Journal of New Approaches in Civil Engineering
(ISSN PRINT: 2588-6886) -(ISSN ONLINE: 2588-7122)-Vol.2, No.2, Pages: 49-64

Effects of Fiber Volume Fraction and Aspect Ratio on Mechanical Properties of Hybrid Steel Fiber Reinforced Concrete

Mohammad Jamshidi Avanaki[1], Mohammad Abedi[1], Abdollah Hoseini[1*],

Mohammad Sadegh Maerefat[1]

[1] Ph.D. Candidate, Department of Civil Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran.
[1] M.Sc., Department of Civil Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran.
[1*] Associate Professor, Department of Civil Engineering, Faculty of Engineering, University of Tehran, Iran (hosseiniaby@ut.ac.ir)
[1] Professor, Department of Civil Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran.

ABSTRACT

In recent years, a new type of fiber reinforced concrete (FRC), called hybrid FRC, comprised of fibers of the same material but with different geometry has been developed. The aim of this paper is to investigate the influence of volume fraction and aspect ratio of steel fibers on the basic engineering properties of hybrid steel fiber reinforced concrete. To this end, steel fiber reinforced concrete composites, comprised of different combinations of fiber volume fraction and fiber size/shape, are experimentally tested and compared in terms of compressive, splitting tensile strengths and flexural toughness by four-point bending tests. The results indicate that both micro and macro size steel fibers generally improve various engineering properties of concrete, despite advantages of one on the other for different mechanical properties. Straightforward relations are proposed relating the significant mechanical properties of hybrid steel FRC to the volume fraction of micro and macro steel fibers in the composite.

Key words: *Hybrid Fiber Reinforced Concrete, Micro Steel Fiber, Macro Steel Fiber, Four-Point Bending Test, Compressive Strength, Splitting Tensile Strength.*

1. Introduction

In the construction industry, concrete is probably the most vastly used material worldwide, mainly due to its relatively low cost and the ability to alter its properties for a wide range of different applications. The properties of a concrete mix can be enhanced by adding various additives or components. In this regard, fibers were introduced to enhance the structural performance of hardened concrete under tensile and flexural actions, commonly known as Fiber Reinforced Concrete (FRC).

Nowadays, fiber reinforced concrete is widely used as a reliable design option in structures such as industrial pavement slabs, shotcrete of tunnels and also in the precast industry (Mobasher 2011). In the past few years, application of fibers as a replacement of traditional reinforcement for different structures under bending and shear forces, namely segmental linings of tunnels, has gained great interest [1, 2, 3]. Fibers of different materials (Steel, Polypropylene, Glass, carbon, etc.) and geometries (length, thickness) are used in fiber reinforced concrete [4, 5, 6]. Different fibers are usually employed to meet different requirements, e.g. various loading conditions [7, 8, 9]. In recent years, research on simultaneously taking advantage of the beneficial effects of different types of fibers by incorporating them into a single concrete mix, has led to the development of new cementations materials, called hybrid FRCs [10, 11]. The enhancement in engineering properties of hybrid composites, composed of two different fiber types has been shown in previous research [12, 13, 14, 15, 4]. Previous studies on hybrid composites were mainly focused on cement paste or mortar. However, research on developing exact proportions and methods for combining various fibers to produce and maximize synergistic response is on the agenda [6, 16].

In one type of hybrid FRC, different sizes of a single type (material) of fibers are combined. Typically, "one would combine large macro-fibers that provide toughness at large crack openings with fine micro-fibers that reinforce the mortar phase and enhance the response prior to or just after cracking." [17].

The aim of this paper is to determine and compare the basic engineering properties of hybrid Steel Fiber Reinforced Concrete (SFRC), comprised of six different combinations of fiber volume fraction and fiber size and shape, in terms of compressive, splitting tensile, and flexural toughness by four point bending tests. The focus of this project was to investigate changes in flexural performance of hybrid concrete composites.

In this paper, hybrid composites of different combinations using 0.3% and 0.5% steel fiber volume content of micro and macro size will be investigated. This paper is part of a comprehensive research program on the application of steel FRC in segmental linings of tunnels. The two fiber volume contents, i.e. 0.3% and 0.5%, was chosen based on previous efforts to possibly replace traditional steel reinforcement with steel FRC in tunnel segments [1, 18].

2. Materials and experimental programs

In this study, two types of steel fibers were used with the following properties: Macro fibers: Hooked ends, 50 mm length with 0.8 mm diameter. Micro fibers: Flattened ends, 13 mm length with 0.17 mm diameter. In Tables 1 and 2, properties of the fibers and their volume content in each hybrid mix are shown, respectively. The used fibers are displayed in Figure 1.

Table 1: Properties of fibers.

Fiber type	Geometry	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile strength (MPa)	Elasticity module (GPa)
Macro steel fiber	Hooked	50	0.80	62.5	1169	210
Micro steel fiber	Smooth	13	0.17	76.5	2100	210

Table 2: Fiber volume fraction in concrete mixes.

Mixture No.	**1**	**2**	**3**	**4**	**5**	**6**
Macro steel fiber ratio (%)	0. 5	3	0.3	0.5	0.5	0.3
Micro steel fiber ratio (%)	-	0.5	0.3	0.5	0.3	0.5

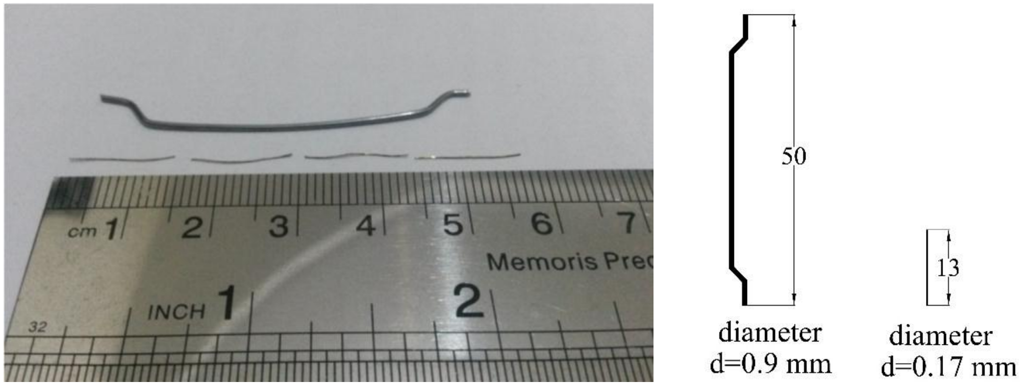

Fig 1. Micro and macro size steel fiber**.**

In all concrete mixes, the following materials and proportions were constantly used (Table 3): 400 kg/m3 of type II Portland Cement, 1172 kg/m3 of natural sand, 631 kg/m3 of 5–19mm gravel and150 kg/m3 of tap water. Oven dried aggregates with allowance for absorption, i.e. 2.9% for sand and 2.0% for gravel, was used. The target 28-day mean compressive strength was set at 40MPa, typical of mixes used for tunnel lining segments.

Table 3: Materials used for all concrete mixtures.

Portland Cement type II (kg/mP^{3}P)	Natural sand (kg/mP^{3}P)	Gravel (kg/mP^{3}P)	Water-Cement ratio
400	1172	632	0.375

In the mixing process, the aggregates followed by cement went into the drum first and were dry mixed for around a minute before adding water. After about 4 minutes, the steel fibers were added and the mixing process continued for a further 2 minutes to assure the proper dispersion of the fibers within the mix. Each concrete mix was sufficient for casting the following specimens (Figure 2):

a- Two 150 mm cubes for compressive testing at 28-days.

b- Two 150×300 mm cylinders for the splitting tensile strength tests.

c- Two 150×150×600 mm beams for the four-point bending test over a span of 450 mm. Flexural behavior of the hybrid composites were studied by 4-point bending tests according to the Japanese Standard/Institute [19].

Fig 2. Specimens of the experimental tests.

The concrete specimens were cured for 28 days before carrying out the tests. Cube and cylinder specimens were tested for compressive and tensile strength, respectively, according to the ASTM standard [20].

Load–deflection curves were determined by loading the 28-day prism specimens as shown in Figure 3. Load and deflection values were measured using a servo controlled hydraulic machine and a Linear Variable Displacement Transducer (LVDT), respectively (Figure 3). Displacement control is the recommended loading strategy to yield complete load deflection relationships, i.e. including post peak regions. The Japanese Standard Test Method JSCE-SF4 recommends a deflection rate in the range of 1/1500 to 1/3000 of the span per minute (Japan Concrete Inst. 1984). This corresponds to 0.20–0.30 mm per minute for the 150×150×600 mm (span of 450 mm) specimens. A deflection rate of 0.25 mm per minute was used. The specimens were loaded until the deflection was greater than 1/150×span of specimen, i.e. more than 3 mm for 150×150×600 specimens. Under 4 point bending tests, all prism specimens should fail inside the middle third of the span in the tension surface (Japan Concrete Inst. 1984).

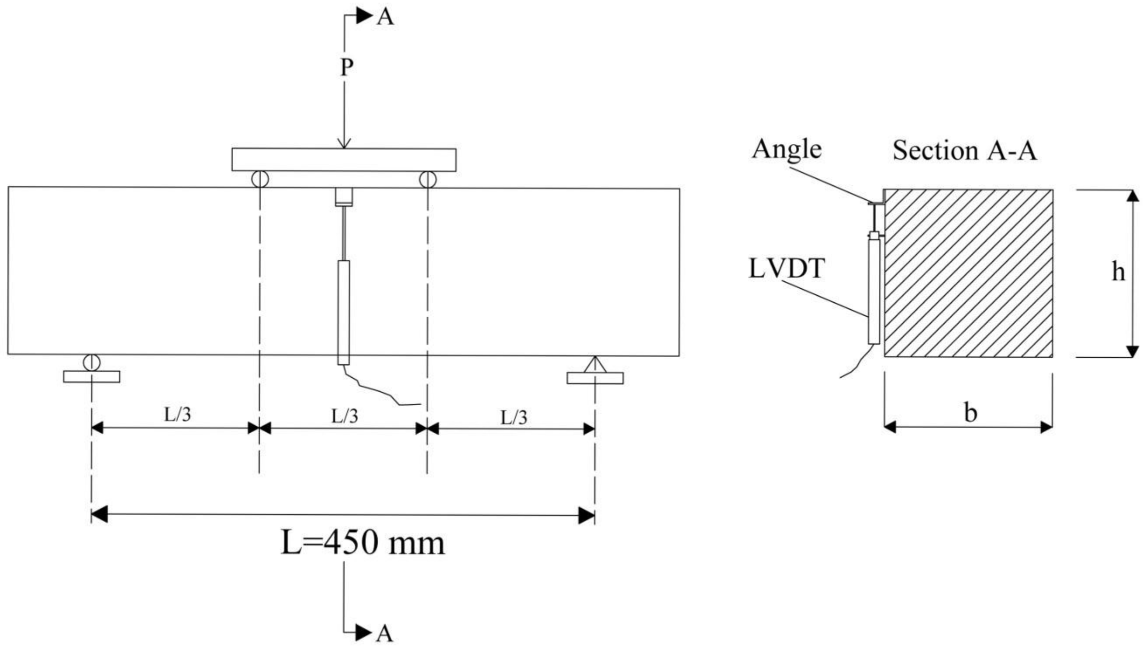

Fig 3. Setup for four-point loading.

3. Results

3.1. Compressive strength

Actual and normalized mean compressive strength values of SFRC mixtures at 28 days along with slump values are listed in Table 4. The compressive strength values are normalized to the compressive strength of plain concrete for each mix. The values presented in parentheses are the corresponding values of coefficient of variation of the results (*CV*), given in percentages. The 28-day mean strength of plain concrete was about 40 MPa. The workability of fresh plain concrete, measured by the slump test, before addition of fibers was almost the same in all mixtures (in the range of 10-12cm) but reduced significantly after addition of fibers, i.e. from 40 to 60% in different mixtures. Nevertheless, this reduction does not imply a problem in terms of production since high energetic vibration is induced in to the molds during the casting.

For single fiber type mixes, addition of steel fibers to plain concrete increased the compressive strength by about 6 and 28MPa corresponding to 15% and 71%, for concrete mixes 1 and 2, respectively. The increase in compressive strength was higher for hybrid composites, ranging from14 to 25MPa (34% to 63%), corresponding to concrete mixes 5 and 6, respectively.

By adding 0.5% volume fraction of micro fibers to concrete mix 1, the compressive strength increased by 14MPa. Adding 0.2% volume fraction of both fibers to concrete mix 3, increased the compressive strength only by 2 MPa.

Table 4: Compression and slump characteristics.

Mix	Macro steel fiber ratio (%)	Micro steel fiber ratio (%)	Slump (cm)	Compressive strength (MPa)	Normalized compressive strength (MPa)
1	0.5	-	7-9	46.44 (4.82)	1.15
2	-	0.5	5-7	68.83(5.91)	1.71
3	0.3	0.3	5-7	58.25 (0.70)	1.45
4	0.5	0.5	4-6	60.83 (3.29)	1.51
5	0.5	0.3	5-7	54.02 (2.49)	1.34
6	0.3	0.5	5-7	65.61 (2.25)	1.63

3.2. Splitting tensile strength

Mean tensile strength values and corresponding percentage of coefficient of variation (*CV*) of the concrete mixes, along with normalized strength values, are displayed in Table 5. Based on the results obtained, macro steel fibers generally increase the tensile strength while the effect of micro fibers is more evident. By adding 0.5% micro fibers, i.e. concrete mix 2, the tensile strength increases 52%, compared to plain concrete while adding the same dosage of macro fibers (concrete mix 1), leads to a tensile strength rise equal to nearly half this amount. As for the hybrid composites, incorporating 0.5% micro and 0.5% macro fibers, i.e. concrete mix 4, increase the tensile strength nearly 96%. Addition of a further 0.2% of both fibers to concrete mix 3, causes a 60% increase in tensile strength. For a constant dosage of 0.5% macro fiber, adding micro fibers up to 0.5% of volume content causes a tensile strength increase of about 50%. While for the same dosage of micro fiber kept constant in a mix, a 0.5% addition of macro fibers leads to 28% rise in tensile strength.

Table 5: Tensile Strength characteristics.

Mix	Macro steel fiber ratio (%)	Micro steel fiber ratio (%)	Tensile strength (MPa)	Normalized tensile strength (MPa)
1	0.5	-	4.23 (4.24)	1.24
2	-	0.5	5.21 (6.86)	1.52
3	0.3	0.3	4.66 (0.64)	1.36
4	0.5	0.5	6.69 (4.61)	1.96
5	0.5	0.3	5.49 (3.29)	1.60
6	0.3	0.5	5.04 (2.21)	1.47

3.3. Flexural strength

From the results of the four-point bending tests, the mean flexural strength (f_b) for each concrete mix was determined from the failure load, i.e. the peak value in the load–deflection relationships, using the following equation:

$$f_b = \frac{PL}{bh^2} \tag{1}$$

where f_b is the flexural strength in *MPa*, *P* the failure load in *N*, *L* the specimen span in mm (in this case L = 450 mm), *b* and *h* are the width and height of the specimen's cross section in mm, relatively. The main benefit of using fibers was the improved ductility in the post-crack region, determined exclusively from load–deflection measurements. Flexural strength values of the concrete mixes are tabulated in Table 6.

Mean load–deflection relationships or curves, based on the LVDT's recorded values, for all the beam specimens are illustrated in Figures 4-7. In the following figures, the "Mic." and "Mac." abbreviations stand for Micro and Macro fiber, respectively. These load–deflection relationships were then used to determine flexural toughness and equivalent flexural strengths.

Table 6: Flexural strength of concrete mixes.

Mix	Micro steel fiber ratio (%)	Macro steel fiber ratio (%)	Failure load (tonf)	Flexural strength(MPa)
1	-	0.5	9.06	12.08
2	0.5	-	11.61	15.48
3	0.3	0.3	11.86	15.81
4	0.5	0.5	15.67	20.89
5	0.3	0.5	13.04	17.38
6	0.5	0.3	11.93	15.90

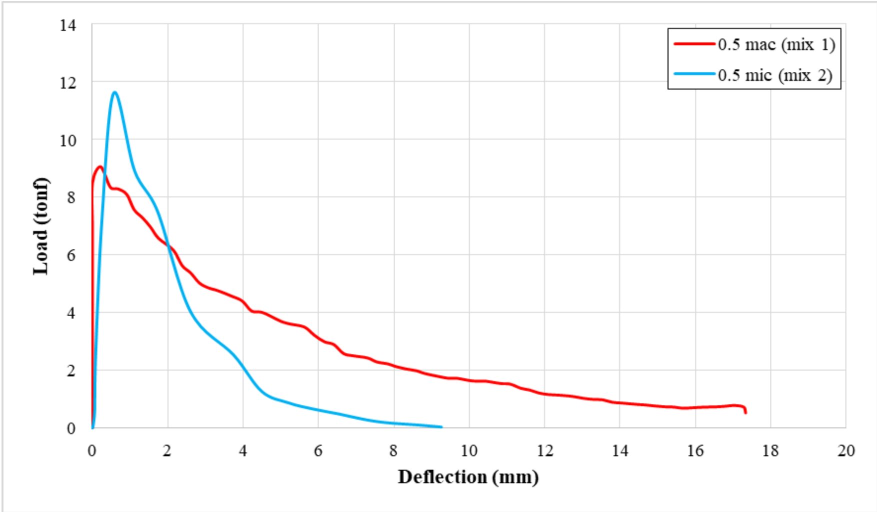

Fig 4. Load- deflection curve for mix 1 and mix 2.

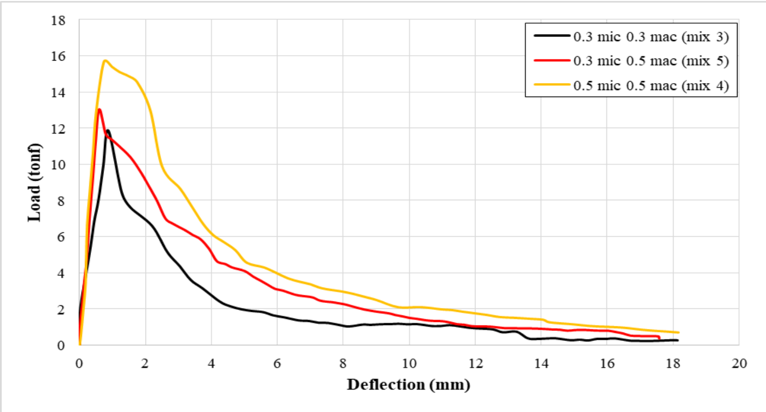

Fig 5. Load-deflection curve for mix 3, mix 5 and mix 4.

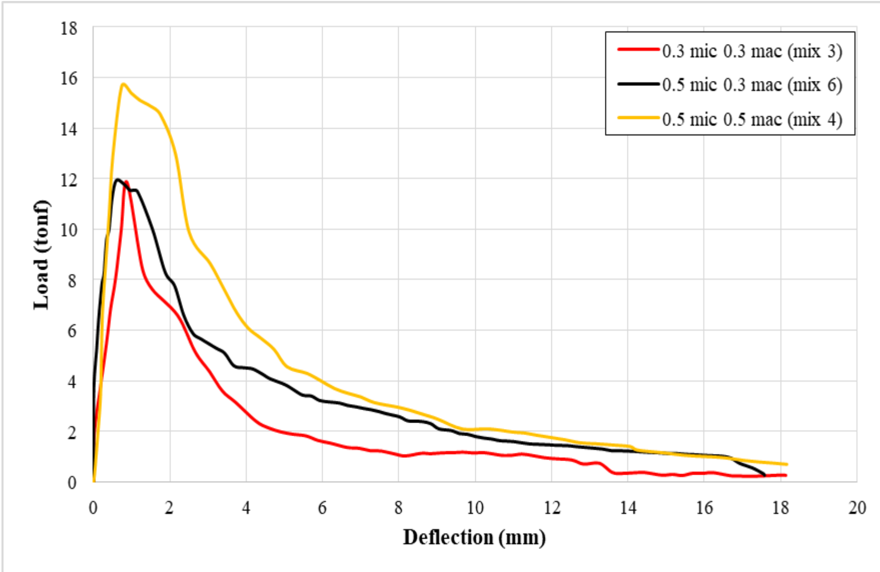

Fig 6. Load-deflection curve for mix 3, mix 6, and mix 4.

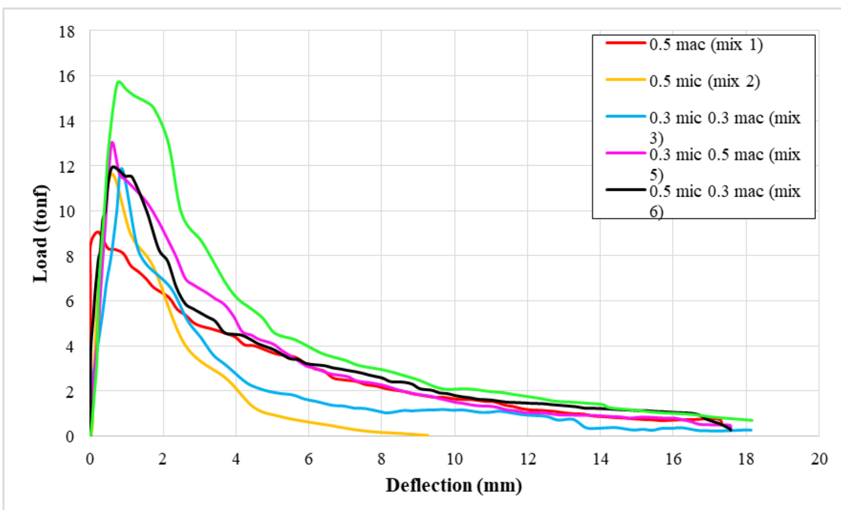

Fig 7. Load deflection curve for all concrete mixes.

By adding 0.5% micro fibers (concrete mix 2), the flexural strength is around 3.5 MPa higher than the mix with the same dosage of macro fibers, i.e. concrete mix 1, but shows less residual post-crack strength. As for the hybrid composites, incorporating 0.5% micro plus 0.5% macro fibers in a concrete mix, i.e. concrete mix 4, increases the flexural strength nearly 5.5 MPa and 9 MPa, compared to the same volume content of individual mixes of micro and macro size fibers, respectively. For a constant dosage of 0.5% macro fiber, adding micro fibers up to 0.5%

Journal of New Approaches in Civil Engineering
(ISSN PRINT: 2588-6886) -(ISSN ONLINE: 2588-7122)-Vol.2, No.2, Pages: 49-64

of volume content, causes a flexural strength increase of about 65%. While for the same dosage of micro fiber kept constant in a mix, a 0.5% addition of macro fibers leads to 35% rise in flexural strength. Thus, it can be concluded that micro fibers play a more significant role in increasing the flexural strength of hybrid composites.

By comparing residual post-crack strength and deflection of different hybrid mixes, hooked end macro size fibers have a more distinct influence in increasing the post-crack properties of concrete than flattened end micro size fibers (especially in larger deflections). This can be put to the fact that in the post-crack region, where cracks tend to expand and open up, macro size hooked end fibers create a more effective bridging mechanism to limit crack propagation, due to their greater length and hooked shaped ends.

3.4. Flexural toughness

Flexural toughness (T_b) is the term used to quantify the energy absorbing capability of concrete; it is the area under the load–deflection curve of concrete in flexure (Figure 8) up until a deflection of 1/150 times the span ($_{\delta}R_{tb}R$), which corresponds to 3mm for 150×150×600mm specimens. The flexural toughness depends on the dimensions of the specimen, affecting the total flexural load it can carry. Values of flexural toughness of the concrete mixes are given in Table 7, and for better insight graphically represented in Figure 8.

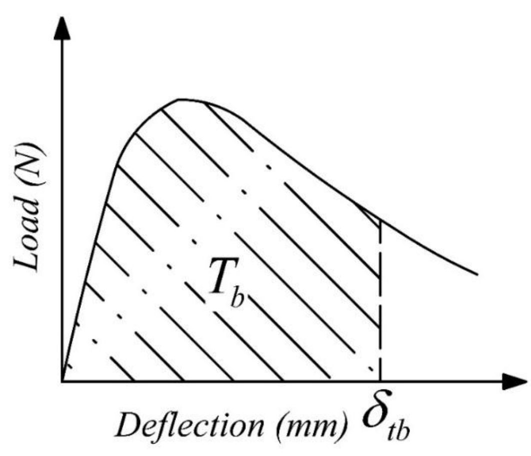

Fig 8. Flexural Toughness definition.

Table 7: Flexural toughness of concrete mixes.

Mix	Micro steel fiber ratio (%)	Macro steel fiber ratio (%)	Flexural toughness (J)
1	-	0.5	210
2	0.5	-	209
3	0.3	0.3	211
4	0.5	0.5	360
5	0.3	0.5	269
6	0.5	0.3	262

Equal volume content of either micro or macro size fibers yielded approximately equal flexural toughness. It can be concluded that in non-hybrid steel fiber reinforced concretes (single type of steel fiber used) flexural toughness is quite independent of steel fiber size. Comparing the single fiber type mixes with the hybrid concrete mix 3, no considerable variation is observable. The highest flexural toughness was for concrete mix 4, which showed the highest tensile strength too. This hybrid composite showed 70% more flexural toughness than either of the non-hybrid concrete mixes 1 or 2.

3.5. Equivalent flexural strength

The Equivalent flexural strength, f_e, is defined using following equation:

$$f_e = \frac{T_b}{\delta_{tb}} \cdot \frac{L}{bh^2} \quad (2)$$

Where f_e is the equivalent flexural strength in *MPa*, R$_b$ Rthe flexural toughness (*J*), R$_{tb}$ Rthe midspan deflection in *mm* (= 3 *mm*) and *L* is the span in *mm*. To obtain f_e, flexural toughness was simply multiplied by (1/$_{\delta tb}$) (· *L bh*/ ^{2})which was a constant value for specimens of the same size. Therefore, it followed the same trends as flexural toughness values for specimens of equal size. Equivalent flexural strength values of the concrete mixes are presented in Table 8.

Table 8: Equivalent flexural strength of concrete mixes.

Mix	Micro steel fiber ratio (%)	Macro steel fiber ratio (%)	Equivalent flexural strength (MPa)
1	-	0.5	9.33
2	0.5	-	9.26
3	0.3	0.3	9.35
4	0.5	0.5	15.98
5	0.3	0.5	11.93
6	0.5	0.3	11.61

3.6. Development of straightforward relations for mechanical properties of SFRC composites

Based on the obtained results, straightforward equations are established to relate the significant mechanical properties of a hybrid SFRC composite to the volume content of micro and macro steel fibers in the composite. These simple relations can help the designer acquire an initial assessment of the anticipated mechanical behavior of the SFRC composite, based only on the specifications of the steel fibers of interest, before conducting complex analyses in the design process. In this regard, polynomial equations are utilized and the corresponding polynomial coefficients are determined (with 95% confidence bounds), resulting in the following equations for compressive strength, splitting tensile strength and flexural toughness (following formula):

$$f_c = 54.33 - 16.63M + 29.96m \quad (3)$$

$$f_t = 6.482 - 13.01M - 2.545m + 16.78M^2 + 14.82Mm \quad (4)$$

$$T_b = 109.1 - 66.73M - 199.7m + 504.3M^2 + 184.2Mm \quad (5)$$

In these equations, f_c and f_t are the compressive and splitting tensile strengths (in *MPa*), respectively. T_b is flexural toughness of the SFRC composite (in *Joules*). Moreover, M and m stand for the volume fraction (in percentage) of Macro and micro steel fibers in the SFRC composite, respectively.

4. Conclusion

The influence of steel fiber geometry and volume content on engineering properties of hybrid steel fiber concrete composites has been investigated. The general results can be summarized as below:

a-Both micro and macro size steel fibers increase the compressive and tensile strength of concrete mixes compared to plain concrete, though micro size fibers being more effective. These beneficial effects are more obvious for hybrid composites.

b- In the load-deflection relationships, as the flexural load increases, the specimen's behavior shifts from the elastic region to its ultimate strength. At this point, its flexural strength is provided by the untracked concrete, and fibers present in the cracked region of its cross section. After reaching its ultimate strength, only the fibers at cross section are present to carry further load.

c- For equal amounts of micro and macro sized fiber, the former plays a more significant role in increasing the ultimate load capacity of the hybrid composite.

d- Micro fibers play a more significant role in increasing the flexural strength of hybrid composites. On the other hand, by comparing residual post-crack strength and ductility of different hybrid mixes, hooked end macro size fibers have a more distinct influence in increasing the post-crack properties of concrete than flattened end micro size fibers (especially in larger deflections).

e- In non-hybrid steel fiber reinforced concretes (single type of steel fiber used) flexural toughness is quite independent of steel fiber size. In hybrid composites, hybridization generally increases flexural toughness, but results vary from negligible up to 70% increase.

Both Micro and Macro size steel fibers generally improve various engineering properties of concrete, despite advantages of one on the other for different mechanical properties. Each fiber size improves certain aspects of a concrete mix. Micro size fibers have a greater effect in increasing compressive and tensile strength, ultimate flexural load capacity and flexural strength prior to and just after cracking. On the other hand, macro size fibers have a more distinct influence in increasing the post-crack performance, due to causing a better bridging mechanism in the concrete composite (especially in larger deflections). Thus, to take full advantage, hybridization is a more preferable option for a steel fiber reinforced concrete mix to be used for practical purposes, such as tunnel lining segments.

Acknowledgment

The authors would like to acknowledge the Construction Materials Institute (CMI) and the Structural Testing Laboratory of the Civil Engineering Department, University of Tehran.

References

[1]- De la Fuente, A., Pablo, P., Ana, B. and Antonio, A. (2012). Experiences in Barcelona with the use of fibres in segmental linings, Tunnelling and Underground Space Technology, 27: 60-71.

[2]- di Carlo, F., Meda, A., Rinaldi, Z. (2016). Design procedure for precast fibre-reinforced concrete segments in tunnel lining construction, Structural Concrete, 17: 747-59.

[3]- Meng, G., Bo, G., Jiamei, Z., Guodong, C. and Qian, Z. (2016). Experimental investigation of the mechanical behavior of the steel fiber reinforced concrete tunnel segment, Construction and Building Materials, 126: 98-107.

[4]- Caggiano, A., Paula, F., Carmine, L., Enzo, M. and Marco, P. (2017). On the mechanical response of Hybrid Fiber Reinforced Concrete with Recycled and Industrial Steel Fibers, Construction and Building Materials, 147: 286-95.

[5]- Li, J., Chengqing, W. and Zhong-Xian, L. (2017). Comparative evaluation of steel wire mesh, steel fibre and high performance polyethylene fibre reinforced concrete slabs in blast tests, Thin-Walled Structures.

[6]- Nehdi, M. L., Manal, F. N., Ahmed, M. S. and Tareq, M. A. (2017). Novel steel fiber reinforced preplaced aggregate concrete with superior mechanical performance, Cement and Concrete Composites, 82: 242-51.

[7]- Sorelli, L. G., Alberto, M. and Plizzari, G. A. (2005). Bending and uniaxial tensile tests on concrete reinforced with hybrid steel fibers, Journal of materials in civil engineering, 17: 519-27.

[8]- Su, Y., Jun, L., Chengqing, W., Pengtao, W., Ming, T. and Xibing, L. (2017). Mesoscale study of steel fibre-reinforced ultra-high performance concrete under static and dynamic loads, Materials & Design, 116: 340-51.

[9]- Ganesan, N., Sahana, R. and Indira, P. V. (2017). Effect of hybrid fibers on tension stiffening of reinforced geopolymer concrete, Advances in Concrete Construction, An Int'l Journal, 5.

[10]-Banthia, N., Yan, C. and Bindiganavile, V. (2000). Development and application of high performance hybrid fiber reinforced concrete, In Proceedings of the fifth international RILEM symposium on fibre-reinforced concrete, 471-80. Lyon, France.

[11]- Ganesan, N., Indira, P.V. and Irshad, P. (2017). RCC frames with Ferro cement and fiber reinforced concrete infill panels under reverse cyclic loading, Advances in Concrete Construction, An International Journal, 5.

[12]- Mobasher, B., and Li, C.Y. (1996). Mechanical properties of hybrid cement-based composites, ACI Materials Journal, 93.

[13]- Mobasher, B. (2011). Mechanics of fiber and textile reinforced cement composites (CRC press).

[14]- Libre, N., Shekarchi, A. M., Mahoutian, M., and Soroushian, P. (2011). Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice, Construction and Building Materials, 25: 2458-64.

[15]- Alberti, M. G., Enfedaque, A., and Gálvez, J. C. (2017). Fibre reinforced concrete with a combination of polyolefin and steel-hooked fibres, Composite Structures, 171: 317-25.

[16]- Zarrin, O. and Khoshnoud, H. R. (2016). Experimental investigation on self-compacting concrete reinforced with steel fibers, Structural Engineering and Mechanics, An International Journal, 59

[17]-Banthia, N., Nandakumar, N. (2003). Crack growth resistance of hybrid fiber reinforced cement composites, Cement and Concrete Composites, 25: 3-9.

[18]- Plizzari, G. A. and Tiberti, G. (2006). Steel fibers as reinforcement for precast tunnel segments', Tunnelling and Underground Space Technology incorporating Trenchless Technology Research, 3: 438-39.

[19]- Japan Concrete Inst. (1984). JSCE-SF4. Standard for flexural strength and flexural toughness, method of tests for steel fiber reinforced concrete, In Concrete library of JSCE, 58-66.

[20]- ASTM. (1993). Annual book of ASTM standards, section 6, vol. 4.02, concrete and aggregates, In. Philadelphia, USA: American Society for Testing and Materials.