Effect of Different Steel Fiber Type and Content in Flexural Behavior of Ultra High Performance Fiber Reinforced Concrete

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ABSTRACT

In the research study, the effect of different fiber contents to flexural behavior of the Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) was investigated experimentally. Various prismatic beam specimens with a dimension of 100×100×400 mm including two types of end-hooked steel fibers (aspect ratios: 30/0.55 and 60/0.75) in macro forms and one short straight steel fiber (aspect ratio: 13/0.16) in micro form were produced. The beam specimens corresponding to a total of 18 mixtures having two different volume fractions (1% and 1.5%) were subjected to series of four-point bending tests in accordance with the ASTM standard C 1609. The experimental test results were discussed in terms of the cracking patterns, flexural strengths and toughness (energy absorption ability).

In addition, a parametric research was conducted to ensure an appropriate homogenous UHPFRC mixture as well as good workability for the steel fiber volume fraction of 1.0%. Hence the prism and cubic samples were produced by modified of the composition of matrix mixtures (i.e. aggregate, water/binder, cement, superplasticizer). The performance of mixtures was evaluated in terms of the slump flow, T 500, compressive strength and workability.

It is apparent from the test results, the use of micro steel fiber significantly improves the flexural performance of the UHPFRC comparing to that of the macro form. It was also noted that the fiber type is decisive in characteristic of the load- deflection curve while the volume content amplifies it with an increasing trend after the first cracking region. When evaluating all UHPFRC matrixes, some of the mixtures under consideration ensured good fiber distribution, workability as well as target compressive strength.

Keywords: *Ultra high performance fiber reinforced concrete, Steel fiber, Flexural behavior*

INTRODUCTION

Over the last two decades, the production of Ultra-High Performance Concrete (UHPC) has become possible with the new developments in concrete technology. The development of concrete mixtures with compressive strengths exceeding 150 MPa without heat or pressure treatment has long been a challenge in terms of influencing parameters such as properties and particle size of materials component, mixture proportions and mixing procedure. This concrete is produced with high density matrix, very low water/binder ratio and special treatments such as curing under heat/pressure. Though these types of special concretes show fantastic compressive strength, they may show very brittle characterization [1-4]. If steel fibers are included to the concrete mixture to decrease brittleness and to increase energy absorption as well as capacity, the term Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is widely used [5]. The UHPFRC ensures various advantages to normal concrete and fiber reinforced concrete such as higher durability, ductility and strength since it has extremely low porosity, dense matrix, high tensile/compressive strength, ductile tensile behavior and bridging opening cracks [6]. Therefore, how to improve the strength and ductility of the UHPFRC remains a key factor in development of the UHPFRC preparations [7].

Today, use of the UHPFRC in various structural applications including bridges, viaducts, piers, harbour, impact-resistant structures as well as repairing and strengthening works has attracted high interest from the research community [4, 8-9]. Since the compressive strengths and elastic modulus of the UHPFRC are much greater than that of the normal concrete, the UHPFRC permits use of members having smaller cross-sectional dimensions. Besides, higher flexural and shear capacity gained through the steel fibers used in the mixture makes it attractive to use in structural members.

Depending on the steel fiber contents, mechanical properties of the UHPFRC exhibits wide diversities. Inclusion of the steel fibers to the concrete substantially enhances its flexural capacity, post-cracking behavior and ductility since the fibers bridge the crack surface and delay the onset of cracks, further they provide an appropriate resistance to the crack opening. On the other hand, inclusion of the fibers at high dosages has potential disadvantages due to poor flowability, workability and higher cost. For instance, the cost of steel fiber of 1.0% by volume applied into the UHPFRC is generally higher than that of matrix. Hence it is important to optimize the amount of fibers without sacrificing the superior performance of the UHPFRC [6]. Recent researches showed that the different fiber types used in the UHPFRC play a role at two different levels depending upon the fiber geometry, length and diameter. The macro fibers limit big cracks and provide toughness while the micro fibers enhance the response prior to or just after the cracking [6, 10-11]. Hence there is need to investigate the flexural behavior of the UHPFRC members having different fiber types and volume fractions.

In the research study, the effect of different fiber contents to flexural behavior of the Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is investigated experimentally. Various prismatic beam specimens with a dimension of 100×100×400 mm including two types of end-hooked steel fibers (aspect ratios: 30/0.55 and 60/0.75) in the macro forms and one short straight steel fiber (aspect ratio: 13/0.16) in the micro form were produced. The beam specimens corresponding to a total of 18 mixtures including two different volume fractions (1% and 1.5%) were subjected to series of four-point bending tests. The experimental test results were discussed in terms of the cracking patterns, flexural strengths and toughness.

EXPERIMENTAL STUDY

A Parametric Study for UHPFRC Mixtures

In the study, a parametric research was conducted to ensure an appropriate homogenous UHPFRC mixture as well as good workability for the steel fibers of 1.0% by volume. Compressive strength exceeding 120 MPa was targeted under standard curing conditions. Thus total of 24 mixtures were prepared by modified of the composition of cement, ground granulated blast-furnace slag, silica fume, aggregate, water/binder ratio, superplasticizer. Finally the performances of UHPFRC mixtures were evaluated by some parameters such as the compressive strength, T 500, workability and fiber dispersion. As the supplementary materials in the matrix, the portland cement CEM I 42.5 R, ground granulated blast-furnace slag (GGBS) and silica fume (SF) were used. Two-fractional quartz sands of 0-0.8 mm and 0-3 mm as well as basalt of 3-7 mm were chosen as aggregate. In order to get the target compressive strength, a very low water/binder ratio (less than 0.20) was used and consequently polycarboxylate ether based superplasticizer (density 1.08-1.14 kg/liter) was used for good workability. All UHPFRC matrix compositions in proportion to the cement weight are presented in Table 1. In the UHPFRC matrix, the end-hooked steel fibers (aspect ratio: 30/0.55) of 1.0% by volume were used.

For each mixture, six cube samples of 100 mm to measure the compressive strength and three 100x100x400 mm prismatic beams to determine the fiber dispersions and orientations were casted. The specimens were stored in a water tank at approximately 20 ± 2°C until the test day (see Figure 1). All specimens were tested at 28 days.

Figure 5 Prism and cube samples

In the parametric study, the prism specimens corresponding to each UHPFRC mixture were tested up to the failure by the four-point bending procedure in the ASTM C 1609 [12]. Afterwards the fiber dispersions were observed. In addition, the compression tests of six cube samples corresponding to each mixture were conducted and average value of them was used to evaluate the test results. In consequence of the conducted slump-flow tests to determine the flowability and workability, the T 500 time to reach a diameter mark of 500 mm was measured. All test results and the observations related to the mixtures can be found at the last five columns of Table 1.

Referring to Table 1, it is apparent that the minimum target strength of 120 MPa couldn't be reached for many UHPFRC mixtures where the basalt aggregate of 3-7 mm was used. It is thought that the use of less fine quartz sands as aggregate may more suitable to ensure the homogenous mixtures. Decreasing the water / binder ratio less than 0.18, the workability of the concrete also tents to decrease though the compressive strength increases, as would be expected. Besides, the high dosage superplasticizer to increase the flowability and workability of the matrix effects in negative manner, like the retardation in hydration of cement and the poor fiber dispersion / orientation.

As a consequence of the several works, the best UHPFRC performance in terms of the considered parameters was obtained for the composition of *Mixture 24* (at the last row of Table 1) when all mixtures are evaluated together (Table 1 and Figure 2). Having said that this investigation was performed on only steel fibers of 30 mm length and volume fraction of 1.0%. The chosen UHPFRC mixture was also studied for other fiber types (short straight: 13 / 0.16 mm and long end-hooked: 60 / 0.75 mm) considered in this study and good results were obtained for the related parameters. The material components of the UHPFRC obtained from the study is given in Figure 3.

Table 10 Properties of UHPFRC Mixtures in Parametric Study and Test Results

Mix No	C	SF	GGBS	SP	0-0.8 Quartz	1-3 Quartz	3-7 Basalt	Binder (kg)	W/B	Slump Flow (cm)	T_{500} (sn)	f_c' (MPa)	Fiber Dispersion	Workability
1	1.0	0.15	0.20	0.040	0.86	0.71	0.29	945	0.18	90	3.3	100	√	√
2	1.0	0.15	0.25	0.040	0.91	0.76	0.30	951	0.18	>90	5.4	104	√	√
3	1.0	0.15	0.20	0.040	0.61	0.49	0.21	1103	0.18	>90	2.7	106	X	√
4	1.0	0.15	0.20	0.030	0.61	0.49	0.22	1103	0.18	90	3.8	107	X	√
5	1.0	0.15	0.20	0.020	0.61	0.49	0.24	1103	0.18	80	5.0	97	X	√
6	1.0	0.15	0.10	0.020	0.57	0.45	0.20	1100	0.18	75	4.3	104	√	X
7	1.0	0.15	0.10	0.025	0.57	0.45	0.22	1100	0.18	85	4.8	101	X	√
8	1.0	0.20	0.10	0.025	0.59	0.47	0.21	1100	0.18	75	4.7	97	X	X
9	1.0	0.15	0.20	0.040	0.86	0.71	0.29	945	0.18	70	5.4	94	X	√
10	1.0	0.15	0.30	0.040	0.88	0.74	0.29	952	0.18	90	4.0	116	X	√
11	1.0	0.15	0.10	0.028	0.57	0.45	0.22	1100	0.18	50	7.1	96	X	X
12	1.0	0.15	0.20	0.025	0.61	0.49	0.23	1100	0.18	60	6.3	107	√	√
13	1.0	0.20	0.20	0.020	0.64	0.50	0.00	1200	0.17	50	3.8	122	X	X
14	1.0	0.20	0.20	0.025	0.64	0.47	0.00	1200	0.18	60	2.4	93	√	X
15	1.0	0.10	0.30	0.024	0.92	0.92	0.00	1000	0.18	70	3.4	113	√	X
16	1.0	0.10	0.30	0.026	0.89	0.84	0.00	1000	0.18	70	3.6	110	√	√
17	1.0	0.10	0.30	0.025	0.90	0.90	0.00	1000	0.16	50	7.5	111	√	X
18	1.0	0.10	0.30	0.021	0.69	0.69	0.00	1100	0.18	60	6.2	114	√	X
19	1.0	0.20	0.40	0.020	0.78	0.78	0.00	1104	0.18	75	3.4	114	X	√
20	1.0	0.20	0.30	0.021	0.73	0.73	0.00	1100	0.18	70	3.9	129	√	X
21	1.0	0.20	0.40	0.021	0.62	0.62	0.00	1200	0.18	75	3.5	116	√	X
22	1.0	0.20	0.40	0.028	0.80	0.80	0.00	1104	0.17	75	3.3	129	X	√
23	1.0	0.20	0.40	0.028	0.64	0.64	0.00	1200	0.17	70	3.3	123	X	√
24	**1.0**	**0.20**	**0.40**	**0.028**	**0.77**	**0.77**	**0.00**	**1100**	**0.18**	**75**	**3.1**	**128**	√	√

Figure 6 Some fiber dispersions: a) mixture–13; b) mixture–9; c) mixture–24

Figure 7 Material components of the UHPFRC

Preparation of Test Specimens

In order to study the influence of different fiber contents to the flexural behavior of UHPFRC beams, the prismatic test beams corresponding to a total of 18 mixtures were produced. In addition, the non-fiber reference specimens were prepared to see contribution of fiber content. Two types of end-hooked steel fibers in the macro fiber mixtures and one type short straight steel fiber in the micro fiber mixtures were used as shown in Figure 4. For the micro-sized fiber, brass coated high-strength steel that have a smooth surface was used. The geometrical and mechanical properties of the fibers are presented in Table 2. For the considered each fiber type, the volume fractions of 1.0% and 1.5% were chosen to obtain the deflection hardening behavior as well as ensure good workability. The specimen definitions used in the study were classified in terms of the used fiber types and volume fractions (see Table 3).

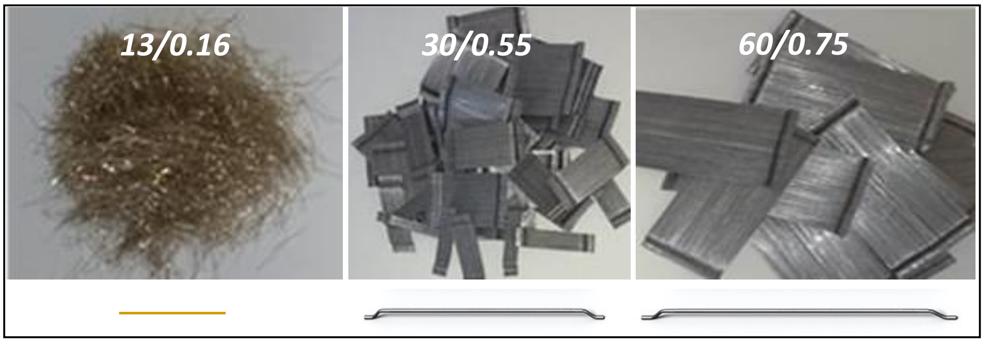


Figure 8 Steel fibers used in the study

Table 2 Properties of Steel Fibers

Fiber Type	Diameter (mm)	Length (mm)	Density (gr/cm^3)	Tensile Strength (MPa)	Elastic Modulus (MPa)
Micro	0.16	13	7.80	2500	210000
Macro (Hooked)	0.55	30	7.80	1345	210000
Macro (Hooked)	0.75	60	7.80	1225	210000

A standard pan mixer with a 90 liter capacity was used to prepare the specimens. The cement, silica fume, ground granulated blast furnace slag and quartz sands were mixed for about 3 minutes. Water and half of the superplasticizer were added into the mixture and mixed for another 5 minutes. Then the rest of superplasticizer was added and mixed for additional 5 minutes. Later the fibers were added carefully and mixed until homogenously distributed. For each mixture corresponding to the different fiber contents, six cube samples of 100 mm and three 100x100x400 mm prismatic beams were casted. The mixture was placed into the prismatic moulds from one end to other by means of a plastic bucket. During the placement process, no vibration was performed to prevent fiber gravitation (see Figure 5).

After the casting, the specimens were covered by plastic sheets and stored at room temperature. Twenty-four hours later, the specimens were taken out of their molds and stored in a water tank at approximately 20 ± 2°C until the test day. All specimens were tested at 28 days. The compression tests of the cube samples were conducted by a testing machine with the maximum load capacity of 3000 kN. For all UHPFRC mixtures, the average compressive strength of 121 MPa was obtained. Noted that regardless of the fiber content, the compressive strengths are much greater than that of the reference specimen (non-fiber).

Figure 9 Preparation of test specimens

Table 3 Fiber Types and Volumetric Fractions of the Test Specimens

Fiber Content	**Specimen**	**Fiber volume content**		
		13/0.16 mm	**30/0.55 mm**	**60/0.75 mm**
Non-fiber	Reference	-	-	-
Specimens with steel fiber	13(1.0)	1.0%	-	-
	13(1.5)	1.5%	-	-
	30(1.0)	-	1.0%	-
	30(1.5)	-	1.5%	-
	60(1.0)	-	-	1.0%
	60(1.5)	-	-	1.5%

Test set-up and procedure

Flexural tests of the beam specimens were conducted by the test set-up available in Structural Mechanics Laboratory at Balikesir University. The four-point bending tests were performed on the simply supported beam specimens with clear span of 300 mm as shown in Figure 6. Three test beams were used to determine the flexural behavior of each mixture. The test was conducted on a servo hydraulic testing machine having a capacity of 200 kN. The test machine is controlled by displacement in whole process to obtain the load versus deflection behavior. The speed of displacement applied throughout all test program was 0.1 mm/min. The mid-span deflections of beam specimens were measured by average values obtained from two LVDT attached to the specimen through a steel frame. The test set-up is shown in Figure 6. The detailed test procedure can be found in the ASTM C 1609 [12].

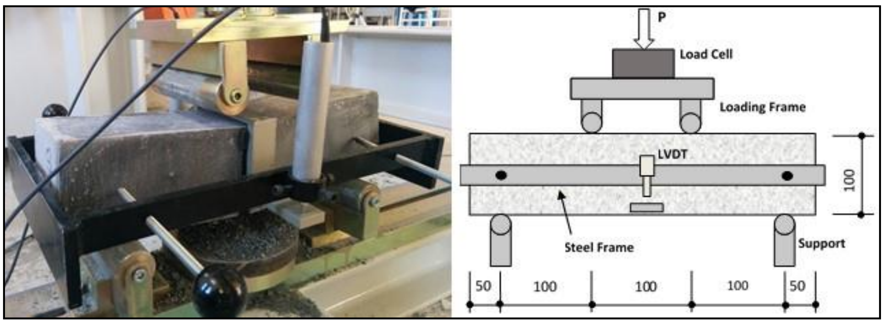


Figure 10 Four-point bending test set-up

Test Results and Discussions

In the study, three beam specimens corresponding to each fiber configuration were tested up to the failure load under the four-point bending procedure and the cracking patterns, load-midspan deflection behaviors and toughness values were obtained. The intermediate one of three responses in terms of the flexural behavior was chosen for the purpose of comparisons and evaluations.

Regardless of the fiber contents, the failures of all UHPFRC specimens exhibited a ductile behavior under the flexural strength testing (see Figure 7). Further, the test beams failed with the development of a single distinctive crack around the half of span so that the fracture mechanism occurred completely associated with the fiber debonding in the interface. At the beginning of the tests, several fine cracks appeared on the bottom of prism and only one crack continued to open up to weaken the fibre bridging effect. The cracking patterns after the fracture are presented in Figure 7.

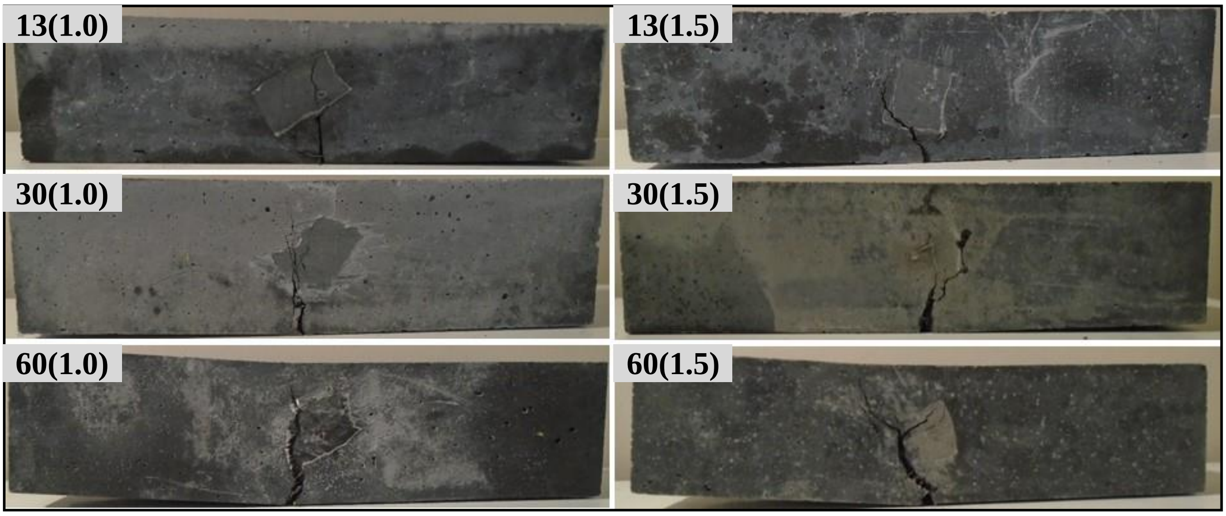


Figure 11 Cracking patterns of the UHPFRC specimens

Influence of Fiber Type to Flexural Behavior

It is known from the past studies that one of the effective parameters to affect the flexural behavior of the UHPFRC beams is the steel fiber type used in the mixture. Thus the load-midspan deflection behaviors including the different fiber configurations were obtained for two volume fractions of 1.0% and 1.5% (see Figure 8). Comparing to the reference (non-fiber) specimen, all fiber types substantially improved the flexural strength and deflection capacity, as would be expected. Enhancements in the flexural strength capacities of the test specimens in comparison with the non-fiber specimen are given in Table 4.

As shown from Figures 8a-b and 9a, the use of micro steel fiber particularly gains significant strength and deflection hardening capacity. It is also apparent from the graphics that the load-midspan deflection behaviors for each fiber types are generally similar in shape and they show an increasing tendency as the volume fraction increases. Depending on the fiber types, the flexural capacity of test specimens including the fibers of 1.0% and 1.5% by volume may be larger 1.6 and 2.0 times than for the non-fiber specimen, respectively (see Table 4). Hereby the test specimens with the micro fiber, which are of particular significance to the flexural behavior of the UHPFRC beams, shows the largest difference among the fiber types.

It should be noted that even though the use of 30 mm steel fiber increases slightly the flexural capacity, it provides significant deflection capacity for the test beam.

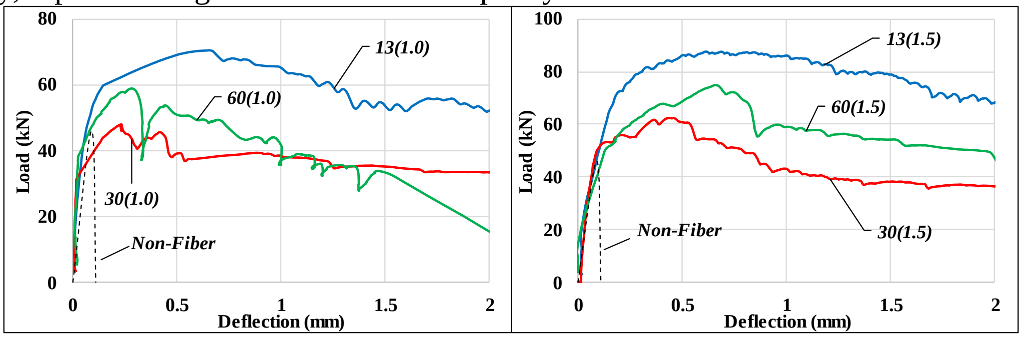


Figure 12 Contributions of different fiber types to flexural behavior of UHPFRC specimens

Table 4 Contribution of Steel Fibers to Flexural Strength compared to the Reference Beam

Specimen	Fiber form	Fiber volume content	
		%1.0	%1.5
13(1.0) / (1.5)	Micro	1.6	2.0
30(1.0) / (1.5)	Macro	1.1	1.4
60(1.0) / (1.5)	Macro	1.3	1.7

The toughness values, which represents the energy absorption ability under bending loads, were calculated using the total area under the corresponding load-deflection curve. Figure 9b compares the toughness performances of the UHPFRC specimens. When the test specimens containing the steel fibers of 13, 30 and 60 mm lengths were compared to each other for any volume fraction, the best toughness performance was obtained in case of the micro fiber of 13 mm were used. Note that the lowermost performance was obtained for the macro steel fiber of 30 mm.

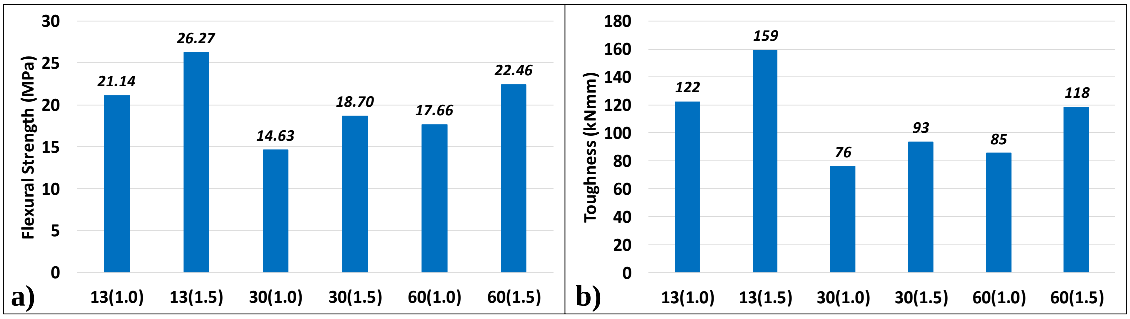
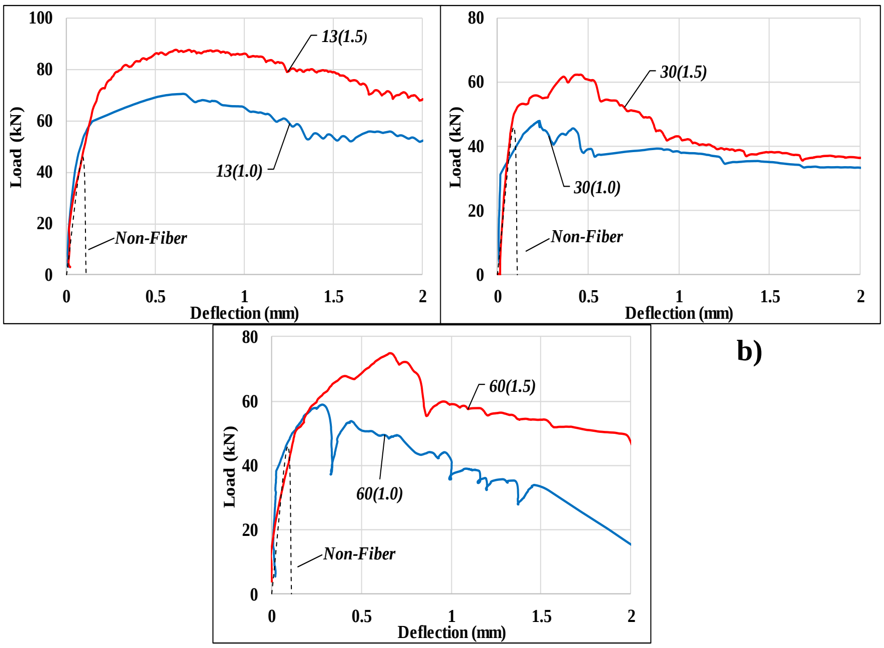


Figure 13 Comparisons of the flexural strengths and toughness values of specimens

Influence of Fiber Volume Content to Flexural Behavior

When the test results are investigated for two volume fractions (1.0% and 1.5%), the considered test parameters show an increasing tendency. The main reason is that the steel fibers increase on both the tensile strength and strain capacity. As shown from the Table 4 and Figure 10, regardless of the fiber type, the flexural capacity of the test specimens increases roughly 25% as the volume content of fibers increases from 1.0% to 1.5%. Hereby it can be concluded that the fiber type is decisive in the characteristic of the load - deflection behavior while the volume content amplifies it with an increasing trend after the first cracking region. It should be also noted that there is no sign whether the volume content is more effective in which the micro or macro steel fiber are used in the mixture.

The results obtained for the flexural strengths may find out for the toughness values, as well. Referring to Figure 9b, as the volume content of fibers increases the toughness values also shows increase in a range of 30% to 39%. Hereby the best toughness performance was obtained for the micro steel fiber of 13 mm.



a) b) c)

Figure 14 Contributions of volume content to flexural behavior of UHPFRC specimens

CONCLUSION

In the research study, the effect of different fiber contents to flexural behavior of the UHPFRC is investigated experimentally. The beam specimens corresponding to a total of 18 mixtures having two different volume fractions of 1.0% and 1.5% were subjected to series of four-point bending tests. In the study, a parametric research was also conducted to ensure an appropriate homogenous UHPFRC mixture as well as good workability for the steel fibers of 1.0% by volume. A total of 24 mixtures was prepared by modified of the composition of UHPFRC mixtures and the performances of mixtures were evaluated by some parameters.

The test results with respect to the UHPFRC specimens presented in this study are summarized below.

- The parametric study showed that the best performance for the considered parameters, which are the slump flow, T 500, compressive strength and workability, was obtained for the composition of *mixture 24*. The chosen UHPFRC mixture was also showed good results for other short and long fiber types.
- The failures of all UHPFRC specimens, regardless of the fiber contents, exhibited a ductile behavior. However, all test beams failed with the development of a single distinctive crack around the half of span so that the fracture mechanism occurred completely associated with the fiber debonding in the interface.
- The use of micro steel fiber particularly gains significant strength and deflection hardening capacity as well as toughness. Noted that even though the use of macro steel fiber of 30 mm slightly increases the flexural capacity, it provides significant deflection capacity to

the test specimens. Depending on the steel fiber type and volume fraction, the flexural capacity of test specimens may be larger *2.0* times than the non-fiber specimen.

- It can be concluded that the fiber type is decisive in characteristic of the load- deflection curve while the volume content amplifies it with an increasing trend after the first cracking region. It should be also noted that there is no sign whether the volume content is more effective in which the micro or macro steel fiber are used in the mixture.

The data presented in the study will help to develop constitutive models for the flexural behavior of structural members where the UHPFRC is used. Experimental studies on the use of mono and hybrid steel fiber in the UHPFRC members have started and they still continue.

ACKNOWLEDGEMENTS

This study was supported by the Scientific and Technological Research Council of Turkey (TUBITAK, Project code: 113M432). The authors gratefully acknowledge TUBITAK. In addition, the authors thank to Mr. Mehmet Yerlikaya from BEKSA-DRAMIX, Mr. Emrah Karatas from BASF.

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