SENSITIVITY OF VARIOUS STEEL-FIBER TYPES TO COMPRESSIVE BEHAVIOR OF ULTRA–HIGH–PERFORMANCE FIBER–REINFORCED CONCRETES

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Abstract

This research investigated the sensitivity of various steel fibre types to compressive behaviour of Ultra-high-performance fibre reinforced concretes (UHPFRCs) by experimental program. The same mortar matrix was used while four types of steel fibres were added with identical volume fraction (2%): twisted fibres (T), hooked fibres (H), long smooth fibres (LS) and hybrid fibres (HB) which includes 1% twisted blended 1% short smooth fibres. There was an important increase in compressive resistance of UHPFRCs compared with mortar matrix without fibres. The order of fibre-type sensitivity in terms of compressive strength and ultimate strain was achieved as follows: T > LS > HB > H. The compressive stress versus strain responses of UHPFRCs were virtually linear within their peak points but dispersed and brittle beyond the peaks.

Résumé

La sensibilité du comportement en compression de bétons fibrés à ultra-hautes performances vis-à-vis de différents types de fibres métalliques a été étudiée expérimentalement. La même matrice cimentaire a été employée avec une même teneur volumique (2 %) de fibres d'acier de quatre types : fibres torsadées (T), à crochets (H), fibres longues et droites (LS) et mélange hybride (HB) comprenant 1 % de fibres torsadées et 1 % de fibres droites courtes. Une augmentation importante de la résistance en compression des BFUP a été obtenue par comparaison à la résistance de la matrice sans fibres. La sensibilité de la résistance en compression et de la déformation ultime vis-à-vis du type de fibres s'établit dans l'ordre suivant : T > LS > HB > H. Les relations contrainte-déformation en compression des BFUP se sont avérées pratiquement linéaires jusqu'au pic, puis dispersées et fragiles au-delà du pic.

1. INTRODUCTION

There has been an urgent demand for enhancing the resistance of civil infrastructure under critical mechanical and environmental conditions including earthquake, impact, blast, and marine conditions. Ultra-high-performance concrete (UHPC) is one of promising construction materials for the goal of enhancing the strength, toughness and durability of civil and military infrastructure because UHPC can produce its ultra-high compressive strength (more than 150 MPa) due to its densified microstructure [1-4].

Like other cement-based materials, UHPC still performs its brittle nature. The addition of steel fibres to UHPC matrix, to develop a composite named ultra-high-performance fibre reinforced concretes (UHPFRC), has been conducted to remedy the brittle under direct tension and bending [1,5-12]. The tensile and flexural behaviours of UHPFRCs were reported to depend much upon the types and volume fraction of fibres added [10,11,13] owing to relevant factors such as average stress, group reduction, random distribution, fibre orientation and interfacial bond strength [14,15].

Ultra-high compressive strength of UHPC or UHPFRC is the most superior property of this material, and thus the compressive behaviour of UHPFRCs should be thoroughly clear. However, there is very little information about the fibre-type dependent compressive behaviour of UHPFRCs. Understanding the compressive behaviour of UHPFRCs would greatly help their successful application in structural members.

This situation has motivated author to conduct the experimental study focussing the sensitivity of various steel-fibre types to compressive behaviour of UHPFRCs. The specific objectives are (1) to investigate the compressive behaviour of UHPFRCs with no fibre and with various fibre types, and (2) to investigate the sensitivity of various steel-fibre types to compressive resistance of UHPFRCs.

2. EXPERIMENTAL PROGRAM

2.1 Materials and preparation of specimens

An experimental program was designed to investigate the compressive performance of UHPFRCs using various steel fiber reinforced, as illustrated in Fig. 1. A part of test results was sketchily reported in [4] by the authors and this paper would provide full information of experimental test. Tab. 1 provides the composition of the UHPC matrix, while Tab. 2 provides the properties of fibers. Fig. 2a shows the photos of material dimensions and composition for producing UHP mortar. Fine silica sand with a diameter smaller than 0.5 mm would be used in the matrix composition, while the average diameter of silica powder was about 10 μm. The silica powder is composed of 98% SiO_2, and its density was 2.60 g/cm^3. Fineness of cement (using Type 1) is 3480 cm^2/g and the diameter of silica fume does not exceed 1 μm.

Firstly, UHPC mortar matrix (UHPFRC with no fiber) is prepared. Cement, silica fume, silica powder, and sand would be mixed in a dry state for about 10 min. Water blended with superplasticizer is then added gradually into the mixture and mixed for 5 to 10 min. Next, the investigated fibers are added into UHPC mortar matrix to produce four UHPFRC series with same 2% fiber content by volume but different fiber types as follows: series 1 contains twisted fibers (T), series 2 contains hooked fibers (H), series 3 contains long smooth fibers (LS) and series 4 contains hybrid fiber including 1% twisted fibers and 1% short smooth fibers (HB). Each series would be produced from single batch of mortar then tested with four specimens at least. The different series are taken from different batches of mortar but same mixing method. All macro types of investigated fibers are same length of 30 mm but different diameters: the diameter of the twisted and long smooth fibers are 0.3 mm while that of the hooked fibers is 0.375 mm. The short smooth fibers (micro type), used together with the twisted fibers in hybrid system, has its length of 13 mm and diameter 0.2 mm. The twisted fibers used in this study had a triangular cross section and had six ribs within the 30 mm fiber length. The shape of all specimens is cylinder with diameter of 100 mm and height of 200 mm. All specimens were smoothed and checked their horizontal planes prior to test.

Table 1: Composition of UHPC matrix

Cement (Type 1)	Silica Fume	Silica Sand	Silica Powder	Superplasticizer	Water
1.00	0.25	1.10	0.30	0.067	0.20

Table 2: Properties of steel fibres investigated

Fiber type	Length / Diameter (mm)	Density (g/cc)	Tensile strength (MPa)	Elastic modulus (GPa)
Twisted	30/0.3*	7.9	2428†	200
Long smooth	30/0.3	7.9	2580	200
Hooked	30/0.375	7.9	2311	200
Short smooth	13/0.2	7.9	2788	200

*Equivalent diameter †Tensile strength of fiber after twisting.

2.2 Test setup and procedure

The tests were conducted using a universal test machine with displacement control and the applied loading velocity was 1 mm/min. The frequency of data acquisition under compression tests was 1 Hz. Fig. 2b shows the test setup and typical shape of compression specimen. Three linear variable differential transformers (LVDTs) were installed in two aluminum cages to measure the net deformation of the specimen. The gauge length of the compressive specimen was 100 mm.

3. TESTING RESULT AND DISCUSSION

3.1 Compressive stress versus strain responses of investigated UHPFRCs

Fig. 3 shows the compressive behavior of five UHPFRCs series. In Fig. 3, brittle failure with sudden load drop after the limit of proportionality (LOP) was observed regardless of tested series. The brittle failure also were revealed by the large explosion when the specimens crushed. Generally, the compressive stress versus strain responses of all specimens in each series are consistent and linear within their LOP but scatter beyond this point.

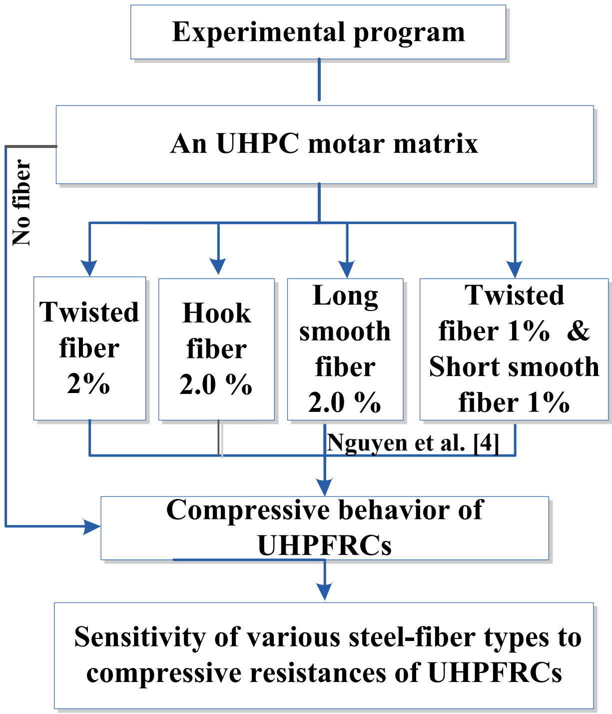

Figure 1: Flowchart of experimental program

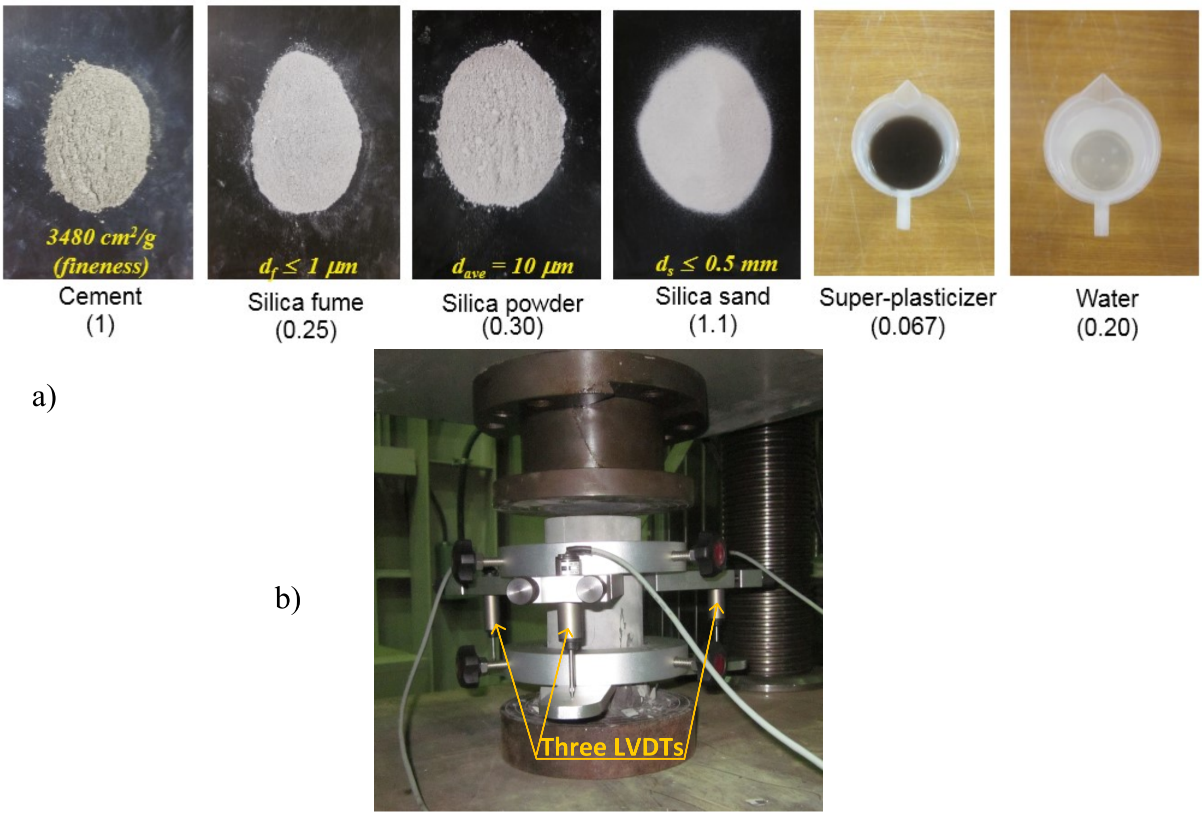

Figure 2: Specimen preparation: a) Material dimensions and composition for producing UHP mortar; b) Test setup for compression test

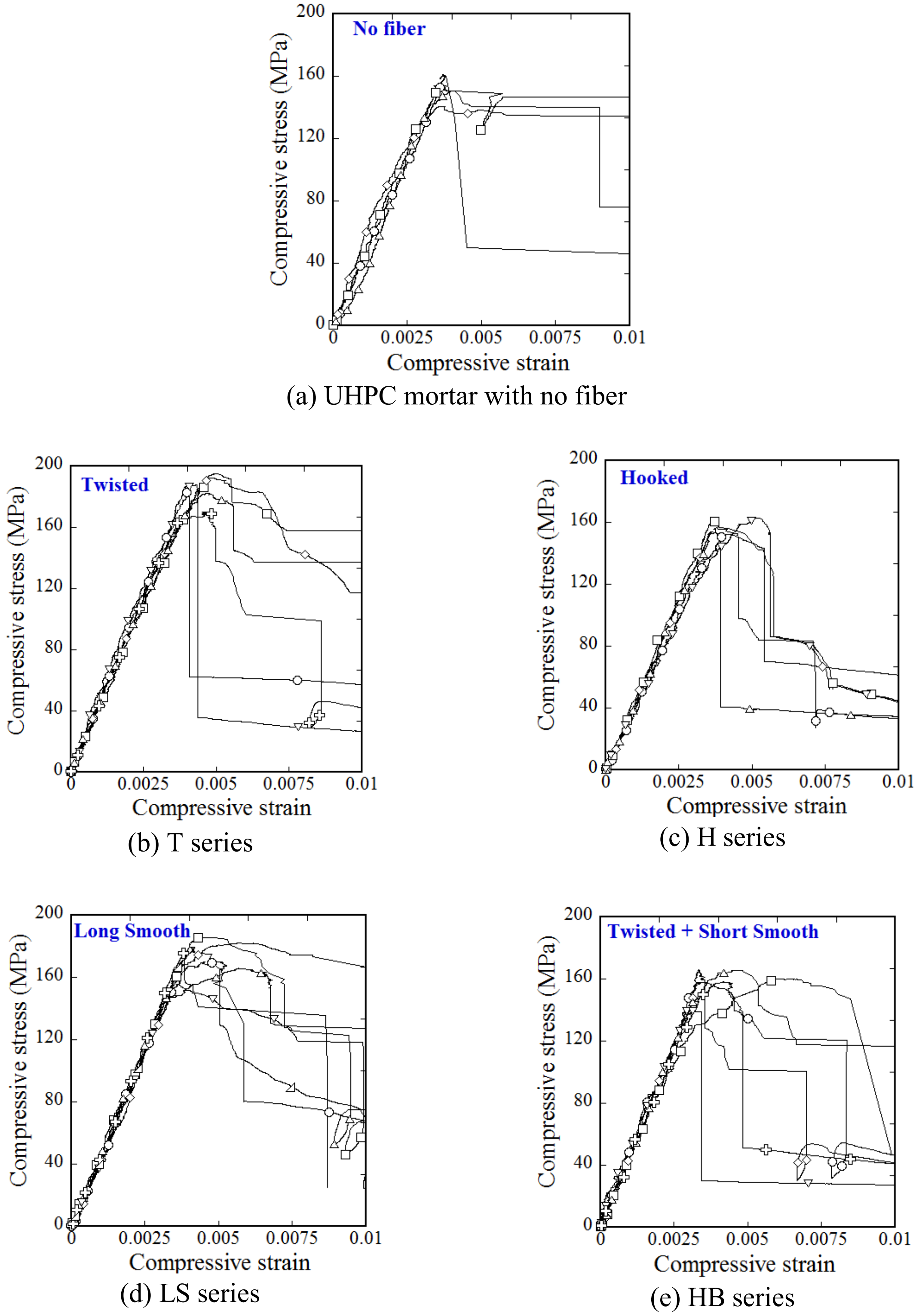

Figure 3: The measured stress versus strain curves of UHPFRCs using various fiber types

Tab. 3 provides the average value of parameters describing compressive resistance of UHPFRCs at LOP (also failure point). With addition of steel fibers into UHPC matrix, there are enhancements in compressive strength, ultimate strain as well as elastic modulus, although their enhancements are different according to fiber types. The averaged compressive strengths of UHPC, T-, H-, LS- and HB-series are 150.61 MPa, 185.53 MPa, 157.35 MPa, 174.75 MPa and 161.53 MPa, respectively. Besides, the averaged ultimate strain corresponding to the peak stress of UHPFRCs are 0.38%, 0.46%, 0.40%, 0.46% and 0.42% for UHPC, T-, H-, LS- and HB-series, respectively. The averaged modulus of elasticities are derived from 39.71 GPa to 45.21 GPa.

Table 3: Average value of parameters describing compressive resistance of UHPFRCs at LOP

Series	Compressive Strength (MPa)		Ultimate Strain (%)		Elastic modulus (GPa)	
	Average	Deviation	Average	Deviation	Average	Deviation
No fiber-	150.61	8.97	0.38	0.018	39.71	3.52
T-	185.53	8.90	0.46	0.037	43.30	3.36
H-	157.35	4.39	0.40	0.063	40.49	3.25
LS-	174.75	8.42	0.46	0.084	44.41	1.77
HB-	161.53	3.95	0.42	0.104	45.21	3.47

3.2 Sensitivity of various steel-fibre types to compressive behaviour of UHPFRCs

Figs. 4 and 5 show the comparative compressive strength and ultimate strain of UHPFRCs, respectively. As shown in these figures, the twisted fibers produces the highest enhancement in both strength and ultimate strain, whereas hooked fibers produces the lowest enhancement in strength and hybrid fiber produces the lowest enhancement in ultimate strain.

To investigate the sensitivity of fiber types to compressive resistances of UHPFRCs, the compressive strength and ultimate strain of each series containing added fiber were normalized by those of UHPC matrix, respectively, as shown in Figs. 6 & 7. In Fig. 6, the T-series exhibits the stiffest slope, i.e., the most sensitive to compressive strength. The order of fiber-type sensitivity in term of compressive strength of investigated UHPFRC was observed as follows: T > LS > HB > H. Similarly, the ranking of fiber-type sensitivity in term of ultimate strain was observed as follows: T =LS > HB > H, as shown in Fig.7. It is very well-matched in ranking of compressive strength and strain capacity.

Role of steel fibers in UHPFRCs under compression is thought to depend mainly on the interfacial bond strength which resists crack-opening or surface-sliding in failure process of specimens. The geometries of various steel fibers investigated are different in length, diameter, and section shape resulting the interfacial bond strength. Consequently, the addition of different fibers in an identical UHPC matrix produced different compressive resistances according to the types of steel fiber. The fact that twisted fibers produce the best performance on compressive behavior is consistent with their effect on tensile behavior of UHPFRC [10]. However, the effect of other fiber types are more complex: they produce different ranking of performance in terms of tensile and compressive resistances of UHPFRC.

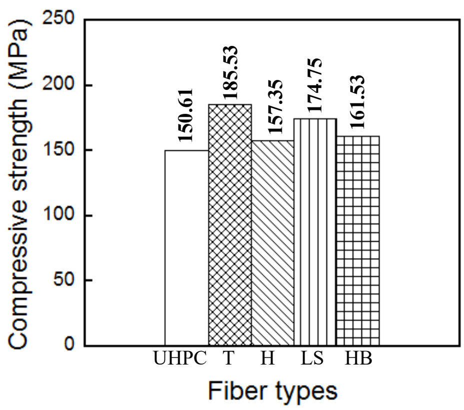

Figure 4: Comparative compressive strength strain of UHPFRCs

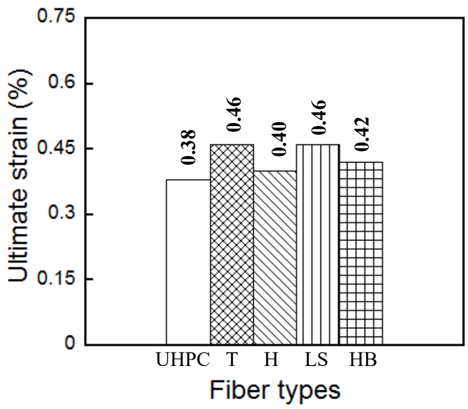

Figure 5: Comparative ultimate strain of UHPFRCs

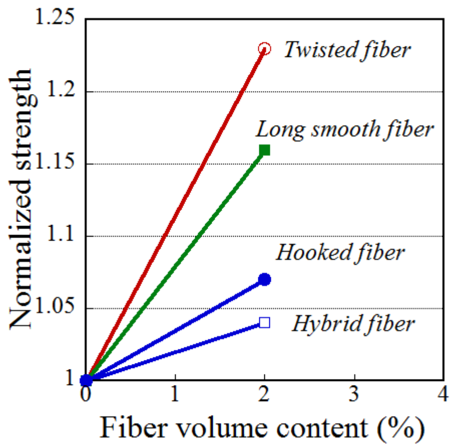

Figure 6: Sensitivity of fiber types to compressive strength of UHPFRCs

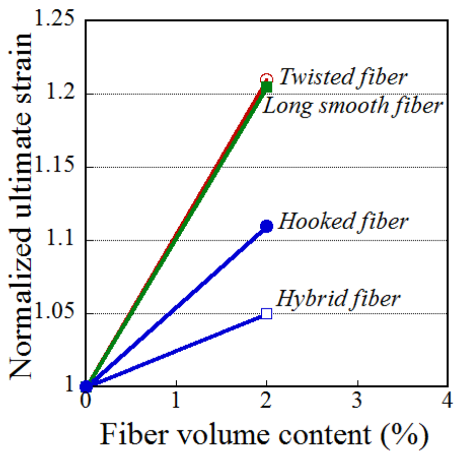

Figure 7: Sensitivity of fiber types to ultimate strain of UHPFRCs

4. CONCLUSIONS

This paper experimentally investigated the sensitivity of various steel fiber types to compressive behaviors of UHPFRCs. The following conclusions could be drawn from this study:

- The general shape of the compressive behaviours of investigated UHPFRCs was similar: almost linear within their LOP but dispersed and brittle beyond their LOP.
- There were enhancements in compressive strength, ultimate strain and elastic modulus of UHPFRCs, although the enhancements were different according to fibre types added.
- UHPFRC with twisted fibre produced the best performance: compressive strength was 185.53 MPa (normalized strength 1.23) and ultimate strain was 0.46% (normalized ultimate strain 1.21).
- The sensitivity of fibre types to both compressive strength and ultimate strain of UHPFRCs was ranked as follows: T ≥ LS > HB > H.

– The role and ratio of micro fibres and macro fibres in hybrid system would be further studied to maximize compressive resistance of UHPFRCs with total amount of fibre volume content less than 2.5%.

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