for fiber-reinforced concrete with artificial and natural sand as fine aggregate. This research evaluated the dosage rate of volume fraction 0, 0.5, 1.0, 1.5, and 2.0 percent and found that there is a reliable increase in the strength of plain concrete while artificial sand is used instead of natural sand because there is a better bond with cement paste. In the same direction, a minimum volume fraction of 2% for steel fiber has been proposed to enhance the mechanical strength and post-cracking performance of SFRC [8].

Other researchers have evaluated the type and aspect relations of steel fiber on concrete properties [9, 10]. The hooked and crimped steel fibers with a dosage of 0.5%, 0.75%, and 1% volume fractions on high-performance concrete mix were studied on [9]. This investigation concluded that volume fractions of 0.75% and 1% for steel fibers are needed to increase the first crack load and, specimens with hooked steel fiber had a slightly better behavior compare with crimped steel fibers. Additionally, fibers with the largest aspect ratio have the best efficiency in improving the flexural performance of steel fiber-reinforced concrete, i.e. the mix with steel fiber with an aspect ratio of 125 duplicated the value of residual flexural strength of steel fiber of aspect ratio of 105 [10].

Also, the steel fibers have been used with other fibers in hybrid configuration [11, 12]. Steel fibers alone and combining two types of steel fiber with polypropylene fiber as reinforced for hollow-core concrete slabs applications are evaluated on [11]. Results show that the ductility ratio of slabs with only steel fibers and hybrid configuration reach 297.4% and 386.5% respectively, compared with plain slabs specimens. In the next study, an experimental investigation on a hybrid combination of glass and steel fibers using between 0.25% and 0.50% of volume fraction on high-performance concrete was carried out [12]. Results of testing concrete beams validated that the presence of fiber reduces deflection, meanwhile, increases load-bearing capacity up to 22% compared to plain concrete specimens. Moreover, steel fiber provides more strength to concrete mixes compared to glass fibers in a hybrid concrete mix.

RESEARCH IMPACT

In this experimental study, steel fiber–reinforced concrete (SFRC) was investigated under monotonic loading and compared with unreinforced concrete behavior. The mechanical properties of SFRC like the first and maximal flexural strength, critical deflection, and flexural toughness (FT) were determined. Results from this investigation will augment the referents of the application of SFRC particularly on seismic regions where this type of concrete has an expansive prospect, as well that can be integrated to validated/calibrate the nonlinear numerical models of SFRC materials used on finite elements software o prediction of toughness properties of SFRC for different dosage (e.g. [13, 14]).

MATERIALS

General-purpose cement (GPC) supplied by Argos (Colombia) that comply with [15] was used as a binder. Blue metal 25 mm (1 in) gravel naturally fractured and fine blue metal gravel with a fineness modulus of 3.1 were used as coarse and fine aggregate respectively, all of them in accordance to [16-17]. Superplasticizer (SP) Sika® ViscoCrete® 2100 that meets [18] required was added to provide better workability and reach the compressive strength of the concrete.

Steel fibers type I (Cold-drawn wire) produce under [19] specifications were supplied by [20], the mechanical and physical properties of the fibers and fiber shape are presented in Table-1 and Figure-1 correspondingly. The aspect ratio of this fiber (i.e. 80) meets the guidelines that taking into account the maximum aggregate size [10].

Figure-1. Typical Steel Fibers used. Photo provided via Supercam [20].

MIX DESIGNS AND SAMPLES

A mix of plain concrete without fibers (named control) and, two mixes with 25 and 75 Kg/m^3 (i.e. volume fraction of 0.0%, 0.3%, and 0.9%) were prepared and denoted as SFRC25 and SFRC75, respectively. These fibers amount was designed in agreement with the limits established by [2]. Also, taking into account the aforementioned normative, a target flexural strength of 3.4 MPa (500 psi) and a compressive strength of 27.5 MPa (4000 psi) at 28 days were selected and, the fine-to-coarse aggregate ratio was adjusted. Table-2 shows the mixture proportion of the designed concrete specimens.

EXPERIMENTAL WORK

Specimens

Aggregates and cement powder were first mixed in order to cover the aggregates with cement for 3 min. After that, half of the mix of water and superplasticizer was blended on the dry mix and mixed for 2 min. Then, the remaining part of water and superplasticizer was added and mixed again for 6 min. The fibers were added slowly to produce a uniform spreading during 5 more minutes. All of this procedure was performed in a bulk concrete mixer. Finally, the fresh concrete was placed on a mold of 500 X 150 X 150 mm (20 by 6 by 6 in) to build the molded prism beam specimens for the flexural toughness test indicated on [21]. After molding, the specimens were maintained for a period of 24h with an initial curing temperature of 20 ± 4°C and demolded at the end of this time to be stored in a moist room for 28 days in agreement with [22].

Test Setup and Procedure

Once the beam specimens were curing, these were subject to flexural strength on third-point loading configuration according to [23]. A universal hydraulic press machine capable to induce a controlled displacement increase rate of 0.05 mm/min at the mid-span and a load–applying and support blocks configure to a free test span of 450 mm (18 in) were used to conduct the test. The load and deflection values were recorded from a software Data Management (i.e. Controls of machine MC8 of the “Nueva Granada” Military University). Other details about the test procedure can be accessed elsewhere (e.g. [24]).

Table-1. Properties of fibre.

Fibre type	Length (mm)	Density (kg/m^3)	Diameter (mm)	Tensile strength (MPa)	Young's modulus (GPa)	Shape
Steel (cold-drawn wire)	60*	7850	0.75*	1166*	210	Hooked ends

* Values from Supercam (2018)

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Table-2. Mixture proportions of concrete mixes.

Mix ID	w/b[a]	Binder (kg/m^3)	Fibre weight [Kg/m3]	Fibre ratio (vol.%)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	SP (l/m^3)
Control	0.46	426	0	0	615	1001	4.2
SFRC25	0.46	426	25	0.32	615	1001	4.2
SFRC75	0.46	426	75	0.89	615	1001	4.2

SP: superplasticizer; Control: Plain concrete; SFRC: steel fibre–reinforced concrete; last number in the name of specimen denotes the quantity of fiber used
[a]Water-to-binder ratio.

RESULTS AND DISCUSSIONS

First Cracking Flexural Strength

The 28-day compressive strength under monotonically loaded concrete cylinders (over 5 samples by mix) tested under [25] was found to be 28.22 ± 0.56, 27.88 ± 0.29, and 24.98 ± 0.19 MPa (average ± standard deviation) for Control, SFRC25, and SFRC75, correspondingly. Figure-2 shows the flexural strength identified as first cracking as is described by [21] for all mixes. These values represent the average and standard deviation of four (4) molded prism specimens. The figure is depicted that flexural strength is increased by the presence of fibers (i.e. increased from 2.96 to 4.69 MPa as a quantity of 25 Kg/m^3 of steel fibers is added.) as is expected (due to that improved the facility to resist cracking and spalling) without any significant difference between the maximum initial flexural strength due to dosage of fibers (4.69 ± 0.33 MPa and 4.39 ± 0.32 MPa on SFRC25 and SFRC75, respectively). The last result is correlated with the 28-day compressive strength tested in concrete cylinders for SFRC75 that was an 89.6% of SFRC25 mix and, this reduction has been related with the presence of the hooked end of steel fibers [26].

Flexural and Post-Cracking Behavior

Figure-3 depicts the flexural strength versus deflection curves of the best control, SFRC25, and SFRC75 mixes. It is seen that the flexural strength and deflection at the first peak of the curve increased for mixes with steel fibers (SFRC25 and SFRC75), as well, the deflection at peak value of flexural strength of SFRC75 presents a higher value than the control mix (i.e. 157% of deflection on control mix on Figure-3(a)). Also, Figure-3(a) is shown that all mixes followed a linear trend-line (i.e. same slope) at the initial portion of the elastic behavior (before 0.02 mm) where there are no significant cracks in the concrete.

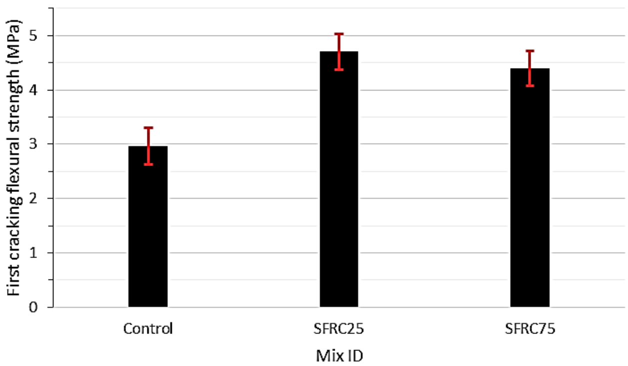

Figure-2. Flexure strength of SFRC and control mixes.

In contrast with the first cracking flexural strength (see Figure-2), in the plastic and hardened zone, the fiber amount governed the increased in the post-cracking (residual) strength that allows reaching a common maximum deflection value close to 10 mm for SFRC mixes [9, 26]. Thereby, SFRC75 mix had the best ductile behavior in pre-cracking (Figure-3(a)) and post-cracking zone (Figures-3(b) and 3(c)) compared with SFRC25 mix. As shown in Figure-3(b), once the SFRC25 mix reaches the peak flexural strength, it has a sudden fall dropping from 4.9 to 0.8 MPa due to the limited quantity of fiber volume fraction. By contrast, a notable strain hardening performance of SFRC75 mix between 0.08 to 1.00 mm (Figure-3(b)) was developed. This property is attributed to the facility to resist cracking (narrowing crack width) and spalling by the presence of fibers [2, 9, 26].

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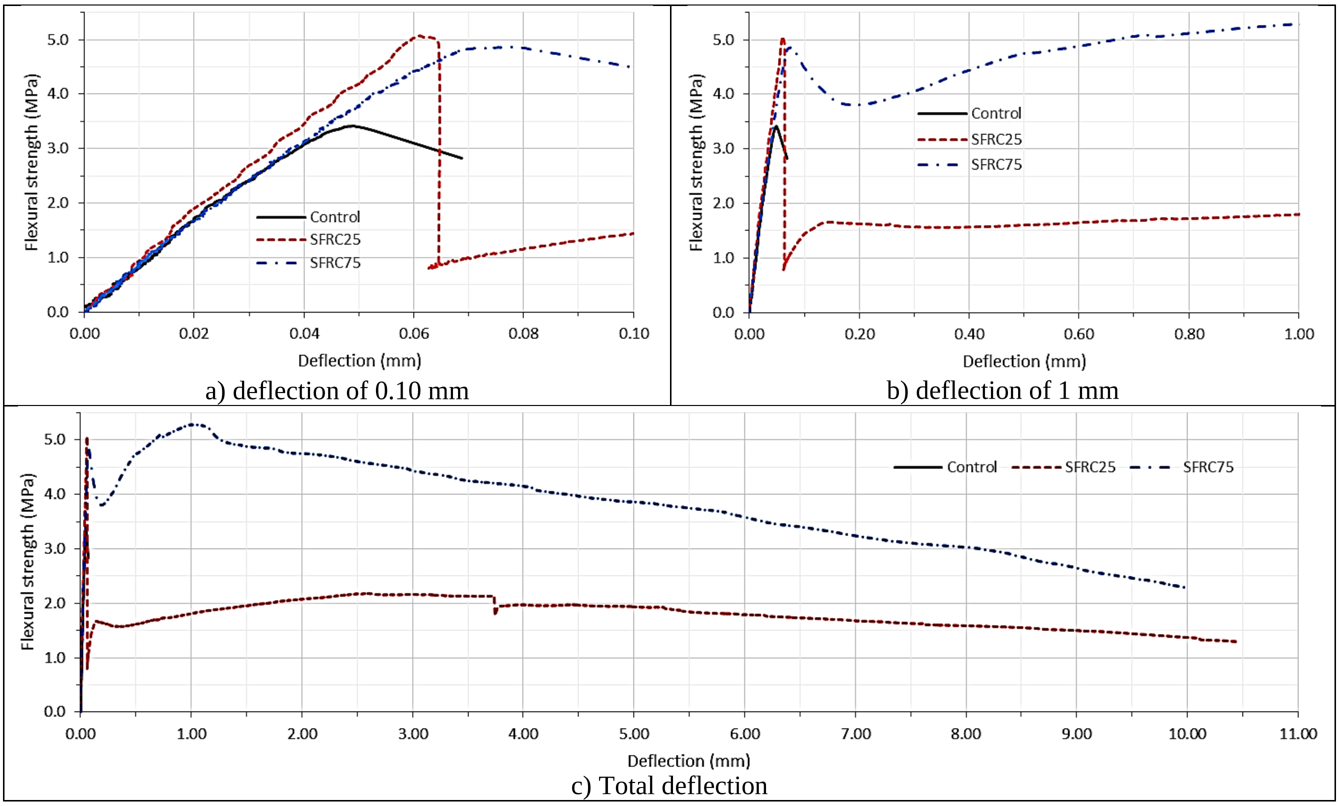

a) deflection of 0.10 mm

b) deflection of 1 mm

c) Total deflection

Figure-3. Best flexural strength versus deflection curves of control and SFRC mixes.

Toughness

The flexure toughness (FT) parameters are presented using different normalized and proposed methods (i.e. ASTM C1018 [21], JSCE [27], and ACI 544 [2] and, Banthia and Trottier [28]). These methods can be reviewed elsewhere (e.g. [26]). However, there are some important aspects to be considered to understand the depicted results next:

a) The first-crack takes place when the curve present its first definite change at the slope (i.e. it is similar to yield point concept of stress-strain curve). The deflection reported at this point is named as first-crack deflection (δ).
b) In the ASTM C1018 method [21], the ratios called toughness indices (I_N) and residual strength ($R_{N,\ M}$) factors are parameters for measure the behavior and retained strength of concrete mix and, these values are related with deflection of 3.0, 5.5, 10.5 and 15.5 times δ.
c) FT factor in the JSCE method [27] is the evaluation of retained strength of concrete mix to a deflection of span/150 (δ_{150}) related to δ.
d) Banthia and Trottier [28] method uses the first flexural strength peak to separate the pre-peak and post-peak region and, in this study, two typical values of deflection of L/150 and L/250 are used to compute the post-crack strength (PCS_m). This method has been recommended to study the influence of fibers on residual flexural strength [10].
e) The toughness index (I_t) in the ACI 544 method [2] is estimated from the areas of the force-deflection curve of fiber reinforced concrete and concrete without fibers within a deflection value up to 1.9 mm.

Table-3 are shown the FT for all mixes and each value is the average of 4 samples (i.e. the average of four (4) molded prism specimens). In the case of the control mix, toughness index values were not computed because there was no post-cracking in this mix. The SFRC25 mix is depicted as the best post-peak behavior for all toughness indices indicated on the ASTM C1018 method (i.e. I_5, I_{10}, I_{20}, I_{30} values of 6.7, 11.7, 22.4 and 34.0, correspondingly). Nevertheless, the SFRC75 mix kept similar values of these indices that correspond to 76%, 84%, 91%,| and 94% of reported I_5, I_{10}, I_{20}, I_{30} values for SFRC25 beams, respectively. Also, residual strength factors reflect this trend with a slight difference, the $R_{5,\ 10}$ and $R_{10,\ 20}$ values for SFRC75 mix attained a 95% and 99% of the values shown by SFRC25 mix and, $R_{20,\ 30}$ is located two percentage points above SFRC25 beams reported value. By contrast, analyzing the JSCE standard method results, the FT of SFRC75 mix (i.e. 3.1) is double the magnitude of the SFRC25 concrete matrix (i.e. 1.5). It is indicated that the JSCE procedure is sensitive to the quantity of fiber in the mixes.

The PCS_m at L/200 of SFRC25 and SFRC75 mixes by Banthia and Trottier [28] are 0.49 and 1.05, correspondingly, which show that SFRC75 had the highest post-crack flexural strength. Moreover, based on the ACI 544 method [2], the toughness index (I_t) of SFRC75 mix is 71.6, which was 114% higher than SFRC25 specimens. This last result complies with ACI 544 method as long as

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the largest amount of fiber proportion mix it has the best post-peak behavior.

Resuming the FT results for all types of concrete mixes, it is clear that SFRC75 that incorporates the largest steel fiber fraction (75 Kg/m^3 or 0.9 % of vol.) has the best ductility properties. In this way, the mechanical properties of SFRC75 may be much more preferred than SFRC25.

Table-3. Flexural toughness assessment of SFRC and Control mixes.

Method	**28 days**			
	Mix ID			
		Control	**SFRC25**	**SFRC75**
ASTM C1018	Area under the curve			
	δ	0.34	0.7	0.6
	3δ	-	1.9	2.9
	5.5δ	-	3.4	5.6
	10.5δ	-	6.5	11.7
	15.5δ		9.8	18.4
	Toughness index (I_N)			
	I_5	-	6.7	5.1
	I_{10}	-	11.7	9.9
	I_{20}	-	22.4	20.5
	I_{30}	-	34.0	32.2
	Residual strength factor ($R_{N, M}$)			
	$R_{5, 10}$	-	99.8	95.0
	$R_{10, 20}$	-	107.0	106.3
	$R_{20, 30}$	-	115.2	117.4
JSCE standard SF-4	δ_{150}	3.0		
	D_f	-	33.6	70.8
	FT	-	1.5	3.1
Banthia and Trottier (1995)	L/m	L/150		
	$E_{post, m}$	-	32.7	69.8
	PCS_m	-	0.50	1.06
	L/m	L/200		
	$E_{post, m}$	-	23.9	51.8
	PCS_m	-	0.49	1.05
ACI 544	I_t	1.0	33.5	71.6

D_f: area to the deflection at span/150; L/m: fractions of span; $E_{post, m}$: post-peak energy values to a deflection of L/m; the area under the curve is presented on N-m,

CONCLUSIONS

In this study, flexural properties and toughness assessment of steel fiber-reinforced concrete are tested and computed for different volume fractions. The next conclusions can be drawn from the experimental results:

a) The SFRC75 mix results in the best bending behavior as the fiber amount governed the increased in the post-cracking (residual) strength. It has an average first cracking flexural strength value of 4.39 MPa and a mean ultimate fractural strength value of 5.23 MPa, which is 1.5 times that of the mix without fibers (2.96 MPa).
b) The average deflection of SFRC75 at the first flexural strength peak gives out 0.08 mm, which is 1.6 times of mix without fibers (0.05 mm).
c) A noteworthy strain hardening performance of SFRC75 mix starting from a deflection of 0.08 up to 1.00 was developed. This property is attributed to the facility to resist cracking of steel fibers.

d) There is not a significant difference in the results of toughness and residual strength indices based on the ASTM C1018 method for the different steel fibers proportion in the concrete specimens. It is seen that this method is normalized by the quantity of fiber added to the mix. However, from JSCE standard, Banthia and Trottier and, ACI 544 methods perspective, results point to the FT increased as the amount of fibers is augmented and, SFRC75 mix presents the highest FT value.
e) Additionally, future experimental studies on cyclic load on SFRC specimens may help to identify the degradation of mechanical properties like the cycle of failure and retained force capacity for different loading paths.

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