Influence of micro-structural parameters and thermal cycling on the properties of CARDIFRC

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Abstract. This paper gives an overview of the influence of micro-structural parameters on the mechanical properties of CARDIFRC which is a high-performance fibre-reinforced cement-based material. Since its development in 2002, several investigations have been made with a view to examine how its properties vary when its micro-structure is altered and when it is subjected to thermal cycling.

Keywords. Ultra high performance fibre reinforced cement-based composite; CARDIFRC; micro-structure; mechanical and fracture properties; thermal cycling.

1. Introduction

CARDIFRC is a class of ultra high performance fibre-reinforced cement-based composite (UHPFRCC) characterized by high compressive strength (in excess of 200 MPa), splitting/flexural strength (up to 30 MPa) and high energy absorption capacity (in excess of 17,000 J/m²). This has been made possible by the use of large amounts (up to 6% by volume) of brass-coated short steel fibres of two lengths (6 and 13 mm long, 0.16 mm diameter) in a cement matrix densified by the use of silica fume. The matrix contains only very fine graded quartz sand, instead of ordinary river sand and coarse aggregates. By optimizing the grading of fine quartz sands, the water demand was considerably reduced without affecting the workability of the mix. This was achieved using novel mixing procedures described in the patent GB2391010 (Karihaloo *et al* 2005). The method of its production and its mechanical and fracture properties were reported in a series of papers (Benson & Karihaloo 2005a,b; Benson *et al* 2005). The results of fatigue and shrinkage tests on this material were recently reported by Nicolaides *et al.* (2010). Computer tomography imaging and sectioning of specimens have confirmed that the production procedures ensure a remarkably homogeneous mix with a uniform distribution of fibres in thin sections (<50 mm thick) (Benson *et al* 2005).

The optimum design of UHPFRCC mixes tries to balance the intrinsic competition between the tensile strength f_t and toughness G_F – toughness decreases with increasing strength. The simultaneous maximization of f_t and G_F requires the solution of a dual-objective optimization problem in which each objective (f_t and G_F) is given a weighting depending upon its importance. As both objectives are equally important in the development of optimum UHPFRCC

mixes, the dual-objective problem is replaced by a single design objective involving the maximisation of a ductility measure—the so-called characteristic length of the mix (Karihaloo 1995)

$$l_{ch} = \frac{EG_F}{f_t^2},$$

where E is the Young modulus of the mix. The mathematical optimization strategies require a knowledge of the constitutive equations relating the mechanical response parameters (E , f_t , G_F and compressive strength f_c) to the mix and fibre parameters (water to binder ratio, w/b , maximum size of fine aggregate, g , volume fraction of aggregate, V_a , surfactant to water ratio, sp/w , fibre length, L , fibre diameter, d , and fibre volume fraction, V_f), collectively called the micro-structural parameters. These constitutive equations have been obtained by Lange–Kornbak & Karihaloo (1998), and Wang & Karihaloo (2000) using micromechanical principles.

The mathematical optimization problem that is solved by standard nonlinear mathematical programming techniques is to maximise $l_{ch}(\underline{X})$ by choosing the vector of mix and fibre variables $\{\underline{X}\} = \{V_a, g, L, d, V_f, w/b, sp/w\}^T$ (i.e., micro-structural variables) in such a way as to satisfy the constitutive relations and any prescribed bounds (inequality constraints) on these variables, e.g., $0.15 \leq w/b \leq 0.25$, $0.01 \leq V_f \leq 0.08$. Moreover, these variables may be restricted to have certain fixed values (equality constraints) as, for instance, $L = 6$ or 13 mm, $d = 0.16$ mm.

CARDIFRC mixes can be broadly grouped into two classes depending upon the maximum size of the quartz sand and the relative amounts of short (6 mm) and long (13 mm) fibres (the total volume fraction is 6%), designated mixes I and II in table 1. It is worth mentioning that the short fibres enhance the strength, whereas the long fibres enhance primarily the toughness of CARDIFRC.

Both classes of mixes have been used extensively in small quantities for retrofitting damaged concrete flexural members at ambient temperatures (Alaee & Karihaloo 2003a,b) and after thermal cycling between ambient temperature and 90°C (Farhat *et al* 2007, 2010), with highly promising results. However, in view of the high cost of this material primarily because of the expensive brass-coated steel fibres, and because of low water to binder ratio, many systematic studies have been undertaken in Cardiff University over the last five years to investigate how

Table 1. Mix constituents of CARDIFRC (kg/m³).

Constituents (kg)	Mix I	Mix II
Cement	855	744
Microsilica	214	178
Quartz sand:		
9–300 μ m	470	166
250–600 μ m	470	–
212–1000 μ m	–	335
1–2 mm	–	672
Water	188	149
Superplasticiser	28	55
Fibres:		
6 mm	390	351
13 mm	78	117
Water/cement	0.22	0.20
Water/binder	0.18	0.16
Superplasticiser/water	0.15	0.37

the mechanical and fracture properties of this material will change when its micro-structural parameters are altered from those given in table 1. This paper summarizes the results of these systematic studies.

2. Mechanical and fractional properties

For ease of future comparison, we reproduce in table 2 the mechanical and fracture properties of the original CARDIFRC mixes I and II whose proportions are given in table 1 (Benson & Karihaloo 2005b). The theoretical values were estimated from the constitutive relations given in Benson & Karihaloo (2005a).

3. Influence of water and superplasticiser

The production procedures described in the patent GB2391010 (Karihaloo *et al* 2005) ensure that the CARDIFRC mixes are workable under normal ambient temperatures of around 20°C. However, the workability may suffer if the ambient temperature is higher. It is then necessary to increase the amount of water or superplasticiser. The increase in either of these is expected to lead to a reduction in strength of the resulting mixes. Table 3 shows how an increase in the superplasticiser to water ratio from 0.15 to 0.21 for mix I and from 0.37 to 0.43 for mix II affects the strengths and specific fracture energy of the mixes.

Before comparing the values in table 3 with the corresponding values of the original CARDIFRC mixes (table 2), it is important to point out that the specific energy G_F reported in table 3 has been determined by the procedure that ensures that it is independent of the specimen size (Abdalla & Karihaloo 2003; Karihaloo *et al* 2003). Acoustic emission studies have confirmed the validity of this procedure (Muralidhara *et al* 2010). The size independent

Table 2. Mechanical and fracture properties of CARDIFRC mixes I and II.

Mechanical properties		f_c (MPa)	f_t (MPa)	E (GPa)	G_F (N/m)
Experimental	Mix I	207	12 ¹ , 24 ²	46	17000 ³ , 17000 ⁴
	Mix II	185	13.5 ¹ , 25 ²	55	20500 ³ , 21000 ⁴
Theoretical	Mix I	184	18	45	13247
	Mix II	219	21	48	18635

¹Direct tensile strength ²Indirect (split cylinder) tensile strength ³Direct tension

⁴3-point bend test (value not corrected for specimen size dependence)

Table 3. Influence of superplasticiser.

Mechanical Properties		f_c (MPa)	f_t (MPa) ¹	G_F (N/m)
Mix I	SP/W = 0.18	149.8	23.1	22908
	SP/W = 0.21	135.6	22.3	19387
Mix II	SP/W = 0.4	151.7	22.4	17875
	SP/W = 0.43	148.2	22.1	16060

¹Indirect (split cylinder) tensile strength

Table 4. Mix proportions of CARDIFRC mix II with increased water content.

Constituents (kg/m ³)	Mix II (1) (5%)	Mix II (2) (10%)	Mix II (3) (15%)
Cement	744	744	744
Microsilica	178	178	178
Sand			
9–300 μ m	166	166	166
212–1000 μ m	335	335	335
1–2 mm	672	672	672
Water	156.45	163.9	171.35
Superplasticiser	55	55	55
Fibres			
6 mm	351	351	351
13 mm	117	117	117
Water/Cement	0.21	0.22	0.23
Water/Binder	0.17	0.18	0.19
Superplasticiser/Water	0.35	0.335	0.32

Table 5. Influence of water.

Mechanical properties	f_c (MPa)	f_t (MPa) ¹	E (GPa)	G_F (N/m)
Mix II (1) (w/c = 0.21)	202.1	27.2	48.1	28549
Mix II (2) (w/c = 0.22)	189.5	25.5	47.6	25477
Mix II (3) (w/c = 0.23)	184.9	23.4	46.2	20167

¹Indirect (split cylinder) tensile strength

value is generally larger than the traditional size-dependent value. As expected from the micro-mechanical constitutive relations (Benson & Karihaloo 2005a), an increase in superplasticiser to water ratio decreases the strengths; the decrease is more significant in compressive strength rather than the indirect tensile strength.

The water content of mix II was increased by 5 to 15% without altering the superplasticiser content, as shown in table 4.

The influence of this increase in the water content on the mechanical and fracture properties of the resulting mixes can be judged from table 5. The trend of change is consistent with expectations.

4. Influence of the amount and size of steel fibres

As mentioned in the introduction, the prohibitive cost of CARDIFRC (80% of the cost is due to the use of 6% by volume brass-coated steel fibres) makes it unattractive for large volume application. For this reason, studies were conducted on CARDIFRC mix II in which the 13 mm long brass-coated fibres (volume fraction 1.5%) were replaced by cheaper Dramix fibres (30 mm long and aspect ratio 55 with hooked ends, 2.5% by volume) and the amount of short brass-coated fibres was reduced. The volume fraction of short brass-coated fibres ranged from 0.5 to 2.0% in comparison with 4.5% in the original mix II (table 1). The mix proportions are given in table 6.

Table 6. Mixes containing 30 mm long Dramix fibres and 6 mm long brass-coated fibres.

Constituents (kg/m ³)	Mix II (1) (0.5% 6 mm, 2.5% 30 mm fibres)	Mix II (2) (1.0% 6 mm, 2.5% 30 mm fibres)	Mix II (3) (1.5% 6 mm, 2.5% 30 mm fibres)	Mix II (4) (2.0% 6 mm, 2.5% 30 mm fibres)
Cement	744	744	744	744
Microsilica	178	178	178	178
Sand				
9–300 μm	166	166	166	166
212–1000 μm	335	335	335	335
1–2 mm	672	672	672	672
Water	149	149	149	149
Superplasticiser	55	55	55	55
Fibres				
6 mm	39	78	117	156
30 mm (Dramix)	195	195	195	195
Water/Cement	0.2	0.2	0.2	0.2
Water/Binder	0.16	0.16	0.16	0.16
Superplasticiser/Water	0.37	0.37	0.37	0.37

Table 7. Influence of the amount and size of fibres.

Mechanical properties	f_c (MPa)	f_t (MPa) ¹	E (GPa)	G_F (N/m)
Mix II (1) (0.5% 6 mm, 2.5% 30 mm fibres)	167.1	21.1	46.2	32531
Mix II (2) (1.0% 6 mm, 2.5% 30 mm fibres)	171.7	23.0	46.4	31514
Mix II (3) (1.5% 6 mm, 2.5% 30 mm fibres)	176.9	23.7	47.4	32059
Mix II (4) (2.0% 6 mm, 2.5% 30 mm fibres)	182.4	26.5	47.4	31950

¹ Indirect (split cylinder) tensile strength

The influence of the amount and size of fibres on the mechanical and fracture properties of the resulting mixes can be judged from table 7.

As expected from the micro-mechanical constitutive relations, the short fibres enhance the tensile strength, whereas the long fibres enhance the toughness G_F . It will be noticed that the short fibres have little influence on G_F which remains practically unchanged because the volume fraction of the long fibres is unchanged. It is also clear that the longer the fibres, the higher the toughness. This is in complete agreement with the predictions of the constitutive relations. However, the amount of long fibres cannot be increased indefinitely because they reduce workability of the mix.

5. Influence of casting direction

In view of the importance of the fibres to the mechanical and fracture properties of CARDIFRC, studies were conducted on mix I to investigate the influence of the direction of casting on these properties, because it was expected that the fibres would be reoriented during the flow. For this, specimens were cast either horizontally or vertically. The results are shown in table 8.

As expected, the direction of casting does not have any noticeable influence on small cubes (100 mm) used for determining the compressive strength. There is only a marginal influence on

Table 8. Influence of the direction of casting.

Mechanical properties	f_c (MPa)	f_t (MPa) ¹	E (GPa)	G_F (N/m)
Horizontally cast	188.4	25.4	43.9	29708
Vertically cast	189.1	19.3	43.9	6325

¹Indirect (split cylinder) tensile strength

the split cylinder strength obtained on cylinders (100 × 200 mm). However, the most noticeable effect is on G_F which is determined in 3-point bending on beam specimens (100 × 100 × 500 mm) over a loaded span of 400 mm. The beams cast horizontally have the fibres distributed favourably in the regions subjected to tension during the flexural test, but not so in beams cast vertically but tested horizontally. The fibres in the latter are not distributed in the most favourable orientation relative to the applied tensile stresses during the flexural test.

6. Influence of age

In view of the large amounts of cement and silica fume and the low water to binder ratio in CARDIFRC, there is insufficient water available for the completion of primary and secondary chemical reactions during the curing of specimens. For this reason, there are large quantities of unhydrated cement (and therefore micro-silica) present in hardened CARDIFRC. One sees this powder drop as debris during testing. However, the presence of unhydrated cement and silica fume has a beneficial self-healing effect on CARDIFRC exposed to normal environmental conditions, especially humidity. We tested many cubes and beams two years after they had been cast. The results are shown in table 9.

As expected, due to the continued primary and secondary chemical reactions of unhydrated cement and micro-silica because of the moisture present in the natural environment, the compressive strength increases by approximately 5% during two years, but the most significant improvement is in the toughness G_F . The latter is due to the fact that the continued hydration leads to continued improvement and densification of the interface transition zone between the fibres and the surrounding matrix, as a result of which the pull-out resistance of the fibres is greatly increased, thus enhancing the toughness.

7. Influence of thermal cycling

In order to be able to use CARDIFRC in hot climatic conditions where the temperature on exposed concrete surfaces can reach 90°C on a typical hot summer day and drop to around 25°C

Table 9. Influence of age.

Mix	Compressive strength at early age (MPa)	Compressive strength after 2 years (MPa)
Mix I	193.6	205.3
Mix II	207.0	217.3
Mix	Independent specific fracture energy at early age, G_F (N/m)	Independent specific fracture energy after 2 years, G_F (N/m)
Mix I	22909	37615
Mix II	17875	34525

Table 10. Influence of thermal cycling.

Number of thermal cycles	Compressive strength (MPa)	Split cylinder strength (MPa)	Modulus of rupture (MPa)	Elastic modulus (GPa)
0	200.0	32.2	37.0	48.0
30	224.3	30.7	33.5	49.0
90	225.0	31.0	33.7	49.0
120	206.5	28.4	40.8	48.3
180	205.0	28.3	38.4	48.2

during the evening and night, studies were conducted to investigate the influence of thermal cycling on the mechanical properties of CARDIFRC mix I (Farhat 2004; Ewaze 2010). The specimens were heated slowly to a maximum temperature of 90°C from the room temperature (about 25°C) in about 20 min to avoid any risk of thermal shock during heating. The maximum temperature was maintained for 8 h before the specimens were cooled down to the room temperature in 15 h and 40 min. This 24 h heating, hold and cooling cycle reflects the temperature fluctuations during a day and night in hot arid climate. The mechanical properties of CARDIFRC mix I were measured at room temperature after subjecting it to between 30 and 180 thermal cycles. The results are summarized in table 10.

It is evident from table 10 that thermal cycling has little or no effect on the mechanical properties of CARDIFRC. The room temperature properties can be safely used for design purposes.

8. Conclusions

The changes in the mechanical and/or fracture properties of the original CARDIFRC mixes I and II induced by an alteration in their micro-structure are in full agreement with the predictions of the micro-mechanical constitutive relations between these properties and the micro-structural parameters (Benson & Karihaloo 2005a). In particular, the present studies have confirmed that the short steel fibres make the most contribution to the tensile strength of CARDIFRC, whereas the long fibres are mostly responsible for its high toughness, thus supporting the use of hybrid fibres in CARDIFRC.

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