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Fatigue life and self-induced volumetric changes of CARDIFRC

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A class of ultra-high-performance fibre-reinforced cementitious composites (UHPFRCC) has been developed at Cardiff university and registered under the trade name CARDIFRC. The method of its production and its mechanical and fracture properties were reported previously in a series of papers in Magazine of Concrete Research. Here the results of recent fatigue and shrinkage tests on this material are reported. As with the mechanical and fracture properties, it is shown that an even and uniform distribution of fibres throughout the bulk of the material is crucial to its superior fatigue performance and to the reduction in the shrinkage strains.

Introduction

In recent years there has been a growing interest in the fatigue behaviour of concrete subjected to repeated loading. The fatigue strength of concrete is defined as the fraction of the static strength that it can support repeatedly for a given number of cycles. Fatigue failure occurs when a concrete structure fails catastrophically at less than the design load after being exposed to a large number of load reversals. Concrete fatigue is a result of damage accumulation from the progressive growth of small imperfections existing in the material by repetitive loads. These imperfections may be caused by shrinkage or the application of external loads. The latter leads to progressive bond deterioration between coarse aggregates and the cement paste or to the development of cracks existing in the cement paste.

The addition of fibres to concrete has a twin effect on its fatigue performance. By bridging the microcracks, the fibres can retard the crack growth process, thus increasing its fatigue life. But if they are not properly bonded to the surrounding mix, they can form the nuclei of additional defects and thus reduce the fatigue life of concrete. In the ultra-high-performance fibre-reinforced cementitious composite (UHPFRCC) under investigation, the bond between the fibres and surrounding mix has been strengthened and densified by the use of silica fume and superplasticiser and it is the aim of this study to reveal how this has influenced its fatigue life.

A characteristic feature of the UHPFRCC under investigation is its very low porosity and the discontinuous capillary pore structure of the cement paste. Moreover, because of a low water-to-binder ratio, changes in temperature and moisture content (i.e. relative humidity) can induce volume changes during hardening far in excess of those observed in conventional concretes. These self-induced volume changes are best measured volumetrically commencing from the moment of casting. However, such measurements are difficult to make in practice, and so instead linear measurements are made on specimens after the initial setting period. This has led to considerable disagreement in the scientific community on merits of each method (Jensen and Hansen, 1995, 2001). It is not the intention here to argue in favour of one or the other method. The present researchers' aim is limited to revealing the role of fibres in the reduction of the considerable self-induced volume changes. For this the simpler linear measurement technique is used and the self-induced volume changes are compared for specimens with and without fibres.

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CARDIFRC

CARDIFRC is a new class of UHPFRCC characterised 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/m^2). This has been made possible by the use of large amounts (up to 8% by volume) of brass-coated short steel fibres of two lengths (6 and 13 mm long, 0·16 mm diameter) in a cementitious 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 optimising 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 by Karihaloo *et al.* (2005). Computer tomography imaging and sectioning of specimens have confirmed that these procedures ensure a remarkably homogeneous mix with a uniform distribution of fibres in thin sections (<50 mm thick) (Benson *et al.*, 2005). The mix proportions of a mix of the CARDIFRC class and its typical properties are given in Tables 1 and 2 (Karihaloo *et al.*, 2005).

Experimental set-up

Fatigue experimental set-up

The fatigue tests were carried out in three-point bending in a stiff self-straining testing frame, fitted with a 2500 kN dynamic–static actuator. The beams (35 × 90 × 360 mm) were simply supported over a span of 280 mm. The choice of a thin beam (35 mm deep) was dictated by the fact that CARDIFRC is mainly intended for use in the form of thin strips in small-volume applications (e.g. retrofitting of damaged concrete structures) owing to the high cost of fibres (Alaee and Karihaloo, 2003; Alaee *et al.*, 2002; Karihaloo *et al.*, 2002). Moreover, the novel mixing procedures (Benson and Karihaloo, 2005a; Karihaloo *et al.*, 2005) ensure an even and uniform distribution of the fibres within the mix in such thin strips. In view of the high cost of fibres, a commercial variant of the material has been developed in collaboration with a leading concrete construction company. It differs from the original CARDIFRC mixes through

(*a*) a reduction in the cost by replacing expensive brass-coated small steel fibres with less expensive longer steel fibres
(*b*) the avoidance of the need for vibratory compaction by creating a self-compacting mix
(*c*) the creation of a sustainable and environmentally friendly material with a low carbon footprint.

This commercial mix is currently undergoing a thorough performance evaluation. A recent cost analysis by the industrial partner who can procure the ingredients at much lower wholesale prices has shown that this commercial variant is highly competitive even in very large-volume applications for which steel is preferred at present.

Four short cylindrical clamps were arranged on the supports to prevent the beam from moving, during the cyclic load application. These clamps did not actually come in contact with the specimen, unless it started to move from its original position. None of the specimens were observed to move during fatigue testing. The load amplitude, the frequency, the applied number of cycles and the magnitude of central displacement at failure were digitally controlled. Four types of measurement were recorded for each test beam

(*a*) the load from the load cell of the testing machine
(*b*) the vertical deflection at the mid-span
(*c*) the time parameter
(*d*) the number of cycles to failure.

The vertical deflection was measured by a single linear variable differential transducer (LVDT) placed underneath the testing beam, at the mid-span. The specific LVDT was calibrated for a very narrow range of deformation (±2·5 mm), because the deformation of the beam during its fatigue life was expected to be very small. A mechanical stop was installed 10 mm below the beam at its mid-span in order to prevent damage to the LVDT should the beam fail suddenly.

The cyclic tests were carried out in the load ranges between 10% and 90%, 10% and 85%, and 10% and 80% of the monotonic flexural strength. Fatigue specimens were not all cast from the same batch, in order to explore the possible effect of batching on the consistency of the experimental results. The monotonic flexural strength was also measured in three-point bending on specimens of the same dimensions, and the mean

Table 1. Mix proportions for optimised CARDIFRC I (per m^3)

Constituents: kg	Mix I
Cement	855
Microsilica	214
Quartz sand:	
9–300 μm	470
250–600 μm	470
212–1000 μm	—
1–2 mm	—
Water	188
Superplasticiser	28
Fibres, 6 mm	390
Fibres, 13 mm	78
Water/cement ratio	0·22
Water/binder ratio	0·18

Table 2. Typical material properties of CARDIFRC I

Material properties	Mix I
Indirect tensile strength: MPa	27
Fracture energy: J/m^2	17 000
Compressive strength: MPa	200
Modulus of elasticity: GPa	48

value from at least five specimens was 46·4 MPa. The fatigue tests were performed in load control. Each specimen was first subjected to three slow cycles up to 50% of the monotonic flexural strength of the material to remove any slack in the test set-up before any recordings were made. This stress level was chosen because it lies well within the elastic range of the material. It should be noted that, unlike most previous studies on the fatigue of fibre-reinforced concrete (FRC), the specimens tested in this study were not pre-cracked before cyclic loading (Cachim *et al.*, 2002).

The specimens were subjected to a sinusoidal cyclic fatigue loading with a frequency of 6 Hz. The choice of frequency of the sinusoidal load was dictated solely by the time it would take for the test beam to reach a minimum of 10^6 cycles. The test was stopped after the specimen failure or after one million load cycles, whichever occurred first. A few specimens were tested up to 20×10^6 cycles (Farhat *et al.*, 2007).

Self-induced shrinkage experimental set-up

For the self-induced shrinkage experiments prismatic specimens (with or without fibres – SF and SNF respectively) with dimensions 50 × 50 × 250 mm were used. It is known from the literature that for cement-based materials containing large quantities of cement and mineral–chemical admixtures (cement replacement materials and water-reducing agents), the setting of the mix is considerably delayed (Brooks *et al.*, 2000; Morin *et al.*, 2001). Moreover, in many cases reported in the literature where linear measurements of self-induced shrinkage deformations were performed, a minimum setting time of 12 h was selected (Jiang *et al.*, 2005; Yang *et al.*, 2005). Similar observations have been reported for high-performance cement-based composites with water-to-cement (w/c) ratio as low as 0·17. Cheyrezy and Behloul (2001) have selected 19 h as the setting time of reactive powder concrete, a cement-based composite very similar in composition to CARDIFRC. In the light of these findings the specimens remained in the steel moulds for about 17 h in order for them to harden sufficiently well for handling, after which the specimens were demoulded and acoustic vibrating wire gauges were bonded to the ends.

After bonding the gauges, the beams were carefully wrapped, taking care not to cause any damage to the gauges. The specimens were wrapped with vinyl acetate sheets and aluminium adhesive tape, ensuring the adiabatic conditions needed for the test, as well as minimising any moisture exchange with the surrounding environment. After wrapping the specimens and insulating them properly, they were connected to a data acquisition system. For the first seven days, readings were recorded every 15 min. The interval between the readings was increased progressively after this initial period. The choice of small time step between the readings in the first seven days was dictated by the knowledge that the bulk of the self-induced shrinkage strains occur in this period. This has been confirmed by the measurements, as will be clear in the following sections. After day 20 the development of shrinkage strains seems to have stabilised sufficiently for the interval between the readings to be substantially increased.

Experimental results and discussion

Fatigue

The fatigue life of specimens (i.e. the number of cycles to failure, N) is shown in Table 3. It is clear that the test results are highly consistent for the load ranges between 10% and 85% and between 10% and 80%; all eight specimens sustained in excess of 10^6 cycles without failure. Moreover, none of these eight specimens had developed any visible cracks on the surface. On the other hand, in the load range 10–90% some specimens failed below 10^6 cycles and some did not. It can therefore be safely assumed that the fatigue limit of CARDIFRC is approximately at 85% of its monotonic flexural strength. Below this limit none of the tested specimens failed, not even after a few of them had been subjected to 20×10^6 cycles (Table 3). That the observed fatigue limit is very high, not often associated with cement-based materials, is consistent with the response of CARDIFRC in direct tension (Benson and Karihaloo, 2005b), which shows that its elastic range extends to about 85% of its ultimate tensile strength. However, in contrast to conventional FRC, this extended elastic range of CARDIFRC is followed by a very substantial strain hardening range.

In order to verify whether or not any internal cracks had developed in the specimens that had sustained at least 10^6 cycles without failure, they were tested post-

Table 3. Flexural fatigue test experimental results (CARDIFRC 360 × 90 × 35 mm)

Load amplitude range: % P_u	Fatigue life: N				
	N_1	N_2	N_3	N_4	Average fatigue life: N
10–90	10^6	21 564	9315	10^6	—
10–85	10^6	10^6	10^6	20×10^6	10^6*
10–80	10^6	10^6	10^6	20×10^6	10^6*

*The average fatigue life considers only the first 10^6 cycles sustained by specimen No. 4.

fatigue in static three-point bending. The purpose of this static testing was to compare the post-fatigue flexural strength and the static load–deflection envelope with the pre-fatigue test results. As mentioned earlier, none of these specimens had any visible cracks on the external surfaces at the end of fatigue testing. The specimens tested at 80%, 85% and 90% P_u in fatigue showed a small increase in their flexural strength (Table 4). This increase in flexural strength was believed to be dependent on the maximum flexural fatigue stress (S_{max}). This observation confirms previously noted results in the literature, that prior cycling may lead to an improvement in strength (Naaman and Hammoud, 1998; Naaman and Harajli, 1990; Parant *et al.*, 2007; Ramakrishnan *et al.*, 1996; Rossi and Parant, 2008). It was suggested that this increase in strength is due to densification of the material, caused by stress cycling. However, it is likely that there are other mechanisms also involved in the increase of the post-fatigue flexural strength in UHPFRCCs which remain to be explored.

Self-induced shrinkage

Twelve prisms having dimensions 50 × 50 × 250 mm have been made for each type of mix (with and without fibres). The effect of fibres on the reduction of self-induced shrinkage strains is pronounced, as can be clearly observed in Tables 5 and 6. The inclusion of fibres results in 74% decrease in the self-induced shrinkage strains. Although there are findings suggesting that both unhydrated cement grains and hydration products can act as a restraint on the self-induced shrinkage in plain cement-based matrices (Bentz and Jensen, 2004; Farhat *et al.*, 2007; Jensen and Hansen, 1996), it is the additional restraint provided by the large volume (6%) of small fibres used in CARDIFRC that is responsible for the bulk of the reduction in the self-induced shrinkage strains. Figure 1 shows the variation of the self-induced shrinkage strain with time for mixes with and without fibres (up to 75 days).

Table 4. Experimental peak loads and tensile/flexural strengths of intact CARDIFRC beams (360 × 90 × 35 mm), tested in three-point bending, after they have been subjected to fatigue loading

Beam number	10–90% P_u		10–85% P_u		10–80% P_u	
	P_u: kN	f_t: MPa	P_u: kN	f_t: MPa	P_u: kN	f_t: MPa
1	14·65	55·81	12·65	48·19	14·30	54·48
2	—	—	14·64	55·77	13·70	52·19
3	—	—	14·30	54·48	12·40	47·24
4	12·88	49·07	13·33	50·78	13·60	51·81
Avge strength		52·44		52·30		51·43

Table 5. Average shrinkage strain (με) values (with coefficient of variation (COV)) for mixes with (SF) and without fibres (SNF) at the end of each time interval

	Time: days						
	1	2	3	4	5	6	7
Average shrinkage strain, SF: με	99·42	160·17	212·09	250·11	278·94	305·03	328·34
COV	9·29	7·66	6·81	5·86	5·59	5·04	4·91
Average shrinkage strain, SNF: με	143·82	248·52	329·91	391·19	442·31	485·23	521·63
COV	2·37	2·09	2·04	2·07	1·94	1·92	1·89

Table 6. Average shrinkage strain (με) values (with COV) for mixes with (SF) and without (SNF) fibres at the end of each time interval

	Time: days						
	10	20	30	40	50	60	75
Average shrinkage strain, SF: με	404·78	496·89	479·53	515·69	518·57	540·73	577·00
COV	3·98	2·87	2·61	2·20	2·21	1·97	1·66
Average shrinkage strain, SNF: με	589·16	678·22	754·25	775·53	842·41	903·01	1000·24
COV	1·87	2·11	2·32	1·63	1·58	1·62	1·45

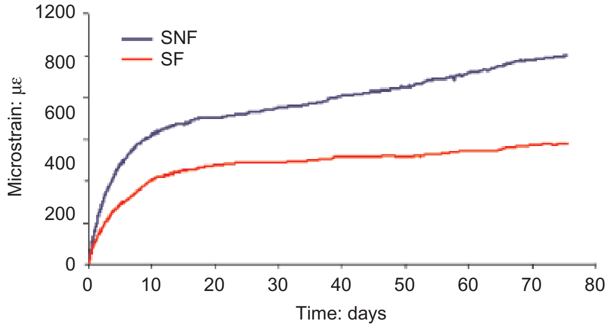

Figure 1. Shrinkage strain variation with time for mixes with (SF) and without (SNF) fibres (up to 75 days)

Conclusions

CARDIFRC exhibits excellent fatigue strength, up to 85% of its flexural strength, without any significant internal damage. This is consistent with its uniaxial tensile response (Benson *et al.*, 2005), which is linear up to at least 85% of the tensile strength. This excellent fatigue behaviour can be attributed to the following factors: the absence of large aggregates (i.e. internal sites of stress concentrations); strong interfacial bond between the fibres and matrix; and the even and uniform distribution of fibres within the specimens, which prevent the growth and coalescence of any microcracks.

The shrinkage strains, which are primarily of autogenous and chemical nature, with perhaps a small contribution from drying despite the precautions taken to prevent loss of moisture to atmosphere, are, as expected, large for this kind of material because of the high content of cement and the low w/c ratio. The development of these strains is especially rapid up to the first 10 days, but the increase thereafter takes place at a substantially reduced rate. The presence of fibres is found to have a substantial beneficial effect in restraining the shrinkage of CARDIFRC matrix. In fact, the strains are reduced to levels expected of high-strength concretes. Moreover, the fibres prevent the formation of shrinkage cracks, as none were observed on the surfaces of the specimens even after 75 days.

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