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Effects of Fibre Geometry and Volume Fraction on the Flexural Behaviour of Steel-Fibre Reinforced Concrete

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ABSTRACT: This work aims in studying the mechanical behaviour of concrete, reinforced with steel fibres of different geometry and volume fraction. Experiments include compression tests and four-point bending tests. Slump and air content tests were performed on fresh concrete. The flexural toughness, flexural strength and residual strength factors of the beam specimens were evaluated in accordance with ASTM C1609/C1609M-05 standard. Improvement in the mechanical properties, in particular the toughness, was observed with the increase of the volume fraction of steel-fibres in the concrete. The fibre geometry was found to be a key factor affecting the mechanical performance of the material.

KEY WORDS: *fibre geometry, fibre volume fraction, fibre-reinforced concrete, flexural toughness, four-point bending, steel-fibres*

Introduction

Unreinforced concrete has low tensile strength and low strain capacity at fracture. When subjected to tension, the unreinforced concrete initially deforms elastically. The elastic response is followed by micro-cracking, localised macro-cracking, and finally fracture occurs. Fibrous materials have been and are being developed to provide improved mechanical properties to otherwise brittle concretes. Introduction of fibres into the concrete results in post-elastic property changes, that range from subtle to substantial, depending upon a number of factors, including matrix strength, fibre type, fibre modulus, fibre aspect ratio, fibre strength, fibre surface bonding characteristics, fibre content, fibre orientation, and aggregate size effects. In recent years, the use of fibres for enhancing the mechanical properties of concrete increased significantly. Considerable research, development, and applications of steel-fibre reinforced concrete (SFRC) are currently taking place [1].

The reinforcing fibres can be found in different shapes. Their cross sections include circular, rectangular, half-round, and irregular or varying shape. They may be straight or bent, and come in various lengths [2]. In general, fibre length varies from 12.7 mm to 63.5 mm. The most common fibre diameters are in the range of 0.45–1.0 mm. For normal weight concrete, fibre contents vary from as low as 30 kg m^{-3} to as high as 157 kg m^{-3}, although the high range limit is usually about 95 to 118 kg m^{-3} [3].

The effect of fibre shapes and fibre volume fraction has been of great interest in recent years [4–10]. A number of studies led to the development of new fibre geometries to optimise the fibre-concrete bond [11, 12], reduced the rebound and offer high toughness in shotcrete [13].

The effect of steel fibres on the compressive strength of concrete has also been studied. According to Williamson [14], an increase in compressive strength of concrete, tested using 150 mm × 300 mm cylindrical specimens, was observed ranging from negligible in most cases up to 23% for concrete containing 2% by volume of fibres. In another case, the use of steel fibres in concrete, with different fibre volumes and aspect ratios, increases the compressive strength of the material by about 4–19% [6]. In general, the addition of fibres does not significantly increase the compressive strength but it does increase the compressive strain at ultimate load [3].

The influence on the other hand of steel fibres on the flexural strength of concrete and mortar is much greater than in the case of the tensile or compressive properties of these materials [2]. The use of steel fibres in concrete significantly increases the flexural strength of the material. Furthermore, the increase of the flexural strength of SFRC is significantly improved with increasing the fibre aspect ratio (i.e. fibre length/fibre diameter ratio) and fibre volume fraction [6].

Next to the above, the ability of fibre-reinforced concrete composites to absorb energy has long been recognised as one of the most important benefits of the incorporation of fibres in plain concrete [15]. A concrete beam containing steel fibres suffers damage by gradual development of single or multiple cracks with increasing deflection, but retains some degree of structural integrity and post-crack resistance even under considerable deflection. A similar beam without steel fibres fails suddenly at a small deflection by separation into two pieces [1]. Experimental investigations have shown that the increase of the volume fraction of steel fibres contributed to the enhancement of the flexural toughness [16–18].

The present study investigates the effect of the geometry and volume fraction of steel fibres on the compressive strength, the flexural strength and toughness, as well as on the slump and air content properties of fresh concrete. Two different geometries of steel fibres were used in this study. For each one of the two geometries, three different volume fractions of fibres were selected.

Materials

Two geometries of fibres, waved fibres and fibres with hooked ends were used in this work. For each of the two geometries, three different fibre volume fractions were used in the concrete mixes; 0.5, 1, and 1.5% by concrete volume. In total, seven different mixture compositions were prepared, one of which was plain, unreinforced, concrete. The properties of the fibres are given in Table 1, and the mix proportions of the concrete mixtures are given in Table 2.

The mixtures consisted of 23% coarse aggregates (maximum aggregate size was 10 mm) and 77% sand, while water/cement ratio was 0.50.

Table 1: Fibre properties

Mixture code	Geometry	V_f (%)	d (mm)	l (mm)	l/d ratio
Plain	–	–	–	–	–
H0.5	Hooked ends	0.5	0.75	31	41
H1	Hooked ends	1	0.75	31	41
H1.5	Hooked ends	1.5	0.75	31	41
W0.5	Waved	0.5	0.75	25	33
W1	Waved	1	0.75	25	33
W1.5	Waved	1.5	0.75	25	33

V_f, fibre volume fraction; l, fibre length; d, diameter; l/d, fibre aspect ratio.

Table 2: Mix proportions of concrete mixtures (kg m^{-3})

Material	Plain	H0.5	H1	H1.5	W0.5	W1	W1.5
Cement II42.5	440	440	440	440	440	440	440
Water	220	220	220	220	220	220	220
Sand	1225	1215	1205	1193	1215	1205	1193
Coarse aggregate	366	363	360	356	363	360	356
Superplasticizer	3	3.2	3.7	4	3.2	3.7	4
Fibres	–	39	79	118	39	79	118
Sum	2254	2280	2308	2331	2280	2308	2331

Experiments

Characterization of fresh concrete

Slump tests [19] and air content tests [20] were performed on all the fresh concrete mixtures. The quantity of the superplasticizer was adjusted in every mixture, in order to maintain the workability of the fibre reinforced concretes at the same level.

Compression testing

Three cubic specimens of $150 \times 150 \times 150$ mm in size were prepared for each of the concrete mixtures. Compression tests were conducted after 28 days of concrete curing, on a compression testing machine with maximum load of 2000 kN.

Four-point bending testing

To establish the flexural toughness, the flexural strength and the residual strength factors of the beams, the ASTM C1609/C1609M-05 [21] standard was followed. The four-point bending tests were conducted on beam specimens sized $100 \times 100 \times 400$ mm (three specimens for each concrete mixture), with span length of 300 mm. The tests were conducted on a servo-hydraulic Instron 8801 machine with 100 kN maximum load. The loading and support system was designed in accordance with ASTM C78-02 [22] and was capable of applying third point loading to the specimen without eccentricity or torque. The displacement rate was 0.08 mm min^{-1} (see Figure 1A).

An accurate measurement of deflection is very important to characterise the toughness of SFRC. In flexural toughness tests of SFRC, it is common practice to measure the beam midpoint deflection between the tension face of the beam and a fixed reference on the machine crosshead. This method of deflection measurement includes, in addition to the

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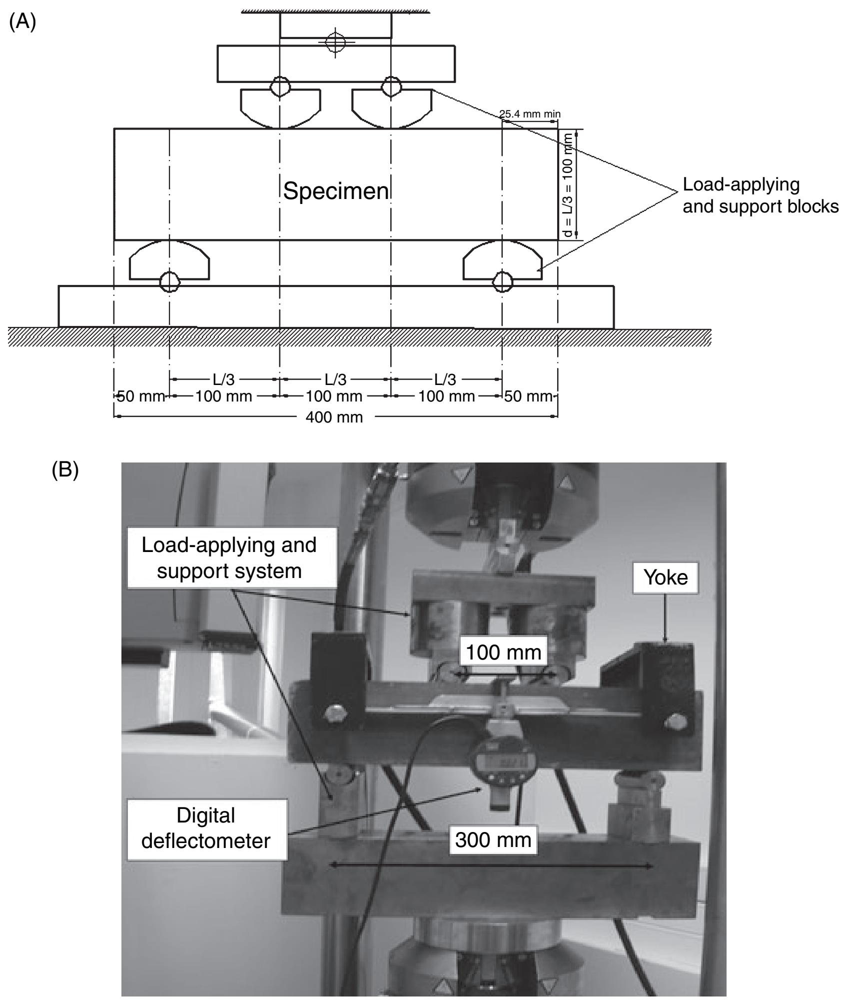

Figure 1: (A) Schematic of load applying support system, (B) four point bending test set-up

beam net deflection, the local deformations of the beam at the loading points, the elastic and inelastic deformations of the loading fixture/supports, and the initial specimen rocking. A more accurate deflection measurement can be obtained when the beam midpoint deflection is measured in relation to the beam's neutral axis at its support. This method allows for the measurement of the beam's net deflection [23].

Therefore, to measure the beam midpoint deflection in relation to the beam neutral axis at its support, a digital deflectometer Mitutoyo 543-450B was mounted on a yoke (Figure 1B).

Testing arrangement includes a load frame, a controller and two computers (Figure 2). The first computer controls the machine (crosshead movement, loading rate) and the second records the data (load – deflection).

The test terminates at a net deflection of 2 mm (i.e. 1/150 of the span). In this test method, identification of the toughness indices, as in the ASTM C1018 [24] standard method, is not required. On the contrary, the specimen's toughness $T_{100,2.0}$, is calculated, as the energy equivalent to the area under the load-deflection curve up to a net deflection of 2 mm. Moreover, the first-peak strength, the peak strength and the residual strengths corresponding to net deflections of 0.5 mm and 2 mm are calculated [21].

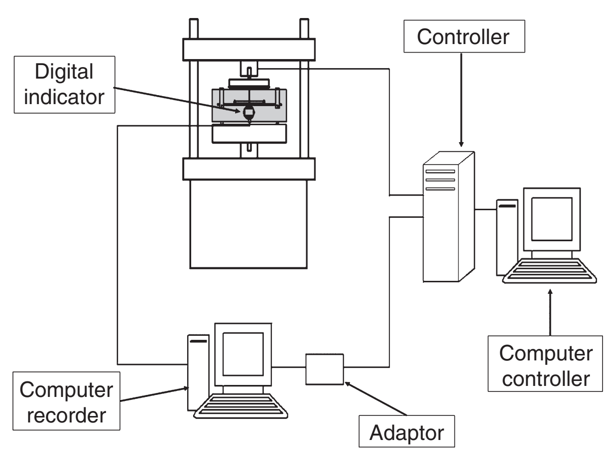

Figure 2: Experimental lay-out

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Results and Discussion

Properties of fresh concrete

As discussed earlier, the slump properties as well as the air content of the fresh unreinforced and reinforced concrete mixtures were measured in order to investigate the effect of fibre inclusion on the workability of the obtained systems. The results on the fresh concrete are shown in Table 3.

It can be observed that the addition of steel fibres in the concrete reduced the slump compared to the plain concrete. The slump in fibre reinforced mixtures ranged between 50 and 75 mm, while the slump of the plain concrete was 140 mm, which indicates a reduction higher than 50%.

The properties of SFRC in its freshly mixed state are influenced by the aspect ratio of the fibres, fibre geometry, fibre volume fraction, matrix proportions, and the fibre-matrix interfacial bond characteristics [1]. Because of the unique properties of SFRC, workability measurements or slump requirements are somewhat different from those of conventional concrete [3]. In the typical ranges of volume fractions used for cast-in-place SFRC (0.25 to 1.5 volume percent), the addition of steel fibres reduces the measured slump of the composite as compared to a non-fibrous mixture in the range of 25–102 mm.

As expected, the air content increases with the increasing of fibre volume fraction. Mixtures with high fibre volume fraction (H1, H1.5, W1 and W1.5) present higher air content than mixtures with low fibre volume fraction (H0.5, W0.5).

Compressive strength

The influence of the fibre geometry and volume fraction on the compressive strength of the obtained mixtures can be found in Table 4.

Table 3: Properties of fresh concrete

Tests	Plain	H0.5	H1	H1.5	W0.5	W1	W1.5
Slump (mm)	140	70	70	50	75	75	70
Air content (%)	2.90	2.70	3.5	3.6	2.70	3.20	3.60

Table 4: Compressive strength

Mixture code	Plain	H0.5	H1	H1.5	W0.5	W1	W1.5
Compressive strength (MPa)*	46.6	50.4	43.9	50.2	49.8	46.0	54.8
Standard deviation	1.59	1.01	0.45	1.17	1.91	1.21	0.25

*Mean value from three specimens.

As observed in Table 4, for both fibre geometries, the addition of fibres in the concrete mix at fractions of 0.5% and 1.5% V_f increased the compressive strength. On the contrary, the compressive strength of the concrete with 1% V_f was lower than that of unreinforced concrete specimens. This can be explained by the fact that the incorporation of fibres into the mixtures makes consolidation more difficult, leading to an increase of the entrapped air. As it is observed in Table 3, for both types of steel fibres, the air content of specimens with 1% V_f was found to be higher than the air content of specimens with 0.5% V_f as well as than the plain concrete specimens. According to Johnston 1992 [9], fibres have little intrinsic effect on the compressive strength. Instead, their effect is indirect and dependent mainly on whether the type and amount of fibre decrease the degree of consolidation achieved in the matrix.

It can additionally be observed, that the concrete mixtures with waved fibres exhibit higher compressive strengths than the concrete mixtures with hooked fibres, with the exception of the mixtures W0.5 and H0.5 which have comparable compressive strengths.

Flexural properties

A set of parameters that result from the load-deflection data for each specimen are given in Table 5. The first-peak strength (f_1) and the peak strength (f_p) were calculated using first-peak load (P_1), peak-load (P_p) and Equation 1.

$$f = \frac{PL}{bd^2} \tag{1}$$

where, f is the flexural strength (modulus of rupture) (MPa), P is the load (N), L is the span length (300 mm), b is specimen's average width at fracture (100 mm), and d is specimen's average depth at fracture (100 mm).

The residual strengths $f_{100,0.50}$ and $f_{100,2.0}$ were obtained by inserting the residual loads $P_{100,0.50}$ and $P_{100,2.0}$ corresponding to a net deflection equal to 0.50 mm and 2 mm using a specimen with a depth of 100 mm, into Equation (1) to estimate the corresponding flexural strengths. The specimen's toughness $T_{100,2.0}$ was then determined as the energy equivalent to the area under the load-deflection curve up to a net deflection of 2 mm (i.e. 1/150 of the span).

The significant influence of the fibre volume fraction on the mechanical properties of fibre-reinforced concrete is observed in Table 5. The effect of fibre volume fraction on the mechanical properties of

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Table 5: Four-point bending tests results (mean values from three specimens)

Mixture Code	P_I (N)	f_I (MPa)	P_P (N)	f_P (MPa)	$P_{100,0.50}$ (N)	$f_{100,0.50}$ (MPa)	$P_{100,2.0}$ (N)	$f_{100,2.0}$ (MPa)	$T_{100,2.0}$ (J)
Plain	14867	4.45	14867	4.45	–	–	–	–	–
H0.5	12645	3.80	12645	3.80	6145	1.85	5510	1.65	13
H1	15120	4.55	15157	4.60	9667	3.20	6323	2.00	16
H1.5	17160	5.15	19210	5.80	18565	5.60	13640	4.10	33
W0.5	13243	3.95	13243	3.95	3827	1.15	1503	0.45	7
W1	15770	4.75	15770	4.75	9560	2.85	4353	1.30	15
W1.5	19930	6.00	19930	6.00	10953	3.30	3963	1.20	17

concrete, for each type of fibre geometry, is shown in the curves in Figure 3. As it is shown in Table 5 and Figure 3, the increase in volume fraction raises the first-peak strength, the peak strength, the residual strength and especially the flexural toughness. Mixtures with hooked-ended fibres (H0.5, H1, H1.5) present higher toughness and residual strength ($f_{100,0.50}$, $f_{100,2.0}$) than mixtures with waved fibres (W0.5, W1, W1.5). On the contrary, mixtures W0.5, W1, W1.5 present higher first-peak strength and peak-strength compared to mixtures H0.5, H1, H1.5.

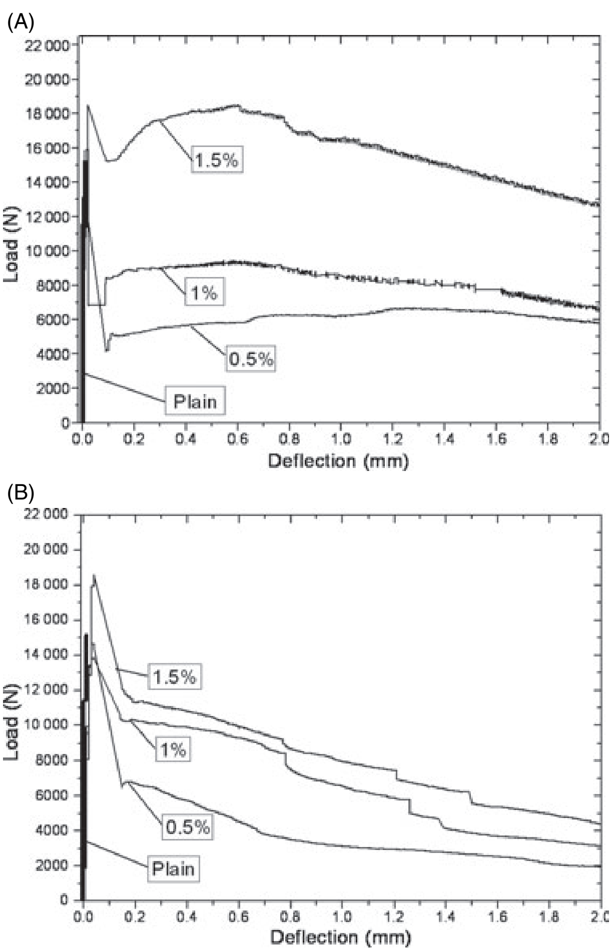

Figure 3: Comparison of typical load-deflection curves with different fibre volume fractions and plain concrete specimens for (A) hooked-ended steel fibres, and (B) waved fibres

Post-cracking load-deformation characteristics greatly depend on the choice of fibre geometry and the volume percentage of the specific fibres used [2]. The unreinforced concrete specimens failed catastrophically by a single crack by separation into two pieces (Figure 4A). On the contrary, the fibre-reinforced concrete specimens, even those with small V_f (0.5%), retained post-cracking ability to carry the load (Figure 4B). This behaviour of fibre concrete, leads to the enhancement of energy absorption compared to unreinforced concrete.

Figure 5 shows the variation of the mean value of the specimen's toughness $T_{100,\ 2.0}$ for each concrete mixture, as a function of the fibre volume fraction. It

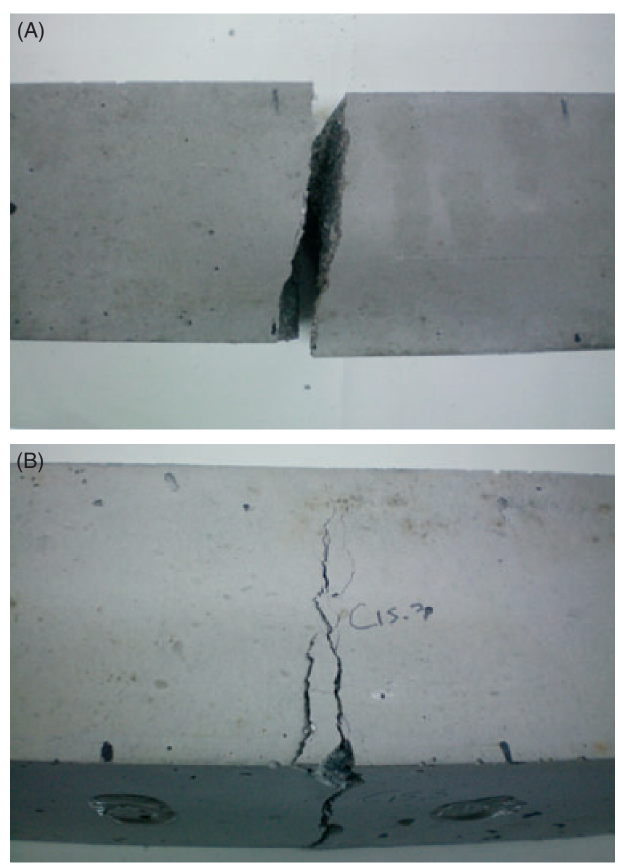

Figure 4: Specimen's failure (A) plain, unreinforced concrete, (B) fibre-reinforced concrete with waved fibres 1.5% V_f

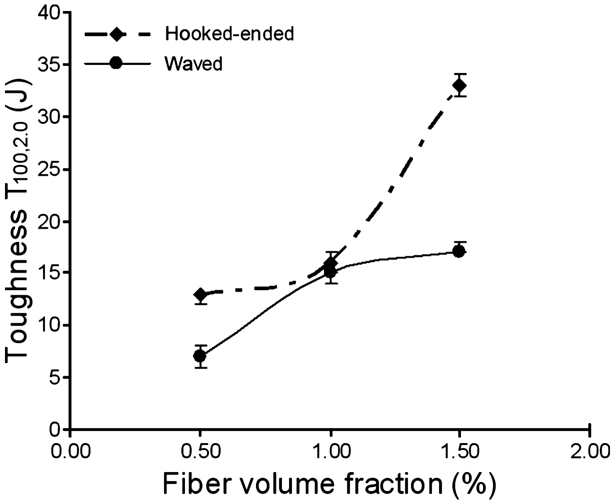

Figure 5: Toughness $T_{100,2.0}$ versus fibre volume fraction for hooked-ends fibres and waved fibres

is obvious that an increase in fibre content leads to significant improvement of energy absorption in the concrete specimens. The mixtures with hooked-ended fibres appear to have improved toughness properties compared to the mixtures with waved fibres. This behaviour is similar for each one of the three volume fractions.

Conclusions

In the current paper the effect of fibre geometry and fibre volume fraction has been investigated for steel fibre reinforced concretes. Specifically the compression strength, the flexural strength and toughness were studied as a function of the above parameters and compared to unreinforced concrete. The effect of the fibre inclusion on the slump and air content properties of fresh concrete has been also evaluated.

The test results led to the conclusion that the fibres play an important role, not only in the fresh state of the concrete, but also in the mechanical properties of hardened concrete specimens.

Concerning fresh concrete, the addition of steel fibres in the concrete mixture reduced the slump in the range of 65–90 mm, compared to plain concrete. The air content increased with the raising of fibre volume fraction. Mixtures with high fibre volume fraction (1 and 1.5% by concrete volume) presented higher air content than mixtures with smaller fibre volume fraction (0.5% by concrete volume). This is due to fact that consolidation of fibre-reinforced concrete becomes more difficult with increasing the fibre volume fraction, leading to an increase of air content in the material.

Incorporation of fibres in concrete had small effect on the compressive strength. It was also observed that concrete mixtures with waved fibres exhibited higher compressive strengths than concrete mixtures with hooked-ended fibres, with the exception of the mixtures W0.5 and H0.5 which showed comparable compressive strengths.

Plain concrete specimens failed catastrophically by a single crack, and separation into two pieces. On the contrary, the fibre-reinforced concrete specimens, even those with small fibre volume fraction (0.5%), retained post-cracking ability to carry out loads.

The increase in the volume fraction of the fibres in the concrete mixture increased the first-peak strength, the peak strength, the residual strength and especially the flexural toughness of the specimens.

Specimens with hooked-ended fibres (H0.5, H1, H1.5) exhibited higher values of toughness and residual strength ($f_{100,0.50}$, $f_{100,2.0}$) than specimens with waved fibres (W0.5, W1, W1.5). On the contrary, concrete mixtures W0.5, W1, W1.5 showed higher first-peak strength and peak-strength than the mixtures H0.5, H1, H1.5.

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