Advances in Concrete Construction, *Vol. 10, No. 3 (2020) 257-269*
DOI: https://doi.org/10.12989/acc.2020.10.3.257

Effect of macro and micro fiber volume on the flexural performance of hybrid fiber reinforced SCC

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(*Received June 17, 2020, Revised August 19, 2020, Accepted August 21, 2020*)

Abstract. The aim of this study is to investigate the flexural performance of hybrid fiber reinforced self-compacting concrete (HFRSCC) having different ratio of micro and macro steel fiber. A total of five mixtures are prepared. In all mixtures, the sum of the steel fiber content is 1% and also water/binder ratio is kept constant. The amount of high range water reducer admixture (HRWRA) is arranged to satisfy the workability criteria of self-compacting concrete. Four-point bending test is carried out to analyze the flexural performance of the mixtures at 28 and 56 curing days. From the obtained load-deflection curves, the load carrying capacity, deflection and toughness values are investigated according to ASTM C1609, ASTM C1018 and JSCE standards. The mixtures containing higher ratio of macro steel fiber exhibit numerous micro-cracks and, thus, deflection-hardening response is observed. The mixture containing 1% micro steel fiber shows worst performance in the view of all flexural parameters. An improvement is observed in the aspect of toughness and load carrying capacity as the macro steel fiber content increases. The test results based on the standards are also compared taking account of abovementioned standards.

Keywords: hybrid fiber reinforced; self-compacting concrete; toughness; load carrying capacity; deflection

1. Introduction

Concrete is a brittle material and also has poor toughness. However, the inclusion of randomly distributed fibers into the concrete improve some properties such as ductility, flexural strength, flexural toughness, etc. which depend on the aspect ratio, type and size of the fibers (Kovacs and Balazs 2004, Shah *et al*. 1995, Johnston 2001, Sharma and Bansal 2019). This type of composites are generally known as fiber reinforced cementitious composites (FRCC) which have potential to show higher flexural performance compared to unreinforced concrete. After first crack, the concrete with no fibers immediately fail in tension while in FRCC after initial cracking, deflection-hardening response can be exhibited in bending. This behavior is related with the multiple cracking process that cause an increase in toughness of a material (Hannant 1983).

Most traditional FRCCs that include 0.1-3% short randomly distributed fibers show strain-softening behavior in which the composites fail after the formation of single crack in tension (Zollo 1997). In order to exhibit strain-hardening behavior, the fiber volume fraction must exceed a critical value. To ensure pseudo strain-hardening response with minimum fiber content, it is preferred to aim low critical fiber volume fraction. The critical fiber volume fraction can be calculated by using the parameters including interfacial bond, fiber aspect ratio, matrix toughness and maximum cracking opening (Li 1993). It is related with some factors such as type, distribution and dimension of fibers, strength of matrix and the bond properties between fiber and matrix, etc. (Naaman 2002). FRCC can exhibit deflection-hardening behavior with multiple cracking in flexure but the composites that show deflection-hardening response do not mean that they also exhibit strain-hardening behavior under direct tension (Naaman and Reinhardt 2006). If FRCC show multiple cracking under tension or flexure, it means that the composite is ductile and exhibits both deflection-hardening and strain-hardening response (Committee 2003). These composites have higher ductility, flexural strength and toughness. According to the study of Naaman (2002), in order to exhibit deflection-hardening in bending, the cracking strength needs to be about three times higher than the average post-cracking strength in tension.

The performance of FRCC is related with some factors such as the geometry, material properties and volume content of fiber and also interface and matrix properties. The most critical parameter is type and quantity of fibers. There are lots of studies about the influences of fibers types on the flexural performance of FRCC (Kim *et al*. 2008, Felekoglu *et al*. 2009). In order to improve the flexural performance of FRCC, the use of two or more type of fibers into the matrix is a promising method. These types of composites are called hybrid fiber reinforced cementitious composites (HFRCC). Especially, macro and micro fiber inclusion has a vital role on material and structural levels. In general, macro fibers are long and thick ones while micro fibers are short and thin. In brittle matrix, they blend together (Rossi *et al*. 2005). In the literature, it was found

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http://www.techno-press.org/?journal=acc&subpage=7
ISSN: 2287-5301 (Print), 2287-531X (Online)

that when compared with FRCC containing one type of fiber, the HFRCC show favorable effect on ductility and tensile strength (Yao *et al*. 2003, Sivakumar and Santhanam 2007). However, in order to improve flexural performance, in general, most researchers aimed to use optimum quantity of micro fiber mixed with one type of macro fiber (Sahmaran and Yaman 2007, Benson and Karihaloo 2005). According to the study of Park *et al.* (2012), the development of multiple cracking process, strain capacity and post-cracking strength are different in accordance with type of macro fiber as the volume content of micro fiber increases. Kim *et al*. (2011) found that when the quantity of micro fibers increase in hybrid system, the development of toughness, deflection capacity and equivalent bending strength are affected in according to the type of macro fiber. In the other study carried out by Yoo *et al*. (2016), it was concluded that after limit of proportionality (LOP), with an increase in fiber length, the toughness and flexural load are increased and also, the number of micro-cracks of the beams containing longer fiber length are higher. Gesoglu *et al.* (2016) studied the effect of micro-steel and hooked-steel fibers on the mechanical properties of Ultra-high Performance Cementitious Composites and they found that especially the hooked end steel fiber offer longer tail on the post peak part of the load-deflection curves. Also, the concrete with hooked end steel fibers exhibits strain hardening behavior with a substantial extension in the tail.

There are some experimental and theoretical studies and standards with the intend of measuring the flexural toughness properties of FRCC. According to determination of first crack point, in the calculation of flexural toughness, there are two different methods. One of them is ASTM C1018 (1997) and the other one includes ASTM C1609 (2012), JSCE (1984), etc. Nataraja (2000) said that the main problem of ASTM C1018 method was to determine the location of first crack but JSCE method was so simple that it was not depend on the deflection type. In the study of Kim (2008), in the deflection-hardening materials, due to the difficulties in the application of ASTM C1609, the first crack point was determined according to ASTM C1018. The research of Banthia and Trottier (1995) showed that there were some limitations in all methods for the determination of flexural toughness of FRCC. Therefore, in the determination of flexural toughness of FRCC, the comparison of these different methods was so sense.

Due to the use of high prices of steel fibers and superplasticizers, the production of FRCC becomes expensive. However, self-compacting concrete (SCC) become more promising method because of reducing the labor cost, the using of waste material as mineral admixture instead of viscosity modifying agent (VMA), etc. Therefore, considering the cost-benefit analysis, it can be said that SCC with fiber is more economical than FRCC. Hybrid fiber reinforced self-compacting concrete (HFRSCC) show high performance in hardened state and is desirable for the structures.

The aim of this study was to investigate the influences of micro and macro steel fiber contents on the flexural behavior of HFRSCC. For this purpose, the mixtures with different volume content of micro and macro steel fibers were used. The flexural performance of the hybrid fiber reinforced SCC was evaluated according to ASTM C1018, ASTM C1609 and JSCE in order to specify the most appropriate code in terms of the assessment of toughness parameters. The load carrying capacity, energy absorption and ductility of the mixtures were evaluated by using toughness parameters at certain deflection points under flexural load to study the specimens with fiber reinforced in terms of the strength and deflection capacity.

Table 1 The chemical composition of PC and FA

	PC (%)	FA (%)
SiO_2	19.41	63.04
Al_2O_3	5.58	21.63
Fe_2O_3	3.67	6.77
CaO	58.85	1.07
MgO	2.12	-
SO_3	3.16	0.10
K_2O	0.69	-
Na_2O	0.61	-

2. Experiments

2.1 Materials

In this study, Portland Cement (PC) CEM II 42,5R with specific gravity of 3.06 g/cm^3 and specific surface of 4891 cm^2/g and fly ash (FA) with specific gravity of 2.3 g/cm^3 were used as binder. Fly ash was also used to improve the viscosity of all SCC mixtures as the viscosity modifier instead of the viscosity modifying agent. Their chemical compositions were shown in Table 1. Three groups of aggregates that differ from each other according to maximum aggregate size were used. In the finest aggregate group, the maximum aggregate size was 2 mm and its specific gravity and water absorption were 2.43 and 1.57%, respectively. In the second group, the aggregate sizes were in the range of 2-4 mm, and the specific gravity was 2.64 and water absorption was 0.6%. The aggregate sizes of the third one were between 4 to 8 mm and it had specific gravity of 2.68 and water absorption of 0.2%. Two types of steel fibers having the commercial code of Dramix 65/60 and OL 13/.16 named as macro and micro steel fiber, respectively, were used. Dramix 65/60 was double hooked end while OL 13/.16 was straight. The mechanical properties and aspect ratios of the fibers were listed in Table 2. A modified polycarboxylic polymer based high range water reducer admixture (HRWRA) was added into the mixtures to enhance the fresh properties of concrete. The amount of PC and FA was kept constant while the mixture proportion of HRWRA was changed in order to provide suitable workability.

2.2 Specimen preparations

In the mixture design, in order to investigate the influence of micro and macro steel fiber on the flexural behavior, water/binder (w/b) ratio was kept constant as 0.28 and only the volume content of macro and micro steel fibers

Table 2 Properties of macro and micro steel fibers

Fiber	Length (mm)	Diameter (mm)	Aspect Ratio (L/d)*	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Density (kg/m^3)
Dramix 65/60	60	0.92	65	2300	210	7850
OL 13/.16	13	0.15	87	3000	200	7200

*L/d is length to diameter ratio

Table 3 Mixture proportions (kg/m^3)

Mix ID	PC	FA	Water	Steel fiber		Aggregate			HRWRA
				Dramix 65/60	OLI 13/.16	0 - 2 mm	2 - 4 mm	4 - 8 mm	
MI0_MA1	350	250	167	78.5	0	605.1	453.8	453.8	7
MI0.25_MA0.75	350	250	167	58.9	19.6	602.2	451.6	451.6	10
MI0.5_MA0.5	350	250	167	39.25	39.25	598.8	449.1	449.1	13.5
MI0.75_MA0.25	350	250	167	19.6	58.9	597.4	448	448	15
MI1_MA0	350	250	167	0	78.5	593.5	445.1	445.1	19

were changed while a total volume of steel fibers was 1% and constant for all mixtures. Five mixtures, which's names were listed in Table 3, were prepared. The abbreviation MI and MA refer to micro and macro steel fiber, respectively, and the numbers next to each abbreviation is the percentage of fibers added into the mixtures. For instance; MI0.75_MA0.25 means that the mixture contains 0.75% micro steel fiber and 0.25% macro steel fiber. In the mixtures, the finest aggregate (0-2 mm) was used 40% of the total aggregates while the other ones (2-4 mm and 4-8 mm) were 30%. To achieve self-compactibility and to arrange the slump-flow diameter between 650-800 mm, fly ash replaced by cement, high amount of fine aggregate and HRWRA were possibly added to all mixtures. Mixtures with no and 0.25% micro fiber content had highest slump-flow diameter with 800 mm while it was 670 mm for the ones with 0.75% and 1% micro fiber content. As for the mixtures having both 0.5% micro and 0.5% macro steel fiber, they had the slump-flow diameter of 770 mm.

In the mixture preparation, during 3 minutes, all groups of aggegates and steel fiber were mixed with 2/3 of mixing water. Then, PC, FA and the rest of the water with HRWRA were added and mixed at 7 minutes. Then, the self-compactibility of the mixtures was measured by slump-flow test. The mixture proportions were decided after being sure that the spread of the concrete was between 650 and 800 mm. For uniform fiber distribution and good workability, the adequate flowability of the mixture was necessary. Then, HFRSCCs were placed into the moulds and to prevent the fiber protrusion and provide good consolidation, a tamping was applied on the side surfaces of moulds by using plastic tamper. Meanwhile, uniform fiber distribution was observed. The specimens were stayed 24 hour at room temperature and then they were put into water tank. Three of the specimens for each mixture were cured 28 days in tank and the other three of them were taken out from the tank after 56 days.

2.3 Test setup

The beams were subjected to four-point bending test and in Fig. 1, the test specimen and setup were shown. The dimensions of the specimens were 100x100x400 mm^3 and the clear span was 300 mm. The loading direction was 90° rotated from the casting position. To measure the deflection at center, a frame was placed to the specimen by using four screws at the supports and a Linear Variable Differential Transformer (LVDT) was located into this special frame setup. Before starting to apply load to beam, a calibration was done to LVDT. The tests were conducted to beams at 28 and 56 days and three specimens were tested for each mixtures and curing days.

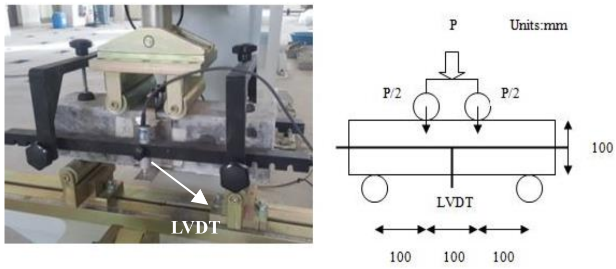


Fig. 1 Test specimen and setup

3. Parameters about the flexural performance of HFRSCC

As seen in Fig. 2, the flexural behavior of HFRSCC was classified as deflection-hardening and deflection-softening. In deflection-hardening response, after the first crack, a higher load carrying capacity is observed but in deflection softening behavior, the load carrying capacity decreases. In Fig. 2, according to ASTM C1018 (1997), LOP is the limit of proportionality and defined as the first cracking point where the nonlinearity of the load-deflection curve started. However, ASTM C1609 uses the first peak point but because of the reason that in the mixtures that perform deflection-hardening behavior, it is hard to define the first peak strength, as it was also proven by Kim (2008), instead of first peak strength, LOP was used in this study. In Fig. 2, P_{LOP} and δ_{LOP} are the load and corresponding deflection value at LOP. According to ASTM C1609 (2012), the strength value was calculated as shown in Eq. (1)

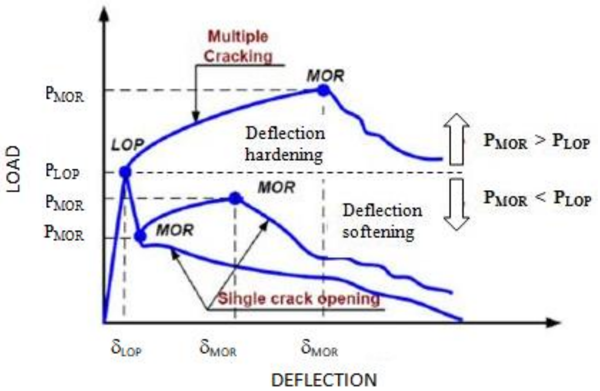


Fig. 2 Typical load-deflection curve of HFRSCC under flexure (Kim 2008)

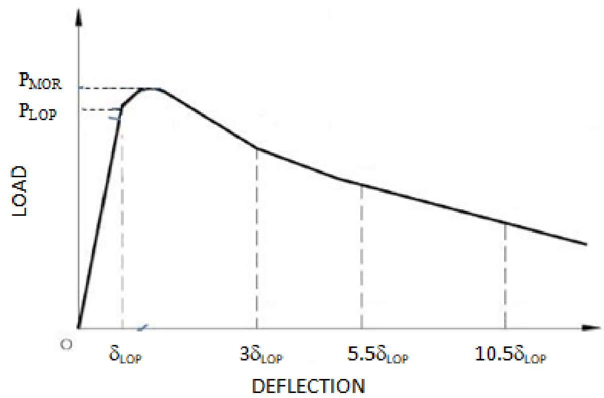
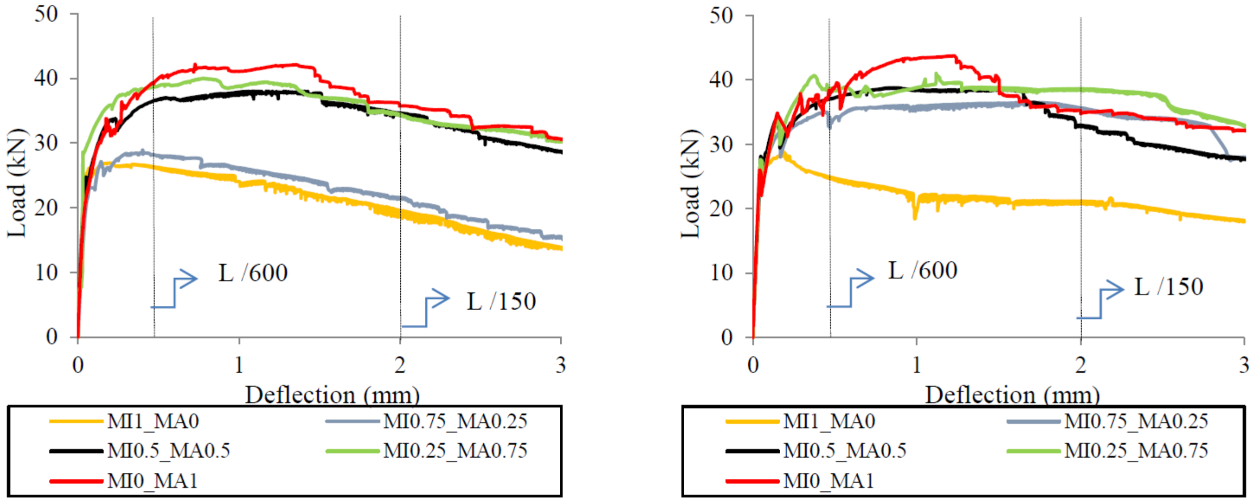


Fig. 3 Typical load-deflection curve of HFRSCC and deflection parameters based on ASTM C1018 (1997)



(a) 28 days (b) 56 days

Fig. 4 Four-point bending test results of HFRSCCs with different micro and macro steel fiber content

$$f = P.\,(L/(bh^2)) \tag{1}$$

where f is strength (MPa), P is load (N), L, b and h are length, width and height of the specimens (mm), respectively. The area under the load-deflection curve up to LOP point is the first crack toughness, T_{LOP}. In Fig. 2, the modulus of rupture is defined as MOR in which the softening part of the load-deflection curve started after the point LOP. The stress value at MOR was also calculated using Eq. (1).

Besides, in ASTM C1609, L/600 and L/150 points are defined. L is the test span and L/600 and L/150 is the 1/600 and 1/150 of the span. The load and corresponding deflection values, toughness and stress at L/600 and L/150 were also calculated. Due to the reason that L is 300 mm in this study, the deflections at point 0.5 mm and 2 mm were used. In the calculation of toughness, the areas under the load-deflection curve up to L/600 and L/150 points were used in that time and also, the stress values were evaluated by using Eq. (1). The same prefixes P, δ, T and f were used for LOP, MOR, L/600 and L/150 calculations.

As given in Fig. 3, in ASTM C1018, the flexural toughness is calculated at the deflections of δ_{LOP}, δ_{3LOP}, $\delta_{5.5LOP}$ and $\delta_{10.5LOP}$. As mentioned before, the flexural toughness calculated at deflection δ_{LOP} is the first crack flexural toughness. The toughness at point δ_{3LOP}, $\delta_{5.5LOP}$ and $\delta_{10.5LOP}$ were named as $T_{3\delta}$, $T_{5.5\delta}$ and $T_{10.5\delta}$, respectively and these parameters were calculated from the areas under the load deflection curve until δ_{3LOP}, $\delta_{5.5LOP}$ and $\delta_{10.5LOP}$, respectively. Besides, in ASTM C1018, there are flexural toughness indices which are I_5, I_{10} and I_{20} and these values were calculated by using Eqs. (2), (3) and (4) as follows

$$I_5 = T_{3\delta} \;/\; T_{\delta LOP} \tag{2}$$

$$I_{10} = T_{5.5\delta} \;/\; T_{\delta LOP} \tag{3}$$

$$I_{20} = T_{10.5\delta} \;/\; T_{\delta LOP} \tag{4}$$

The calculation of flexural toughness factor based on JSCE is given in Eq. (5) as the following

$$FTF = (T_{L/150} \,/\, (L/150)) * (L/bh^2) \tag{5}$$

where $T_{L/150}$ was the area under load-deflection curve up to 2 mm deflection.

To sum up, in order to investigate the flexural properties of the self-compacting concrete reinforced with macro and

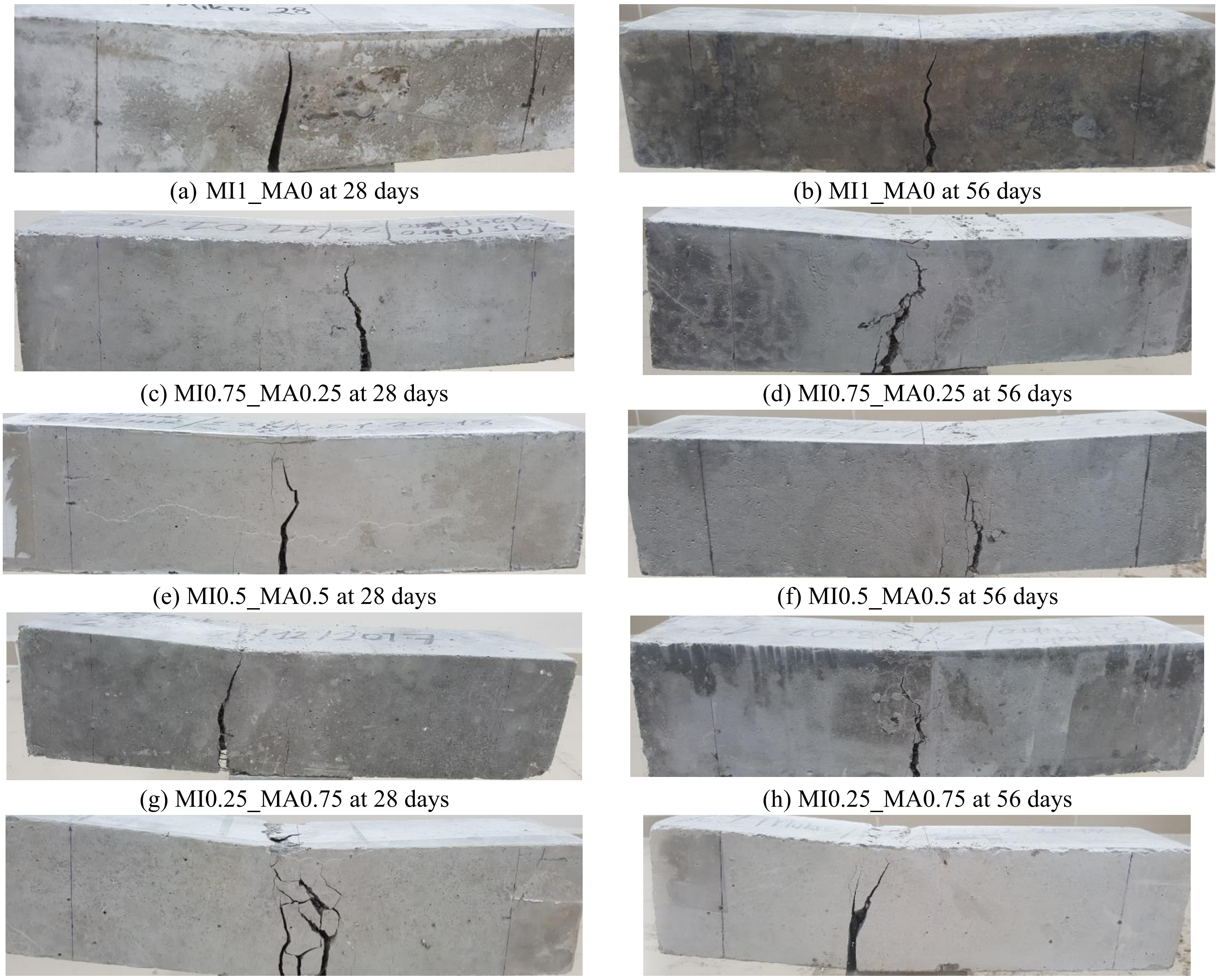
Table 4 Flexural properties of HFRSCCs at 28 day

		MI1_MA0	MI0.75_MA0.25	MI0.5_MA0.5	MI0.25_MA0.75	MI0_MA1
LOP	δ_{LOP}	0.07	0.14	0.14	0.17	0.17
	f_{LOP}	7.82	8.13	9.34	10.57	10.13
	T_{LOP}	1.26	2.81	3.32	4.64	4.26
3*LOP*	δ_{3LOP}	0.21	0.43	0.43	0.50	0.52
	f_{3LOP}	8.06	8.53	10.82	11.66	12.11
	T_{3LOP}	4.90	10.80	13.04	17.26	16.72
5.5*LOP*	$\delta_{5.5LOP}$	0.38	0.80	0.79	0.92	0.95
	$f_{5.5LOP}$	7.97	7.97	11.18	11.56	12.33
	$T_{5.5LOP}$	9.52	20.99	26.22	33.76	34.61
10.5*LOP*	$\delta_{10.5LOP}$	0.73	1.52	1.50	1.76	1.82
	$f_{10.5LOP}$	7.61	7.17	11.32	10.96	10.88
	$T_{10.5LOP}$	18.57	39.44	53.27	65.74	69.63
L/600	$\delta_{L/600}$	0.50	0.50	0.50	0.50	0.50
	$f_{L/600}$	7.85	8.41	11.02	11.65	12.00
	$T_{L/600}$	12.63	12.66	15.61	17.14	15.88
L/150	$\delta_{L/150}$	2.00	2.00	2.00	2.00	2.00
	$f_{L/150}$	7.85	6.48	10.40	10.33	10.71
	$T_{L/150}$	47.33	50.04	71.17	74.10	76.06
MOR	δ_{MOR}	0.20	0.40	0.98	1.13	1.35
	f_{MOR}	8.07	8.68	11.34	12.00	12.66
	T_{MOR}	4.54	9.89	33.64	41.84	44.85

Table 5 Flexural properties of HFRSCCs at 56 day

		MI1_MA0	MI0.75_MA0.25	MI0.5_MA0.5	MI0.25_MA0.75	MI0_MA1
LOP	δ_{LOP}	0.13	0.16	0.14	0.15	0.15
	f_{LOP}	8.35	9.50	10.12	10.07	10.45
	T_{LOP}	2.73	3.85	3.48	3.65	3.67
3LOP	δ_{3LOP}	0.38	0.48	0.42	0.45	0.45
	f_{3LOP}	7.66	10.07	11.01	11.52	11.14
	T_{3LOP}	9.56	14.38	13.04	14.75	14.24
5.5LOP	$\delta_{5.5LOP}$	0.69	0.87	0.77	0.82	0.82
	$f_{5.5LOP}$	7.16	10.78	11.55	11.33	12.75
	$T_{5.5LOP}$	17.35	28.36	26.25	28.93	29.23
10.5LOP	$\delta_{10.5LOP}$	1.33	1.66	1.47	1.57	1.57
	$f_{10.5LOP}$	6.56	10.91	11.55	11.60	11.26
	$T_{10.5LOP}$	31.33	56.95	53.21	57.95	60.71
L/600	$\delta_{L/600}$	0.50	0.50	0.50	0.50	0.50
	$f_{L/600}$	7.42	10.21	11.17	11.50	11.68
	$T_{L/600}$	12.62	15.20	15.99	16.74	16.84
L/150	$\delta_{L/150}$	2.00	2.00	2.00	2.00	2.00
	$f_{L/150}$	6.47	10.67	9.84	11.55	10.57
	$T_{L/150}$	45.68	69.16	72.36	74.55	76.17
MOR	δ_{MOR}	0.19	0.91	0.95	1.21	1.23
	f_{MOR}	8.63	10.80	11.63	12.09	13.12
	T_{MOR}	4.57	29.87	34.89	44.37	46.80

micro steel fiber, in total seven deflection points were used. Deflections at LOP and MOR were important for deflection-hardening and deflection-softening response of the mixtures. Deflection points at L/600 and L/150 were used as it was defined in ASTM C1609. L/600 and L/150 were defined as the point prior and after the peak load, respectively. The deflection points at 3LOP, 5.5LOP and 10.5LOP were used according to ASTM C1018. According to these seven deflection points, the mixtures were analyzed in the aspect of energy absorption, load carrying capacity and ductility to evaluate the strength and deformation capacity of the specimens. Also, for toughness, the flexural toughness indices based on ASTM C1018 and flexural toughness factor based on JSCE were used and the results were discussed to show whether these parameters can be used to estimate the toughness or not.



(a) MI1_MA0 at 28 days
(b) MI1_MA0 at 56 days
(c) MI0.75_MA0.25 at 28 days
(d) MI0.75_MA0.25 at 56 days
(e) MI0.5_MA0.5 at 28 days
(f) MI0.5_MA0.5 at 56 days
(g) MI0.25_MA0.75 at 28 days
(h) MI0.25_MA0.75 at 56 days
(i) MI0_MA1 at 28 days
(j) MI0_MA1 at 56 days

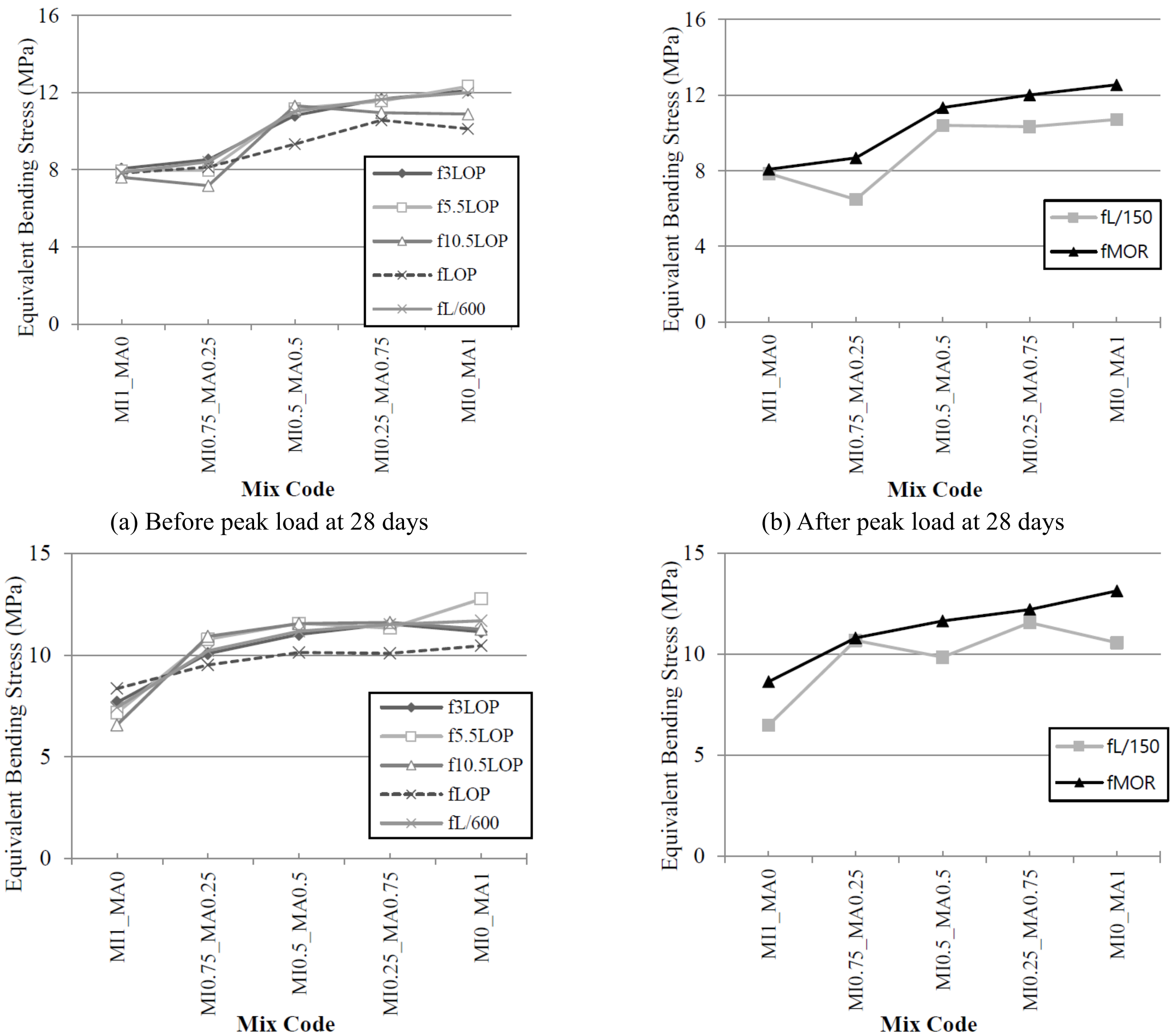
Fig. 5 Cracking behavior of HFRSCC under four-point bending test

4. Test results and discussions

4.1 Load-deflection curves

Fig. 4 shows the load-deflection curves of HFRSCC having different percentages of micro and macro steel fiber at 28 and 56 days and also the values obtained from the test results were listed in Tables 4 and 5. These curves were plotted by using the average values of three specimens obtained from four-point flexural tests for each mixture. The units of the abbreviations of δ, f and T were mm, MPa and N-m, respectively. It is clear from the Fig. 4 that, in all FRCC mixtures, the initial elastic portion of the graphs was similar. At both 28 and 56 days, the mixtures with no macro steel fiber exhibited deflection-softening behavior after the initial elastic portion. However, in the case of addition higher percentage of macro steel fiber, deflection-hardening behavior became more obvious. Especially, for MI0_MA1 mixtures, under bending test, deflection-hardening response was so apparent at 28 and 56 days.

In the comparison of flexural performance of mixtures according to the micro and macro steel fiber content, macro steel fiber inclusion had a positive effect on load carrying capacity that the highest load carrying capacity and MOR were obtained in the mixture containing 1% macro steel fiber and no micro steel fiber. That is, to develop more ductile behavior for mixtures, it would be necessary to use more macro steel fiber. According to the load-deflection curves, it can be said that the micro steel fiber had small influence on the post-peak response due to bridging micro-cracks on the specimens while macro steel fibers showed an important effect on post-peak portion of the curve which caused an improvement on the flexural behavior of the mixtures. This result is also consistent to the study of Haddadou *et al*. (2014) and Wu *et al*. (2016). Besides, after peak load, a sudden drop was observed in the mixtures having higher volume of micro steel fiber and it caused to a deflection-softening behavior but a gradual decrease in load after peak load became more obvious when the macro steel fiber content increased. However, MI0.75_MA0.25 specimen had higher load carrying capacity at 56 days than that at 28 days though it contained too much micro steel fiber with 0.75% by volume while all other specimen had more and less similar load carrying capacity. Because, at



(a) Before peak load at 28 days

(b) After peak load at 28 days

(c) Before peak load at 56 days

(d) After peak load at 56 days

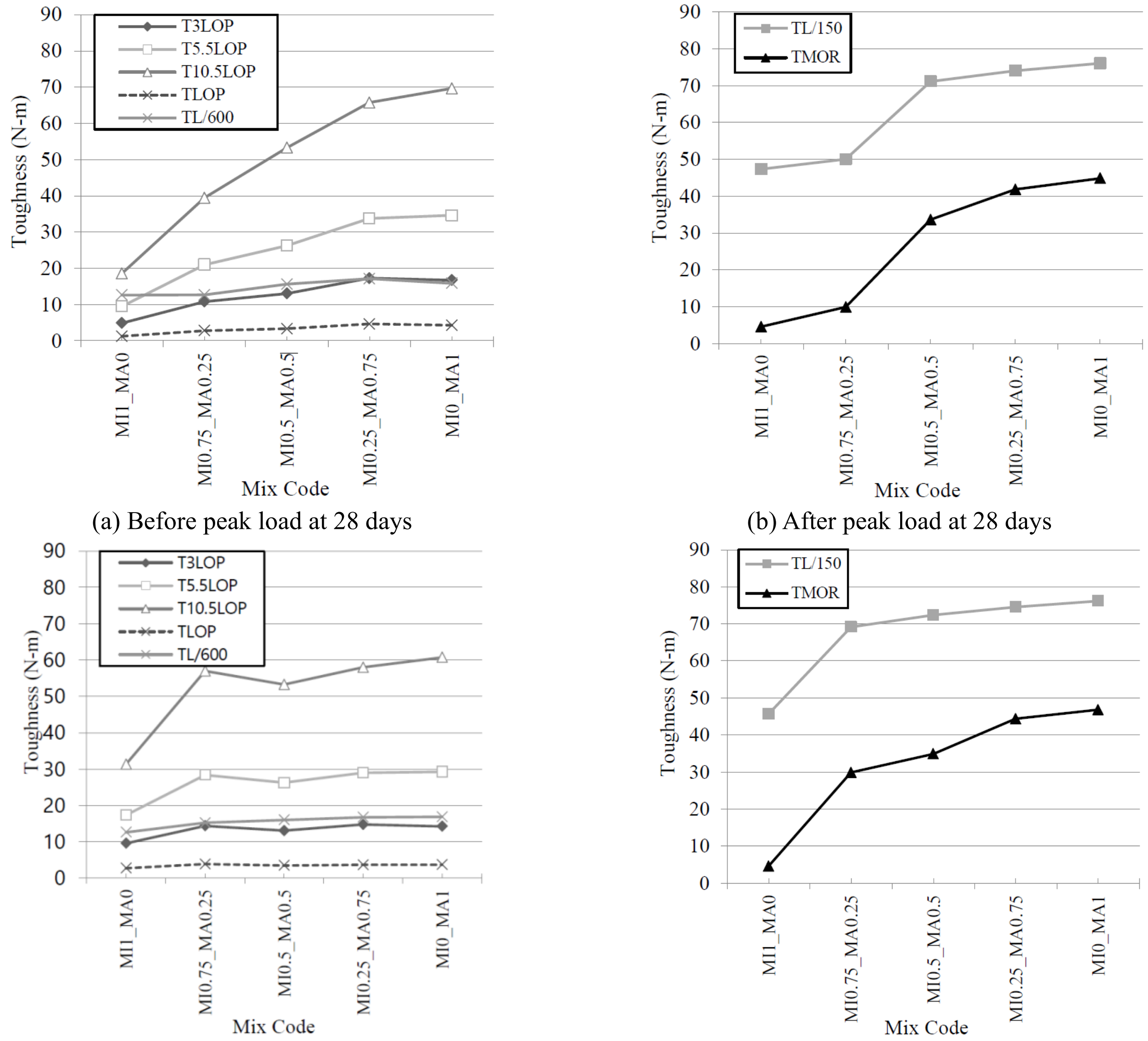
Fig. 6 Effect of macro and micro steel fiber content on equivalent bending stress

later ages, the micro steel fibers showed a better bridging effect of micro-cracks due to the maturity of matrix as well as the presence of 0.25% macro steel fiber in the specimen of MI0.75_MA0.25. Also, the ultimate load capacity and the corresponding deflection values (δ_{MOR}) increased as the macro steel fiber content in the mixture increased at both 28 and 56 days. The similar results were also obtained in the study of Naaaman and Reinhardt (1995). Especially, at 28 days, the mixtures having low volume of macro steel fiber (MI1_MA0 and MI0.75_MA0.25), showed a sudden drop in performance with a greater deformation after the ultimate load. Besides, at 28 and 56 days, in all mixtures the deflection values corresponding to peak load values increased with increasing macro fiber content. This result coincides with findings from the study of Lawler *et al* (2005).

The cracking behavior is important to characterize the flexural behavior of HFRSCC specimens. The multiple cracking behavior is related to the type of steel fiber added into the mixture. It is also seen from Fig. 5 that when the inclusion of macro steel fiber increased, the multiple cracking behavior of the specimens became more obvious at both 28 and 56 days. In the mixtures containing 1% or 0.75% micro steel fiber for 28 days and only 1% micro steel fiber for 56 days, one localized crack was observed which caused a deflection-softening manner. Especially, the ones having 1% and 0.75% macro steel fiber exhibited more micro-cracks than the others and as it was also proven from the load-deflection curves, a deflection-hardening response was observed. In the study of Ghanem and Obeid (2015), it was stated that 65/60 macro steel fiber provided better bond characteristics and energy absorption capacity. As it was also proven by the studies in the literature (Rashiddadash *et al*. 2014, Pajak and Ponikiewski 2013) the hooked end steel fibers caused deflection hardening behavior while straight steel fibers result in deflection softening behavior.

4.2 Equivalent bending stress (load carrying capacity)

The influence of macro and micro steel fibers on load carrying capacity of HFRSCC before and after peak load at 28 and 56 days were shown in Fig. 6. For each of 28- and



(a) Before peak load at 28 days (b) After peak load at 28 days

(c) Before peak load at 56 days (d) After peak load at 56 days

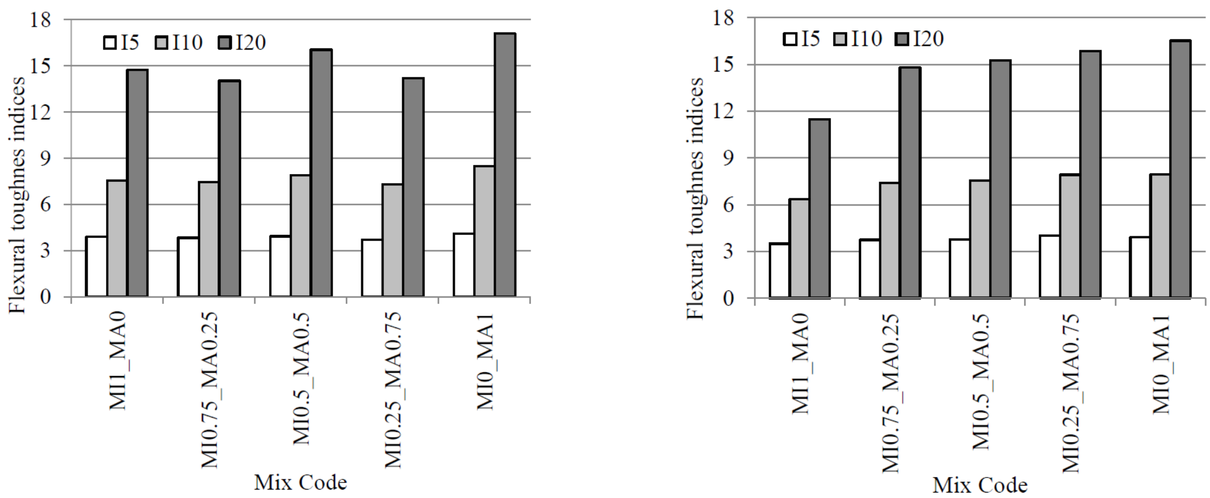
Fig. 7 Effect of macro and micro steel fiber content on toughness

56-day curing periods, seven equivalent bending stress values at different deflection points were calculated by using Eq. (1) which is based on ASTM C1609. The deflection points of δ_{LOP}, δ_{3LOP}, $\delta_{5.5LOP}$ and $\delta_{10.5LOP}$ were chosen from ASTM C1018 and the other points L/150 and L/600 were from ASTM C1609 as previously explained. The Figs. 6(a) and (c) explain the development of resistance against flexural load in the increasing part of load-deflection curves while in the Figs. 6(b) and (d), the influence of macro and micro steel fibers on the softening tendencies against flexural load resistance in the decreasing part of load- deflection curves were described.

It was seen from Fig. 6(a) that the equivalent bending strength in the mixtures MI0.5_MA0.5, MI0.25_MA0.75 and MI0_MA1 at LOP was not so apparent because f_{MOR} was 9.34, 10.57 and 10.13 MPa, respectively. However, as the deflection point increased, the effect of steel fibers became more obvious. This result shows that after LOP, the fibers became more active through fiber bridging and thus, the type of steel fibers affects the bridging forces more (Kim *et al*. 2011). In general, there was an increasing tendency for the equivalent bending stress values when the volume fraction of macro steel fiber replaced by micro steel fiber increased. In terms of equivalent bending stress at MOR, for both 28 and 56 days curing period, the ones having only 1% macro steel fiber perform the best while the mixtures having only 1% micro steel fiber was the worst. In the other words, as it was also pointed out by the study of Li *et al*. (2017), the HFRSCC mixtures showing deflection-hardening behavior exhibited higher load carrying capacity after first peak load.

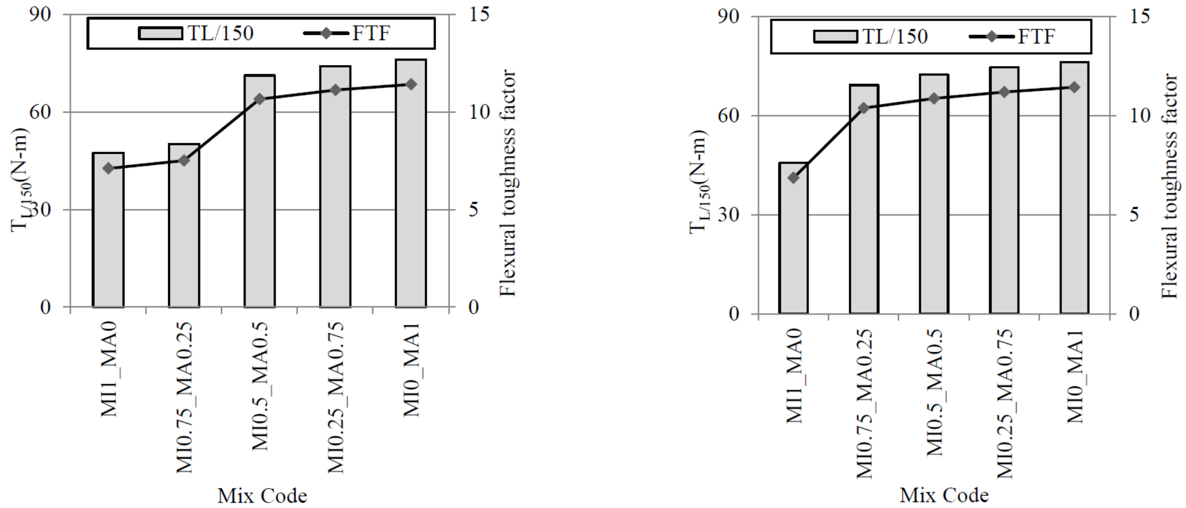
The deflection point L/600 was selected as in the part of before the peak load in the load-deflection curve and it means that it is in the hardening portion. However, as seen in Figs. 6(a) and (c), at both 28 and 56 curing days, the mixture having 1% micro steel fiber was in the softening range at L/600. As previously said, the mixture containing 1% micro steel fiber exhibited deflection-softening response.

As seen in Fig. 6(c), a variation in the equivalent bending stress at LOP was observed as the macro and micro steel fiber content changed. In the case of 1% addition of



(a) 28 days (b) 56 days

Fig. 8 Flexural toughness indices based on ASTM C1018



(a) 28 days (b) 56 days

Fig. 9 Flexural toughness and flexural toughness factors based on ASTM C1609 and JSCE, respectively

macro steel fiber, f_{LOP} had the highest value with 10.45 MPa.

Besides, except the mixture MI1_MA0, it can be said that at 56 days, the equivalent bending stress before peak load was in general so similar to each other at all deflection points. As shown in Fig. 6(d), the use of macro steel fiber with the blends of micro steel fiber caused a linear increase in the equivalent bending stress values at MOR when micro steel fiber content decreased while equivalent bending stress values for L/150 were not affected by the blends of micro with macro steel fiber. In contrast, f_{MOR} of MI1_MA0 was 8.62 MPa which was quite lower compared to other mixtures and it means that this mixture softened much more quickly than the other mixtures. This can be attributed to the fact that as the micro cracks grow and turn into macro cracks, the micro steel fibers become insufficient to bridge the cracks and they were pulled out. Because of the absence of macro steel fiber, the crack width increased and the load carrying capacity was so low. This result coincides with findings from the study of Gesoglu *et al.* (2016).

4.3 Toughness (energy absorption)

The energy absorption capacity which can be defined as toughness of materials was so important for the structures to resist against dynamic loads. The toughness performance of the mixtures with different percentages of micro and/or macro steel fibers were illustrated for 28 and 56 days in Fig. 7. As previously defined, the toughness values were calculated by using the area up to a pre-defined deflection under the load-deflection curves. Figs. 7(a) and (c) showed the influence of micro and macro steel fiber on toughness in the ascending portion of load-deflection curves at 28 curing days while Figs. 7(b) and (d) illustrated the toughness of the mixtures at 56 days in the descending portion of the curves.

As can be seen in Fig. 7(a), toughness at LOP were almost the same in all mixtures. The same observation was also valid for all mixtures at deflection L/600 but as the deflection points increased, the differences between the toughness values of the mixtures also increased. As can be seen in Tables 4-5, $\delta_{10.5LOP}$ was the highest deflection point.

Because of this reason, at $\delta_{10.5LOP}$, toughness values were the highest because the resistance against flexural load increased. The mixture containing 1% macro steel fiber at 28 days were the toughest one with the toughness value of 69.63 N-m while the one having only 1% micro steel fiber showed the lowest toughness response with 18.57 N-m at $\delta_{10.5LOP}$. In Fig. 7(b), the toughness values at L/150 and MOR showed a tendency to increase in all mixtures. At 28 days, T_{MOR} of the mixture having 1% macro steel fiber was 44.85 N-m which was the highest one. It showed that this mixture absorbed more energy than the other ones and also it was attributed to the higher ductility in the hardening portion.

At 56-day specimens, in all mixtures similar trends were observed in the prior part of the peak load (Fig. 7(c)). Although in all deflection points, the lowest toughness values were observed in the mixture having 1% micro steel fiber, especially at the deflection points LOP, 3LOP and L/600, the toughness values were so close and as the deflection values increased, the energy absorption capacity of the mixtures in general slightly increased. This can be attributed to the fact that in low deflection points the type of the fiber causes insignificant influence on toughness since the cracking behavior is influenced by the matrix strength rather than the fiber bridging. This is consistent with the study of Yoo *et al*. (2017). In Fig. 7(d), it was shown that at the deflection point L/150 the similar toughness values were calculated within the range of 69.15 N-m to 76.16 N-m except the mixture containing 1% micro steel fiber with 45.68 N-m. At MOR, the toughest mixture was again MI0_MA1 as in the case of at 28 curing days and it was 46.80 N-m. As the content of the macro steel fiber in the mixtures increased, an increasing trend was observed in the aspect of toughness after 56 days curing. This can be attributed to the improvement in fiber bridging capacity due to the increasing content of macro steel fiber (Yoo *et al*. 2016).

4.3.1 Flexural toughness indices according to ASTM C1018

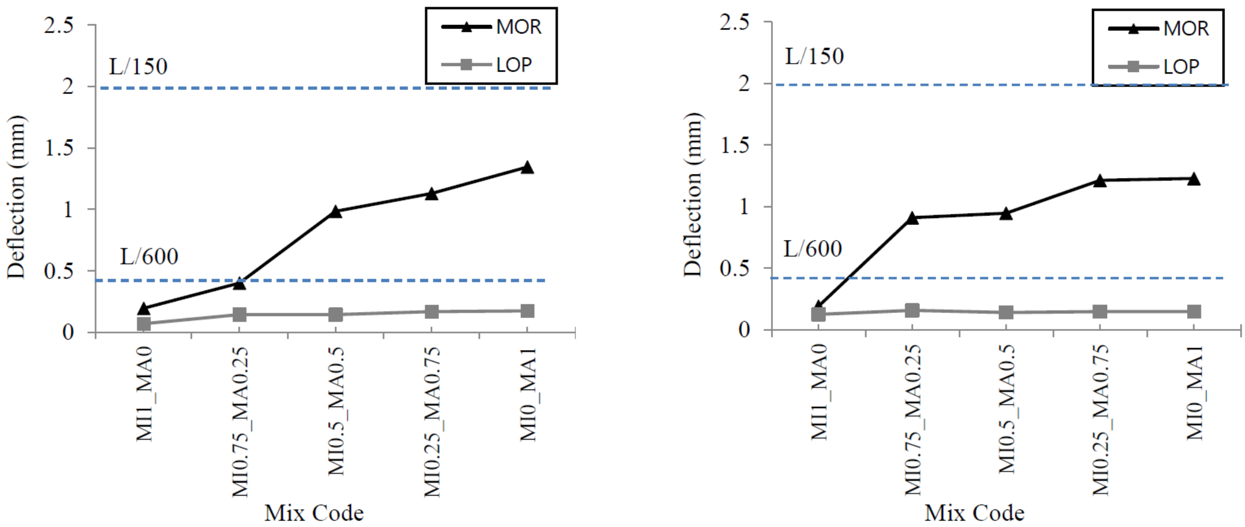
The flexural toughness indices (I_5, I_{10} and I_{20}) were calculated according to ASTM C1018 (1997) and illustrated in Fig. 8. In all HFSCC mixtures, the first crack toughness values were so small and close to each other and it was around 3.30 N-m for both 28 and 56 days. As the deflection points increased, the post-crack flexural toughness values also increased and at $\delta_{10.5LOP}$, the maximum toughness values were observed. Within this scope, with the effect of the first crack toughness values, the indices I_5 were the smallest ones in all mixtures and they were so close to each other. They were in the range of 3.9 to 4.1 and 3.5 to 4.0 at 28 and 56 curing days, respectively. I_{10} indices of all mixtures were also so close to each other for 28 and 56 days. However, at 28-day specimens, MI0.25_MA0.75 mixture had the smallest I_{10} indices with 7.3 while the highest value was calculated as 8.5 in the mixture MI0_MA1. As for 56 day specimens, the smallest value was 6.4 which was observed in MI1_MA0 and in the mixture MI0_MA1 the highest I_{10} value with 8.0 was calculated as in the case of 28 days. Besides, I_{20} indice of the mixture MI0.75_MA0.25 was the smallest with 14.0 and the mixture with 1% macro steel fiber had the highest I_{20} value with 17.1 at 28 days. At 56 days, the smallest I_{20} indice was calculated in the mixture containing 1% micro steel fiber with 11.5 and as the micro steel fiber content decreased, an increasing trend was observed and as result of this, MI0_MA1 had the highest I_{20} indice with 16.5. Moreover, MI0.25_MA0.75 had higher I_{20} indice at 56 days than that at 28 days while the flexural toughness indices results of all the other specimens were more or less similar at 28 and 56 days. This condition can be also observed from Fig. 4(b) that at 56 days, the load-deflection curve of MI0.25_MA0.75 continued as constant after peak load. This may be attributed to optimum fiber hybridization and also the stronger matrix interface in terms of the crack-bridging of micro steel fiber and thus, increase in toughness at point $\delta_{10.5LOP}$. When the variation tendencies between the calculated toughness values of the HFRSCC mixtures containing different percentages of micro and macro steel fibers and the toughness indices based on ASTM C1018 were compared, it was noticed that there was a contradiction. As it was also proven by the other researchers (Li *et al*. 2017, Benson and Karihaloo 2005, Yu *et al*. 2015), the indices did not reflect the load-deflection curves accurately and suitable for the evaluation of flexural behavior of HFRCC. This might be due to the difficulty in the determination of the first crack deflection value in the load-deflection curves which was so vital and one of the main problem in ASTM C1018 method (Nataraja *et al*. 2000).

4.3.2 Flexural toughness indices according to JSCE

In Fig. 9, according to JSCE (1984), the flexural toughness and toughness factors of HFRSCC mixtures with different ratios of micro and macro steel fibers were illustrated. At 28 days specimens, the flexural toughness values were in the range of 47.33 to 76.06 N-m and there was an increasing trend as the content of macro steel fiber increased. The same observation was also valid for flexural toughness factors calculated based on JSCE. The smallest factor was 7.10 which was observed in the mixture MI1_MA0 and this value increased to the highest point 11.41 in the mixture of MI0_MA1. After 56 days curing, as in the case of 28 days, while the macro steel fiber content increased, the toughness and toughness factors were also increased. The flexural toughness and toughness factor values were between 45.68 N-m to 76.17 N-m and 6.85 to 11.43, respectively. Hence, JSCE was suitable to calculate the flexural behavior of HFSCC mixtures. However, in this method, only the area under the load-deflection curve up to the deflection point L/150 was used. Therefore, it was unable to analyze the post-peak and pre-peak range of the load-deflection curves.

4.3.3 Comparison of ASTM C1609 and JSCE

According to the results mentioned above, it was noticed that the calculated flexural toughness parameters were in similar trends (Fig. 9). But, the important point is to determine which one of these methods was the most appropriate one to measure the flexural performance of HFRSCC. In ASTM C1609 method, the toughness values at L/600 and L/150 were taken into consideration. It means



(a) 28 days (b) 56 days

Fig. 10 Effect of macro and micro steel fiber on δ_{LOP} and δ_{MOR}

Table 6 Ductility index values

Mix Code	28 day			56 day		
	δ_{LOP}	δ_{MOR}	D-Index	δ_{LOP}	δ_{MOR}	D-Index
MI1_MA0	0.07	0.2	2.86	0.13	0.19	1.46
MI0.75_MA0.25	0.14	0.4	2.86	0.16	0.91	5.69
MI0.5_MA0.5	0.14	0.98	7.00	0.14	0.95	6.79
MI0.25_MA0.75	0.17	1.13	6.65	0.15	1.21	8.07
MI0_MA1	0.17	1.35	7.94	0.15	1.23	8.20

that the fiber influence on the pre-peak and post-peak behavior in load-deflection curve can be distinguished.

Besides, equivalent bending stress values are also calculated in ASTM C1609 method. However, the flexural toughness factor in JSCE method is only related with a linear function of $T_{L/150}$ (Wang *et al.* 2012). Thus, FTF based on JSCE was calculated according to the area under load-deflection curve up to specified (L/150=2 mm) deflection. Therefore, this method failed to evaluate the effect of fibers on pre-peak behavior in load-deflection curve.

4.4 Deflection (ductility)

Deflection capacity is important for the ductility of the mixtures. In Fig. 10, deflection characteristics of the mixtures at LOP and MOR were illustrated. As shown, at both 28 and 56 curing days, δ_{LOP} were not affected from the macro and micro steel fiber content because the values at LOP were so close to each other and between 0.070 and 0.195 mm. The insignificant difference in deflection at LOP can be attributed to the fact that the first cracking behavior is more affected by the matrix strength instead of fiber bridging mechanism (Yoo *et al.* 2016). The mixture containing 1% micro steel fiber had the lowest deflection capacity at MOR which was also below the L/600 deflection point for all curing ages. As previously mentioned, the mixture MI1_MA0 performed deflection-softening response. δ_{MOR} values of all mixtures at 28 and 56 days were lower than the L/150 deflection point. The best performance occurred in the mixture having 1% macro steel fiber where δ_{MOR} was 1.35 mm at 28 days and 1.23 mm at 56 days because of its extended deflection-hardening behavior. Actually, δ_{MOR} of the mixture with 0.75% macro steel fiber at 56 days was so close to the mixture MI0_MA1 and it was 1.21 mm. It showed that at 56 days, the ductility level of these two mixtures was almost the same. Because of the deflection-hardening branch of the mixtures having higher percentage of macro steel fiber, at MOR point, higher deflection value was observed especially after 56 curing day. Deflection values of MI1_MA0 at MOR was nearly 0.19 mm at both 28 and 56 days and at LOP it was 0.07 mm and 0.13 mm at 28 day and 56 day, respectively. The mixture of MI1_MA0 exhibited the deflection-softening behavior that the deflections at MOR and LOP were so close to each other for 28 and 56 days curing ages. In conclusion, it was obvious that, the inclusion of macro steel fiber into the mixture increased the ductility of the specimens.

Moreover, the ductility index (D-Index) was calculated for all specimens as given in Table 6. D-Index was the ratio between the deflection at MOR to deflection at LOP. The ductility of specimens decreased as the micro steel fiber increased such as MI1_MA0 had the lowest ductility index. Because, micro steel fiber could bridge only the cracks having certain width and also due to the absence of macro steel fiber, deflection-softening response was observed.

5. Conclusions

Micro and/or macro steel fiber reinforced SCC prismatic specimens with the dimensions of 100x100x400 mm^3 exposed to four-point bending was investigated in terms of load carrying, toughness as per different specifications and ductility to evaluate the flexural performance of mixtures. Based on the results obtained and the analysis made, the following conclusions can be drawn;

• Especially the mixtures containing 1% and 0.75% macro steel fiber exhibited more micro-cracks than the other mixtures and, thus, the deflection-hardening behavior was observed as result of multiple-cracking behavior. Furthermore, in the 56-day specimens, the multiple-crack formation was more obvious.
• The highest load carrying capacity (f_{MOR}) was obtained from the specimen with only 1% macro steel fiber for all curing days. In terms of equivalent bending stress, the performance of the mixtures increased with increase in macro steel fiber content.
• At 28 and 56 days, the mixture containing only 1% macro steel fiber were the toughest one while the one having only 1% micro steel fiber showed the lowest toughness response. At the low deflection points such as δ_{LOP}, δ_{3LOP} and $\delta_{L/600}$, the toughness values were so close to each other and as the deflection values increased, the energy absorption capacity of the mixtures were slightly increased. However, at L/150 and MOR, all mixtures showed a tendency to increase and T_{MOR} of the mixture having 1% macro steel fiber was the highest one. As the content of the macro steel fiber in the mixtures increased, an increasing trend was observed in the aspect of toughness.
• The inclusion of 1% micro steel fiber into the mixtures caused the lowest deflection capacity at MOR which was also below the L/600 deflection point for all curing days. And this mixture with 1% micro steel fiber exhibited deflection softening response.
• The best ductility performance occured in the mixture having 1% macro steel fiber (that is, δ_{MOR} was 1.35 mm at 28 days and 1.23 mm at 56 days) because of its extended deflection-hardening behavior.

In the comparison of flexural toughness indices based on ASTM C1018 and flexural toughness factor based on JSCE, it was concluded that the indices in ASTM C1018 did not reflect the load-deflection curves accurately and was not suitable for the evaluation of flexural behavior of HFRCC. In JSCE, the toughness and toughness factor values were consistent to each other but the analysis of the post-peak and pre-peak range of the load-deflection curves was unable due to taking into consideration only L/150 deflection point. Because of these reasons, in order to distinguish the influence of fiber on the pre-peak and post-peak behavior in load-deflection curve by using the deflection points based on both ASTM C1609 and ASTM C1018, the flexural parameters based on ASTM C1609 method can be more suitable.

Acknowledgments

In this study, the financial support was provided by Scientific Research Projects Committee of Inonu University, Turkey (Project No: FYL-2017-595). Their support was gratefully acknowledged.

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