

CARDIFRC[®] – Development and mechanical properties. Part I: Development and workability

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Part I of this three-part paper describes the various steps that led to the development of a class of high performance short steel fibre-reinforced cementitious composites (HPFRCCs) which has been patented under the trade name CARDIFRC[®]. This class of materials generally contains no coarse aggregates and is characterised by high tensile/flexural strength and high toughness. A method is proposed for quantifying the workability of such a mix without fibres in terms of its fracture toughness.

Notation

$A_0, B_1, C_1, D_1,$	coefficients in formula (5)
E_1, F_1, G_1, H_1	
a_o	crack length
d	diameter of fibre (mm)
E	Young's modulus of CARDIFRC [®] (GPa)
E_b	Young's modulus of binder (GPa)
E_f	Young's modulus of fibre (GPa)
f_c	compressive strength (MPa)
f_t	tensile strength (MPa)
g	maximum size of coarse aggregate (mm)
G_F	specific fracture energy (J)
H	dimensionless factor
$K_{Ic,m}$	matrix fracture toughness
L	length of fibre (13 or 6 mm)
sp/w	superplasticiser to water ratio
V_a	aggregate volume fraction
V_f	volume fraction of fibre
w/b	water to binder ratio
α	constant (1/mm)

Introduction

High-performance fibre-reinforced cementitious composites (HPFRCCs) have been made possible by recent advances in processing technology which permit inclusion of large amounts of short steel fibre in the cementitious matrix without affecting the workability of the matrix. These advances are based on the exclusion of coarse aggregate and the use of silica fume and surfactants which reduce water demand and densify the matrix thereby improving the fibre–matrix interfacial bond.^{1–4}

The first HPFRCCs were developed in Denmark¹ and France,^{5–7} and called DENSIT and reactive powder concrete (RPC), respectively. They exhibit very high compressive strength (up to 200 MPa), tensile/flexural strength (up to 30 MPa), high energy absorption capacity, namely toughness (up to 40 000 J/m²) and remarkable durability characteristics.^{1,7–9} Attempts were made at Cardiff University,^{8,9} the first of their kind in the UK, to reproduce RPC with materials widely available in the UK, some of which are already used by the local concrete industry. These attempts followed the mix proportions and processing methods reported in open literature^{5–7} but they were only partially successful; the mixes produced exhibited mechanical properties that fell well short of those reported in the literature.

Attempts were also made at Cardiff University⁹ to prepare the HPFRCC mixes optimally designed by Lange-Kornbak and Karihaloo^{10,11} using mathematical optimisation techniques. However, it became apparent that many of these mixes were too stiff to be worked in a pan mixer. The optimum design of HPFRCC mixes tries to balance the intrinsic competition between the

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(MCR 41270) Paper received 22 April 2004; last revised 14 October 2004; accepted 1 February 2005

tensile strength f_t and toughness G_F – toughness decreases with increasing strength.

The simultaneous maximisation of f_t and G_F requires the formulation and solution of a dual-objective optimisation 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 HPFRCC mixes, the dual-objective problem is replaced by a single design objective involving the maximisation of a ductility measure¹² – the so-called characteristic length of the mix

$$l_{ch} = \frac{EG_F}{f_t^2} \quad (1)$$

where E is the Young modulus of the mix. This ductility measure has the added advantage of revealing the competition between f_t and G_F . The mathematical optimisation 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). These constitutive equations which are obtained using micromechanical principles are^{11–13}

$$E = \frac{E_m[n + \Theta + V\Theta(n - 1)]}{[n + \Theta - V(n - 1)]} \quad (2)$$

$$f_t = \frac{K_{Ic,m}}{\sqrt{\pi a_0}}(1 - V_f) + \frac{h}{4}LV_f\alpha K_{Ic,m}\sqrt{\frac{E_f}{dE_b}} \quad (3)$$

$$G_F = \frac{h}{24}L^2V_f\alpha K_{Ic,m}\sqrt{\frac{E_f}{dE_b}} \quad (4)$$

In equation (2) V is the volume fraction of the discrete phase, Θ is a factor depending on the geometry (i.e. aspect ratio) and stiffness of the discrete phase, and n is the ratio of Young modulus of the discrete phase to that of a continuous phase E_m (i.e. of the matrix). To calculate the Young modulus of an HPFRCC mix, equation (2) is applied twice. It is applied first to a two-phase system in which the continuous phase is the cement–microsilica binder paste and the discrete phase is the fine aggregate, and then to a system in which the cement–microsilica–fine aggregate mortar is the continuous phase and the steel fibres the discrete phase. The values of n , V , E_m and Θ have different values in the two steps. This calculation will be made for CARDIFRC[®] in Part III of this paper.

In equations (3) and (4), $K_{Ic,m}$ is the fracture toughness of the HPFRCC matrix without fibres, E_f is the Young modulus of steel fibres, and E_b the Young modulus of the cement–silica binder. Parameter h is a dimensionless factor that takes into account the bending of steel fibres during their pull-out from the matrix, α is a constant (with the dimension of inverse length)

that takes into account crack trapping and deflection induced by the presence of fibres, and a_0 is proportional to the maximum size (in mm) of fine aggregate used in the mix.

The mathematical optimisation problem that is solved by standard non-linear mathematical programming techniques is to minimise $l_{ch}(\underline{X})$ by choosing the vector of mix and fibre variables $\{\underline{X}\} = \{V_a, g, L, d, V_f, w/b, sp/w\}^T$ in such a way as to meet the constitutive relations (2)–(4) and any prescribed bounds (inequality constraints) on these variables, for example, $0.15 \leq w/b \leq 0.25$, $0.01 \leq V_f \leq 0.08$. 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. It will be noted that no consideration is given to the workability of the resulting optimum mixes.

The unsuccessful attempts to reproduce RPC, DENSIT and the optimum mixes with materials widely available in the UK however, provided valuable clues on how to improve the batching, mixing and processing techniques in order to produce HPFRCCs with superior mechanical performance. This paper will describe the various steps that led to the development of a class of HPFRCCs that has been patented under the trade name CARDIFRC[®]. It will also describe a method of quantifying the workability of this class of HPFRCCs in terms of the fracture toughness of its matrix ($K_{Ic,m}$ appearing in equations (3) and (4)). This paper is Part I of a three-part paper. Part II is devoted to an assessment of the distribution of fibres in the mix using destructive and non-destructive techniques. Part III describes how the tensile response of the material was measured using a novel test specimen and testing arrangement and compares the measured mechanical properties of CARDIFRC[®] mixes (E , f_c , f_t , G_F) with the theoretically predicted values using equations (2)–(4) and a theoretical equation for f_c . It should be mentioned that this class of HPFRCCs has many potential applications in small quantities, for example for durable and reliable jointing of pre-cast concrete elements, for the repair and strengthening (i.e. retrofitting) of damaged concrete structures, for the construction of structures used for the containment and retention of hazardous materials, etc. It has already proved successful for retrofitting damaged concrete flexural members.^{14–17} It is not expected however that CARDIFRC[®] will be used in large quantities because of the high cost of fibres.

Development of CARDIFRC[®]

An extensive investigation was undertaken¹⁸ in order to examine the role of key parameters, namely the grading of quartz sands, fineness of microsilica, the amounts of short- and long-steel fibres, and of water and superplasticiser in the manufacture of HPFRCCs.

This investigation was conducted in three stages. In the first stage, the influence of key mix variables on the workability was thoroughly investigated. This involved hundreds of mixes, but their workability was only judged by the ease of mixing. The second stage of experimentation was devoted to studying the influence of the sequence of mixing the dry constituents on the workability of the mix. At this stage the problems associated with the separation and uniform dispersion of a large amount of steel fibres were also overcome. Finally, the best possible method of fluidising the dry mix was established by trial and error.

In the first two stages, only small amounts of HPFRCC were produced using a planetary mixer. From these two stages, two 'optimum' mixes were identified. In stage three, the feasibility of producing these two optimum mixes on a large scale, using a standard pan-mixer, was examined.

This exhaustive investigation delineated the most important steps necessary for the manufacture of a class of HPFRCC with excellent mechanical properties. These steps ensure maximisation of the dry density of mixes, even and random distribution of short steel fibres up to a volume fraction of 8% and fluidisation of the dry mix with a minimum of water and superplasticiser.

The maximisation of the dry density has resulted in a grading curve for the constituent materials that is continuous over a particle size ranging from 0.5 μm (microsilica) to 2 mm (quartz sand). In some mixes of this class, the upper limit of the size range may be only 600 μm . The constituent materials are microsilica, Portland cement and different grades of commercially available quartz sands. The commercially available short steel fibres of two lengths (6 and 13 mm) and diameter 0.16 mm are added to the dry constituents through vibrating apertured surfaces. This ensures that the fibres are not clumped together and fall into the rotating mixer in an even manner so that they are randomly distributed in the dry mix. The use of two fibre lengths has been dictated by constitutive modeling,^{11,12} which shows that short fibres are necessary for enhancing the tensile/flexural strength, while long fibres increase the toughness. These fibres are made of high-strength steel and are brass coated to prevent corrosion.

The procedures of mixing the dry constituents, of ensuring even fibre distribution and of fluidisation with a mixture of water and superplasticiser to obtain the above class of HPFRCC have been patented (GB 0109686.6) under the trade name CARDIFRC[®]. These procedures¹⁸ are summarised below, and the mix proportions of two typical mixes from this class are given in Table 1.

Place the coarsest quartz sand in the mixing pan and add the finest constituent (microsilica). Mix thoroughly for at least 2 min, then add the next finest constituent (cement), followed by the next coarsest quartz sand and then the least coarse quartz sand (for mix Type II only).

Table 1. Mix proportions for optimised CARDIFRC[®] mix Type I and mix Type II (per m^3).

Constituents: kg	Mix I	Mix II
Cement	855	744
Microsilica	214	178
Quartz sand:		
9–300 μm	470	166
250–600 μm	470	–
212–1000 μm	–	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

Note, before each addition the constituents are thoroughly mixed for at least 2 min.

Twenty-five percent of the long 13 mm fibres are placed in a sieve (12 mm aperture size) and the sieve is then agitated over the opening in the mixing pan so that the fibres are separated and fall in a 'shower' into the pan. After approximately 2 min of mixing, the next 25% of the fibres are added and mixed in the same way. This process is repeated until all of the fibres have been added. The short 6 mm fibres are then added in the same incremental manner (5 mm aperture size sieve).

Mix the water and two-thirds of the superplasticiser together, and add one-half of the water/superplasticiser mixture to the mixed dry constituents and mix for approximately 2 min. Following this, add half of the remaining water/superplasticiser mixture and mix for approximately 2 min prior to adding half of the remaining water/superplasticiser mixture, which again should be mixed for approximately 2 min. All of the remaining water/superplasticiser mixture should then be added and mixed for approximately 2 min. Finally, add the remaining one-third of the superplasticiser and mix until the constituents are thoroughly mixed and wetted.

Quantification of workability

As mentioned above, during the development of CARDIFRC[®] the workability of the mixes was judged by the ease of mixing, placing and finishing but was not otherwise quantified. All mixes were very flowable (slump greater than 300 mm) in the absence of fibres. The workability of the whole class of mixes without fibres will now be quantified.

Traditional workability tests, namely slump and Vebe time, are not suitable for quantifying the workability of the matrix, which is an extremely fluid mix in the absence of fibres. These tests were designed for much

stiffer mixes. The mix constituents of this matrix make it more like a sandy soil because it consists of graded sand and smaller particles in the form of cement and microsilica. The cone penetration test (CPT),¹⁹ a test designed for determining the liquid limit of a soil, is more suitable for quantifying the workability of the matrix without fibres. The standard apparatus and measurement procedure was used. Constant workability of the mixes, as measured by the cone penetration, was ensured by adjusting the amount of superplasticiser.

Penetration values of 20, 22 and 24 mm were chosen as the three target values to be achieved for each of the mixes made. As a rough guide, a cone penetration value of 20 mm is equivalent to a slump in excess of 250 mm and a cone penetration of 25 mm to a slump in excess of 300 mm. The maximum penetration measurable from the CPT is 25 mm; the matrix approaches this limit easily, hence three lower values were chosen. This provides us with three fixed targets for workability. For each target value, the workability will be quantified by measuring the fracture toughness $K_{Ic,m}$ of the mix without fibres. It is worth emphasising that in the design of CARDIFRC[®] mixes it is the value of the matrix fracture toughness $K_{Ic,m}$ that is required (see equations (3) and (4)) rather than the toughness G_F of the mix with fibres. Tests have shown that the addition of short steel fibres up to 6% by volume reduces the CPT value to 3.5 mm from a value of 24 mm for the mix without fibres. However, the mixes with fibres were still very plastic and workable.

For the matrix mixes without fibres, three penetration readings were taken from each sample and an average value determined. If the average penetration value equalled the target value then the mix was cast in moulds for fracture toughness specimens, otherwise it was returned to the mixer and further superplasticiser added and mixed, and the CPT repeated.

Mix Types I and II (Table 1), which have optimum workability and mechanical properties (f_c , G_F), were used as the base mixes. A total of thirty-two mixes were prepared for each cone penetration depth testing. The mixes differed by the total volume fraction of quartz sands, V_a , which was varied from 38 to 60%, in steps of about 5% (a total of four different volume fractions), the water to binder (cement plus microsilica) ratio, w/b , which was varied from 0.16 to 0.22 in steps of 0.02 (a total of four different w/b ratios), and the maximum size, g , of the quartz sand which was either 0.6 or 2 mm (Table 1). Depending upon the latter, the mixes are classified as Type I or Type II. All 16 mixes of Type I had a total solid volume fraction ($V_a + V_b$) of 0.78 (same as for mix Type I in Table 1), where V_b is the volume fraction of binder and those of Type II had a total solid volume fraction of 0.80 (same as for mix Type II in Table 1). Thus, when V_a was increased, V_b was correspondingly decreased.

To measure $K_{Ic,m}$, four beams 50 mm × 50 mm × 250 mm were cast from each of the 16 mixes of each

Type once the desired workability (i.e. cone penetration depth) was achieved. The depth of the beam was chosen to be at least 25 times the maximum aggregate size (600 μm in Type I mixes and 2 mm in Type II mixes) in order to avoid errors in the measurement of $K_{Ic,m}$ due to size effect.²⁰ Thus, 64 beams of each mix Type were cast for each CPT depth.

After curing, the beams were notched at mid-span to half the beam depth (3 mm notch width) and tested in three-point bending (knife edge load) over a loaded span of 200 mm. The fracture toughness $K_{Ic,m}$ was calculated from the standard formula for a notched three-point bend specimen.²⁰ The 16 mean values of $K_{Ic,m}$ of each mix Type for each of the three CPT depths were represented by an expression (5) containing 16 terms in the three variables w/b , sp/w and V_a . As the sp/w was the most important parameter for achieving the required CPT for each pair of the other two variables, it was given more weight in the selection of the terms in the expression (5). The 16 unknown coefficients in this expression were determined by solving a system of 16 linear simultaneous equations in these unknowns using the 16 measured mean values of $K_{Ic,m}$ of each mix Type for each CPT depth. The unknown coefficients so determined are given in Table 2. Absence of an entry in the table means that the corresponding coefficient was negligibly small.

$$\begin{aligned}
 K_{Ic,m} \approx & A_0 + B_1(w/b) + B_2(w/b)^2 \\
 & + C_1(V_a) + C_2(V_a)^2 + D_1(sp/w) + D_2(sp/w)^2 \\
 & + D_3(sp/w)^3 + E_1(w/b \times V_a) + E_2((w/b)^2 \times V_a) \\
 & + F_1(w/b \times sp/w) + F_2(w/b \times sp/w)^2 \\
 & + F_3((w/b)^2 \times sp/w) \\
 & + G_1(sp/w \times V_a) + G_2((sp/w)^2 \times V_a) \\
 & + H_1(w/b \times V_a \times sp/w)
 \end{aligned} \quad (5)$$

It should be noted that no tests were performed on mixes of Type I to cone penetration depths of 22 and 24 mm. However, guided by the results of both types of mix for the cone penetration depth of 20 mm, it may be assumed that the results of mix Type II are also applicable to mixes of Type I for these two cone penetration depths.

Conclusions

Based on an extensive investigation into batching, mixing and processing procedures, a class of HPFRCCs has been developed and patented under the trade name CARDIFRC[®]. It should, however, be noted that it is the procedure of mixing and of ensuring an even distribution of fibres in the mix, not the mix proportions themselves, that is patented.

For the matrix without fibres, the CPT was found to be a very accurate method of quantifying the work-

Table 2. Coefficients in equation (5)

Coefficient	mix Type I CPD \approx 20 mm	mix Type II CPD \approx 20 mm	mix Type II CPD \approx 22 \pm 0.5 mm	mix Type II CPD \approx 24 \pm 0.5 mm
A_0	-253.0	-94.0	83.0	18.0
B_1	1435.0	782.0	-778.0	-196.5
B_2	-683.3	-1566.0	1767.0	507.9
C_1	83.8	376.8	-232.5	12.8
C_2	-35.1	11.5	-30.5	40.1
D_1	2382.0	-76.4	271.0	-182.0
D_2	-85.6	956.8	-263.7	353.9
D_3	218.9	-882.9	-	-
E_1	1024.0	-3201.0	2378.0	40.9
E_2	-6977.0	6609.0	-5553.0	-17.2
F_1	-8392.0	2027.0	-3597.0	2197.0
F_2	-3789.0	-4981.0	1427.0	-2435.0
F_3	-21070.0	-6865.0	9757.0	-7583.0
G_1	-5411.0	-1212.0	333.5	-210.4
G_2	943.2	894.3	-58.7	-2.3
H_1	28860.0	4988.0	-1113.0	1855.0

ability of a mix in terms of the variation of its fracture toughness $K_{Ic,m}$ with the mix variables (w/b , sp/w and V_a) for use within the experimental limits of $K_{Ic,m}$. As expected, sp/w was the most significant variable and this can be seen by its appearance in a larger number of terms of the relation (5) than the other two variables (V_a and w/b).

The two companion papers will describe methods for the assessment of the distribution of fibres in specimens made from CARDIFRC[®] mixes (Part II) and compare their measured mechanical properties with theoretical predictions (Part III).

Acknowledgements

This work is supported by the UK EPSRC grant GR/R11339. The authors would like to acknowledge Dr Farshid Alaei's assistance with the development of CARDIFRC[®].

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Discussion contributions on this paper should reach the editor by 1 February 2006