HIGH PERFORMANCE FIBRE REINFORCED CEMENTITIOUS COMPOSITES WITH CRIMPED STEEL FIBRES

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Abstract

Tensile strength and ductility are the most important characteristics of High Performance Fibre Reinforced Cementitious Composites (HPFRCC). In this regard, parameters such as: type of fibre, properties of matrix and characteristics of their interface play the main role in the behaviour of HPFRCCs. The effect of straight and hooked steel fibres on the mechanical properties of FRCs has been extensively investigated. However, only limited investigations have been done on the properties of cementitious matrices reinforced with crimped steel fibres. The aim of this study is to achieve a HPFRCC using crimped steel fibres. The performed activities in this investigation can be divided into three stages: to achieve a very dense cementitious material to be used as an appropriate matrix, to find the optimum shape of crimped fibre to be compatible with the matrix, and finally to obtain a cementitious composite (using the matrix and the fibres found in the previous stages) with high tensile strength and ductility. In the first stage of this study, 140 mixes were cast and tested. A workable mix with the compressive strength of 170N/mm^2 was selected for the following stages. To find an optimum shape of reinforcing fibres, pull-out tests were performed on single crimped fibres with different wave length and amplitude, embedded in the matrix. The length and diameter of fibres were 20mm and 0.3mm, respectively. Among the tested shapes of crimped fibres, 2mm wave length and 0.4mm wave amplitude were found to be the optimum values. Finally, in the last stage of the study it was found that the addition of 4% (by volume) the crimped fibres to the matrix produces a workable HPFRCC with tensile strength of 24N/mm^2 and fracture energy as high as 9500N/m (i.e. about 160 times larger than that of ordinary concrete).

Keywords: high performance, cementitious, composite, crimped fibre

1 Introduction

The use of fibre reinforced concrete (FRC) in pavements, slabs, pre-fabricated members and explosion-resistant structures goes back to mid-1960s. Many investigations have been conducted in this field and different types of fibre and matrix have been studied. In 1990s, a new generation of FRCs, i.e. High Performance Fibre Reinforced Cementitious composites (HPFRCC) was developed using fracture mechanics of fibre reinforced

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concrete [1]. HPFRCCs exhibit strain hardening and multiple cracking characteristics under uniaxial tensile stress and therefore, they are more ductile than conventional FRCs. Recently, many types of HPFRCC have been developed [2]. Due to the unique characteristics of HPFRCCs, the application of this material is continually increasing. The aim of the present study is to find a HPFRCC using crimped steel fibres.

2 Experimental program

The main stages of the experimental program are as follows:
- To find a cementitious material with high compressive strength and sufficient workability to be used as the matrix of FRC;
- To Design the shape and geometry of steel fibre to be compatible with the matrix;
- To cast and test main specimens of FRC.

2.1 Materials

The constituents should all be widely available to the concrete industry and thus it was decided that the mix constituents should all come from commercial sources. The Portland Cement (Type II) of Shahrood factory was used in all mixes. Two kinds of Micro-silica - produced in Semnan and Azna - were used. In all experiments Micro-silica was added in powder form rather than as a slurry. Three different types of superplasticizer -PCE, NSF and Seko Dense- were utilized in the mixes. No coarse aggregate was used in the mixes. The fine quartz aggregate used was dried sand with the maximum size of 4.75 mm.

In this research in order to produce crimped fibres quickly and precisely, a simple machine was designed and used. The machine was capable of producing different crimped fibres with various length, diameter, wave height (amplitude) and wave length, at a rate of 1.5-2 kg per hour. The fibres used in the mixes were crimped shape, made of 0.3mm high carbon steel wire with 1800-1900MPa ultimate tensile strength.

2.2 Cementitious material as matrix of FRC

The objective of this stage of the investigation was to attain a cementitious material with high compressive strength and appropriate workability. Two FRC mix designs (RPC [3] and DSP [4]) with desirable mechanical properties were selected (Table 1). To improve the mechanical properties as well as the workability, ten mix groups with various constituents, mixing sequences and curing regimes were developed and tested (Table 2).

Table 1 Mix proportions of RPC & DSP

	Agg/C	SF/C	Quartz Sand				W/(C+SF)	SP/(C+SF)
			0-300 μm	0-0.25 mm	0.25-1 mm	1-4 mm		
RPC	1.1	0.25	100%	---	---	---	0.22	0.019
DSP	1.58	0.25	---	14%	29%	57%	0.15	0.06

In each mix design the amount of cement, silica fume and aggregate were not changed, and only with varying the amount of water to binder ratio (W/(C+SF)), and superplasticizer to binder ratio (SP/(C+SF)) different FRC mixes were developed. In total, more than 140 mixes were cast by a planar mixer and, cube specimens (100×100×100mm) were tested in compression after 7 days.

Table 2 Matrix mix

Mix No		MIX-A1	MIX-A2	MIX-A3	MIX-A4	MIX-A5
Mix ratios	AGG/C	1.1	2	1.1	1.1	1.34
	S.F/C	0.25	0.25	0.15	0.25	0.25
	AGG.	50% (0.1-0.25mm)	50% (0.1-0.25mm)	50% (0.1-0.25mm)	100% (0-0.6mm)	50% (0-0.3mm)
		50% (0-0.3mm)	50% (0-0.3mm)	50% (0-0.3mm)	----	50% (0.3-1.2mm)
f_c (MPa) 7days-20 °C		88	61	72	73	73
Mix No		MIX-A6	MIX-A7	MIX-A8	MIX-A9	MIX-A10
Mix ratios	AGG/C	1.58	1.58	2.5	2.9	2.9
	S.F/C	0.25	0.15	0.15	0.15	0.15
	AGG.	14% (0-0.3mm)	14% (0-0.3mm)	14% (0-0.3mm)	10% (0-0.3mm)	7% (0-0.3mm)
		28.5% (0.3-1.2mm)	28.5% (0.3-1.2mm)	28.5% (0.3-1.2mm)	25% (0.3-1.2mm)	10% (0.3-1.2mm)
		57.5% (1.2-4.75mm)	57.5% (1.2-4.75mm)	57.5% (1.2-4.75mm)	65% (1.2-4.75mm)	10% (1.2-2.4mm)
		----	----	----	----	73% (2.4-4.75mm)
f_c (MPa) 7days-20 °C		128	84	70	90	76

Mix-A6 with the highest compressive strength and reasonable workability was found to be an appropriate matrix for a high performance FRC. To add fibres to this matrix, this mix was cast in large scale using a drum mixer.

2.3 Design shape and geometry of steel fibre

The shape of fibres is one of the effective parameters on the mechanical characteristics of FRC. In this regard, the second stage of this investigation was set to find the optimized shape of fibres to be compatible with the selected matrix in the previous stage. For this purpose, crimped fibres with various shape and length were buried in the selected matrix and pull-out test was separately performed on each fibre. To appreciate the contribution of mechanical anchorage of crimped fibres, a number of tests were also carried out on straight fibres. To provide tensile strength simultaneously with ductility, the optimized shape of steel fibre was defined to provide maximum pull-out force and to fail in pulling out mode rather than yielding of steel.

In this investigation the diameter, the total length and wave length of crimped fibres were fixed (0.3mm, 20mm and 2mm, respectively) (Fig. 1) whereas the amplitude of wave was variable. Having performed pull-out test on different crimped fibres, those with 0.4mm amplitude were found to be the most effective crimped fibres. These fibres were pulled-out with a force close to the ultimate tensile strength of fibres and waves were straightened after pulling out. The tests showed that the pull-out force of these fibres is almost twice more than that of the straight fibres. In fact, this is due to the mechanical anchorage of crimped fibres in the matrix. It was also observed that with increasing the amplitude of the waves more than 0.4mm, fibres would yield before pulling out. Although this behaviour may be acceptable for increasing the tensile strength of FRC, it is not desirable for improving their ductility.

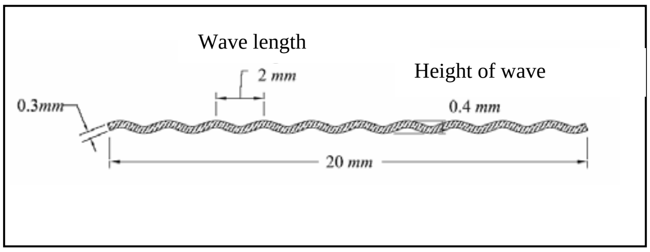

Fig. 1 Optimized crimped fibre

2.4 Main specimens of FRC

The aim of this stage was to combine the achievements of the last two stages and find a high performance FRC with crimped fibres. Therefore, the mix design developed in the first stage was cast again but, with different percentage of optimized crimped fibres. In each mix, a notched beam (500×100×100 mm) for fracture energy test, a beam without notch for four-point bending test, two cylinders and two or three cubes were cast. Table 3 shows the mix design of FRCs developed in this stage and Mix-A6 from the first stage.

Table 3. Mix design of FRCs in the third stage (Kg/m^3)

Concrete mix	**MIX-A6**	**SFRC-1**	**SFRC-2**	**SFRC-3**	**SFRC-4**	**SFRC-5**
Portland Cement	813	796	791	787	782	***777***
Fine Quartz Sand(0-0.3mm)	183	180	179	178	176	***175***
Fine Quartz Sand (0.3-1.2mm)	367	359	357	355	353	***351***
Fine Quartz Sand (1.2-4.75mm)	734	719	715	710	706	***702***
Silica Fume	203	199	198	197	195	***194***
Superplasticizer(PCE)	15.2	14.9	15.8	16.7	17.6	***18.5***
Water	175	171	170	169	168	***167***
Steel Fibre(volume percent)	Without fibre	157(2%)	196(2.5%)	236(3%)	275(3.5%)	***314(4%)***
W/C	0.215	0.215	0.215	0.215	0.215	***0.215***
W/(C+S.F)	0.172	0.172	0.172	0.172	0.172	***0.172***
S.P/(C+S.F)	1.5%	1.5%	1.6%	1.7%	1.8%	***1.9%***

3 Results

3.1 Compressive strength

The test results showed that the addition of fibres to the matrix, cause only 16-28% improvement in compressive strength whereas, the absorbed energy of FRCs under compressive stress is 12-15 times greater than that of the mix without fibres (MIX-A6).

3.2 Four-point bending test

The test results of four-point bending showed that the flexural strength, the deformation and the absorbed energy of FRCs are considerably increased in comparison with those of the mix without fibres. For instance, the flexural strength and the total absorbed energy of SFRC-5 in this test were around 3 and 30 times more than those of its matrix (i.e. MIX-A6).

3.3 Splitting test

From the splitting test results of FRCs it is also concluded that the addition of crimped fibres to the matrix can significantly improve the indirect tensile strength of FRCs (almost 3 times more).

3.4 Fracture energy test

Fig. 2 compares the flexural behaviour of a notched beam made of FRC with that of the same specimen made of Mix-A6. The results are also summarized in Table 4. It can be seen that the addition of fibres increases the fracture energy up to 160 times. That means the ductility of new composites (FRCs) are very high and they can be used where the absorption of energy is an essential property of structural material.

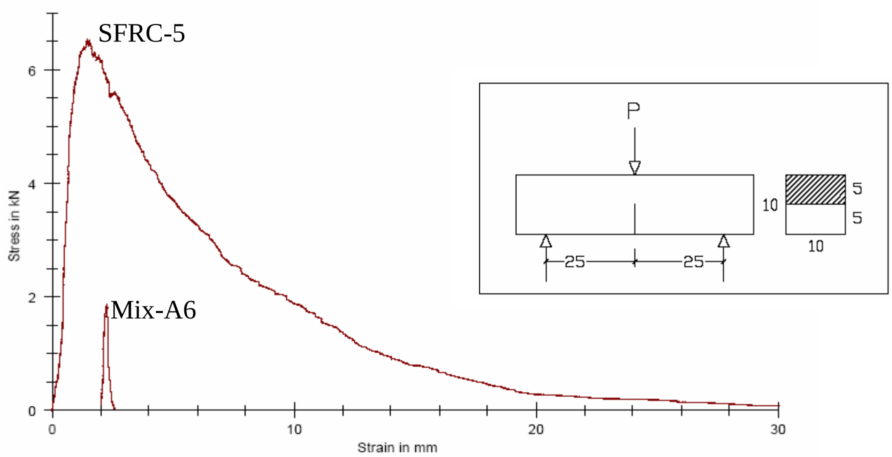

Fig.2 Comparison of behaviour of FRC and matrix notched beam under three-point bending

Table 4 Results of fracture energy test (28days-20 °C)

Concrete mix	MIX-A6	SFRC-1	SFRC-2	SFRC-3	SFRC-4	SFRC-5
Area under P-δ curve ($N.m$)	0.3	16.1	30	39	39.2	47.5
Fracture energy(G_f) (N/m)	60	3220	6000	7800	7840	***9500***

Comparing the mechanical properties of FRCs with those of the matrix demonstrates that the tensile strength and ductility of the developed FRC is very high. This improvement is due to the bridging action of fibres at crack planes. In fact, crack forms with a rather low force and energy level. But, fibres provide a means of arresting the crack propagation. High pull-out force and considerable energy dissipation are two main factors which indirectly improve the tensile strength and ductility of the developed cementitious material. It can be concluded that study on the pull-out behaviour of crimped fibres can lead to a cementitious material with high tensile strength and high ductility (high performance fibre reinforced concrete).

4 Conclusions

- To achieve a High Performance Fibre Reinforced Cementitious Composite (HPFRCC) using crimped steel fibres, matrix and fibres should be appropriately selected. The matrix has to be strong and dense enough to hold the fibres tightly and no local failure happens during the pull-out of fibres. The geometry of crimped fibres should also be compatible with the matrix.
- In this investigation, a cementitious material with 128MPa 28-day compressive strength was found to be suitable for the matrix of HPFRC. Likewise, crimped fibres with 0.3mm diameter, 20mm total length, 2mm wave length and 0.4mm amplitude were found to be compatible with the selected matrix
- Finally, a fibre reinforced concrete with 4% volume fraction of crimped steel fibres was found to exhibit promising mechanical properties; 23.4MPa tensile strength and 9500N/m fracture energy.

Acknowledgements

The authors are grateful to Mr. Jamei for his contribution to this study.

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