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RESEARCH ARTICLE

Effects of fiber strength on fracture characteristics of normal and high strength concrete

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Abstract

The effects of steel fiber strength on the mechanical properties of steel fiber reinforced concretes, such as compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, fracture energy and characteristics length have been investigated within the scope of this study. Steel fibers with two different tensile strength of 1100 and 2000 MPa, and two different volume fractions of 20 and 60 kg/m^3 *were used in the production of normal and high strength concretes. Test results showed that the improvement of mechanical properties and fracture behavior by incorporation of high strength fibers is more significant in case of high strength concrete compared to normal strength concrete. This superior performance can be attributed to the lesser number of broken fibers and increased debonding process with increase of fiber strength.*

Keywords

Steel fiber · Fiber strength · High strength concrete · Mechanical properties · Fracture energy

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1 Introduction

Plain concrete is a brittle material with low tensile strength and strain capacity. This undesired behavior can be improved by inclusion of short discrete fibers into the matrix which prevent or control initiation, propagation, or coalescence of cracks [1]. Steel, glass, carbon, wood, synthetic and natural fibers are used for this purpose. The inclusion of fibers in concrete substantially improves many of its engineering properties such as tensile strength, flexural strength, fracture toughness, resistance to fatigue, impact, wear and thermal shock [2–7]. The most important effect of fiber inclusion is to prevent crack propagation in concrete. The extension and propagation of microcracks that occur due to the internal stresses in concrete are prevented by stress transfer capability of randomly distributed fibers [8–10].

The performance of steel fiber reinforced concrete (SFRC) depends on the properties of concrete and the fibers. The aspect ratio (length/diameter), volume fraction and distribution of fibers influence the performance of SFRC [9, 11]. Fiber efficiency is mainly controlled by the resistance of the fibers to pull-out, which in turn depends on the bond strength at the fiber – matrix interface. The pull-out type of failure is gradual and ductile when compared with the more rapid and possibly catastrophic failure that may occur if the fibers break in tension [12]. Since the high strength concrete is more brittle than normal strength concrete [13, 14] fiber performance in high strength matrix becomes more important parameter. Bayramov et al. [11] have examined the fracture surfaces of SFRC after splitting tensile test and reported that the fibers (tensile strength of 1050 MPa) with the aspect ratio of 65 ($l/d = 65$) were pulled out of the matrix while the fibers with the aspect ratio of 80 ($l/d = 80$) were broken in the concrete matrix strength of 60 MPa. Later, Şahin et al. [15] have investigated the effects of steel fiber strength (tensile strengths of 1100 and 2000 MPa) on mechanical and fracture properties of high strength concretes. They have reported the significant influence of fiber tensile strength on fracture energy and characteristic length of high strength concrete for the aspect ratios of 80 and 85. The effectiveness of tensile strength of steel fibers in crack bridging performance of high strength SFRCs has been shown in this study for these aspect ratios. Although some researchers have already reported the mechanical mismatch between concrete strength and steel fiber tensile strength [15–17], more data are needed for understanding the effects of fiber strength on the enhancement of mechanical properties of high strength concretes. In this study, the effects of the fiber strength on the mechanical properties have been investigated in normal and high strength SFRCs produced with lower aspect ratio ($l/d = 55$) in relatively low (20 and 60 kg/m^3) dosages. The selected fiber dosages are the most common dosages used in the field applications and are sufficient for obtaining ductile behavior according to Balaguru et al. [18]. Test results showed that, most of the mechanical properties of high strength concrete increased by high strength fiber inclusion. The higher mechanical performance via high strength fiber inclusion also provides the possibility of reducing the required fiber content compared to normal strength fibers. This may lead to an economical SFRC design. The reduction of steel fiber dosage by using high strength fibers also helps the reducing the negative effects of steel fiber inclusion on workability.

2 Materials and experimentation

CEM I 42.5 R type Portland Cement (PC) and silica fume (SF) with 92.26% SiO_2 were used in this study. Specific gravity and specific surface (Blaine) values of PC were 3.11 and 374 m^2/kg, respectively. The specific gravity of SF was 2.2 and its specific surface was 20000 m^2/kg (by Nitrogen adsorption). Natural river sand and limestone fines were used as fine aggregates. Their specific gravities were 2.57 and 2.63, respectively and their water absorptions were 2.3% and 1.3%, respectively. As coarse aggregate, crushed limestone was used with a maximum size of 15 mm. The specific gravity and water absorption of crushed limestone were 2.66 and 0.33%, respectively. All of the properties of aggregates were in conformity with the Turkish Standard for Concrete Aggregates (TS 706- EN 12620) [19]. A high-range water reducing admixture (SP) on complying with ASTM C 494 [20] and TS EN 934-2 [21] was used.

Two different cold drawn hooked-end steel fibers with low and high carbon contents were used (Fig. 1). Length, diameter and aspect ratio (l/d) of these fibers were 30 mm, 0.55 mm and 55, respectively. The tensile strength values of low and high carbon fibers were 1100 MPa and 2000 MPa, respectively. These fibers were identified as NSF (normal strength steel fiber) and HSF (high strength steel fiber), respectively.

Ten different concrete mixtures including plain concretes were designed and tested in this experimental study. Two concrete classes (normal and high strength concrete), two fiber dosages (20 and 60 kg/m^3) and two fiber strength (normal and high strength) were the main variables of this study. Table 1 summarizes the mixture designs of plain normal strength concrete (NSC) and high strength concrete (HSC). In case of fiber inclusion, aggregate amounts were reduced in order to maintain 1 m^3 of concrete volume. The concrete mixtures were prepared using a drum mixer with horizontal axis. In the first stage, cement, silica fume and all aggregates were dry-mixed and then, the mixture of water and high-range water reducing admixture has been added to the dry mixture. Finally, steel fibers were carefully scattered to the wet mixture and additional 1 minute of mixing was applied to provide a uniform distribution of fibers. Fresh concrete mixtures were cast into steel molds and vibrated on a vibration table to ensure a sufficient compaction. In order to keep a constant slump value at about 70±10 mm for NSC and 120±10 mm for HSC, the dosage of the superplasticizer has been changed. After demolding, all specimens were stored in lime saturated water at 20° C up to 28 days. The specimens were denoted as: the concrete class (NSC or HSC), the number following the concrete class indicates the fiber dosages as kg/m^3 and the last symbol denominates the fiber strength class (NSF or HSF).

Tab. 1. Mixture proportions of plain concretes (kg/m^3)

	NSC	HSC
Portland cement	300	470
Silica fume	–	55
Natural sand (0-5 mm)	480	396
Crushed limestone (0-3 mm)	545	450
Crushed limestone (5-15 mm)	850	850
Water	180	180
SP	–	3.8

The compressive strength, modulus of elasticity and splitting tensile strength were measured on 100/200 mm cylindrical test specimens, and the flexural strength and fracture energy were determined on 100x100x600 mm notched prismatic beam specimens. At least three specimens were tested for each mixture to obtain the average value.

Flexural tests were performed on notched prismatic specimens using a closed loop deflection-controlled testing machine according to RILEM 50-FMC [22]. All of the beam specimens have the same notch depth, equal to one-third of the beam height. SFRCs were tested at a loading rate of 0.2 mm/min. Load-deflection curves after maximum load cannot be obtained for plain concretes at this loading rate because of the brittle nature of these concretes. Thus, plain concretes were tested at a loading rate of 0.02 mm/min. The specimens were loaded at their mid-span and the clear distance between the simple supports was 500 mm. The fracture energy values (G_F) were determined according to the test procedure of RILEM 50-FMC technical committee [22] and they were calculated by using Eq. (1). Load-deflection curves were used for evaluating the fracture energy. The cut-off point was chosen as 5 mm mid-span deflection for SFRCs. Therefore, the fracture energy levels measured here are based on the area under the complete load-deflection curve up to a specified deflection (5 mm).

$$G_F = \frac{W + mg\delta(L'/L)}{A_{net}} \quad (1)$$

where W is area under the load-deflection curve up to 5 mm, m

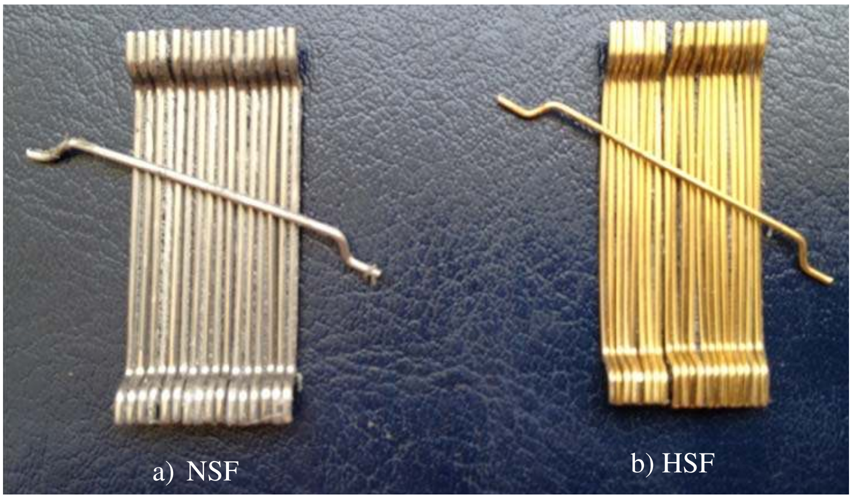

Fig. 1. Steel fibers used in the experimental study

is weight of the beam, g is the gravity acceleration, δ is the final deflection of the beam (5 mm for in this work), L and L' are length and span length of the beam, respectively and A_{net} is the net cross-sectional area of the beam. Similar method in order to calculate the fracture energy of SFRCs also has been used by various researchers [11, 15].

The toughness indexes were calculated according to ASTM C1018 [23]. ASTM C1018 describes the I_5, I_{10} and I_{20} toughness indexes to identify the pattern of material behavior up to the selected deflection criteria. These indexes were calculated as the ratio of the area under the load-deflection curve up to 3, 5.5 and 10.5 times the first crack deflection divided by the area up to the first crack deflection, respectively. Balaguru et al. [18] suggest the using of I_{30}, I_{50} and I_{100} rather than I_5 and I_{10} for the evaluation of fiber reinforced concrete. Thus, these toughness indexes were also determined by using the areas under the curves up to 15.5, 25.5 and 50.5 times the first crack deflection value, respectively.

The characteristic length (l_{ch}) is an index representing the brittleness of concrete, proposed by Hillerborg et al. [24] (Eq. (2)). This index is a function of G_{F}, tensile strength (f_{t}) and elasticity modulus (E_{c}).

$$l_{\text{ch}} = \frac{G_{\text{F}} E_c}{f_t^2} \tag{2}$$

3 Results

The fresh state properties of mixtures and the effects of steel fiber tensile strength on the compressive strength, splitting tensile strength, flexural strength, fracture energy, toughness indexes and characteristic length values of concretes are discussed below.

3.1 Fresh state properties

Fresh state properties of all mixtures are presented in Table 2. Not surprisingly, fiber inclusion caused to a greater amount of SP demand compared to plain concrete mixtures due to the negative effect of steel fibers on workability. The unit weight of fresh concretes somewhat increased with the increasing steel fiber content.

3.2 Compressive strength, elasticity modulus and splitting tensile strength

Table 3 shows the test results of the compressive strength and elasticity modulus values of all the concretes. The average 28-day compressive strength of plain NSC and HSC were found as about 35 and 81 MPa, respectively. According to Neves and Fernandes de Almeida [25], the influence of fibers on the compressive strength may be seen as the balance between positive effect of microcrack bridging and negative effect of additional voids caused by the fiber inclusion. If the fibers are stiff enough, high numbers and well bonded to the matrix, they can prevent the microcrack developing. On the other hand, fiber addition causes some perturbation of the matrix, which may result fiber blockage and formation of voids. These voids can be seen as defects where microcracking starts. In the present study, no significant compressive strength changes were observed for NSC and HSC series with the fiber inclusion independent from the fiber strength and dosage. Nevertheless, it was reported that the addition of steel fibers into concrete may have a positive effect on increasing ductility rather than the compressive strength [25]. Fibers control crack opening at macro level. This leads to increase the energy absorbing capacity of the composite.

Increase in fiber dosage and fiber strength has no effect on the modulus of elasticity of NSC and HSC as shown in Table 3, maybe due to the low dosages of steel fiber inclusion. Some researchers reported increase in modulus of elasticity with the fiber inclusion while some others reported decreasing values [26, 27]. Elasticity modulus increase with fiber inclusion can be attributed to the higher elasticity modulus of steel fiber and the decrease of shrinkage cracks owing to the fiber arresting the cracking. On the other hand, decrease in modulus of elasticity can be explained by the fibers parallel to the load directions which can act like voids, and the eventual additional voids caused by the fiber addition.

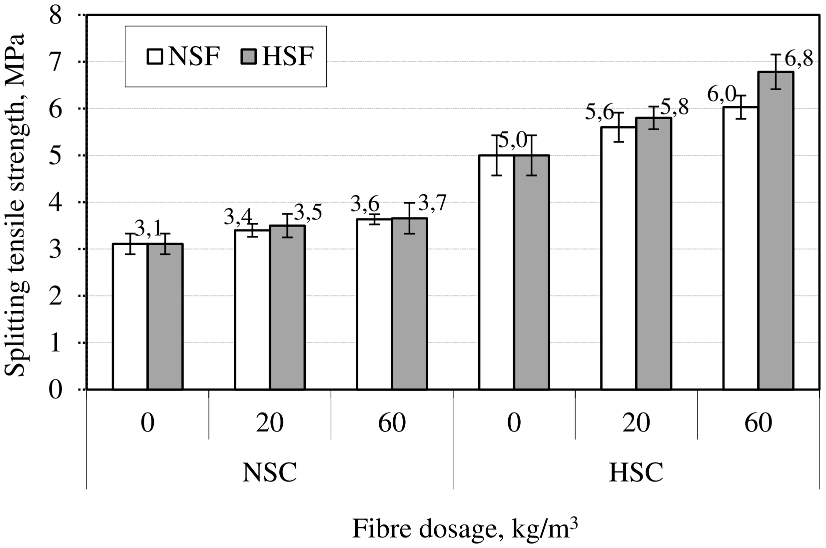

Fig. 2. The influence of fiber strength and content on the splitting tensile strength of concretes (the error bars show ± standard deviation)

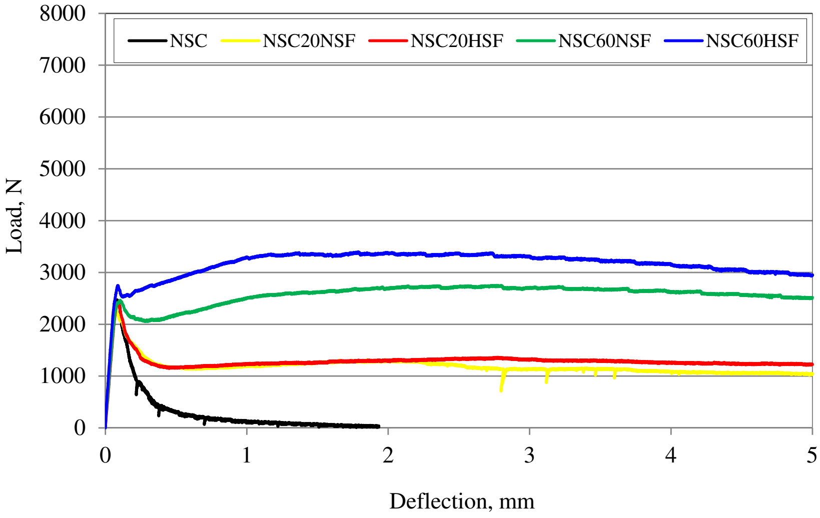

Fig. 3. Load – mid-span deflection curves of notched NSC

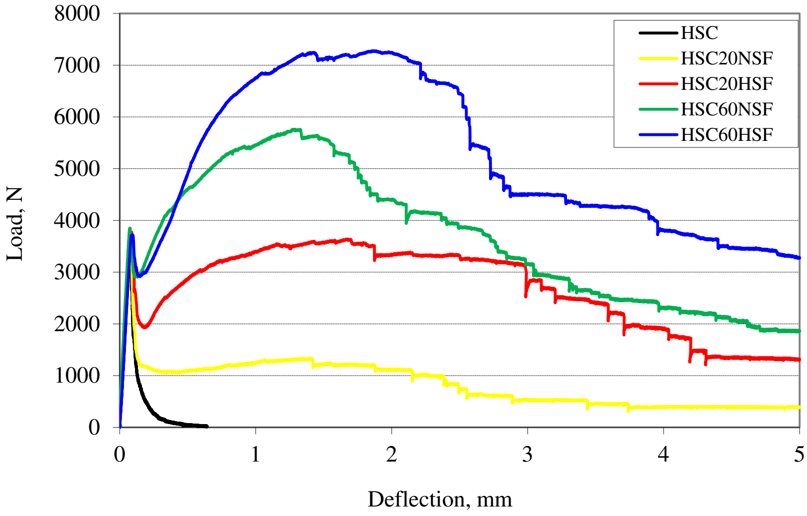

Fig. 4. Load – mid-span deflection curves of notched HSC

Tab. 2. Fresh state properties of concretes

	SP (kg/m^3)	Slump (mm)	Air content (%)	Unit weight (kg/m^3)
NSC	–	60	1.2	2374
NSC20NSF	1.3	80	0.8	2384
NSC20HSF	1.3	80	0.9	2389
NSC60NSF	2.6	80	1.2	2437
NSC60HSF	2.6	70	1.1	2428
HSC	3.8	125	1.9	2414
HSC20NSF	5.4	130	1.6	2431
HSC20HSF	5.4	125	1.4	2436
HSC60NSF	6.3	130	1.5	2476
HSC60HSF	6.3	120	1.3	2463

Tab. 3. Compressive strength and elasticity modulus of concretes

	Compressive strength (MPa)	Elasticity modulus (GPa)
NSC	35.5 (2.3)	26.2 (1.6)
NSC20NSF	36.4 (0.9)	27.3 (1.9)
NSC20HSF	36.2 (0.6)	27.9 (0.8)
NSC60NSF	36.6 (1.3)	24.9 (1.4)
NSC60HSF	36.1 (0.7)	25.2 (1.7)
HSC	81.2 (4.7)	41.6 (3.3)
HSC20NSF	81.1 (2.6)	40.6 (2.8)
HSC20HSF	82.0 (2.3)	42.0 (2.5)
HSC60NSF	80.4 (1.9)	39.8 (2.1)
HSC60HSF	81.2 (1.7)	41.0 (1.8)

(Standard deviations are given in parentheses.)

Splitting tensile strength of concretes increased parallel to fiber dosage and fiber strength as shown in Fig. 2. The effect of steel fiber strength to splitting tensile strength of concretes was more significant for HSC series. For example, increase of splitting tensile strength for NSC was about 16% and 19% for NSF and HSF at 60 kg/m^3 steel fiber dosage, respectively. These values were 20% and 36% for HSC series at same fiber dosage, respectively. Inspection of fractured surfaces of high strength concretes showed NSFs were generally broken into two parts. However, HSFs were generally pulled out from the matrix without breaking.

Increasing of splitting tensile strength of SFRC (in spite of no significant change in compressive strength) resulted in an increase of tensile strength/compressive strength ratio with the increasing of fiber volume and fiber tensile strength.

3.3 Load-deflection relationship

Load versus mid-span deflection curves of notched prismatic samples prepared from different NSC and HSC are presented in Fig. 3 and 4, respectively. Flexural load–deflection curves were drawn using with one specimen graph that represents closest to the average mechanical performance. The behavior of the concretes changed dramatically with fiber inclusion. Higher fiber content and fiber strength resulted in much higher load-retaining capacity at larger deflections. At constant fiber dosage, load-retaining capacities of composites with NSC matrix were higher than HSC matrix had composites. However, in the case of HSF reinforced composites, the retaining load value at 5 mm deflection was higher for HSC matrix compared to NSC.

All test series with 60 kg/m^3 steel fiber exhibited deflection-hardening behavior that generates a higher load carrying capacity behind the first cracking. HSC with 20 kg/m^3 HSF was also exhibited this behavior. Deflection-hardening materials are useful in structural applications where bending prevails [28]. Load carrying capacity, deflection correspond to ultimate load and ultimate deflection levels of plain concretes increased significantly with the increase of fiber volume fraction and fiber strength. The descending branch of the flexural load-deflection curves tended towards gently after maximum load for high steel fiber volume and high steel fiber strength. High load carrying capacity after the peak load indicates improved toughness and the reinforcing effect of the steel fibers. Sudden load drops were observed in the descending branch of steel fiber reinforced concretes for both fiber strengths. This behavior is related to the broken of the fibers and/or pulled out of fibers from the matrix. Similar behavior was also reported for ultra-high performance fiber reinforced composites [29, 30].

HSC series exhibited higher first crack load values compared to NSC series. However, the post-peak drop is steeper for high strength concrete as shown in Figures 3 and 4. This behavior was also reported by Balaguru et al. [18] and higher fiber volume fractions were advised for HSCs due to its more brittle post-peak failure pattern. A smoother drop of post-peak load has been observed in case of HSF usage compared to NSF. In other words, inclusion of high strength fibers improves the brittle post-peak failure behavior of the composites.

3.4 Flexural strength, Fracture energy and Characteristic length

Flexural strength values of all the concretes tested in this research are presented in Fig. 5. The influence of fiber strength to flexural strength of composites was negligible at 20 kg/m^3 fiber dosage. Nevertheless, for 60 kg/m^3 fiber dosage, flexural strength increase of NSCs reached to 25% and 41% for NSF and HSF, respectively. These increases were more remarkable for HSCs, as 51% and 104%, respectively. The fracture process of SFRC consists of progressive debonding of fibers, during which slow crack propagation occurs. Final failure occurs due to unstable crack propagation when the fibers pull out and the interfacial shear stresses reach the ultimate bond strength. The increase in flexural strength can be attributed to the bonding and load carrying capacity of fibers following matrix cracking [26]. In case of high strength fiber, fibers are capable of carrying higher loads. Thus, flexural strength of HSF reinforced high strength concretes increased significantly.

There is a need for development of high energy absorbing materials that will mitigate the hazards for structures subjected to dynamic forces, such as seismic, impact, and blast. Thus, comparing energy absorption capacity provides useful information for such applications [31]. The effect of fiber strength and content on energy absorption capacity has been illustrated in Fig. 6 using fracture energy values. Hillerborg et al. [24] introduced the concept of fracture energy to define the softening behavior of concrete. The fracture energy (G_F) is the energy needed to develop a crack completely and it is one of the important material properties in the design of concrete structures. On contrary to the other mechanical properties, the fracture energy of plain HSC was found lower than plain NSC, as indeed would be expected. This phenomenon can be explained by the fracture surface of these concretes A tortuous surface was observed on the fracture surface of NSC in contrast to flat and smooth surface of HSC. As the aggregates are stronger than the matrix in NSC, cracks run around the aggregates following a characteristic load. Usually a damaged band with a width of about twice the maximum diameter of the aggregates is formed at the final stage. Due to the mechanical interaction between aggregates and matrix, the fracture energy of the composite material becomes considerably higher than the fracture energies of both the aggregates and the matrix. However, cracks in HSC may run through the aggregates since the mechanical properties of the matrix and aggregates are quite similar. A comparatively narrow crack band forms in case of HSC. As expected the maximum load increases however the high strength material reacts in a more brittle manner with a lower fracture energy in plain HSC [32].

The greatest positive effect of fiber inclusion and fiber strength has been observed in energy absorption capacity. The fracture energy of 60 kg/m^3 steel fiber reinforced NSC is about 17 times and 19 times higher than plain concrete for NSF and HSF, respectively. These increases were 32 times and 53 times for steel fiber reinforced HSC, respectively. These significant increases in fracture energy can be attributed to the ability of the steel fibers to arrest cracks at both micro- and macro-levels. At micro-level fibers inhibit the initiation of cracks, while at macro-level fibers provide effective bridging and impart sources of toughness and ductility [33]. The increase in the value of the flexural fracture toughness can be attributed to the fiber pull-out and fiber debonding in the fracture process. However, fiber pull-out appears to be the most significant process concerning fracture behavior of cement based composites. The increase in fracture toughness with increasing fiber volume fraction stems from a great number of fibers forming a bridge in the crack and a more tortuous crack propagation path [26]. And increase in fracture toughness with fiber strength is related to the increase of fiber debonding process.

Visual examination on fracture surfaces after the flexural test showed that some fibers were broken while the others were pulled-out from the matrix. In case of steel fiber reinforced NSC, most of the fibers were pulled out form the matrix for both fiber type. However, this behavior was considerably different for HSC case. Most of the fibers were broken and a small part of the fibers were pulled out for NSF. However, the amount of broken fibers was very low and the dominant failure type was pull-out the fibers in case of HSF. Similar results were also reported by Şahin et al. [15]. Debonding and pulling out process of the fibers require more energy; this can be achieved by using HSF in HSC. This positive effect was more pronounced at higher fiber contents in this research.

The toughness indexes of NSCs and HSCs are given in Fig. 7 and 8, respectively. At a constant fiber dosage, toughness indexes of HSC are generally lower than NSC in case of NSF usage. However, in case of HSF usage, toughness indexes of HSC exceed the indexes of NSC. The toughness indexes at a given fiber dosage for NSC are similar for NSF and HSF. Nevertheless, significantly higher toughness indexes in HSC are obtained for HSF compared to NSF. The differences between the mixtures are more marked for toughness indexes at large deflections such as I_{50} and I_{100}. Thus, indexes for higher deflection should be used for the evaluation of SFRCs rather than I_5, I_{10} and I_{20} as advised by Balaguru et al. [18].

Fig. 9 shows the characteristic length values of NSC and HSC according to their fiber strength and fiber contents. As shown in Fig. 9, in all cases NSC have a higher characteristic length compared to HSC, meaning that brittleness increases with the increasing of concrete strength. The inclusion of high strength fibers resulted in higher characteristic length values especially for HSC case with high fiber contents, indicating that the concrete becomes more ductile. However, for a given fiber dosage and fiber strength, characteristic length of HSCs were lower than NSCs due to their higher tensile strength values. The improve-

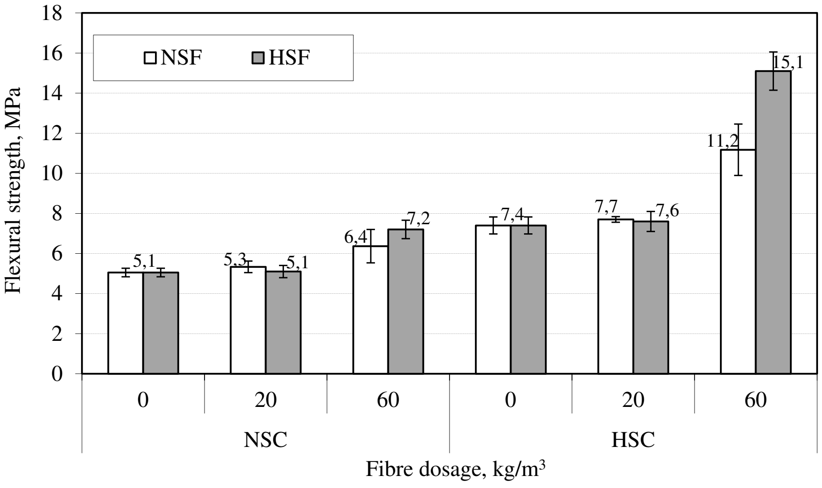

Fig. 5. The effect of fiber strength and content on flexural strength of concretes (the error bars show ± standard deviation)

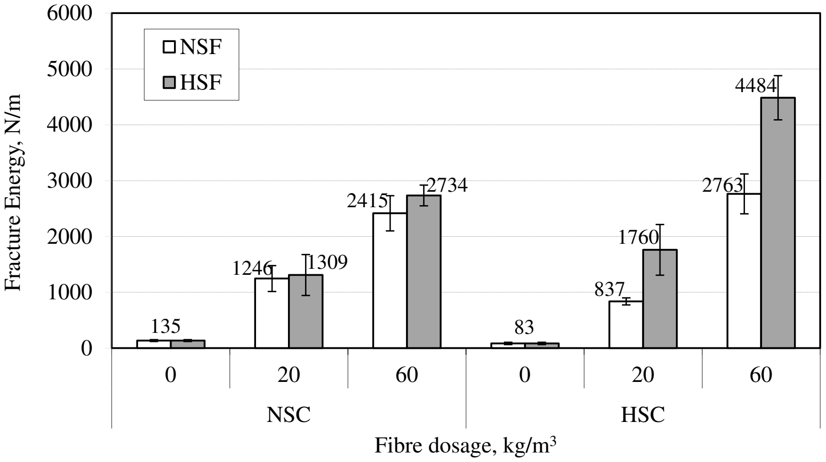

Fig. 6. The effect of fiber strength and content on fracture energy of concretes (the error bars show ± standard deviation)

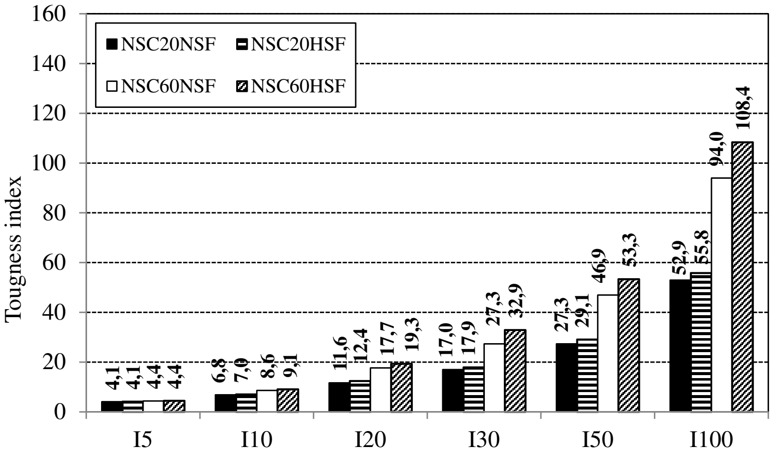

Fig. 7. Toughness indexes for NSC

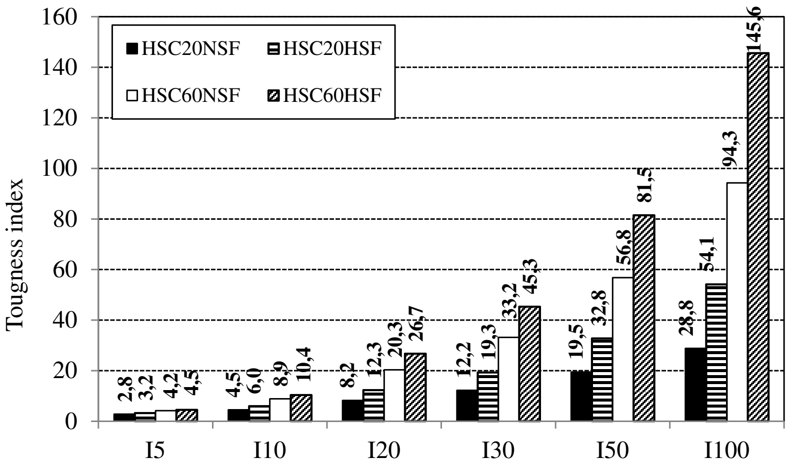

Fig. 8. Toughness indexes for HSC

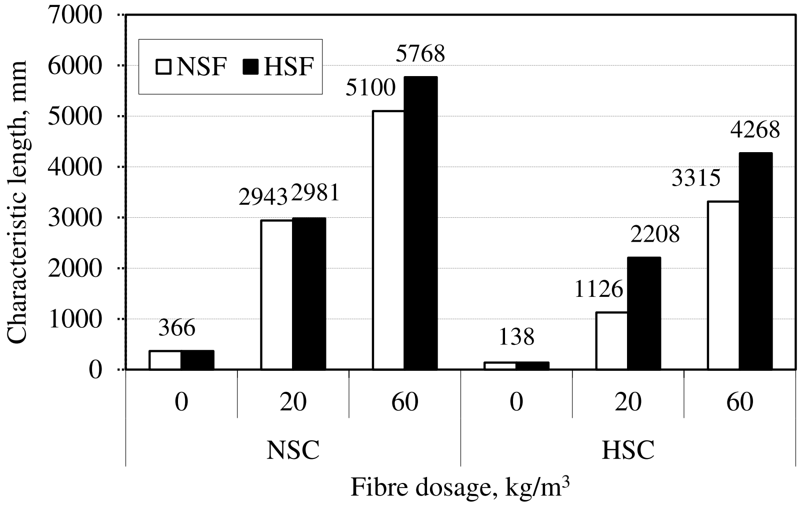

Fig. 9. The effect of fiber strength and content on characteristics length of concretes

ment of characteristic length with fiber strength was considerably lower compared to fracture energy and toughness indexes owing to the considering of tensile strength of concrete in the calculation of characteristic length.

4 Conclusions

Based on the experimental results of this investigation the following conclusions can be drawn:

- The mechanical mismatch between steel fibers and concrete have a significant role in fracture behavior of steel fiber reinforced concretes. For high strength concrete, usage of high strength steel fiber with a tensile strength of 2000 MPa recommended according to the test results. However, high strength steel fiber usage seems to be unnecessary for normal strength concrete.
- Splitting tensile strength, flexural strength, fracture energy and toughness indexes of the steel fiber reinforced high strength concrete have been significantly improved by fiber strength. The improvement of mechanical properties and fracture behavior of high strength concrete by using high strength fibers is related to the lesser number of broken fibers and increased debonding process.
- As a general conclusion, high strength steel fibers can be used preferably in high strength fiber reinforced concrete in two ways. If high strength steel fibers are added with the same dosage of normal strength fiber, flexural performance of composites improves significantly; in this case they act as mechanical performance developer. The other way is the reduction of steel fiber dosage compared to normal strength fibers. In this case, similar mechanical performance with normal strength fiber can be obtained by inclusion of less amount of fibers. This provides the production of a more economical fiber reinforced concrete due to the reduction of fiber dosage. Besides, it improves the workability of concrete at a constant superplasticizer dosage or it can reduce the superplasticizer dosage in case of constant workability.

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