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Flexural Characteristics of Fibre Reinforced Concrete with an Optimised Spirally Deformed Steel Fibre

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A B S T R A C T

In this paper, the flexural performance of Fibre Reinforced Concrete (FRC) with an optimised spirally deformed steel fibre developed by the authors is evaluated experimentally. For comparison purposes, concrete specimens with commercially available steel fibres (hooked-end and crimped) are tested and included in the study. The research findings indicate that the optimised spirally deformed steel fibre considerably enhances flexural characteristics of concrete compared with existing fibres on the market. Moreover, the deflection-hardening response (even in the presence of wide cracks) can also be achieved even with low spiral fibre dosages common in practice. Therefore, such a composite, i.e. concrete reinforced with spirally deformed steel fibre, can be deemed as a structural material.

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NOMENCLATURE

f_{ck}	Characteristic cylinder strength of concrete, MPa	L	Clear span between the supports
$f_{ck,\,cube}$	Characteristic cube strength of concrete, MPa	Pe, p	Peak elastic load, kN
f_m	Target mean cylinder strength of concrete for concrete mix design, MPa	Pp, pc	Peak post-cracking load, kN
f_r	Modulus of rupture, MPa	$T\ DX$	Toughness (area under the load vs. net deflection curve from 0 to L/X
f_u	Ultimate stress of steel, MPa	Vf	Fibre volume content
f_X^D	Residual strength at net deflection of L/X		

1. INTRODUCTION

The employment of steel reinforcing bars makes concrete a suitable composite material for various structural and non-structural applications. Such bars, however, reinforce concrete against tension only locally where the cracks in reinforced concrete (RC) members can freely initiate and propagate until encountering rebar. The need for multi-directional and closely spaced reinforcements for concrete led to fibre reinforced concrete (FRC). FRC is a cement-based composite material reinforced with discrete and randomly distributed fibres [1]-[3]. There are various fibre materials such as steel, carbon, and polypropylene; however, steel is the most suitable for structural applications due to its high modulus of elasticity and ductility [3,4].

The fibres act as crack growth arrestors (crack bridging mechanism), leading to a delay in the formation and propagation of the crack, reduction in crack widths, and consequently enhancement of post-cracking characteristics and ductility of concrete [4]. However, the structural applications of FRC are limited mainly because of the poor performance of the fibres at the cracking levels expected at the ultimate loading. After the initial

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stage of the fibre pullout process (peak pullout load), as the fibres are pulled out from concrete, their resistance usually decreases with the continuous slippage known as slip-softening behaviour. The continuous decay of pullout load would not result in a major contribution of fibres to the ultimate load bearing capacity. In other words, the overall internal force transferred by the fibres across the cracked sections (bridging contribution of fibres) is generally less than the internal force transferred through the sections before cracking [5,6].

There are examples of steel fibres on the market such as brass-coated straight, and twisted fibres which are engineered in terms of surface coating and geometry (shape) for compatibility with certain high- and ultra-high-performance concretes (HPC and UHPC) to achieve higher rates of increase in the fibre-matrix interface friction which could result in a hardening pullout response [7,8]. These fibres are relatively expensive and demand restrictive requirements on the concrete composition; hence their applications as structural reinforcement are limited in the construction industry.

Hajsadeghi et al. [9-10] developed a new generation of steel fibres which possesses slip-hardening response in normal concrete (an optimised spirally deformed fibre) in order to advance the adoption of such discontinuous fibres in the structural design of RC members.

Optimised spirally steel fibres [9] are applicable in energy absorption applications such as earthquake resistant structures [11], impact loading [12] and shrinkage control of concrete structures [13]. Besides, the most important feature of this optimised fibre is providing deflection hardening behaviour even in low volume fraction of fibres as it is subject of current research.

This paper presents the flexural characteristics of normal concrete with the incorporation of spirally deformed steel fibre to evaluate its contribution to the load bearing capacity of the basic concrete matrices. To this end, a set of fibrous concrete prisms are tested under flexure, where specimens with commercially available steel fibres (hooked-end and crimped) are included in the testing programme as the reference.

2. EXPERIMENTAL PROGRAM

2. 1. Materials

Two different concrete mix designs are used in the programme with the 28-day target mean strengths (f_m) of 35 MPa and 45 MPa [14]. To increase the consistency of fibrous concrete, superplasticizer (High Water Reducing Admixture-HWRA) with the amount of 1 percent of the cement content is added to all mixes [15]. The dry composition per cubic meter of matrices is presented in Table 1. To decrease the risk of fibre balling during the mixing process, coarse aggregate with 95 percent of particles finer than 10 mm is used for the mixes. The fine and coarse aggregates conform to the requirements given in BS EN 12620 [17].

The newly-designed steel fibre with spiral configuration developed by Hajsadeghi et al. [9-10] having material strength (f_u) of 1500 MPa is employed in the experimental programme. To compare the effectiveness of the new fibre in enhancing the flexural characteristics of concrete with its counterparts, two types of commercially available steel fibres (hooked-end and crimped) are incorporated into the study. The ultimate strength (f_u) of the hooked-end and crimped fibres material is 1000 MPa and 1500 MPa, respectively. The geometrical properties of the fibres are shown in Figure 1.

The concrete strength (f_m), fibre volume content (V_f), and fibre type are considered as the experiment parameters, which are listed in Table 2. The steel material is assumed to have a density of 7850 kg/m^3 for calculating the required amount of fibres for the various volume fractions.

The concrete workability is assessed using the slump cone test [13]. The slump of all concrete batches with their corresponding I.D. is listed in Table 3. The mixes are labelled such that the specifications of each mix can be identified from the mix I.D. For instance, the label “P-35” represents the plain concrete (non-fibrous concrete) with target mean cylinder strength of 35 MPa; also, the label “N-0.5-45” indicates that the mix is reinforced with the new fibre at the fibre content of 0.5% having a target mean strength of 45 MPa.

To ensure proper mixing, ACI PRC-544.3-08 [15] methodology was taken into account. Moreover, a particular centrifuge mixer type was utilized (Figure 2a) to guarantee a uniform and homogenous mixture. Some photos were taken during the mixing procedure, which revealed uniform mixing (Figure 2b).

ACI 544.4R-18 [19] recommendations was considered in the design and selection of fibre dosage.

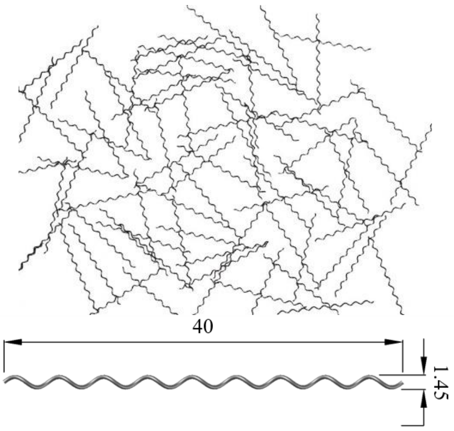
TABLE 1. Concrete mix design

Target strength (MPa)	Cement [1] (kg)	Water (kg)	Super plasticizer [2] (kg)	Fine aggregate [3] (kg)	Coarse aggregate [3] (kg)
f_m = 35	350.0	188.3	3.5	880	988
f_m = 45	423.1	188.3	4.25	802	993

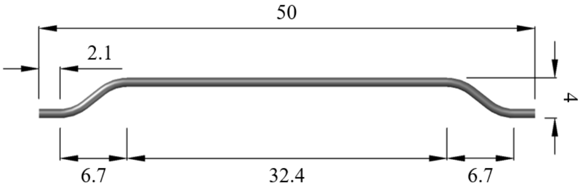
[1] 42.5 type Portland cement [16]

[2] Sika ViscoCrete® 1200 series

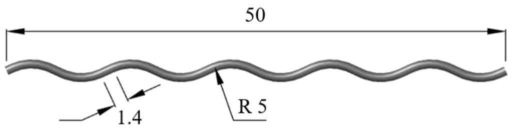
[3] Saturated Surface-Dry (SSD) condition



(a) Spirally deformed fibre (SD-9-1.45-0.4-40), d_f = 0.4 mm



(b) Hooked-end fibre, d_f = 0.9 mm



(c) Crimped fibre, d_f = 0.9 mm

Figure 1. Steel fibres (dimensions are in mm)

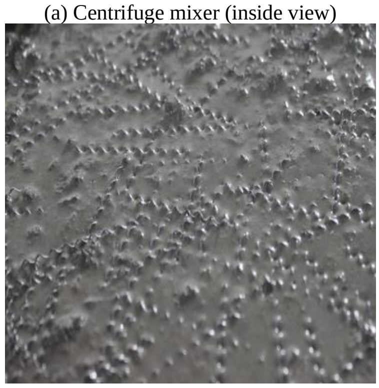
TABLE 2. Experimental parameters

f_m (MPa)	V_f (%)	Fibre type
35, 45	0, 0.2, 0.35, 0.5, 0.65	Spirally deformed
35	0.5	Hooked-end, Crimped

TABLE 3. Slump cone test results

Concrete Type		Mix ID	V_f (%)	f_m (MPa)	Slump (mm)
Plain		P-35	-	35	198
		P-45	-	45	136
Fibrous	Newly-designed	N-0.2-35	0.2	35	168
		N-0.2-45		45	112
		N-0.35-35	0.35	35	139
		N-0.35-45		45	91
		N-0.5-35	0.5	35	99
		N-0.5-45		45	63
		N-0.65-35	0.65	35	79
	Hooked-end	H-0.5-35	0.5	35	121
	Crimped	C-0.5-35	0.5	35	77

(a) Centrifuge mixer (inside view)



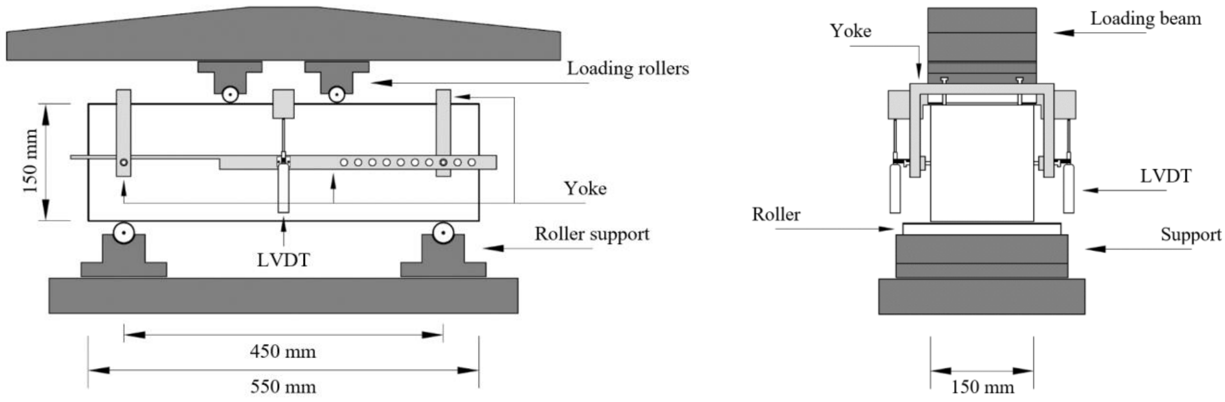
(b) Uniform distribution fibres after mixing procedure

Figure 2. Mixer and a sample of a mixed matrix

Furthermore, the optimised spiral fibre has been proposed recently by authors for the current paper and the design procedure is in progress by authors.

2. 2. Test Setup ASTM C1609/C1609M - 12 [20] is adopted to conduct the four-point loading flexure tests to characterize the flexural performance of FRC specimens modulus of rupture (f_r), residual flexural strengths, and toughness. The dimensions of the specimens, respectively width, height, and length, are 150 mm, 150 mm, 550 mm with a span length of 450 mm.

The test was performed using a 300 kN capacity closed-loop controlled universal testing machine (UTM). The loading arrangement and instrumentation setup of the flexure test are shown in Figure 3. As required in the standard [20], the clear span between the supports is 450 mm, and the distance between the four loading points is 150 mm (third-point loading). A rectangular jig that surrounds the specimen and is clamped to it at mid-depth directly over the supports, i.e. yoke, is employed to measure the net mid-span deflection (see Figure 3). Two linear variable differential transducers (LVDTs) with a total stroke of ±15 mm and precision of ±0.001 mm are mounted on the LVDT slots of the yoke to measure the mid-span deflections on each vertical face of the specimen. The average value is considered as the mid-span net deflection of the specimen.



(a) Front view (b) Side view

Figure 3. Flexural test setup

The testing machine was set so that the net deflection of the specimens increases at the constant rate of 0.1 mm/min. For net deflection beyond 0.6 mm, the loading rate increases to 0.3 mm/min with an increment of 0.05 mm/min. During the test, the testing data, including load and displacement from the UTM and deflection from two LVDTs are collected with the frequency of 3 Hz. The test continues at least up to 12 mm net deflection for all the specimens. After completion, the specimens were removed from the machine, and the cross-sectional dimensions adjacent to the failure crack are measured [14].

2. 3. Experimental Results The average results of the compression tests of the cylinder and cube concrete specimens on the 28th day after casting are summarised in Table 4, in which the variation of each test set is also provided.

TABLE 4. Compression test results

Mix ID	f_{ck} * (MPa)	$f_{ck, cube}$ * (MPa)
P-35	35.9±1.9	45.9±1.8
P-45	46.0±2.2	55.9±2.4
N-0.2-35	35.3±2.1	45.8±2.3
N-0.2-45	46.5±1.6	55.6±2.5
N-0.35-35	35.4±0.7	44.7±0.3
N-0.35-45	46.0±1.7	55.2±3.4
N-0.5-35	36.7±0.8	47.5±1.6
N-0.5-45	47.3±0.6	58.2±1.0
N-0.65-35	34.2±1.1	44.5±0.6
H-0.5-35	35.7±0.5	43.9±0.5
C-0.5-35	35.1±1.0	44.6±0.4

* Average results based on three specimens

As evident from the table, the mix designs yield compressive strengths close to the corresponding target values. Besides, as anticipated, the inclusion of fibres does not influence the compressive strength. However, since the concrete batches are made separately, the variation in the peak strengths is reasonable due to slight differences in the moisture content of the aggregates and the mixing and casting process.

The flexure tests are conducted in accordance with ASTM C1609/C1609M - 12 [20]. In Figure 4, a concrete prism reinforced with new steel fibre under flexural testing is shown. For each batch of concrete, three specimens were prepared and tested on the 28th day after casting, where the average results are considered as the FRC behaviours.

The load-deflection curves of the FRC specimens with the new fibre and existing fibres on the market (hooked-end and crimped) under four-point bending are shown in Figures 5 and 6, respectively. The results of flexure tests are summarised in Table 5.

As shown in Figures 5 and 6, the flexure response of FRC specimens are characterized by a linear part up to the elastic limit load (pre-cracking stage before fibres

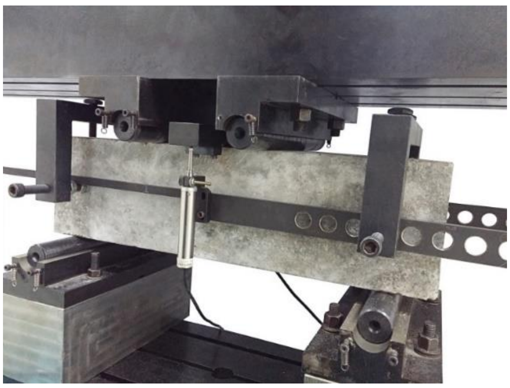


Figure 4. Fibrous concrete prism under flexural testing

contributions are activated), followed by a sudden load decay to a specific load which depending on the fibre type and volume content continues with a different trend (deflection-hardening or deflection-softening). The sudden load decay in the responses could be attributed to the low fibre volume contents used in this research so that wider cracks are needed to activate an adequate overall fibre bridging action. As evident from Figure 5 and Table 5, increasing the fibre content improves the flexure performance of FRC specimens with the new fibre by decreasing the severity of the sudden load drop as well as enhancing the post-cracking response.

Besides, the specimens with the new fibre (f_{ck} = 35 MPa / V_f = 0.5%) possess a relatively more severe sudden load decay compared with those containing hooked-end and crimped steel fibres (40.9% vs. 25.8% load decay, on average). This is likely attributable to the higher initial pullout stiffness of these commercially available fibres than the new steel fibre (spirally deformed fibre) [9-10].

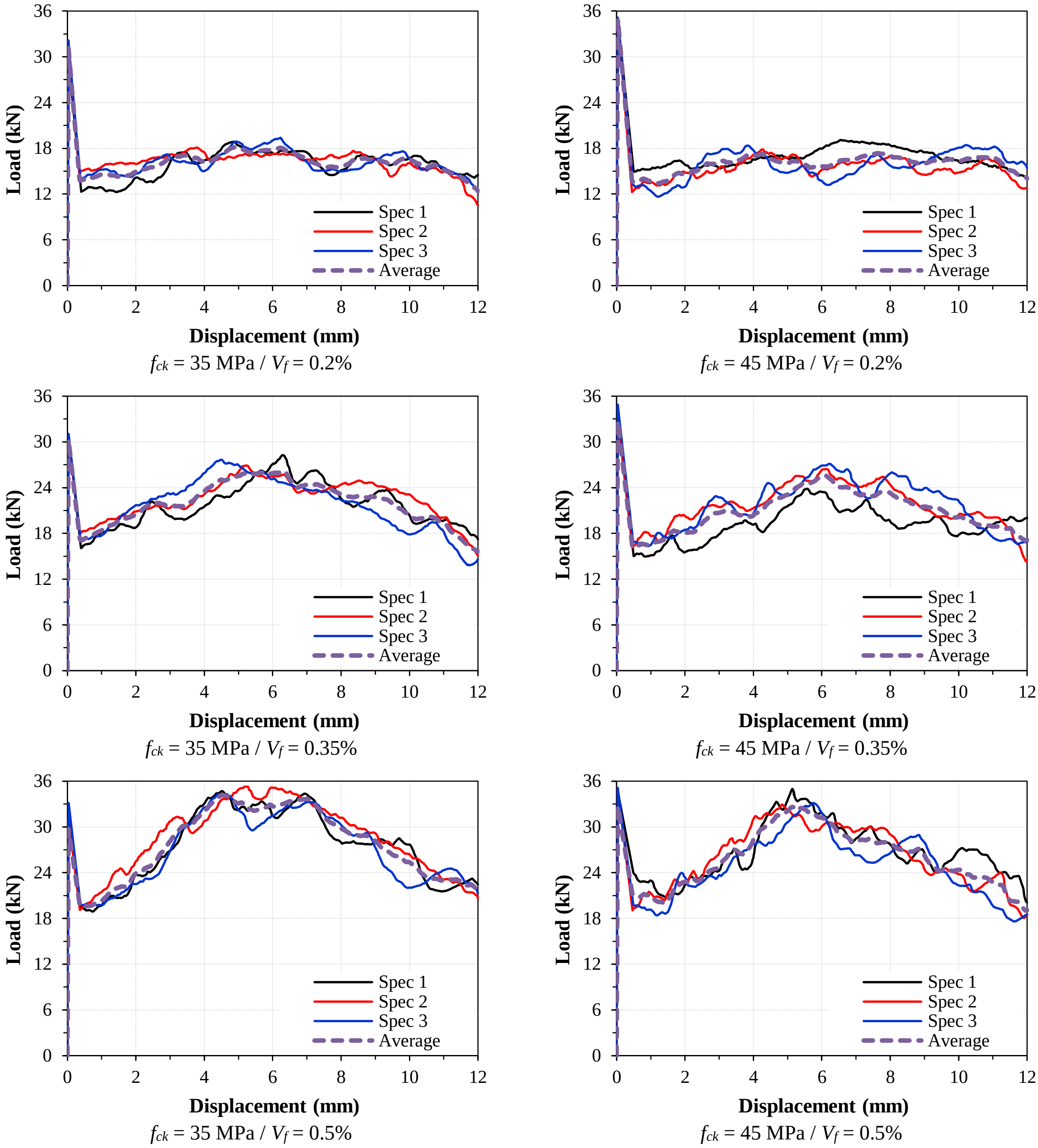
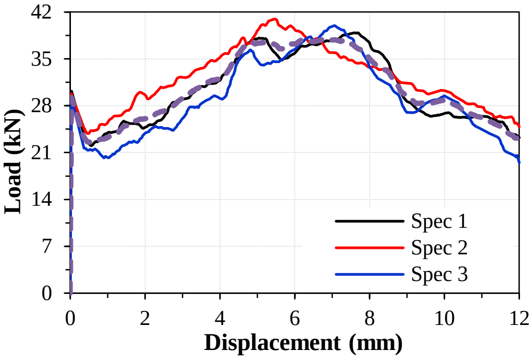
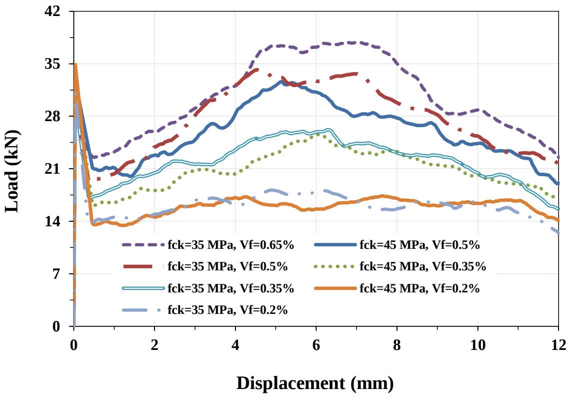


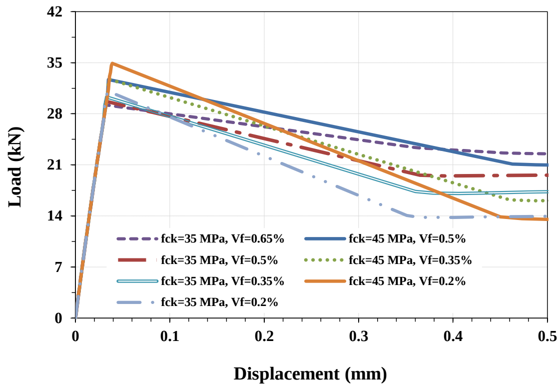
Figure 4. Individual and average flexural responses of FRC containing the new fibre. (Continued on the next page)



f_{ck} = 35 MPa / V_f = 0.65%

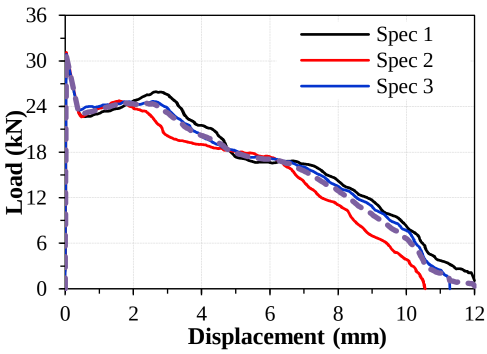


Comparison of average responses

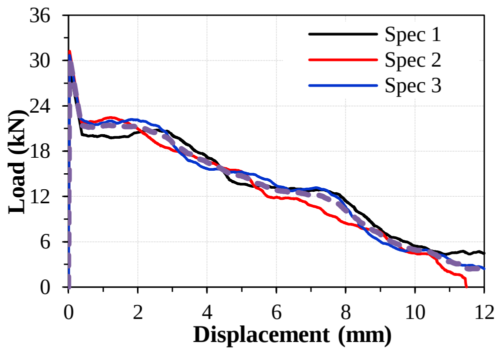


Comparison of average responses in primary displacement

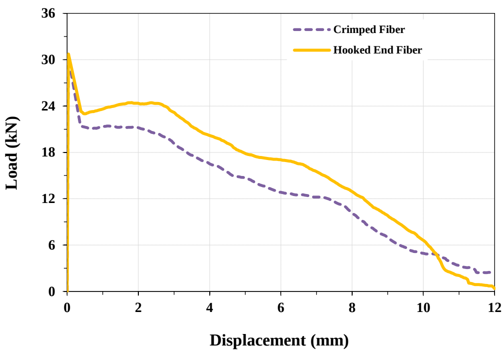
Figure 5. Individual and average flexural responses of FRC containing the new fibre (Continue from previous page)



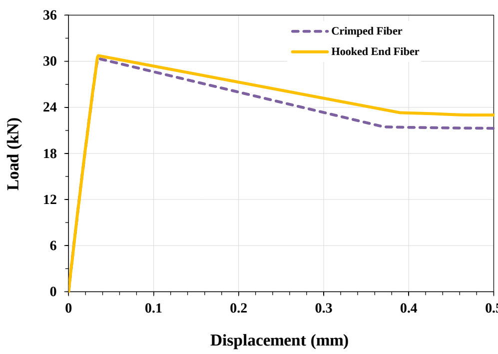
f_{ck} = 35 MPa / V_f = 0.5% / Hooked-end



f_{ck} = 35 MPa / V_f = 0.5% / Crimped



Comparison of average responses



Comparison of average responses in primary displacement

Figure 6. Individual and average flexural responses of FRC containing commercially available fibres

TABLE 5. Flexural tests results

ID (Mix / Specimen)	f_r (MPa)	$P_{e,p}$ (kN)	$P_{p,pc}$ (kN)	f^{D}_{45} [1] (MPa)	T^{D}_{45} [2] (kN.mm)	Response
P-35	4.06±0.11	30.42	-	-	-	-
P-45	4.56±0.18	34.17	-	-	-	-
N-0.2-35	4.15±0.19	31.14	18.17	2.20	165.4	Softening
N-0.2-45	4.65±0.04	34.90	17.37	2.18	163.5	Softening
N-0.35-35	4.09±0.07	30.29	26.20	2.72	228.0	Softening
N-0.35-45	4.57±0.14	32.75	25.57	2.69	214.8	Softening
N-0.5-35	4.21±0.21	29.72	34.20	3.38	286.0	**Hardening**
N-0.5-45	4.65±0.05	32.69	32.63	3.25	267.5	Softening
N-0.65-35	3.95±0.08	29.21	37.88	3.85	315.6	**Hardening**
H-0.5-35	4.10±0.07	30.74	23.30	0.80	168.8	Softening
C-0.5-35	4.05±0.12	30.36	19.70	0.61	136.6	Softening

[1] Residual strength at net deflection of 10 mm (*L*/45)

[2] Toughness (area under the load vs. deflection curve from 0 to 10 mm

However, inclusion of 0.5% of the optimised spiral fibre results in the peak post-cracking load ($P_{p,pc}$) greater than the peak elastic load ($P_{e,p}$), i.e. deflection-hardening response [21], as well as superior post-cracking characteristics (higher toughness and residual strengths at various deflections) compared with hooked-end and crimped steel fibres. The results indicate that the new fibre greatly contributes to the load bearing capacity of the specimens which is more pronounced at large deflections e.g. 6 mm deflection.
To better understand differences between the load-deflection response of specimens, a comparative diagram using average responses is provided in Figures 5 and 6.

3 CONCLUSION

The contribution of the optimised spirally deformed steel fibre developed by the authors to the flexural performance of normal concrete specimens was investigated in this paper.

Findings of the experimental programme reveal that contrary to the existing fibres on the market, the newly-designed steel fibre has significantly improved the post-cracking characteristics of fibrous specimens, including the residual strength, especially at more considerable deflections, which is indicative of its effectiveness as structural reinforcement for concrete, contrary to those commercially available on the market. The authors perform another research project that aims to construct industrial facilities to produce a high volume of such fibre. In that way, the production of a high volume of optimised spiral fibres will be possible.

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Persian Abstract

چکیده

این مقاله به مطالعه آزمایشگاهی رفتار خمشی بتن مسلح به الیاف مارپیچ فولادی پرداخته است. این الیاف توسط نویسندگان مقاله حاضر بهینه و معرفی شده است. با هدف مقایسه، نمونه های بتنی ساخته شده با الیاف فولادی متداول (الیاف قلاب دار و الیاف موجدار) نیز مورد آزمایش قرار گرفته است. نتایج تحقیق نشان می دهد الیاف فولادی مارپیچ به طور قابل ملاحظه ای نسبت به الیاف متداول فولادی، مشخصات خمشی را بهبود می دهد. پاسخ سخت شدگی کرنش حتی در بازشدگی های قابل ملاحظه ترک ها و با به کارگیری درصدهای نسبتا پایین الیاف حاصل شده است. در نتیجه کامپوزیت های سیمانی مسلح به الیا.ف مارپیچ به عنوان یک مصالح سازه ای با عملکرد بالا قابل معرفی می باشند.