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Using hooked-end fibres on high performance steel fibre reinforced concrete

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Abstract

Concrete is a brittle material. Numerous studies were performed on increasing the ductility of concrete. Steel fibres were widely used in concrete because of its advantages on the toughness, ductility and strength properties of steel fibre reinforced concretes (SFRCs). Owing to improving the bond properties between fibre and matrix, hooked-ended steel fibres are mostly preferred in SFRCs. In this study, the effect of type of hooked-end fibres on a high performance concrete (HPC) were investigated by an experimental research. Three different hooked-ended steel fibres were added in four different volume fraction in a high performance concrete. Fracture energies and mechanical strengths of concretes were determined by flexural tensile strength tests. Test results showed that there were significance effects of types of hooked-end on post cracking behaviour and fracture energy of high performance steel fibre reinforced concretes (HPSFRCs).
Keywords: high performance concrete, steel fibre, ductility, fracture energy.

1 Introduction

Concrete is a widely used material in constructions and has high compressive strength. It is tensile strength is about 8-12% of it is compressive strength. Steel bars; diameters usually changing between 6-32 mm, were used in reinforced concrete elements. Fibre reinforcement is generally randomly distributed in the whole element, also it can be used in a part of the elements [1]. Steel Fibre reinforced concretes (SFRCs) were widely used in civil engineering structures; industrial floors, airport and highway pavements, tunnels, bridges, hydraulic structures, earthquake and impact resistant structures, etc. [3]. The concrete properties benefited by fibre reinforcement. Energy absorption capacity, load

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carrying capacity, ductility, toughness, fracture energy, tensile and shear strengths and impact resistance are marginally increased by using fibres.

High strength concrete (HSC) is defined as concrete that meets special performance which cannot be achieved by conventional concrete. Also high performance concrete (HPC) is a concrete mixture, which provides high strength and high durability when compared to conventional concrete. HPC is an economical solution for many structural cases to provide adequate durability and is particularly advantageous in compression elements [1, 3–5]. Concrete has some disadvantages like low tensile strength, low ductility and low toughness. These disadvantages getting more significant as increasing of concrete compressive strength. The increment in the mechanical properties of the SFRC will depend primarily on the type of the fibres, their geometrical properties and the amount of fibres added [6]. The main role of dispersed fibres is to control the opening and developing of cracks by bridging the faces of crack [7]. The success of bridging effect generally depends on pull-out mechanisms. Pull-out strength depends on not only bond quality between fibre and matrix but also fibre properties such as hooked-ends and strength. To improve pull-out resistance mechanically deformed fibres are more effective than straight fibres [8–11].

In this study, effect of type of hooked-end on workability, compressive strength, modulus of elasticity, splitting tensile and flexural strengths, and also fracture parameters of concrete were investigated by an experimental study. Three different steel fibres having different hooked-ends were added in very high strength concrete mixture including silica fume. Test results showed that there were significance effects of types of hooked-end on post cracking behaviour and fracture parameters of SFRCs.

2 Materials and mix proportions

2.1 Materials

2.1.1 Cement

CEM I 42.5 R type cement was used. Specific gravity and fineness (Blaine), of cement were 3.11 g/cm^3 and 3320 cm^2/g, respectively. Chemical composition of cement are given in Table 1.

Table 1: Chemical composition of cement (%).

CaO	Cl^-	SO_3	MgO	Na_2O	K_2O	SiO_2	Al_2O_3	Fe_2O_3	L.O.I
62.30	0.01	3.25	2.60	0.23	1.11	18.70	5.48	3.01	2.57

2.1.2 Aggregates

In the aggregate mixture, crushed sand and crushed stone I and II were used as 48%, 27% and %25, respectively. Density and water absorption tests were conducted on aggregates in accordance with TS EN 1097-6. Densities and particle size distributions of aggregates are given in Table 2.

Table 2: Physical properties and particle size distributions of aggregates.

Aggregate	Density (g/cm^3)	Sieve size, mm - % passing							
		0.25	0.5	1	2	4	8	16	32
Crushed sand	2.63	22.5	32.6	48.5	63.0	90.1	100	100	100
Crushed stone I	2.70	0.3	0.3	0.3	0.3	3.3	74.5	100	100
Crushed stone II	2.71	0.2	0.2	0.2	0.2	0.4	0.8	14.8	100

2.1.3 Chemical admixture

A new generation polycarboxylate ether (PCE) based superplasticizer was used in mixtures.

2.1.4 Mineral admixture

Silica fume was used as mineral admixtures in mixtures. Density and specific surface of silica fume were 2.23 g/cm^3 and 2336 cm^2/g, respectively. Chemical composition of silica fume is given in Table 3.

Table 3: Chemical composition of silica fume (%).

CaO	SO_3	MgO	SiO_2	Al_2O_3	Fe_2O_3	L.O.I
0.8	1.34	1.47	85.35	1.42	2.39	3.4

2.1.5 Steel fibres

In this study, three different steel fibres which have same length and aspect ratio and different hooked-end, were used. The properties of fibres were given in Table 4 and photo of fibres was given in Figure 1. Commercially available fibres were used and codes were selected as same as commercial names.

Table 4: Properties of fibres.

Code	Length, l (mm)	Diameter, d (mm)	Aspect ratio, (l/d)	Density, (g/cm^3)	Tensile strength, f_{su} (MPa)
3D65/60 BN	60	0.90	65	7.85	1160
4D65/60 BG	60	0.90	65	7.85	1500
5D65/60 BG	60	0.90	65	7.85	2300

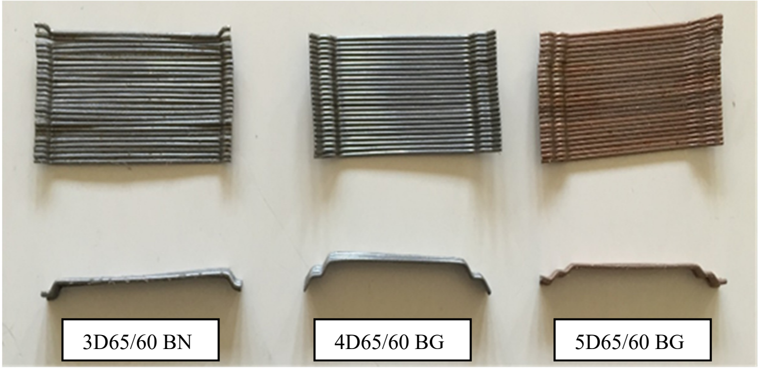


Figure 1: Steel fibres.

2.2 Mixture proportions

A concrete mixture with a water/(cement+silica fume) ratio of 0.30 was produced and steel fibres added in these mixtures at 15, 30, 45 and 60 kg/m^3. Mixture proportions of ingredients are given in Table 5.

Table 5: Mixture proportions (kg/m^3).

Fibre content	Cement	Water	Crush. sand	Crush. stone I	Crush. stone II	Super – plasticizer	Silica fume
0	450	149	847	489	455	5.4	45
15			845	488	454		
30			843	487	452		
45			840	485	451		
60			838	484	450		

3 Methods

3.1 Testing

The flexural tensile strength test was performed on 150 x 150 x 550 mm^3 prismatic notched-specimens by using the beam method according to EN 14651 standard at which load is applied at one third points of the specimen. The notched-specimens with a depth of 25 mm and width of 3 mm were tested by using a closed loop deflection-controlled loading frame of 250 kN capacity and loading rate was 0.2 mm/min. Test setup is given in Fig. 2. Load and the mid-span deflection of the beams were simultaneously recorded and, load–deflection curves for each specimen were also obtained graphically during the test.

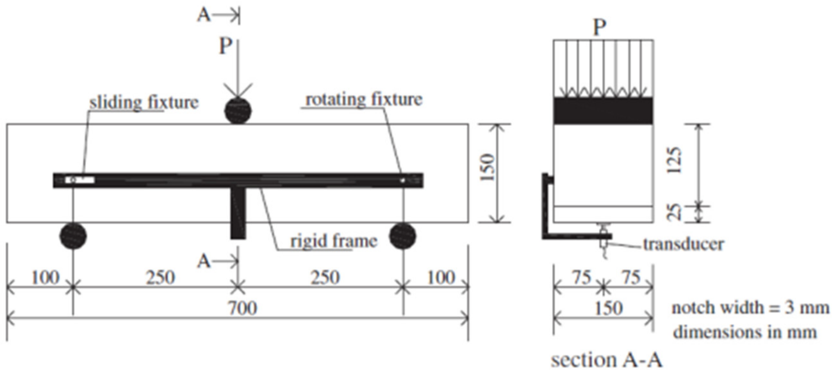


Figure 2: Flexural test setup.

3.2 Calculations

3.2.1 Limit of proportionality (LOP)

$$f_{ct,L}^{f} = \frac{3F_L l}{2bh_{sp}^2} \tag{1}$$

where, F_L is the load corresponding to the LOP, and l, b and h_{sp} are span length, width of the specimen and distance between the tip of the notch and the top of the specimen, respectively.

3.2.2 Fracture parameters

The fracture energy, G_F, was calculated by following equation (2) given RILEM TC-50 FMC [12],

$$G_F = \frac{W_0 + m(1-k^2)\rho\delta}{b(h-a)} \tag{2}$$

where W_0 is the energy represented by the area under the load–deflection curve, m is the mass of the specimen, ρ is the acceleration due to gravity, δ maximum deflection at final fracture (in this study, it is 5 mm), b is the beam thickness, h and a are the depth of the beam and notch, respectively.

The characteristic length (l_{ch}) is proposed by Hillerborg *et al.* [13], and defined as the ratio;

$$l_{ch} = \frac{G_F.E}{f_t^2} \tag{3}$$

where E is the modulus of elasticity and f_t is the tensile strength. In this study, splitting tensile strength, f_{st} was used instead of f_t.

4 Results

4.1 Fresh concrete properties

The properties of fresh concrete and the results of mechanical tests are given in Table 6. Concrete and medium temperatures were kept 22±2°C during casting of concretes.

Table 6: Fresh concrete tests.

Mixture Code	Slump cm	Vebe sn	Density kg/m^3	Concrete temp. °C	Medium temp. °C
Reference	18	3	2408	22.2	23.7
3DV15	18	2.7	2434	23.2	24.8
3DV30	16	3.8	2434	22.4	24.8
3DV45	14	5	2438	22.9	24.8
3DV60	12	7.5	2446	22.3	23.8
4DV15	18	3	2434	23.0	24.8
4DV30	16	4	2440	23.0	25.0
4DV45	13	6.5	2448	21.8	24.6
4DV60	12	9.5	2448	22.6	24.0
5DV15	17	3	2424	22.7	23.9
5DV30	16	4.5	2440	22.2	23.3
5DV45	11.5	7.5	2448	22.0	23.9
5DV60	11	9	2452	22.3	23.8

Slump and Vebe tests results of mixtures are shown in Figure 3. Slump values were decreased with increasing fibre content. However Vebe times were increased with increasing of fibre content. Vebe test is more suggested for assessment of workability of SFRC.

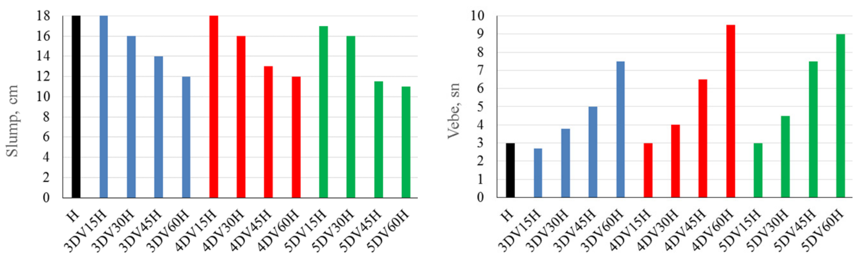


Figure 3: Slump and Vebe values of mixtures.

4.2 Mechanical properties

In order to obtain and compare the mechanical properties, the compressive strength, modulus of elasticity and splitting tensile tests were performed on hardened concretes in accordance with the standards EN 12390-3, ASTM C 469 and EN 12390-6. Results of mechanical properties are given in Table 7. It could not be seen any significant effect of fiber content on the compressive strength and modulus of elasticity (Figure 4).

Splitting tensile strength results are shown in Fig. 5. Splitting tensile strengths were increased with increasing of fiber content. Amount of increments are given above the bars as percentage. 3D, 4D, and 5D hooked ends increased the splitting tensile strengths as average of 28.8%, 26.8% and 29.9%, respectively.

Table 7: Results of mechanical properties.

Mixture Code	Compr. strength (MPa)	Modulus of elasticity (GPa)	Splitting tensile strength (MPa)	LOP (MPa)	Fracture energy (N/m)	Charac. length (mm)
Reference	83.0	41.5	4.11	3.67	-	-
3DV15	80.4	40.8	4.88	3.31	496*	0.83*
3DV30	83.0	39.6	5.29	4.56	1311	1.87
3DV45	80.7	40.9	5.49	4.60	1553	1.99
3DV60	84.0	40.7	5.54	4.31	2215	2.89
4DV15	83.0	41.1	4.90	3.93	550**	0.9**
4DV30	85.5	40.5	5.28	4.24	1283	1.84
4DV45	82.5	41.5	5.43	4.26	1582	2.15
4DV60	81.8	39.3	5.26	4.43	2386	3.30
5DV15	84.3	41.3	4.92	3.95	1521	2.51
5DV30	82.5	39.3	5.32	3.87	2108	2.98
5DV45	83.3	40.6	5.45	4.19	2137	2.88
5DV60	79.9	40.3	5.69	4.56	3292	4.07

*Specimens were broken at average 1.77 mm.
** Specimens were broken at average 3.5 mm.

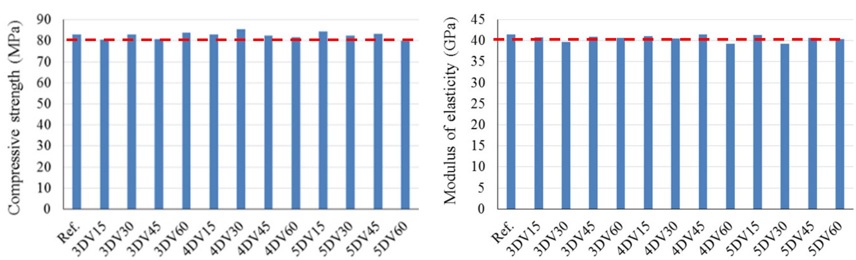


Figure 4: Compressive strength and modulus of elasticity of concretes.

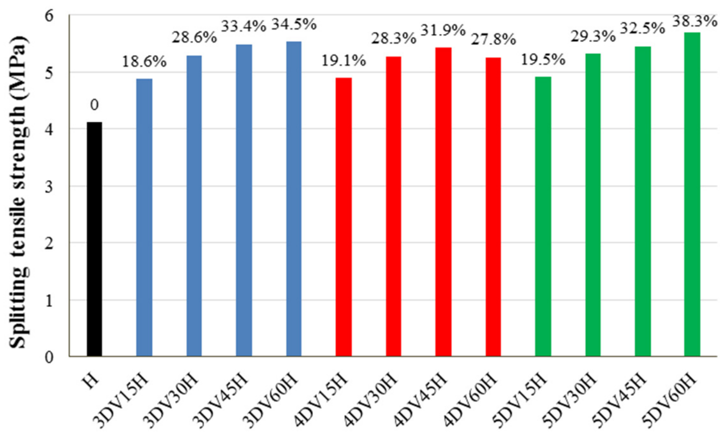
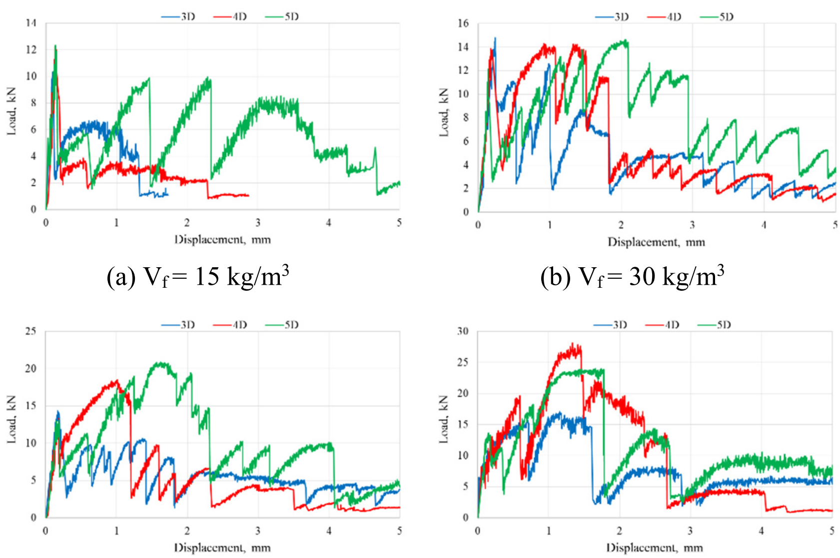


Figure 5: Splitting tensile strength of concretes.

4.3 Limit of proportionality and fracture parameters

The flexural tensile strength tests were performed according to TS EN 14651 which is described in Section 3. Load-displacement curves were obtained from these tests. Tests were stopped at 5 mm displacement. Load-displacement curves for 3D, 4D and 5D fibres in different fibre contents are given in Figure 6.



(a) $V_f = 15$ kg/m^3 (b) $V_f = 30$ kg/m^3

(c) $V_f = 45$ kg/m^3 (d) $V_f = 60$ kg/m^3

Figure 6: Load versus displacement curves.

Different post-cracking behaviours were observed for types of hooked-end. Peak loads were obtained higher than first crack loads in the mixtures consisting 4D and 5D types of fibre and high amount of fibre. After peak loads, load values did not decrease dramatically and could be increase at 60 kg/m^3 fibre content. In low fibre (V_f=15kg/m^3) content mixtures, 3D and 4D type hooked-ended fibres were broken at early displacement.

LOP values can be seen in Figure 7. Generally, LOPs were increased with increasing fibre content. LOP values were about 4.0-4.5 MPa in mixtures consisting of fibres exclude 3DV15. However, any significant effect of type of hooked-end was not observed on LOP.

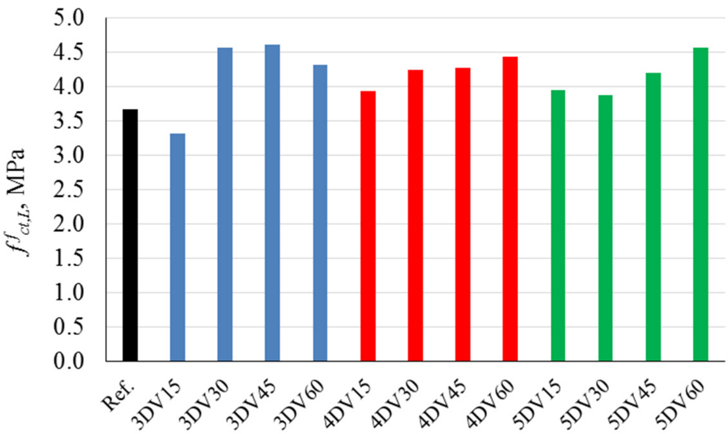


Figure 7: LOP values.

Fracture energies and characteristic lengths were calculated according to Equations (2) and (3), respectively. Fracture energy and characteristic length values of mixtures are given in Figures 8 and 9, respectively. Fracture energies and characteristic lengths of mixtures were increased with increasing of fibre content and also type of hooked end of steel fibres affected fracture parameters. 5D type hooked-ended fibres were the most effective with respect to both of fracture energy and characteristic length. 3D and 4D types hooked-end fibres were exhibited equal performance in both of fracture energy and characteristic length. But, 4D fibres were exhibited better performance than 3D fibres in mixture consisting 60 kg/m^3 fibre.

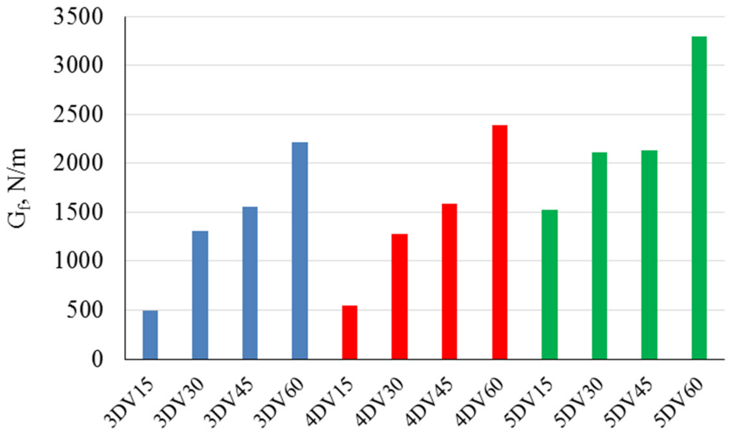


Figure 8: Fracture energy values.

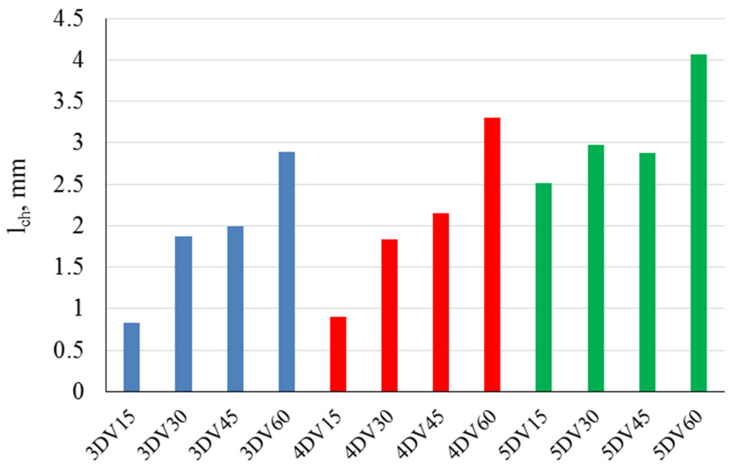


Figure 9: Characteristic length of mixtures.

5 Conclusions

It has been seen that type of hooked and was a significant effect on the properties of SFRC. Further conclusions from the present study can be stated as below;

- Fresh concrete properties were not affected by the type of hooked-end. However, slump values were decreased and Vebe times were increased with increasing fibre content.

- Hooked-end type and amount of steel fibres did not affect the compressive strength and modulus of elasticity, significantly. Splitting tensile strength of concretes were increased with increasing of fibre content. Nevertheless, effect of type of hooked-end were not observed on the splitting tensile strength. 5D hooked-ended steel fibres were increased up the splitting tensile strength as 38.3%.
- Post cracking behaviours were affected by the amount and type of hooked-end of fibres. Also, effect of fibre strength can be take in to consideration at the softening part.
- The LOP and fracture parameters were increased with increasing of fibre content. The effect of type of hooked-end was not observed on the LOP, however 5D type hooked-ended fibres were exhibited better performance on the fracture parameters. About 3300 N/m (J/m^2) fracture energy was obtained by using 5D type steel fibres.

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