Technical Paper

Structural Performance of Ultra-High Performance Fibre Reinforced Concrete Beams

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ABSTRACT

Ultra-high performance fibre reinforced concrete (UHPFRC) is a relatively new construction material. In comparison with conventional high strength concrete UHPFRC usually does not contain coarse aggregates larger than 6-7 mm in size. This paper presents the outcomes of an experimental study of UHPFRC beams subjected to four-point loading. The effect of two parameters was studied, namely the fibre content and the temperature of curing water. Eight UHPFRC beams comprising 6 beams reinforced with rebars and two beams without rebars were tested. Three fibre contents were investigated in this study (1%, 2% and 4% in volume). The study investigated two curing temperatures of water which are 20°C and 90°C. The results presented in this paper include deflections, toughness energy and moment capacity and also includes a comparison with calculations according to EC2 provisions. A minor difference was observed in the deformation and flexural behaviour of beams with fibre contents of 1% and 2%

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(in volume). However, beams with 4% (in volume) fibres exhibited a higher flexural capacity. Only flexural failure was observed and no shear related failure was recorded. Beams with 1% (in volume) fibres for both curing regimes had the highest peak-load toughness energy. Beams reinforced with rebars and cured at 20°C had a significantly higher bending resistance.

Keywords - Ultra-high performance fibre reinforced concrete; curing; flexural behaviour; steel fibres; deflection; moment capacity, toughnes

1. INTRODUCTION

In recent years, ultra-high performance fibre reinforced concrete (UHPFRC) has been investigated focusing on various material parameters. Namaan [1] defined UHPFRC as an ultra-high performance concrete (UHPC) with fibres aiming to improve a wide range of mechanical properties. These improved properties include ductility, high compressive strength, durability, toughness and freeze-thaw resistance [2]. It has been considered in recent years that the compressive strength of UHPFRC usually exceeds 150 MPa [2-4]. UHPC typically has a low water-binder ratio and high particle density resulting in a lower porosity [3, 4], which enhances penetration resistance. It has also been found that the addition of 8% of short, discontinuous steel fibres to UHPC can increase the compressive strength up to 292 MPa and enhances the ductility [5]. However, this high fibre content makes it impractical to cast real structures and also will significantly increase the costs of the concrete produced. Another important difference is that UHPFRC usually does not contain coarse aggregate, with the most aggregate being fine sand with a particle size typically less than 1 mm [6, 7]. Being a relatively new material, UHPFRC has not yet been incorporated into design codes including ACI (American Concrete Institute) Code and Eurocodes. The Association of French Civil Engineering (AFGC) [8] and Japan Society of Civil Engineers (JSCE) [9] have established design recommendations which serve merely as recommendations and are not yet approved codes. Mechanical properties of any concrete including UHPFRC are greatly influenced by the curing method. Hot water curing is used in order to obtain a high early age strength which is higher compared to concrete cured in cold water [10]. At an elevated curing temperature, the rate of hydration increases due to enhanced pozzolanic activity and it assists in modifying the structure of hydrates [11-13]. Silica fume reacts with calcium hydroxide which is released from cement paste, to form additional binder called calcium silicate hydrates (C-S-H). Zanni et. al. [12] observed that the pozzolanic reaction at 20°C is relatively slow compared to 90°C. This study further showed that the C-S-H chains are shorter in concrete cured at 20°C even after 28 days of curing, compared to longer chains which are formed at 90°C, during the same curing period. These additional C-S-H chains created at elevated curing temperature as a result of the pozzolanic reaction, fill up the pores of the concrete matrix to form a denser and compact structure. This results in a higher compressive strength of concrete and improves the bond properties between the steel fibres and the concrete matrix [14]. Yuan and Graybeal [15] investigated the bond behaviour of deformed steel reinforcing bars in UHPFRC elements and reported that the bond strength increases with compressive strength. This is the reason why heat treatment has been applied to enhance mechanical properties of UHPFRC. Kamen et. al. [14] performed four-point bending tests on UHPFRC plates measuring 30 x 200 x 500 mm^3 at the age of 7 and 28 days. The specimens were cured in water at 30°C and 40°C. At 7 days, the specimen cured at 40°C had a load-carrying capacity that was 69% higher than the specimen cured at 30°C. However, at 28 days, the plates were produced with different curing conditions resulted in almost identical load-deflection curves, with similar maximum bending loads. The results show that an elevated curing temperature at early age has beneficial effects on strength development. A number of experimental tests have been conducted on cubes, cylinders and small scale beams by Yang et. al. [16] who investigated the flexural behaviour and deflection patterns of steam-cured UHPFRC beams. Their study was limited to beams containing 2% steel fibres. The study further explored how flexural capacity is affected by different casting procedures. Yang and Bo [17] investigated the effects of hot and cold curing on the flexural behaviour, the ductility and the fracture energy though tests were only carried out with small prisms. According to the study findings, the UHPFRC prisms cured at 20°C, were more ductile and a had higher displacement at the peak stress than the 90°C cured specimens. Yang et. al. [18] determined the flexural strength and fracture energy of 50 × 50 × 200 mm^3 UHPFRC prisms. The prisms were reinforced with 2% (in volume) steel fibres and were cured at different water temperatures. Results from the study indicated that UHPFRC elements cured at 20°C were approximately 20% lower in compressive strength, 10% lower in flexural strength and 15% lower in fracture energy than the elements cured at 90°C. Examining the available research literature demonstrates that UHPFRC has not been sufficiently investigated to cover important structural performance parameters. Available literature mainly discusses the influence of the curing temperature on mechanical properties and the behaviour of UHPFRC structural elements is often based on small UHPFRC specimens such as cylinders, cubes and prisms. Previous studies on the flexural behaviour of medium and large scale beams, reinforced with rebars, were mainly executed with a single curing condition. Insufficient literature therefore makes it difficult to compare different curing conditions and their influence on beams' flexural behaviour and performance. Therefore, a study was conducted on medium scale beams to determine the effects of other parameters such as fibre content variation and curing temperature on the structural performance of UHPFRC concrete beams. The study aims at investigating and comparing the structural behaviour of UHPFRC beams reinforced with steel fibres at 1%, 2% and 4% volumetric ratio. The effect of the fibre content has been investigated for two curing water temperatures: 20°C and 90°C. The paper presents the obtained experimental data of strength, deflection, curvature, and flexural toughness. The paper also provides a comparison of the obtained experimental results with values calculated using EC2.

2. EXPERIMENTAL PROGRAM

Tests were conducted on 8 UHPFRC beams with cross-sections of 100mm x 150mm. The total length and clear span of the beams were 1300mm and 1200mm, respectively (Figure 1). Six beams were reinforced with two 12mm diameter reinforcement bars in the tension region with a concrete cover of 20mm. The beams did not contain any shear reinforcements. No rebars were placed in the remaining two beams.

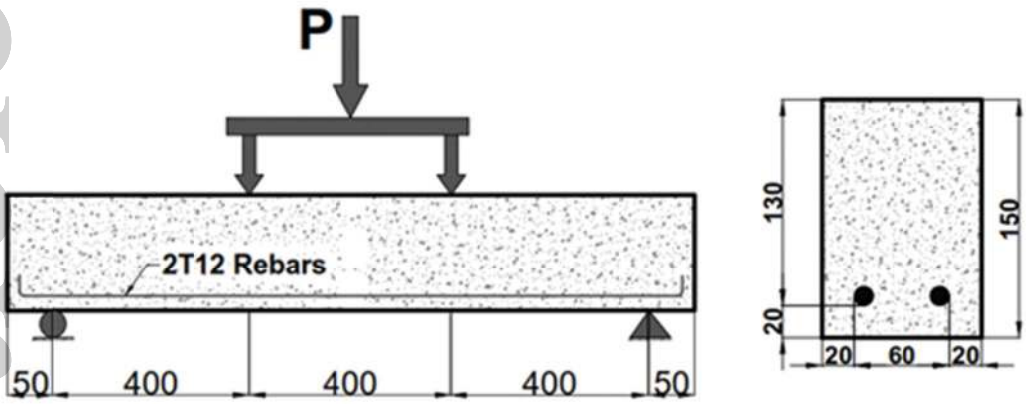

Figure 1. Beam dimensions and loading layout

Details of the test specimens and parameters are shown in Table 1. The tests were divided in two series based on their curing regime. Four beams were cured in hot water at a temperature of 90°C for 7 days and the other beams were cured in water at room temperature i.e. at a temperature of 20°C for 7 days. The beams were designated with three letters as shown in Table 1. The number following the letters represents the amount of fibres per volume in that beam.

Table 1. Details of the tested beams

Beam ID	**Curing regime**	**Fibre content % (volume)**	**Rebars** diameter (mm)
RSC-1	20°C water	1	12
RSC-2		2	12
RSC-4		4	12
USC-2		2	No rebars
RSH-1	90°C water	1	12
RSH-2		2	12
RSH-4		4	12
USH-2		2	No rebars

2.1 Materials

The optimized mix proportions shown in Table 2 were used. The mix included no coarse aggregates. Only fine sand measuring less than 0.6mm in diameter was used. The aggregate size of 0.6 mm was used in this study as it was found to be the most commonly used size in previous research on UHPFRC [6, 7, and 16]. Portland cement, CEM I 52.5N, manufactured by Lafarge was used in this study. To attain a high density of concrete, pozzolanic silica fume, with a density of 2.36kg/dm^3, averaging 1μm in size was added to the mix. The smallest granular particles in the mix, (silica fume) fill up the voids between hydrated cement and fine sand particles which results in a highly compact concrete of low permeability, which can effectively prevent the corrosion of concrete reinforcement. UHPFRC characteristically has a water-cement (w/c) ratio of 0.25 or lower. Although 0.25 or lower values of w/c are recommended to achieve high compressive strengths, it is worth noting that such values do pose challenges in achieving adequate workability. Therefore, a high performance superplasticizer, (HP3 Larsen Chemcrete), was used in the mix. HP3 is a polycarboxylate polymer and realizes a high workability and a water reduction of up to 30%. The material composition of the beams were the same with the steel fibre content being the only variable with 1%, 2% and 4% in volume per beam. Dramix® OL 13/0.2 fibres, manufactured by Bekaert were used in this study. These are straight fibres with a length (l_f) of 13mm, a 0.2mm diameter (d_f) and an aspect ratio (l_f/d_f) of 65. Dramix® fibres are cold drawn steel wires and come in a variety of sizes and configurations. Straight fibres with a minimum high tensile strength of 2000 MPa were applied in this study.

Table 2. Mix proportions and materials

Components	Type	Dosage (kg/m^3)
Cement	CEM I 52.5N	967
Silica fume	Larsen 60%<1μm	251
Sand	Natural sand ≤0.6mm	675
superplasticizer	Larsen Chemcrete HP3	77
Steel fibres	Dramix® OL 13/.2	1% = 79 2% = 158 4% = 316
Water	w/c ≈ 0.25	244

2.2 Casting Process

A 150 litres pan concrete mixer was used for mixing. A dry mix comprising cement, sand and silica fume was poured into the mixer and mixed for 5 minutes. Then, water was added to the dry components and mixed for 2 minutes followed by adding the superplasticiser and the wet components were mixed for another 2 minutes. Finally, the steel fibres were added to the mix and allowed to mix for 3 minutes (total mixing time was 12 minutes). The moulds were placed on a vibrating table, where no specific dominating affect was observed on the fibres orientation. After casting, the moulds were covered with a damp hessian and left in the lab at room temperature. They were demoulded 24 hours after casting. The beams and the accompanying 50mm cubes were left to cure in their designated curing mode.

2.3 Curing

The curing conditions of the water used in this study were: a) hot curing in a tank with water temperature kept constant at 90°C, b) curing in water at room temperature i.e. 20°C. The two tanks used are shown in Figure 2. In both cases the beams were fully immersed in water. The hot-cured beams were left in the curing tank for 7 days while the cold cured specimens were left to cure in an open tank for 7 days. The beams from both streams were then stored in the conditioning room where the temperature and relative humidity were maintained respectively at 21 to 25°C and 40% to 60% respectively until the day of testing.

Figure 2. Left) cold curing tank, right) hot curing tank

2.4 Instrumentations

One of the main objectives of this research was to study the flexural performance of the UHPFRC beams and eventually to determine their ultimate load capacity P_u. A four-point loading according to Figure 1 was carried out and a 200 kN capacity load cell was used to measure the applied load as shown in Figure 3. The applied load was transmitted to the steel spreader beam and subsequently to the beam through two 30mm diameter rollers of which spacing was 400mm. The load was applied in increments of 10% of the estimated beam capacity. There was a two minute interval between each successive load increment to stabilise the load and to monitor and mark the cracks. Two linear variable displacement transducers (LVDTs) were attached at beams' mid-span to measure the deflection as the load was applied. The instrumentation and the test set-up are shown in Figure 3.

Figure 3: Experimental setup for four-point loading

3. EXPERIMENTAL RESULTS

3.1 Concrete compressive strength

The concrete compressive strength was determined using the results obtained from the 50mm cubes tested in a standard compression machine. Nine cubes were cast alongside each beam and these were cured and stored in the same environment as the parent beam. Sets of three cubes were tested at 7 and 28 days and the other set of 3 was tested on the same day when the beam was tested in order to determine the test day strength. The obtained cubes strengths are given in Table 3. The table includes also the strength growth factor due to a higher curing temperature. The results show that the strength gaining factor decreases at increasing concrete age. For example, the 7 days strengths for hot cured specimens ranged between 135 to 164 MPa and were approximately 1.5 to 2 times higher than the cold specimens cured while the 28 days strength growth factor ranged between 1.34 to 1.59. From the results, it can be noticed that the strength of hot cured concrete peaked at 28 days, remaining about constant until the test day while that of cold cured concrete continued to increase steadily. Figure 4 shows the strength development graphs of concrete over a 120 days period for the three fibre contents. The figure shows that the strength gaining rate with time is higher when specimens were cold cured than for concrete cured in hot water. It also shows that the differences between the two regimes reduces with time. This conclusion is true for all the tested fibre contents. Regardless of the curing method beams with 4% fibres (RSC-4 and RSH-4) had the highest compressive strengths reaching 170 MPa at all the stages.

Table 3. Compressive strength of tested cubes.

Curing regime	**Beam ID**	**Fibre** (%)	**7 days**		**28 days**		**Test day**	
			f_c, **(MPa)**	f_c hot/ f_c cold	f_c, **(MPa)**	f_c hot/ f_c cold	f_c, **(MPa)**	f_c hot/ f_c cold
Cold cured at 20° C	USC-2	2	67.6	N/A	87.2	N/A	124.9	N/A
	RSC-1	1	72.9	N/A	97.2	N/A	130.0	N/A
	RSC-2	1	86.8	N/A	93.7	N/A	133.9	N/A
	RSC-4	4	95.3	N/A	131.1	N/A	170.0	N/A
Hot cured at 90° C	USH-2	2	140.0	2.07	152.8	1.59	163.4	1.31
	RSH-1	1	135.7	1.86	154.6	1.52	147.3	1.13
	RSH-2	2	137.6	1.59	142.6	1.34	149.0	1.11
	RSH-4	4	164.9	1.73	176.3	1.59	176.9	1.04

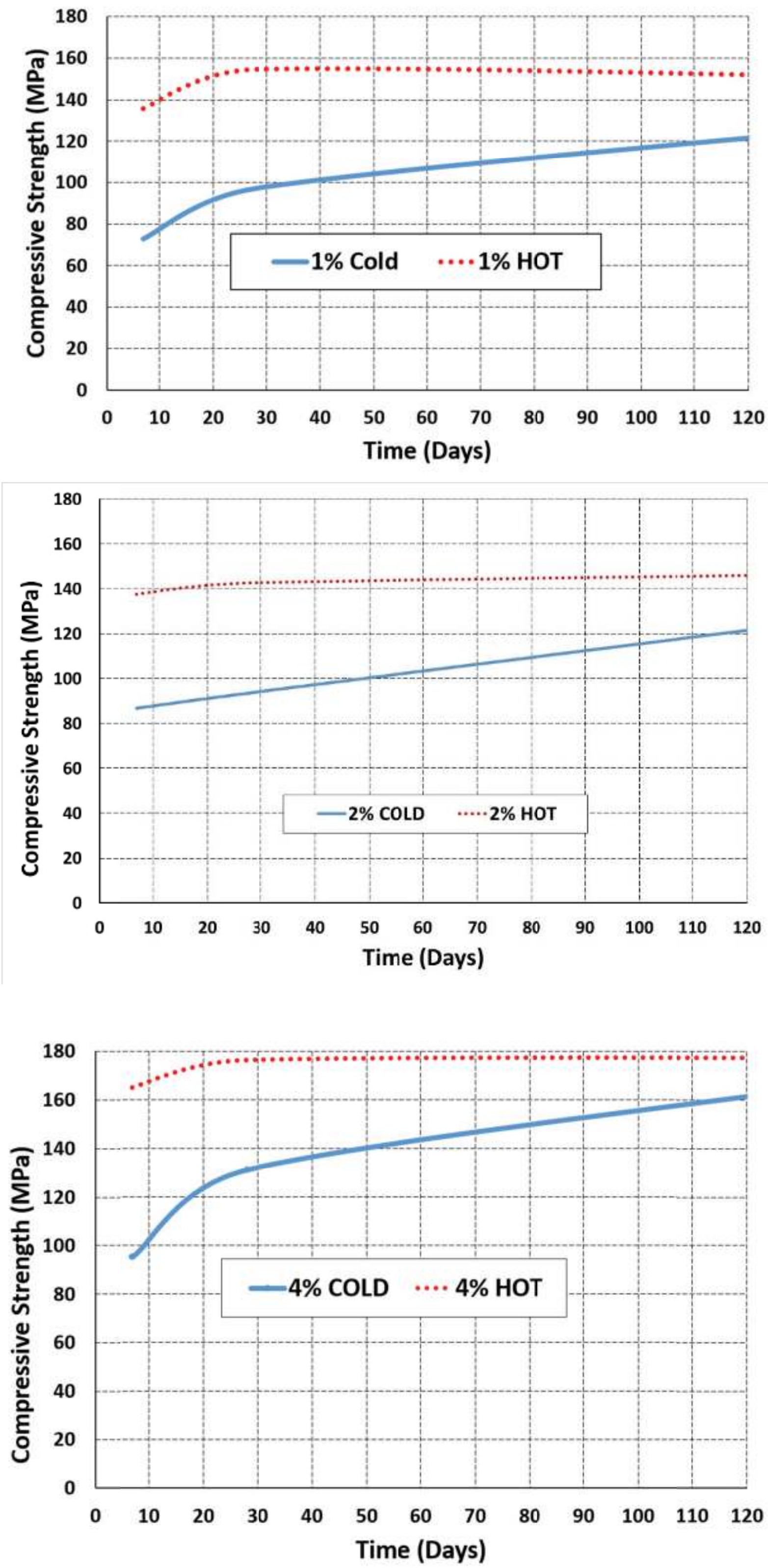

Figure 4. Strength growth for 120 days of concrete cured in cold and hot water.

3.2. BEAM FLEXURAL TESTING

Table 4 presents the experimentally obtained results from testing the concrete beams. The table includes results of maximum deflection, peak load values, and cube compressive strengths. All beams failed due to flexural failure (four beams are shown in Figure 5); no shear failure was observed in any of the failed beams.

Table 4. Deflection and Peak Load Results

Beam ID	Fibre (%)	f_{ck} test day (MPa)	Beam age (days)	*Peak Load P_u* (kN)	Peak load deflection, Δ (mm)
USH-2	2	163.4	200	19.1	2.3
RSH-1	1	147.3	209	79.7	16.7
RSH-2	2	149.0	224	77.9	16.1
RSH-4	4	176.9	220	83.9	12.3
USC-2	2	124.9	180	17.4	5.13
RSC-1	1	130.0	154	88.3	19.4
RSC-2	2	133.9	161	86.2	15.8
RSC-4	4	170.0	148	95.3	15.8

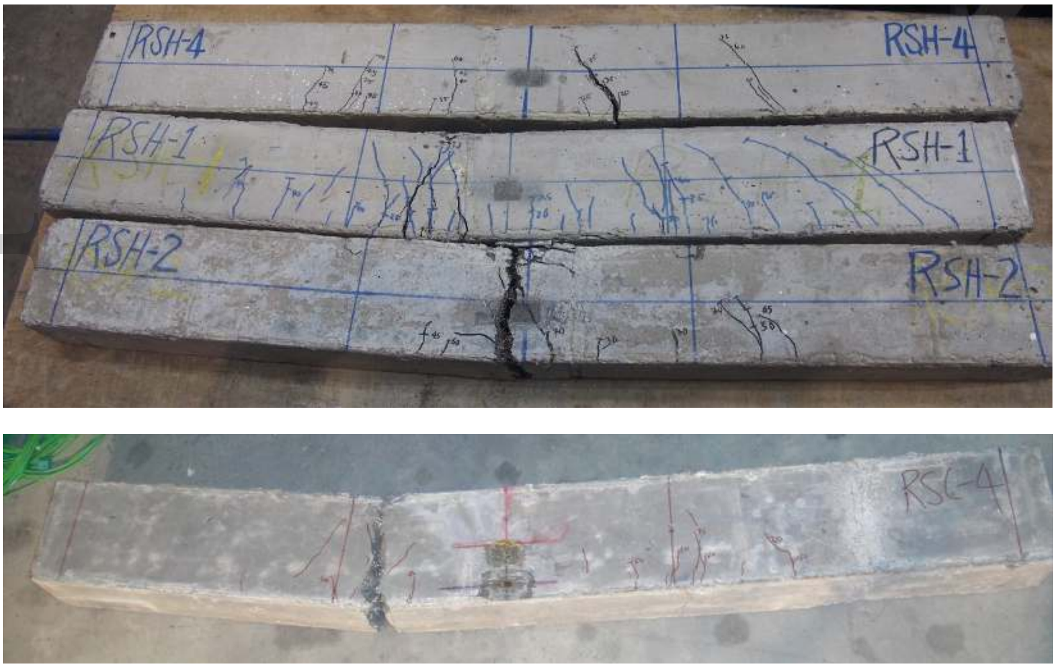

Figure 5. top) beams cured in hot water, bottom) beam cured in cold water

3.3 Effect of the fibre content on flexural strength and deflection

There is a clear noticeable failure pattern which is consistent for all beams of different fibre contents. Figure 6 shows that beams with 4% (in volume) fibres failed at the highest load if compared with beams with 1% (in volume) and 2% (in volume). The flexural strength of the 4% fibres beams was the highest, whereas the strength increase margin for beams with 1% and 2% fibre content is less significant. It is also important to emphasise and it is shown in Figure 6 that all beams showed no sudden failure.

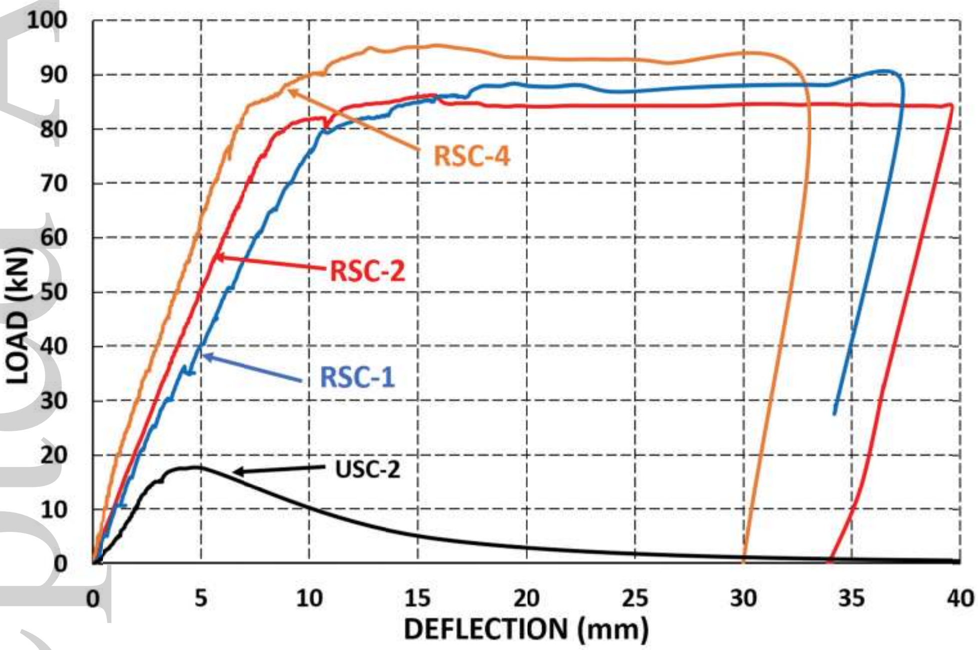

Figure 6. Load-midspan deflection curves for beams cured in cold water.

Figure 6 shows that at the start of loading, a clear linear behaviour in the load-deflection relationship is noticeable for all beams, followed by a clear “plateau phase” before failure takes place. There is not sufficient evidence that concrete with higher fibre contents behaved more ductile. Figure 7 shows the same test results for beams cured in hot water. The general observation that stands out is that beams with 4% fibres had a higher flexural strength and that all beams demonstrated a plateau phase before failure. The specimens with 4% fibres (RSH-4 and RSC-4) in addition to having the highest flexural capacity also exhibited lower deflection values at peak load. The curves are initially linear but deviated to non-linearity with the on-set of cracking. The curves are non-linear after the formation of a number of cracks with this phenomenon being more pronounced as the load approaches the ultimate load. In both series, beams without rebar's showed no "plateau phase" in contrast to beams with rebars. This conclusion can be drawn for both curing temperatures of this study. In terms of stiffness and in the linear range of the curves, Figures 6 and 7 indicate that the beams containing 4% fibres from both curing conditions have a higher stiffness than beams containing lower fibre dosage.

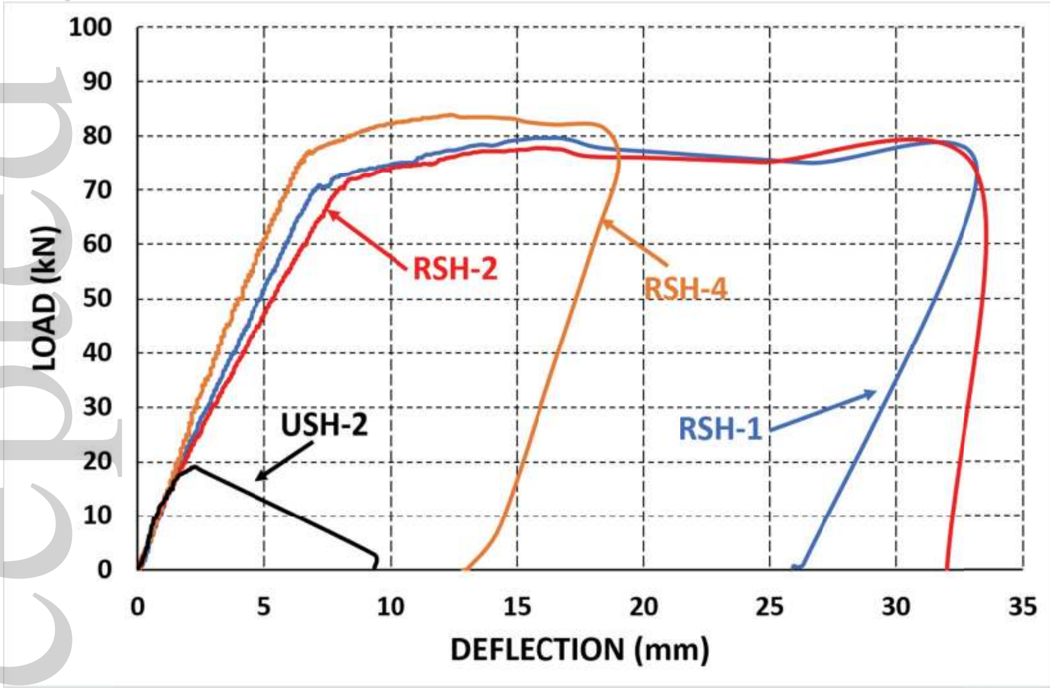

Figure 7. Load-midspan deflection curves for beams cured in hot water

3.4 Effect of the fibre content on cracking patterns

Observations during testing have shown that the variation of the fibre contents had a huge effect on cracking behaviour of beams. The 1% beams had more cracks, which began to form at lower loads while the 4% (in volume) fibre content beams had only a small number of cracks which were only visible at higher loads. This may be attributed to the bond forces between steel fibres and concrete matrix. The more fibres, the higher the transferred stress in the matrix, and the higher the resistance to the creation of cracks. The fibre-matrix bond, the fibre pullout energy and the tensile strength of concrete all increase at increasing fibre dosage. Concrete with a lower fibre dosage will develop cracks at a much lower applied flexural load. With a higher tensile strength of specimens (having a higher fibre dosage) the formation of cracks is counteracted. Fibres prevent further opening of a crack and as a consequence new cracks develop in the vicinity of the initial crack. Cracking patterns of selected beams are shown in Figure 5.

3.5 Effect of curing water temperature

The compressive strengths of hot-cured beams were found to be higher than the cold cured ones. Figure 8 presents a graphical comparison of corresponding beams with the same fibre content for different curing conditions. Except for unreinforced beams, all cold cured beams failed at higher loads than the hot cured. The hot cured unreinforced beam on the other hand failed at a higher load, than the corresponding cold cured beam. The pattern shown by beams without rebars (where hot cured failed at higher loads), supports the finding of Yang et. al. [17], who carried out four-point loading tests on UHPFRC prisms. Hot cured beams with rebars had a higher testing day compressive strength than the cold cured specimens, and were reasonably expected to have stronger steel fibre-matrix and rebar-matrix bonds and therefore should fail at a higher load compared with specimens with rebars. However, they failed at a slightly lower load than the cold-cured specimens. The surprising behaviours could be attributed to factors such as concrete microstructure and the joined contribution of steel fibres and steel rebars. The microstructure of hot cured specimens is a lot denser and harder, with less pores volume due to the presence of additional hydrates. This could render the hot-cured specimens less ductile. At higher loads, as the stresses are distributed from the rebars to the concrete matrix, the more ductile cold-cured specimens would take more stresses than the less ductile hot-cured. This conclusion need to be confirmed by conducting more research. The strain hardening regions of the load-deflection curves in Figure 8 also confirm the more ductile nature of cold-cured beams. In terms of cracking behaviour, the curing temperature had no observed effect on the cracking pattern of beams.

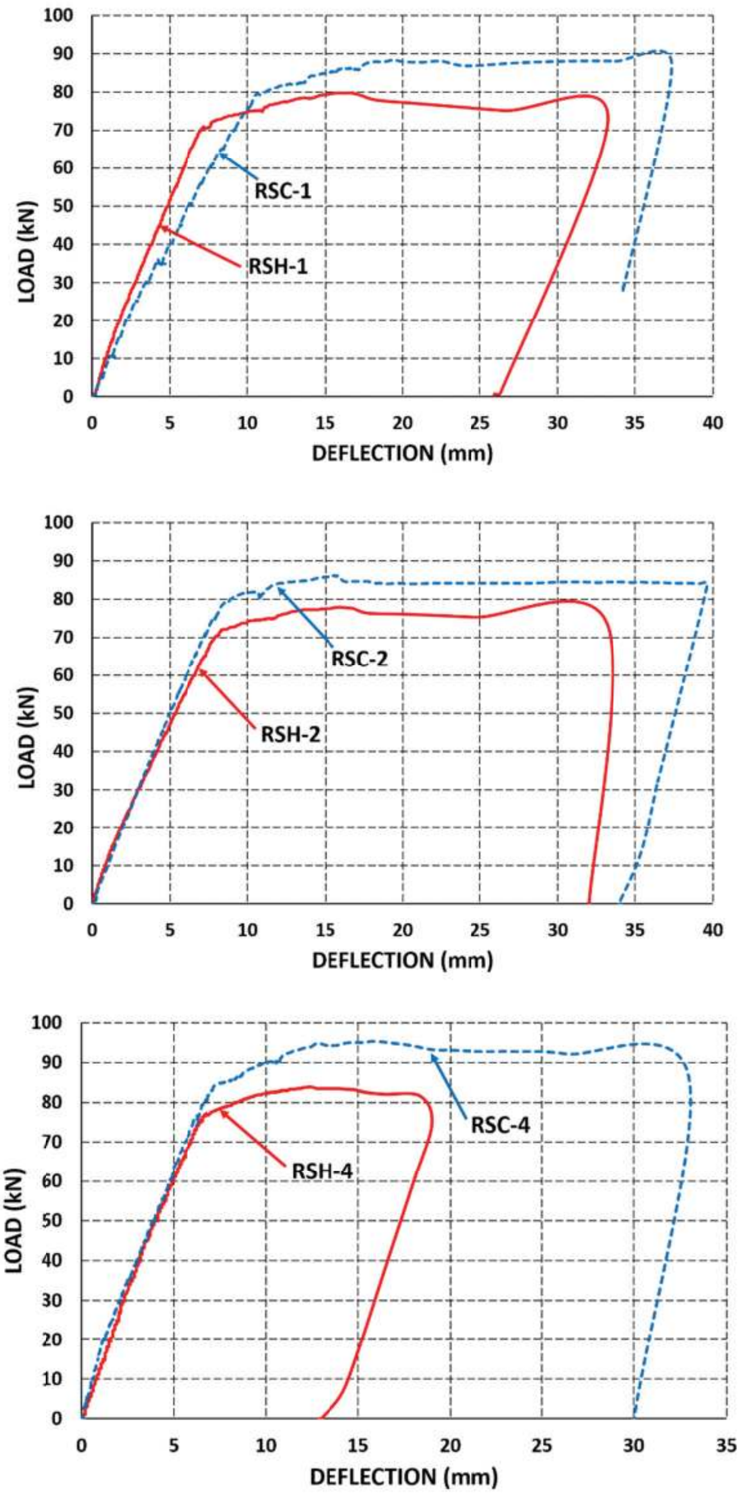

Figure 8. Deflection vs loading of reinforced beams cured in cold and hot water

3.6 Beams without Rebars

As mentioned, two beams without rebars have been tested with the same loading profile (see Figure 1). One beam was cured in water of 20°C temperature and the second was cured in hot water of 90°C temperature (see Table 1). Figure 9 shows the deflections obtained during the loading until failure occurred. The figure shows a clear difference in the behaviour if compared with reinforced beams (Figure 7). The figure shows a sudden brittle failure of the two beams with no "plateau phase" as in the case of beams shown in Figures 6 and 7. Hot cured beams resulted in a slightly higher strength and stiffness when compared to cold cured beams (see Table 4)

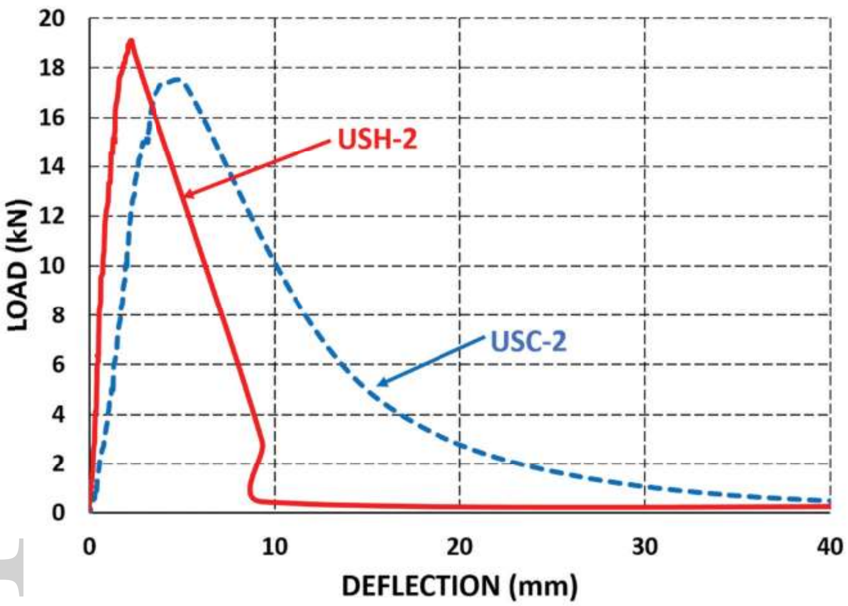

Figure 9. Development of deflection in beams without rebars

4. FLEXURAL TOUGHNESS

Two standards are often applied to evaluate the flexural toughness of fibre reinforced concrete beams and these are the ASTM C1018-97 [19] and Japan Society of Civil Engineering JSCE SF-4 [20]. Both standards make use of the area under the load-deflection curve obtained from testing a simply supported beam using a three-point load. In this study, the ASTM provisions are applied to compute the toughness of the UHPFRC beams. The critical deflection δ at point A in Figure 10 on the load-deflection curve is defined as the first crack deflection, it's also referred to as pre-peak flexural toughness and it is the load before the peak load is reached. This is the point on the load-deflection curve at which the curve deviates from linear behaviour. The area under the graph OAB (Figure 10) indicates as first-crack toughness. The toughness energy at peak load is calculated from the area under the curve OACD. The other points E and F of flexural toughness are known as post-peak points because their location on the load-deflection curves is typically in the strain softening region of the curve, after the peak load was surpassed. They are calculated as multiples of the critical deflection δ as; 3δ, 5.5δ and 10.5δ. In the graph, 3δ (see Figure 10) is represented under the area OACEF. In the tests conducted, all the beams had a smaller strain softening region, and hence the other two values of toughness (5.5δ and 10.5δ), could not be determined graphically. Using these post-peak values, useful ratios (I_5, I_{10} *and* I_{20}) known as toughness indices are then calculated as ratios of post-peak and first crack toughness. Since only 3δ could be extracted from the curves, the only index computed was the I_5 which was calculated with this expression:

$$I_5 = \frac{Area\ OACEF}{Area\ OAB} \tag{1}$$

Table 5, presents the flexural toughness values calculated using Equation 1. From both sets of beams, specimens with 1% fibres (RSH-1 and RSC-1) recorded the highest toughness fracture energy at peak load. The flexural toughness indices of I_5 for the reinforced beams with 1% and 2% fibresb (in volume) and both curing modes range between 3.10 to 3.25. As expected, the beams without longitudinal reinforcements (USC-2 and USH-2), had the lowest toughness. The first crack toughness for the reinforced hot cured beams were quite close to each other, ranging between 260 to 290N-m.

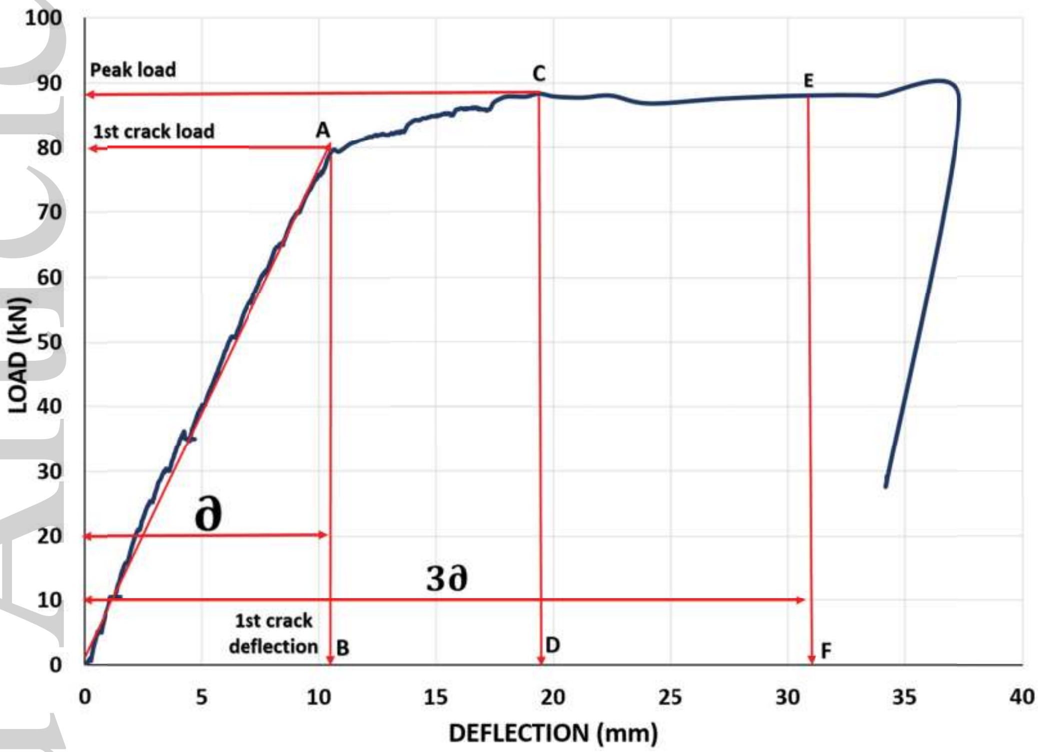

Figure 10. Toughness calculations for RSC-1.

For the cold-cured beams, the first crack toughness of RSC-1 beam was at least 25% higher than the other two beams (RSC-2 and RSC-4). At all three points of consideration (δ, 3δ and peak load), the reinforced cold cured beams showed a higher toughness than the hot cured, hence higher corresponding toughness indices values (I_5). This can be attributed to the higher degree of ductility and can also be observed by the larger strain hardening and softening section for cold cured beams. 3δ toughness values for the hot cured beam with 4% fibre content could not be extracted from its graph as the flexural behaviour was characterised by a relatively early strain softening (shorter plateau). The beams with 1% fibres from both curing series had a higher peak load toughness, whereas there was no trend observed for the 3δ toughness index.

Table 5. Flexural toughness values of beams

	Beam ID	***Toughness at δ (N-m)***	***Toughness at 3δ (N-m)***	***Peak load toughness (N-m)***	***Flexural toughness indices I_5***
Cured with hot water	USH-2	14	23	22	1.64
	RSH-1	250	806	626	3.22
	RSH-2	291	927	620	3.19
	RSH-4	262	N/A	517	N/A
Cured with cold water	USC-2	23	44	37	1.91
	RSC-1	417	1354	858	3.25
	RSC-2	340	1064	682	3.13
	RSC-4	324	1005	752	3.10

5. MOMENT-CURVATURE RELATIONSHIP

The curvature of each beam was derived from the deflection values obtained from the two LVDT's which were positioned at the beam's midspan and the resulting curves are shown in Figure 11 and Figure 12. From the two graphs, it can be observed that the beams with 4% fibre content had higher bending moment capacity. All the beams showed a linear behaviour until the onset of cracks and non-linearity being more prevalent as the load approached the peak load. The unreinforced beams from both series, as expected, had the least load carrying capacity and their failure was characterised by a brittle behaviour. The unreinforced cold cured beam failed at a lower load compared to the corresponding hot cured beam.

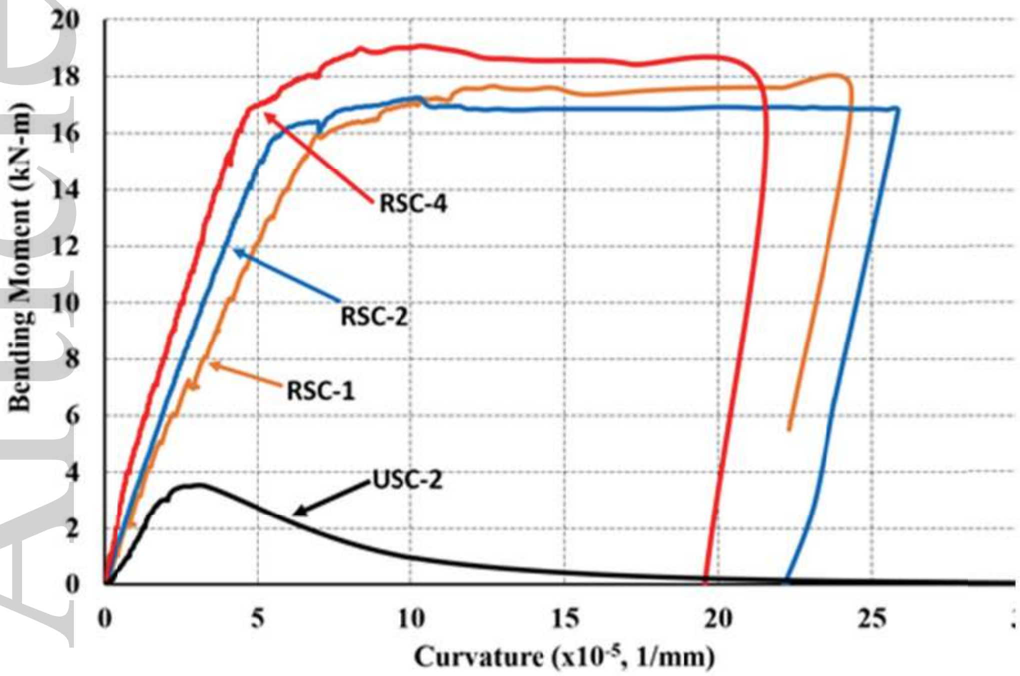

Figure 11. Bending moment-curvature curves for beams cured in cold water

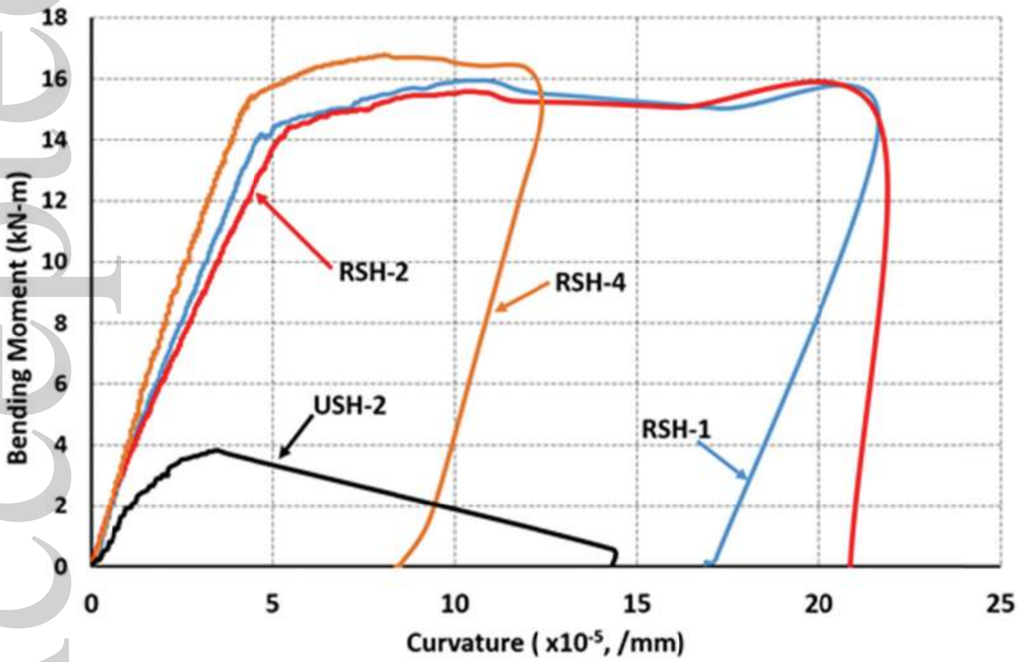

Figure 12. Bending moment-curvature curves for beams cured in hot water

6. CALCULATION OF MOMENT CAPACITY BASED ON EUROCODE 2

Table 6 shows a comparison between experimental and design moments of the reinforced beams calculated using Eurocode 2 [21]. As expected, the results clearly show that the experimental failure moment (M) for the beams is higher than the design moment (M_{ED}) with moment ratios ranging between 0.62 to 0.67 for the cold cured and 0.71 to 0.75 for the hot cured conditions. These ratios confirm the conservative EC2 design approach. The cold cured beams have higher load carrying capacity.

Table 6. Theoretical and experimental Moment Capacity of the tested beams

Curing Regime	Beam ID	Fibre content (%)	Experimental Max. Moment M (kN.m)	Theoretical EC2 moment, M_{ED} (kN.m)	$\frac{M_{ED}}{M}$
Hot Cured	RSH-1	1	15.9	11.91	0.75
	RSH-2	2	15.6	11.89	0.76
	RSH-4	4	16.8	11.95	0.71
Cold Cured	RSC-1	1	17.7	11.84	0.67
	RSC-2	2	17.2	11.86	0.69
	RSC-4	4	19.1	11.92	0.62

7. CONCLUSIONS

The research presented in this paper focused on the structural behaviour of UHPFRC beams. Compressive strengths ranging between 124-176 MPa have been achieved using 1%, 2% and 4% (in volume) microfibers and for curing the concrete in cold (20°C temperature) and hot water (90°C temperature). In general, UHPFRC cured at 90°C water temperature had a higher strength than concrete cured at 20°C particularly at an early age. However, concrete cured with 20°C water temperature showed a higher rate of strength gaining with time. All UHPFRC beams reinforced with conventional rebars for both curing regimes underwent bending failure with no shear failure recorded. The cold 20°C cured UHPFRC beams with conventional rebars had a higher peak strength than the corresponding hot 90°C cured UHPFRC beams. The ductility of cold cured beams was also higher compared to the corresponding hot cured beams. UHPFRC beams without rebars and cured in hot 90°C water had a higher strength than cold cured (20°C water) beams. This supports the finding of Yang et. al. [17]. All UHPFRC beams (cured under both regimes) containing rebars had a higher ductility compared to beams without rebars; this observation was made for all fibres contents tested. UHPFRC beams with a fibres content of 4% (in volume) showed a slightly higher strength, a higher stiffness and an enhanced flexural capacity. However, no significant increase was noticeable when the fibre content was increased from 1% to 2% (in volume). This conclusion can be drawn for both curing modes. UHPFRC beams with 1% fibres from both sets of curing conditions demonstrated the highest toughness at peak load. UHPFRC beams with a lower fibre content had a higher deflection at peak load which can also be observed from the high toughness energy. The curing water temperature had no observed effect on the crack pattern but the beams with lower fibre contents produced more cracks which started to propagate at relatively lower loads. The main recommendation for designers is to avoid hot curing in precast concrete as this may increase the brittleness of concrete. Calculations of the moment capacity of the beams using EC2 have produced lower values than the experimentally obtained values demonstrating the conservative approach of EC2.

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