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Effect of curing, fibre content and exposures on compressive strength and elasticity of UHPC

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The paper presents an experimental study on the evaluation of the compressive strength and modulus of elasticity of ultra-high performance concrete (UHPC) prepared with varying steel fibre contents, cured in water and exposed in air, and subjected to three exposure conditions (after 28 d of curing): laboratory environment, alternate heating–cooling cycles (heating at 60°C for 2 d and then cooling at room temperature for 2 d), and alternate wet–dry cycles (wetting for 2 d in aggressive salt solution and then drying at 30°C for 2 d). The test results indicate that: (*a*) although water-curing is better than exposure in air in improving the strength, the difference is not significant, particularly at a higher fibre content, (*b*) an increase in the fibre content can improve the strength and modulus of elasticity up to a certain extent, but beyond that an increase in the fibre content is not proportionally beneficial and (*c*) the effect of 6-month exposure to wet–dry and heating–cooling cycles on the strength and modulus of elasticity is negligible; indeed, the heating–cooling cycled specimens have strength and modulus of elasticity higher than the specimens not subjected to the cyclic exposures.

Introduction

The type of high-strength concrete developed before the 1990s was basically a brittle material requiring the use of passive reinforcement. A technological breakthrough took place in the 1990s with the development of ultra-high performance concrete (UHPC) in France and Canada, a new generation of cement-based materials, offering excellent mechanical and durability properties. UHPC is also referred to as ultra-high performance fibre-reinforced concrete (UHPFRC) and reactive powder concrete (RPC). The attractive features of this new concrete include high compressive strength (more than 150 MPa), high tensile strength (exceeding 30 MPa) and a good degree of fracture toughness and ductility (Ma and Schneider, 2002; Moallem, 2010; Richard and Cheyrezy, 1995).

The excellent properties of UHPC are achieved by densification of the cement matrix and also by maintaining a dense transition zone between cement matrix and aggregate with the help of fine materials having particle sizes ranging from a maximum of approximately 600 μm, down to less than 0·1 μm. Densification of UHPC is achieved through various measures such as: replacing coarse aggregate by fine quartz sand and fine aggregate by quartz powder; optimising particle packing; using supplementary cementing materials such as silica fume with a very low water-to-cementitious materials ratio; a high dosage of superplasticiser to maintain required fluidity; adding randomly dispersed and short fibres to enhance the tensile and flexural strength, toughness and post-cracking ductility; and implementing post-set heat treatment (Larrard and Sedran, 1994; Ma and Schneider, 2002; Richard and Cheyrezy, 1995; Shah and Weiss, 1998; Sobolev, 2004; Tam *et al.*, 2010; Vernet, 2004; Yanni, 2009).

Some important recommendations regarding the components of UHPC typically made in the literature are as follows: the particle size of the fine quartz sand should range between 150 to 600 μm and the particle size of quartz powder should be less than 10 μm; Type I cement with low C_3A (tricalcium aluminate) content should be used; silica fume may be used in the range of 25–30% by mass of cementitious materials; the water-to-cementitious materials ratio should be in the range of 0·15–0·24 (by mass); and steel fibres used in the UHPC should be 13–15 mm long and 0·2 mm in diameter in the quantity ranging between 190 and 250 kg/m^3 (Ma and Schneider, 2002; Richard and Cheyrezy, 1995; Shah and Weiss, 1998).

Curing of UHPC plays an important role in deciding the overall quality of UHPC. Graybeal and Hartmann (2003) found that the curing method yielded significant variations in compressive strength. Thermal treatment is reported to be highly beneficial in improving the quality of UHPC (Perry and Zakariasen, 2004). Beneficial effects of thermal curing compared to other methods of curing UHPC are widely reported (Graybeal, 2005; Heinz and

Ludwig, 2004; Soutsos *et al.*, 2005). To enhance the mechanical properties, heat treatment may be applied to UHPC by subjecting to temperatures between 60 and 90°C for 48–72 h after completion of setting. However, thermal curing of UHPC is suitable mainly for precast operations. The beneficial effect of the fibre addition to UHPC on its compressive strength is reported by various researchers (Bonneau *et al.*, 1997; Herold and Müller, 2004; Soutsos *et al.*, 2005). However, Schmidt *et al.* (2003) have reported that the compressive strength of UHPC is practically not increased by the fibres. Reda *et al.* (1999) have observed that the increase in compressive strength of UHPC owing to the addition of fibres is not as great as the increase in concrete strength that may be achieved through an appropriate heat treatment.

The experimental work presented in this paper was aimed mainly at exploring the possibility of utilising a typical mixture of UHPC under the exposure conditions prevailing in the Arabian Gulf, which consist of heating–cooling cycles (as a result of wide fluctuations in temperature and relative humidity) and wet–dry cycles (as a result of wetting of foundation concrete by ground water heavily contaminated by sulfate and chloride salts when the ground water table rises and drying of concrete when the ground water table falls). The search for an optimum dosage of fibre content and comparison of the benefits of water curing with the exposure in air (i.e. no curing) for achieving economy in the production of UHPC were also targeted in the present study. To achieve the objectives of the present work, curing methods (water curing and exposure in air), fibre contents and cyclic exposures (wet–dry and heating-cooling cycles) were considered as variables to study their effects on compressive strength and modulus of elasticity of a typical mixture of UHPC.

Experimental programme

Test variables

Test variables considered in this study are as follows: (*a*) two curing methods (water curing and exposure in air), (*b*) three fibre contents (0%, 3·1% and 6·2% by mass of UHPC) and (*c*) two cyclic exposures (6 months' exposure to heating–cooling and wet–dry cycles after 28 d of water curing at temperature 22 ± 2°C) for specimens with 6·2% fibre. For comparison purposes, specimens with 6·2% fibre were also subjected to exposure to laboratory conditions (average room temperature of 22 ± 2°C and humidity of 40–45%) for 6 months after curing in water for 28 d. The alternate heating–cooling cycles comprised first heating the specimens at 60°C for 2 d and then cooling at room temperature for the next 2 d. The alternate wet–dry cycles consisted of first wetting the specimens for 2 d in a purpose-made solution of sodium chloride (NaCl), sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$) to obtain 15·7% Cl^- and 0·55% SO_4^- concentrations and then drying them at 30°C for the next 2 d. The solution used for wetting represents a typical aggressive environmental exposure condition witnessed in the Gulf region of the Middle East.

Mix proportions and preparation of test specimens

The selected mixture of UHPC consisted of a premix material (a mixture of Portland cement, silica fume, quartz powder and fine sand), water, superplasticiser and steel fibres. The proportions of the UHPC mixture are presented in Table 1. The plasticiser used was a high-performance superplasticiser having a polycarboxylate (PC) base that allowed a dense, highly homogeneous mixture to be poured with fewer concerns about segregation. The steel fibres in the mix had a diameter of 0·2 mm and were 12·7 mm long. A planetary mixer was used to mix the ingredients of the UHPC. The prepared mixture was cast into cylindrical moulds for obtaining the test specimens for curing followed by cyclic exposure and finally testing for determining compressive strength and modulus of elasticity.

Compressive strength and modulus of elasticity tests

The compressive strength and modulus of elasticity tests were carried out using the standard test methods recommended by ASTM C39 (ASTM, 2012) and ASTM C469 (ASTM, 2010), respectively. Cylindrical specimens having a diameter of 75 mm and pre-end preparation length of 150 mm were used. The trowelled ends of the cylinders had rough surfaces and therefore, to obtain a smooth surface before testing, all cylinders were cut from their trowelled ends, keeping their final lengths approximately 1·95 times their diameters. The perpendicularity of the cut ends was ensured through perpendicularity testing. Electrical strain gauges were fixed to cylinders, as shown in Figure 1, for measuring strain values required to determine the modulus of elasticity. The cylinders were tested in a 3000 kN-capacity compression testing machine. The failures of specimens without and with fibre are shown in Figures 2 and 3, respectively. For determining modulus of elasticity, stress–strain curves were drawn for each specimen, as typically shown in Figures 4 and 5 for UHPC with and without steel fibres, respectively. The slope of a straight line joining the origin and a point corresponding to 40% of the ultimate compressive strength on the stress–strain curve was taken as the modulus of elasticity (i.e. secant modulus).

Results and discussion

Compressive strength test results of the UHPC mixtures containing different fibre contents (0, 3·1 and 6·2%) and subjected to

Mix component		Weight: kg
Premix material	Portland cement	720
	Silica fume	240
	Quartz powder	217
	Fine sand	1025
Water		136
Superplasticiser		30
Steel fibres		0, 79, 157

Table 1. Mix proportions for 1 m^3 of UHPC

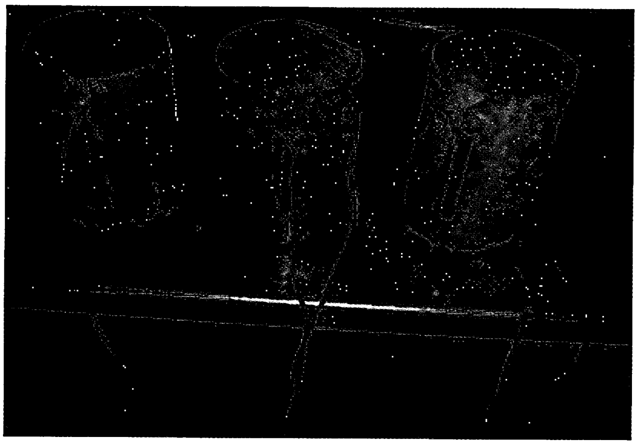

Figure 1. Specimens of UHPC with strain gauges for measuring compressive strength and modulus of elasticity

Figure 2. Failure mode of UHPC without fibre

Figure 3. Failure mode of UHPC with fibre

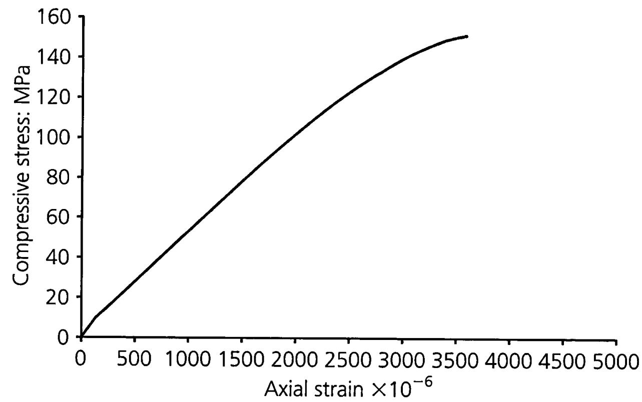

Figure 4. A typical stress–strain curve for determining modulus of elasticity (6·2% fibre)

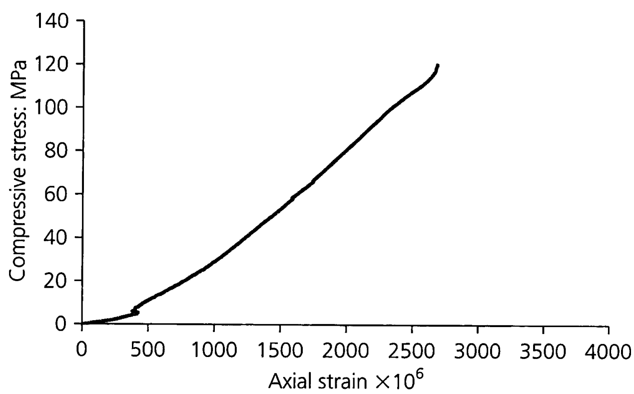

Figure 5. A typical stress–strain curve for determining modulus of elasticity (0% fibre)

two curing regimes (water curing at temperature 22 ± 2°C and exposure in air) for various durations (3, 7, 14 and 28 d) are presented in Table 2. The air-dried specimens were tested in their original state without re-saturating them. The modulus of elasticity test results for the specimens with different fibre contents and tested after 28 d of exposure in air and water curing are given in Table 3. Table 4 shows the results of compressive strength and modulus of elasticity tests conducted on the UHPC specimens containing 6·2% fibres and subjected to three exposure conditions (laboratory, wet–dry cycles and heating–cooling cycles) for 6 months after 28 d of water curing. The results for 28-d water-cured specimens are also included in Table 4 for comparison. The results presented in Tables 2–4 were used to obtain various plots for discussing the effects of curing regimes, fibre content and exposure conditions on compressive strength and modulus of elasticity of the UHPC mixture. Discussion on the effect of each factor considered in this study is presented as follows.

Effect of curing regimes on compressive strength

Figure 6 shows the plots of the data presented in Table 2 primarily to show the effect of curing regimes on compressive strength of the UPHC mixtures with different fibre contents. It can be seen from Figure 6 that the compressive strength increases with the length of curing for both types of curing. At any age, concrete exposed in the air achieved slightly lesser strength than concrete subjected to water curing. However, the difference in strength is mostly negligible at early ages. The differences between strengths

Fibre content: wt%	Curing time: days	Compressive strength: MPa		Relative strength ratio	
		Air exposure	Water-cured	Air exposure	Water-cured
6·2%	3	107	108	0·72	0·66
	7	128	130	0·86	0·80
	14	134	147	0·90	0·90
	28	**149**	**163**	**1·00**	**1·00**
3·1%	3	104	106	0·76	0·68
	7	108	114	0·79	0·74
	14	126	127	0·92	0·82
	28	**137**	**155**	**1·00**	**1·00**
0%	3	84	92	0·75	0·71
	7	109	111	0·97	0·85
	14	110	116	0·98	0·89
	28	**112**	**130**	**1·00**	**1·00**

Table 2. Compressive strength test results

Fibre content: wt%	Modulus of elasticity: GPa	
	Air exposure for 28 d	Water-cured for 28 d
6·2%	49	57
3·1%	48	55
0%	36	39

Table 3. Modulus of elasticity of UHPC with different fibre content and curing methods

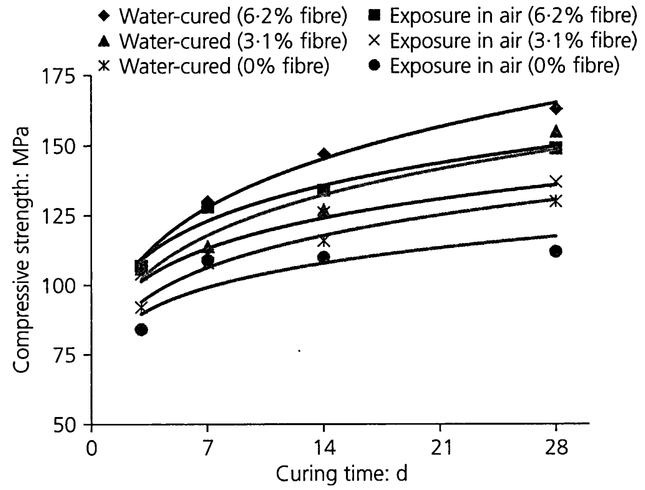

Figure 6. Variation of compressive strength with curing time

of UHPC specimens, exposed in air and water separately for 28 d, were found to be around 16, 13 and 9%, corresponding to the fibre contents of 0, 3·1 and 6·2%, respectively. This indicates that the beneficial effect of water curing as compared to specimens exposed to air is more with less fibre content. The reason behind a smaller effect of water curing on strength with increase in the fibre content may be that the permeability of fibre-reinforced concrete decreases with increase in fibre content (Bhargava and Banthia, 2008), reducing the chances of penetration of curing water into concrete at an early age, which might be beneficial in a better hydration for a better strength.

As the ratios of strength of UHPC at a particular curing time to strength of the same UHPC mixture cured for 28 d do not differ significantly with the fibre content for both curing methods, as can be observed from Table 2, the values of relative strength

Exposure condition	Compressive strength: MPa	Modulus of elasticity: GPa
28-d water cured	163	57
6 months' lab exposure after 28-d water curing	164	59
6 months' wet–dry exposure after 28-d water curing	161	58
6 months' heating–cooling exposure after 28-d water curing	194	62

Table 4. Compressive strength and modulus of elasticity of UHPC subjected to three exposures (6·2% steel fibres)

ratios were averaged for each curing time and plots of curing time against relative strength ratio were obtained as shown in Figure 7 for both types of exposures. It can be noted from Figure 7 that the 3-, 7- and 14-d strength to 28-d strength ratios are higher in specimens exposed in air than the water-cured specimens. Compared to 28-d strength, 3-, 7- and 14-d strengths are 68; 75 and 87%, respectively, for water-cured UHPC and 74, 87 and 93%, respectively for specimens exposed in air. This indicates that the rate of development of strength in the case of air exposure is slightly higher than in the case of water exposure.

Effect of fibre content on compressive strength and modulus of elasticity

The effect of addition of fibre on the mode of failure of UHPC specimens under compression can be seen from Figures 2 and 3. It can be noted that the specimens tested in compression showed different modes of failure. All specimens prepared without fibres (0% fibres) typically exhibited very brittle explosive type failure, as shown in Figure 2, whereas all specimens prepared with fibres either 6·2% or 3·1% typically showed ductile failure, as shown in Figure 3. The ductile failure of UHPC with fibres and brittle failure of UHPC without fibres are witnessed by the trend of the stress–strain curves shown in Figures 4 and 5, respectively.

It can be observed from Figure 8 that an increase in the 28-d compressive strength of UHPC owing to the addition of 3·1% fibres has resulted in a significant increase in compressive strength: 22% in specimens exposed in air and 19% in the case of water-curing. However, a further increase in fibre content from 3·1% to 6·2% has not improved the strength in the same proportion. Compared to the strength for UHPC with 3·1% fibre, the strength of UHPC with 6·2% fibre is just higher by 11% and 6%, respectively for air exposure and water curing.

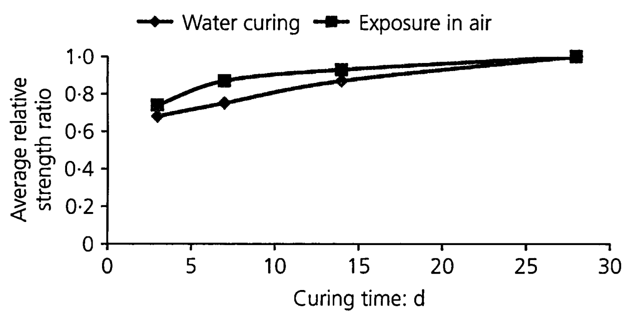

Figure 7. Variation of relative compressive strength ratio with curing time

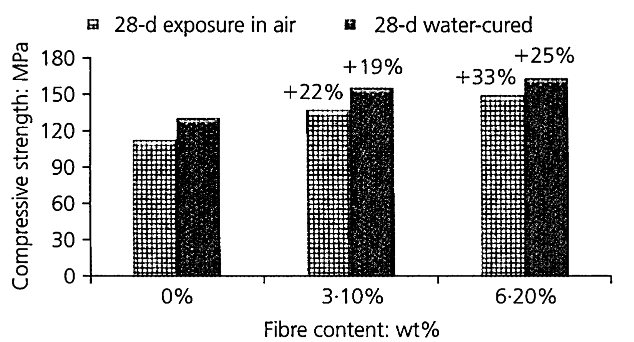

Figure 8. Effect of fibre content on 28-d compressive strength of UHPC

As with the compressive strength, the plot of data showing the effect of fibre content on modulus of elasticity, as shown in Figure 9, illustrates that there is an increase in the modulus of elasticity of UHPC with an increase in the fibre content. The 28-d modulus of elasticity of UHPC with 3·1% of fibre is increased by 33 and 41%, respectively, for air exposure and water curing. However, there was no significant increase in the modulus of elasticity when the fibre content was increased from 3·1 to 6·2%.

These observations regarding the effect of fibre content on compressive strength and modulus of elasticity indicate two things: (*a*) as compared to compressive strength, modulus of elasticity was improved more significantly by adding fibres to UHPC; and (*b*) an increase in the fibre content from 0 to 3·1% showed more positive effect than increase in the fibre content from 3·1 to 6·2%.

Effect of exposure conditions on compressive strength and modulus of elasticity

Figures 10 and 11 show the effect of exposure conditions on compressive strength and modulus of elasticity of UHPC with 6·2% fibre content. It is observed from Figure 10 that even after 6 months of laboratory and wet–dry exposures, the strength of UHPC is almost same as the 28-d water-cured UHPC. However, instead of the negative effect of the heating–cooling cycles on the performance of normal concretes as widely reported in literature (Bairagi and Dubal, 1996; Rao *et al.*, 2006; Sekhar and Rao, 2009; Shokrieh *et al.*, 2011; Sravana *et al.*, 2006), the heating–cooling cycles have improved the compressive strength of UHPC mixture significantly by 19%. The beneficial effect of UHPC observed in the present study is in line with the findings of other researchers (Bonneau *et al.*, 1997; Cwirzen, 2007; Heinz

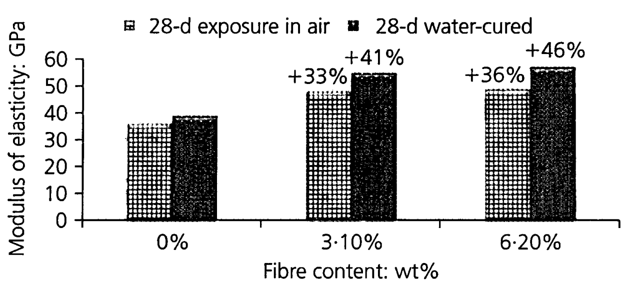

Figure 9. Effect of fibre content on 28-d modulus of elasticity of UHPC

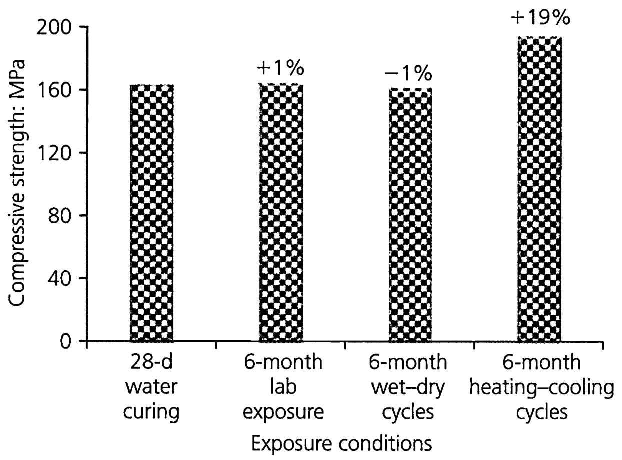

Figure 10. Compressive strength of UHPC (with 6·2% fibre) after 6 months of exposure

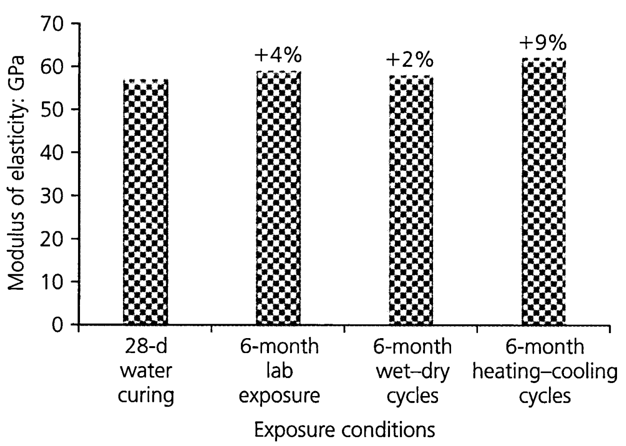

Figure 11. Modulus of elasticity of UHPC (with 6·2% fibre) after 6 months of exposure

and Ludwig, 2004; Theresa *et al.*, 2008). This indicates that, unlike normal concrete, for which it is expected that wet–dry and heating–cooling cycles (heating–cooling on continuously dried specimens) would reduce the strength, there is no negative impact of these exposures on the strength of UHPC. The increase in the strength of UHPC exposed to heating–cooling cycles is attributed to enhanced hydration of cementitious materials. The impermeability of UHPC concrete is very high, which prevents loss of pore water through evaporation. The pore water is humidified when concrete is subjected to heat treatment. This humidification keeps the hydration reaction continuing at a significant rate, reducing the porosity of UHPC, which eventually results in an increase in the strength.

Figure 11 indicates that, like compressive strength, the modulus of elasticity of UHPC exposed to wet–dry and heating–cooling cycles is not reduced as compared to the modulus of elasticity of UHPC water-cured for 28 d. Rather than having a negative impact, all three exposure conditions resulted in a slight increase in the modulus of elasticity as compared to the 28-d modulus of elasticity (4, 2 and 9% increase in cases of lab, wet–dry and heating–cooling cycles exposures, respectively). As with compressive strength, the significant improvement in modulus of elasticity of heating–cooling cycled specimens is attributable to the continuation of hydration at a significant rate because of heat treatment.

Conclusions

The conclusions that can be drawn from this study are listed below.

(*a*) For the same UHPC mixture and at the same curing age, compressive strength is found to be slightly more in the case of water-cured specimens as compared to the air-exposed specimens. The effect of the curing regime is greater for UHPC without fibres than for UHPC with fibres. This study has revealed that the UHPC can develop target strength even without any formal curing (just by exposing to air), eliminating the need for water curing.

(*b*) The addition of fibre is found to be beneficial in improving the compressive strength and modulus of elasticity. At the same fibre content, the increase in modulus of elasticity is more than the increase in compressive strength. However, the beneficial effect of fibres in UHPC was not that significant when the fibre content was increased from 3·1 to 6·2%.

(*c*) The two cyclic exposure conditions, known to have negative effect on the properties of normal concrete, did not affect the performance of UHPC. It was found that the wet–dry cycles had no effect on the compressive strength and modulus of elasticity of UHPC. Furthermore, rather than having a negative impact, the heating–cooling cycles improved these properties.

(*d*) It can be finally concluded that the present study contributed in identifying a typical optimum dosage of fibre content as 3·1% and revealed that the UHPC considered in this study can be prepared without water curing, with no significant loss of mechanical properties, and can withstand the heating–cooling and wet–dry cycles typically prevalent in the Arabian Gulf as well as in other parts of the world having similar exposure conditions.

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