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Fracture and fatigue of a self-compacting version of CARDIFRC mix II

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ABSTRACT

A self-compacting and industrially competitive version of CARDIFRC mix II has been developed. In this paper we describe the mechanical, fracture and fatigue performance of this ultra-high performance fibre reinforced concrete (UHPFRC).

Keywords: *UHPC; Self-compacting; Bi-linear stress-crack opening relation; fatigue life; endurance limit*.

1. Introduction

CARDIFRC is the trade name of two main groups of ultra-high performance fibre-reinforced concrete mixes – Mixes I and II – differing primarily in the maximum size of quartz sand used (0.6 mm in Mix I, and 2 mm in Mix II) [1,2].CARDIFRC Mix II has been converted to a self-compacting and industrially competitive ultra-high performance fibre-reinforced concrete (UHPFRC). Mix proportions are given in Table 1. In this paper, full mechanical, fracture and fatigue characterisation (i.e. size-independent fracture energy and the corresponding bi-linear stress-crack opening relationship, and endurance limit) of this UHPFRC is provided.

Table 1. Mix constituents of the self-compacting UHPFRC version of CARDIFRC Mix II (kg/m3)

Constituent	**Dosage (kg/m^3)**
Cement	450.3
Silica fume	169.5
GGBS	258.0
Quartz sand: 9-300μm 0.212-1 mm	 158.0 318.9
1-2 mm	639.7
Water	141.8
Superplasticizer (SP)	58.5
Fibres: 30 mm Dramix (Vol. 2.5%)	195.0
Water/cement	0.20
Water/binder	0.16
SP/water	0.41
Slump flow spread (mm)	705
t_{500} (s)	2.73

2. Mechanical properties

Compression tests were carried out on cube specimens according to BS EN 12390-3 (2009), whereas split tensile tests were performed on cylindrical specimens according to BS EN 12390-6 (2009). In addition, the modulus of elasticity was measured on a cylindrical specimen according to BS 1881-121 (1983) and the modulus of rupture of beam specimens was determined according to BS 1881-118 (1983). Table 2 shows the mechanical properties of the UHPFRC, together with the coefficient of variation (CoV in %).

Table 2. Mechanical properties of the self-compacting UHPFRC version of CARDIFRC Mix II

Compressive Strength (MPa)	**Split cylinder Strength (MPa)**	**Modulus of Rupture (MPa)**	**Modulus of Elasticity (GPa)**
148.0 (4.5%)	18.5 (6.0%)	20.0 (0.7%)	45.2 (0.2%)

3. Fracture properties

The fracture performance is characterised in terms of size-independent fracture energy obtained by the boundary effect model and the corresponding bilinear stress-crack opening relationship obtained by using the non-linear hinge. For this, six prisms 100 x 100 x 500 mm were casted with the self-compacting UHPFRC. After curing, three prisms were notched to a depth of 10 mm and the remaining three to a depth of 60 mm using a diamond saw (width approximately 2 mm). They were tested in three-point bending over a loaded span of 400 mm. The test was controlled first by a feedback signal from a crack mouth opening displacement (CMOD) gauge until the gauge reached its limit (around 3.5 mm), where after the control switched to mid-point displacement control. The load-CMOD was recorded until the gauge reached its limit, but the load-mid-point displacement continued to be recorded until the displacement reached 30 mm. The load had still not dropped to zero. The area under the load-deflection plot was therefore corrected to account for the unrecorded work-of-fracture using the procedure of Elices et al. [3]. The total work-of-fracture was divided by the projected fracture area (i.e. area of initially un-cracked ligament) of the notched specimen to calculate the specific fracture energy $G_f\,(a/W)$ corresponding to a/W = 0.1 and 0.6. Finally, the size-independent specific fracture energy G_F was determined using the appropriate relations of Hu and Wittmann [4] and the simplified boundary effect model of Abdalla and Karihaloo [5]. The values are reported in Table 3. The size-independent specific fracture energy is 36300 N/m compared to about 20000 N/m for the original Mix II measured in axial tension.

Table 3. Mean size-dependent fracture energies for a/W = 0.1 and 0.6 and size-independent specific fracture energy of UHPFRC version of CARDIFRC Mix II (bi-linear model)

Notch(mm)	**Mean G_f (N/m)**	**a_l (mm)**	**G_F (N/m)**
10	30190	30.3	36300
60	22600		

The unknown parameters of the bi-linear stress-crack opening diagram (the direct tensile strength, the critical crack opening and the co-ordinates of the knee in the bi-linear diagram) are identified in an inverse manner by minimizing the root mean square error between either the recorded and predicted load-CMOD or the load-deflection diagram at many values of the applied central load using the non-linear hinge model of Olesen [6]. The results are shown in Figure 1. The parameters of the tension softening curves obtained using the non-linear hinge model correspond to the measured G_f (0.1) and G_f (0.6), but not to G_F.

Abdalla and Karihaloo [7] proposed a simple method for the determination of the bi-linear softening diagram corresponding to the size-independent G_F of concrete mix by scaling the average parameters of the tension softening diagrams corresponding to the size-dependent fracture energies G_f(0.1) and G_f (0.6). This scaling procedure was followed in this work, giving the tension-softening diagram also shown in Figure 1.

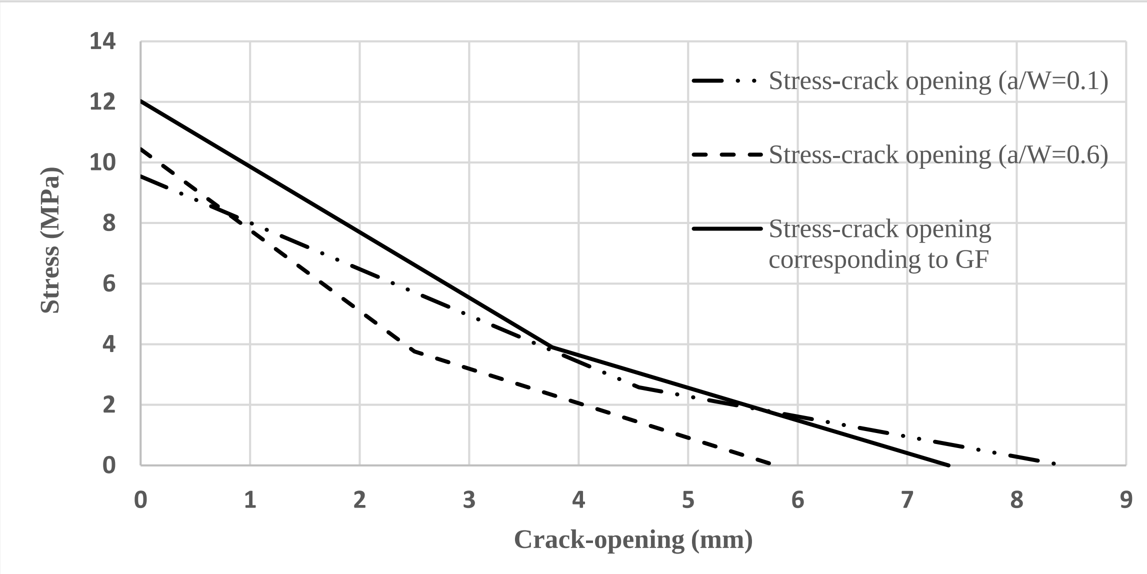

Figure 1. Bi-linear stress-crack opening relationships corresponding to a/W=0.6, 0.1 and G_F

4. Fatigue properties

Fatigue test under tensile cyclic loading was conducted on un-notched three point bend beams. Tests were performed in the sinusoidal load ranges between 0.6 – 4.0 kN, 0.6- 4.5 kN, and 0.6 – 5.5 kN, corresponding to 9.69 - 64.62%, 9.69 - 72.70% and 9.69 - 88.85% of the static three-point flexural strength. This meant that the mean stress level on the specimens during cyclic loading increased with the increase in the upper load limit (Table 4). This has a marked effect on reducing the fatigue life. The cyclic load-central deflection traces of the specimens were recorded every minute, i.e. every 300 cycles. From these the change in compliance of the specimens could be calculated. It was found that the endurance limit of the UHPFRC is around 64% of its static three point flexural strength at a mean stress level of 37.1% of this strength (Figure 2). This corresponds to an endurance limit close to 80% of the static three point flexural strength at zero mean stress.

Table 4. Increase in the mean stress level with increasing upper limit load

Upper Stress limit (%)	**Mean Stress (MPa)**
64.62	8.18
72.70	9.07
88.85	10.85

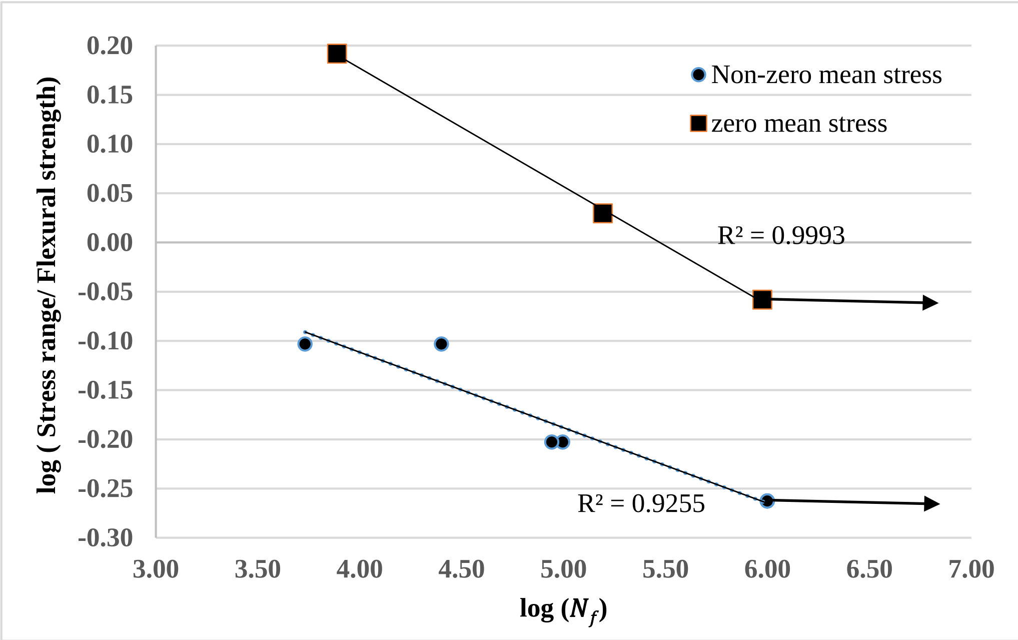

Figure 2. Fatigue life against stress range (logarithmic scale)

5. Conclusions

1. A self-compacting UHPFRC based on CARDIFRC Mix II was developed and fully characterised from both the mechanical and fracture points of view. As expected, the resulting UHPFRC has inferior compressive, tensile and flexural strengths than the original CARDIFRC Mix II. This is due to the absence of thin small brass-coated steel fibres (4.5% by volume; 6 mm long) in the UHPFRC. The UHPFRC is however much tougher thanks to the use of a larger volume fraction (2.5% against 1.5%) of longer steel fibres (30 mm against 13 mm).
2. An inverse approach based on the non-linear hinge model for crack growth from a pre-existing notch was used to identify the parameters of the bi-linear stress-crack opening relation of the UHPFRC.
3. The endurance limit of the test material is around 64% of its static three point flexural strength (Figure 2) at a mean stress level of 37.1% of this strength. This corresponds to an endurance limit close to 80% of the static three point flexural strength at zero mean stress.

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