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Effect of thermal cycles on the engineering properties and durability of sustainable fibrous high-strength concrete

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In this research, the effect of heat–cool cycles (HCCs) on high-strength concrete (HSC) containing steel fibres (SFs), polypropylene fibres (PPFs), and date palm fibres (DPFs), which were named fibrous high-strength concrete (FHSC), was studied. To produce FHSC, three doses of 0.2, 0.6, and 1 percent of each fibre were used. All samples were tested after 28 days of normal water curing and 270 days of exposure to HCCs (continuing the authors' project and research published at 28 and 180 days). This entails heating for 2 days at 60 C in the oven and cooling for another 2 days at room temperature for 270 days. The experiment's findings revealed that fibre reinforcement in concrete enhances its strength and durability. By incorporating the three types of fibres into high-strength concrete, with and without HCCs, the modulus of rupture was significantly increased. In both conditions, including with or without the implementation of HCCs, incorporating the three fibre types into the HSC showed a significant increase in toughness. As a result, natural date palm fibres can produce sustainable FHSC that can withstand harsh environmental conditions. Moreover, compared to the previous study conducted by the authors at 180 days, there is a slight severity in both the pattern of decrease and increase of the studied characteristics at 270 days caused by the effect of thermal cycles and fibres.

KEYWORDS

fibrous concrete, date palm fibre, engineering characteristics, durability, thermal cycles, energy absorption capacity

1 Introduction

Concrete constructions are often subjected to a wide range of environmental conditions during their lifecycle (Khan et al., 2022a; Hakeem et al., 2022c; Zhang et al., 2022). As a result, the resilience of a concrete building is evaluated by how well it can withstand particular exposure circumstances without requiring costly rehabilitation or maintenance (Ma et al., 2017;

Abbreviations: DPFs, date palm fibres; FHSC, fibrous high-strength concrete; HCCs, heat–cool cycles; HSC, high-strength concrete; PPFs, polypropylene fibres; SFs, steel fibres; SPs, super plasticizers; UPV, ultrasonic pulse velocity.

Althoey and Hakeem, 2022; Hakeem et al., 2022d). Concrete is described as a composite material that can last for many decades, if not hundreds, with little or no maintenance (Saeed et al., 2022a; Hakeem et al., 2022b; Qaidi et al., 2022b; Zeybek et al., 2022). Standard concrete is composed of cement, coarse aggregate, and fine aggregate without reinforcing steel (Hakeem et al., 2022a; Althoey et al., 2022b). Modifications to the components and mixture design of ordinary cement concrete can be made to develop several forms of concrete that are acceptable for a variety of environmental circumstances and structural loads (Anas et al., 2022c; Anas et al., 2022f). Several behaviour-related challenges are presented in order to highlight the poor behaviour of ordinary concrete even more (Koushkbaghi et al., 2019; Ahmad et al., 2020; Khan et al., 2021).

The development of ultra-high-performance concrete in the 1990s was a significant advancement in the production of concrete (Ahmad et al., 2016; Qaidi et al., 2022a; Saeed et al., 2022b). This revolutionary concrete was distinguished by its high compressive and tensile strengths and its ductility and fracture toughness (Richard and Cheyrezy, 1995). Furthermore, fibres are being used as discrete three-dimensional reinforcement to address the limitations of ordinary cement concrete and as a replacement for ultra-high-performance concrete (Bajaber and Hakeem, 2021). Fibre-reinforced concrete incorporates fibre into its mix to improve load resistance (Anas et al., 2022a; Anas et al., 2022b). Various types of fibre-reinforced concrete have been created, each with distinct and important advantages because of its various advantages, including good ductility, tensile strength, and fatigue resistance. Fibre-reinforced concrete has a broad variety of applications, including industrial floors, building pavements, slope stabilisation, impact-resistant structures, and tunnel linings (Kaur and Talwar, 2017; Ahmed et al., 2021; Çelik et al., 2022).

The use of proper fibre type can postpone or minimize the beginning and propagation of fractures in concrete under compressive and tensile loads (Bingöl and Balaneji, 2019; Anas et al., 2022e). Available commercial reinforcements are divided into many groups and have characteristics that make them appropriate for certain purposes. Steel fibre (Iqbal et al., 2019), polypropylene fibre (Hussain et al., 2020), carbon fibre (Nassiri et al., 2021), glass fibre (Peled et al., 2005), carbon nanotubes (Hawreen et al., 2019), basalt fibre (Geng et al., 2022), organic fibres (Ahmad et al., 2020), and other materials are examples. When it refers to the mechanical behaviour of concrete, SF is, by far, the best fibre when compared to other industrial fibres. SF has a high tensile strength of more than 1,200 MPa and an elastic modulus of around 200 GPa (Najm et al., 2022b; Nanayakkara et al., 2022). The research has developed a paradigm that supports the feasibility of SF as an outstanding reinforcing material with good tensile, compressive, modulus of rupture, and shear strengths (Alabduljabbar et al., 2019; Tayeh et al., 2022b; Tayeh

TABLE 1 Chemical characteristics of cement.

Composite	Mass (%)
Cao	63.83
SiO_2	19.7
Al_2O_3	6.25
Fe_2O_3	3.45
SO_3	2.25
K_2O	1.08
MgO	0.97
LOI	1.52
Insoluble	0.95

TABLE 2 Physical characteristics of cement.

Composite	Mass
C2S	12.10%
C3S	59%
C3A	10.60%
C4AF	10.40%
Fineness	4,100 cm^2/g
Specific gravity	3.15

TABLE 3 Physical characteristics of the aggregates.

	Characteristics			
Type of aggregate	Fineness modulus	Specific gravity	Water sorptivity (%)	Bulk unit weight (kg/m^3)
Coarse	7.34	2.77	0.69	1630.00
Fine	2.23	2.67	1.31	1535.74

TABLE 4 Steel fibre's physical characteristics.

Length (cm)	6
Diameter (cm)	0.075
Tensile strength (GPa)	0.625
Unit weight (g/cm^3)	7.85
Aspect ratio	80

TABLE 5 Polypropylene fibre's physical characteristics.

Length (cm)	1.2
Diameter (cm)	0.0025
Young modulus (GPa)	5.4
Unit weight (g/cm^3)	0.91
Tensile strength (GPa)	0.550
Elongation at breaking (%)	30

TABLE 6 Date palm fibre's physical characteristics.

	Type of DPF			
Characteristics	Raw fibres	1.5% Sodium-hydroxide treated	3.0% Sodium-hydroxide treated	6.0% Sodium-hydroxide treated
Length (cm)	9	8	8	8
Diameter (cm)	0.09	0.065	0.061	0.069
Strain	0.044	0.058	0.062	0.055
Elongation (%)	4	6	6	5
Tensile strength (GPa)	0.100	0.174	0.234	0.181

TABLE 7 Fibrous high-strength concrete mix proportion (kg/m^3).

Mix ID	Cement	Aggregate		SP	Water	Fibre		
		Coarse	Fine			SF	PPF	DPF
Control	400.0	1105.4	736.93	2.0	176.4	—	—	—
DPF-0.2	400.0	1105.4	736.93	2.0	176.4	—	—	8.0
DPF-0.6	400.0	1105.4	736.93	2.0	176.4	—	—	24.0
DPF-1.0	400.0	1105.4	736.93	2.0	176.4	—	—	40.0
PFF-0.2	400.0	1105.4	736.93	2.0	176.4	—	8.0	—
PFF-0.6	400.0	1105.4	736.93	2.0	176.4	—	24.0	—
PFF-1.0	400.0	1105.4	736.93	2.0	176.4	—	40.0	—
SF-0.2	400.0	1105.4	736.93	2.0	176.4	8.0	—	—
SF-0.6	400.0	1105.4	736.93	2.0	176.4	24.0	—	—
SF-1.0	400.0	1105.4	736.93	2.0	176.4	40.0	—	—

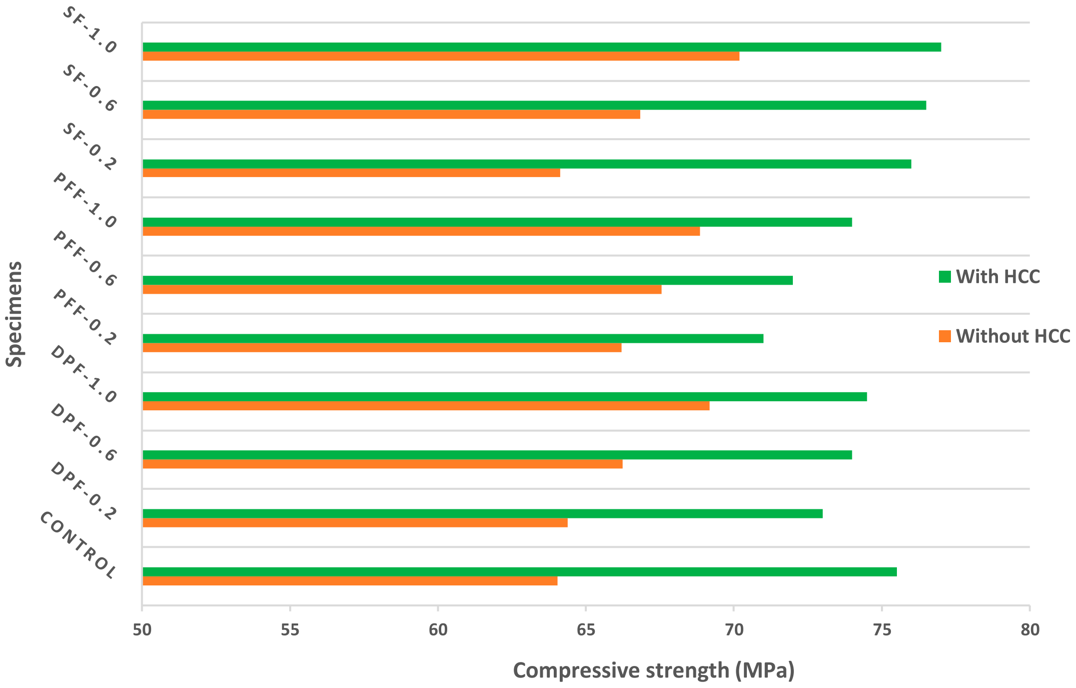
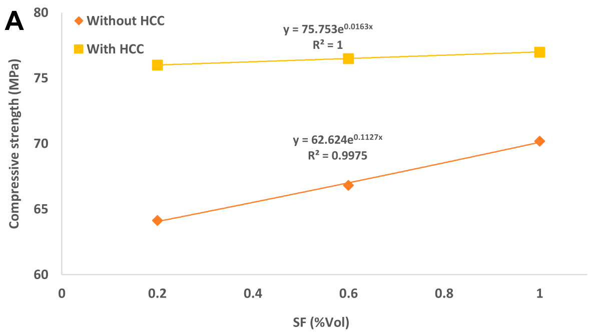
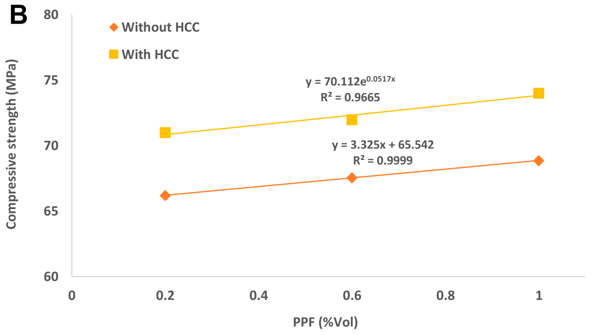


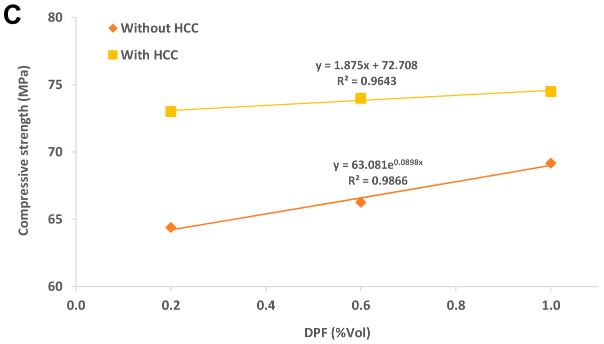
FIGURE 1
Influence of HCCs on the compressive strength of FHSC.



Relationship between the volume of SF and compressive strength



Relationship between the volume of PPFs and compressive strength



Relationship between the volume of DPF and compressive strength

FIGURE 2
Relationship between the volume and compressive strength of SF, PPF, and DPF. **(A)** Relationship between the volume and compressive strength of SF. **(B)** Relationship between the volume and compressive strength of PPF. **(C)** Relationship between the volume and compressive strength of DPF.

et al., 2022c; Unis Ahmed et al., 2022). The experimental results of the modulus of the rupture test, as reported by Azad et al. (2013), show that the samples can withstand higher loads until they reach the cracking load; nevertheless, once they reach the peak load, a softening mode of collapse can be seen, demonstrating significant ductility. Furthermore, it has been established that the introduction of SF enhances the resistance of reinforced concrete beams to shear failure, minimizing the need for stirrups (Khan and Ali, 2019; Lantsoght, 2019; Khan et al., 2020; Khan et al., 2022b).

Mohanty et al. (2002) revealed that the water sorptivity rates of these concrete samples were low when compared to unpalmed and classified composites. An investigation of the modulus of rupture, tensile, and dielectric properties of composites indicated similar findings for these properties when compared to well-known composites like palm and glass, palm and bamboo, and glass made using the same processes (Nanayakkara and Xia, 2019; Najm et al., 2022a). The tensile strength of these glass and palm composites was investigated by Priya et al. (2005). More fabric was added to these composites, which increased their mechanical properties. The matrix and reinforcement were revealed to have good chemical resistance and interfacial bonding. Mishra et al. (2003) used chemically altered sisal fibres as reinforcement in the polyester matrix, in addition to glass fibres, to enhance the mechanical characteristics of the hybrid composites (Anas et al., 2022d; Anas et al., 2022g). The test results reveal that hybrid composites absorb less water than unhybridized composites (Althoey et al., 2022b; Hakeem et al., 2022c).

Civil engineering infrastructures have been built in hot and cold weathering zones such as the desert region. In such cases, the concrete is not only fractured by hot and cold processes, but it is also harmed by shrinkage cracking. As a result, the purpose of this research is to investigate the effect of HCCs on HSC containing various fibres comprising natural SF, PPF, and DPF in different volumetric ratios. Fibre implantation is the most widely used method for enhancing the structural behaviour of concrete (Cao et al., 2018b; Parvez et al., 2019; Khan and Ali, 2020; Xie et al., 2021). Fibres reduce the incidence of cracking, improve early strength under impact loads, and increase the structure's toughness. As a result, the primary goal of this work is to investigate the impacts of three different forms of fibres (steel, polypropylene, and date palm) in HSC without HCCs (curing for 28 days) and with HCCs (treatment for 270 days) and to continue the authors' project and the paper published in 28 and 180 days (Hakeem et al., 2023).

2 Materials and methodology

2.1 Materials

2.1.1 Cement

The FHSC samples used in this study were prepared using normal Portland cement (Type I). Table 1 and Table 2 include information regarding the chemical and physical properties of cement, respectively.

2.1.2 Aggregates

The coarse aggregate in the FHSC was crushed stone with a maximum size of 20 mm. As a fine aggregate, natural dune sand was used, with the bulk of its particles passing through a 4.75-mm sieve. Table 3 shows the physical properties of coarse and fine aggregates.

2.1.3 Fibres

2.1.3.1 Steel fibres

The SFs were bundled with hooks and adhesives at both ends. These bundles of SFs were used to produce FHSC. The physical properties of SF are given in Table 4. The range of fibres required to make FHSC varies from 0 to 1 percent of the concrete volume.

2.1.3.2 Polypropylene fibres (PPFs)

In comparison to SF and DPF concrete, PPFs were used to produce FHSC. The physical properties of PPF were given by the supplier, as shown in Table 5.

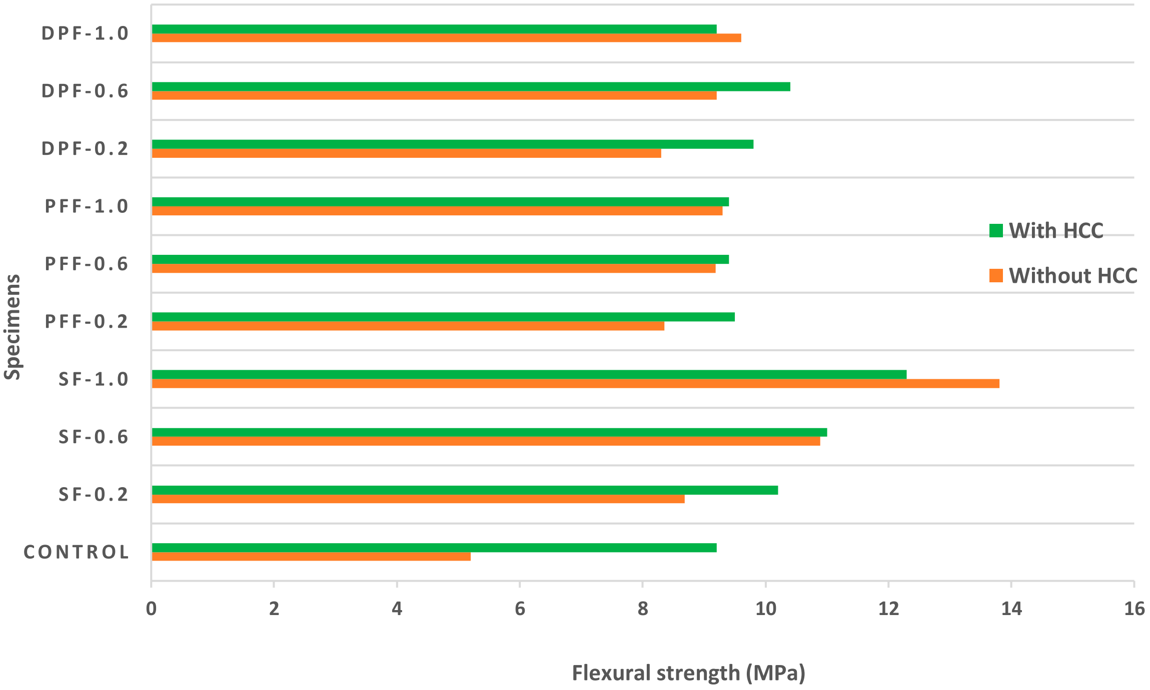


FIGURE 3
Impact of HCCs on the modulus of rupture of FHSC.

2.1.3.3 Date palm fibres

DPFs were obtained from 15- to 25-year-old date palm trees in and around Najran, Saudi Arabia (Althoey et al., 2022a). These trees constitute one of the most accessible diversities and are responsible for a significant volume of agro-waste.

The DPFs were chemically cured using different doses of sodium hydroxide to increase their compatibility with other concrete components and to eliminate any possible impurities from the surface of the fibres. The main effect of this approach is the disruption of hydrogen bonding within the network structure, which is shown here with increasing surface roughness (Kabir et al., 2012). Aqueous sodium hydroxide is used in this case to dissolve oils, wax, and lignin from the cell walls. As a result, alkaline treatment often influences the cellulose fibril, degree of polymerization, and, hence, the extraction of lignin and other non-cellulosic substances. The DPFs were treated by immersing them in a sodium hydroxide solution. Individually, the fibres were immersed in 1.5, 3.0, and 6.0 percent sodium hydroxide solutions. The fibres were submerged in the solution at room temperature for 24 h. Due to the maximum tensile strength of the fibres, the treatment with 3 percent sodium hydroxide was selected based on the impact on the fibres. The physical properties of the DPFs are listed in Table 6.

2.1.4 Superplasticizer

Superplasticizers (SPs) are well-known as effective water reducers in the production of HSC. In this investigation, Glenium® 110M, which is based on polycarboxylate ether, was used as a superplasticizer for water reducers in the production of FHSC.

2.3 Methodology

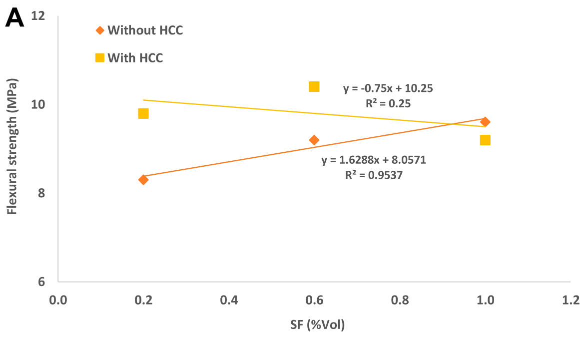
2.3.1 Mix design and sample preparation

The behaviour of the fibres was evaluated using a variety of experiments that focused on particular characteristics of the FHSC. For FHSC, SF, PPF, and DPF were mixed with concrete in variable proportions of 0.2, 0.6, and 1.0 percent by concrete volume, respectively, as shown in Table 7.

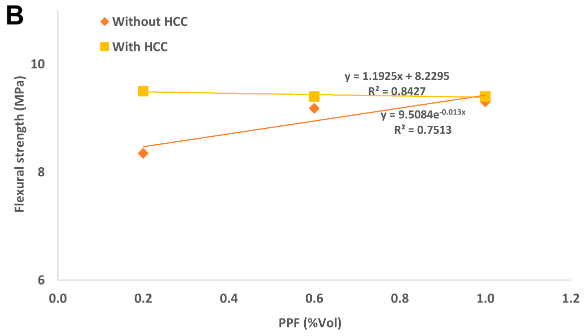
The testing procedure was performed to determine the various hardened characteristics of the FHSC-utilising cylinders (150 mm diameter x 300 mm height), cubes (100 mm), and prisms (100 mm × 100 mm x 500 mm).

2.3.2 Thermal cycle procedure

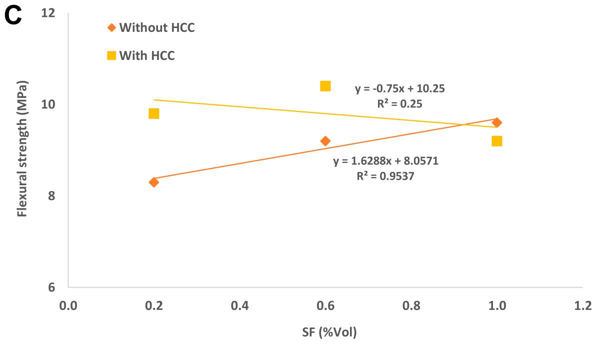
After 28 days of water curing, the samples were placed in an oven and subjected to HCC. An HCC comprised 2 days of heating at 60 °C followed by 2 days of cooling at room temperature 25+-5 °C (one-cycle) for 270 days (continuing the authors' project and research published at 28 and 180 days) (Hakeem et al., 2023). This heat–cool cycle was selected to imitate the daily change in ambient temperature in many parts of Saudi Arabia throughout the summertime. There was enough distance between the samples to allow for a regular flow of hot air during heating and easy heat dissipation during cooling. The compressive strength, modulus of rupture, toughness, ultrasonic pulse velocity, and water sorptivity of the samples were evaluated after 270 days of exposure.



Relationship between the volume of SF and modulus of rupture



Relationship between the volume of PPFs and modulus of rupture



Relationship between the volume of DPF and modulus of rupture

FIGURE 4
Relationship between the volume and modulus of rupture of SF, PPF, and DPF. **(A)** Relationship between the volume and modulus of rupture of SF. **(B)** Relationship between the volume and modulus of rupture of PPF. **(C)** Relationship between the volume and modulus of rupture of DPF.

2.3.3 Investigation of structural properties

2.3.3.1 Compressive strength test

The compressive strength test for FHSC was performed in accordance with ASTM C109 (ASTM, 2020). After 28 days of hydration with regular drinking water, cube specimens (100 mm) were evaluated.

2.3.3.2 Modulus of rupture test

A centre-point loading setup was used to evaluate the modulus of rupture of FHSC prism specimens according to ASTM C293 (International, 2016b). This test was carried out using a Universal Instron machine with a loading capacity of 400 kN and a constant loading rate of 0.0167 mm/s. The displacement was measured using an LVDT mounted in the middle of the FHSC prism samples. The displacement and applied load were automatically recorded in the data logger while the test was being performed on the prism samples.

2.3.3.3 Toughness

The energy retained by the unit cross-sectional area at any displacement terminal point is used to describe the toughness (capacity to absorb energy) of the FHSC samples (Hosen et al., 2022). The toughness of the samples was measured using the area under the load against deflection graphs up to the samples' rupture.

2.3.3.4 Ultrasonic pulse velocity test

To confirm the uniformity and stability of the FHSC samples, the ultrasonic pulse velocity (UPV) test was performed (Hosen et al., 2021). The test was carried out using the FHSC samples in line with ASTM C597 (International, 2016a).

2.3.3.5 Water sorptivity test

The development of surrounding small holes caused by excessive water is an indication of higher-grade concrete. As a consequence, concrete quality parameters such as unit weight, stiffness, and durability are commonly estimated using the water sorptivity test (also known as water absorption). The water sorptivity test for FHSC was made in line with BS 2011 Part 122 (Institution, 1998) using cylindrical specimens (150 mm in height and 75 mm in diameter) after satisfying the curing period requirement of 28 days.

3 Results and discussion

3.1 Compressive strength

Figure 1 presents the experimental results of compressive strength for FHSC samples without HCCs (curing for 28 days) and with HCCs (treatment for 270 days). The compressive strength steadily increased with increasing the fibre content for the FHSC samples without using HCCs, as shown in Figure 1. In contrast, the compressive strength of PPF- and DPF-reinforced concrete samples was somewhat decreased with increasing volume content of fibres when HCCs were used (Hakeem et al., 2023). As a result, the compressive strength might indeed be determined by the strength of the aggregates (Cao et al., 2018b; Khan et al., 2022c; Hosen et al., 2022), notwithstanding the little influence of HCCs on strength (Hakeem et al., 2023). Moreover, compared to the authors' previous study (Hakeem et al., 2023) at 180 days, there is a slight increase in compressive strength at 270 days, which is due to the effect of fibres.

Figures 2A–C show the relationship between compressive strength and the volume of SF, PPF, and DPF without HCCs (curing for 28 days) and with HCCs (treatment for 270 days). Strong R^2 values were found for the FHSC samples in this relationship.

3.2 Modulus of rupture

The modulus of rupture behaviour of fibre-reinforced concrete is essential to safeguard structures from extreme environmental

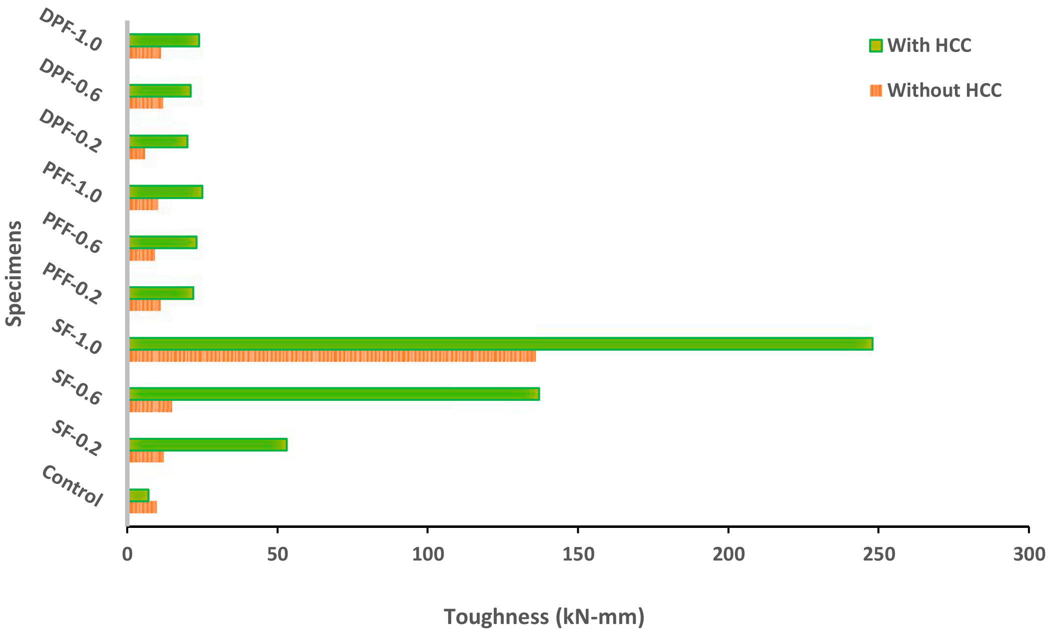


FIGURE 5
Behaviour toughness of FHSC with-and-without HCCs.

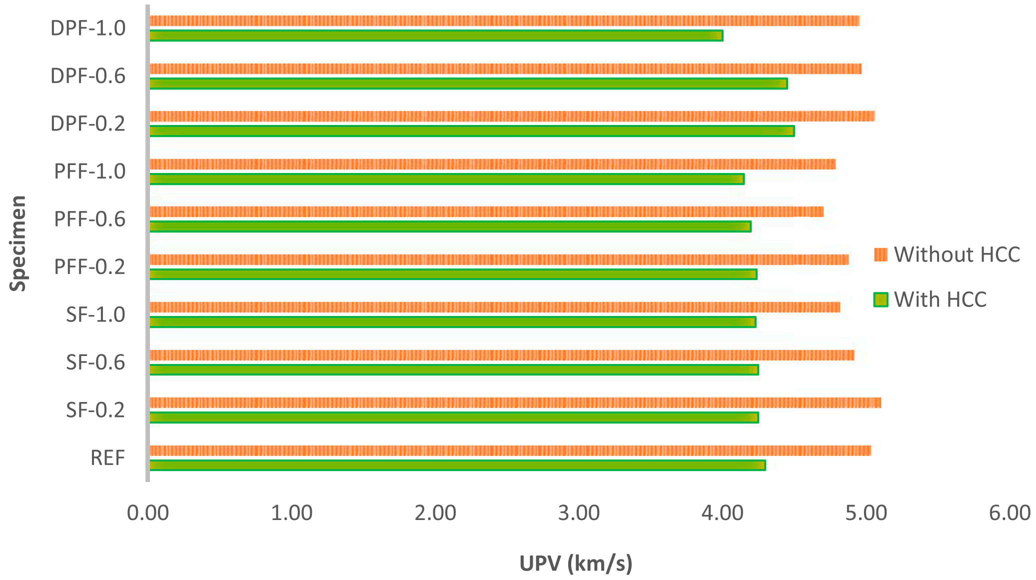
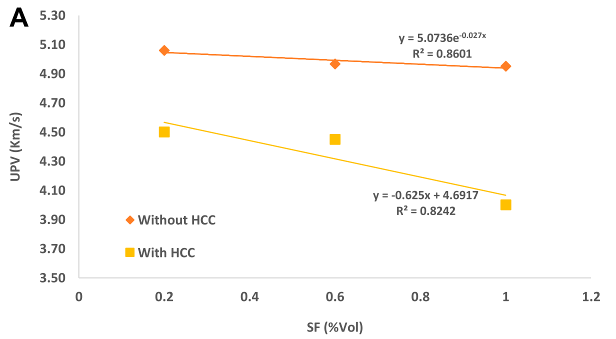
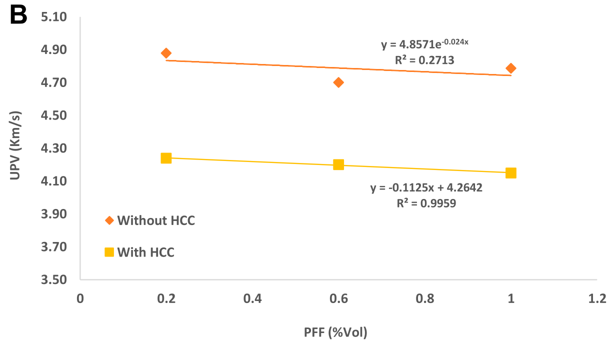


FIGURE 6
Deviations of UPV with and without HCCs for FHSC.

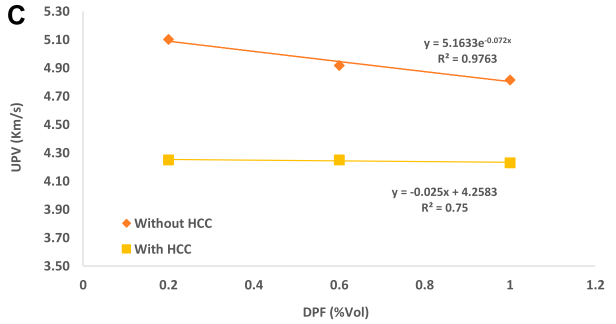
actions comprising excessive temperatures and freeze–thaw cycles (Cao et al., 2018a; Khan et al., 2018; Meskhi et al., 2022). Figure 3 illustrates the development of FHSC and the modulus of rupture. The introduction of SF, PPF, and DPF was increased from 0 to 1 percent and the modulus of rupture was increased by up to 33, 2, and 1 percent, respectively, above the control samples when HCCs were applied. SF considerably increased the modulus of rupture in both conditions as compared to PPF and DPF. Because of their increased capacity to survive extreme weathering impact and flexural rigidity, SFs could be able to delay or resist the formation of initial cracks in the cross-section of the samples (Tayeh et al., 2022a; Qaidi et al., 2022e). DPFs, on the other side, outperformed PPFs in terms of modulus of rupture behaviour due to their longer fibre length (Hakeem et al., 2023).



Relationship between the volume of SF and UPV



Relationship between the volume of PPFs and UPV



Relationship between the volume of DPF and UPV

FIGURE 7
Relationship between the volume and UPV of SF, PPF, and DPF. **(A)** Relationship between the volume and UPV of SF. **(B)** Relationship between the volume and UPV of PPF. **(C)** Relationship between the volume and UPV of DPF.

Kriker et al. (2005), on the other hand, studied the mechanical and physical properties of four distinct types of DPFs. The strength, toughness, microstructure, and continuity index of DPF-reinforced concrete are all reported as a function of curing in hot and water (Tayeh et al., 2022a; Qaidi et al., 2022c; Qaidi et al., 2022d; Qaidi et al., 2022e). It was observed that increasing the amount and length of fibre reinforcement enhanced the post-crack modulus of rupture and toughness coefficients but lowered the compressive strengths and initial crack in both water and hot, dry curing (Hakeem et al., 2023). Moreover, compared to the authors' previous study (Hakeem et al., 2023) at 180 days, there is a slight reduction in the modulus of rupture at 270 days, which is due to the influence of thermal cycle exposure on the concrete.

Figures 4A–C show the relationship between the volume of SF, PPF, and DPF and the modulus of rupture without HCCs (curing for 28 days) and with HCCs (treatment for 270 days). This relationship indicated that without using HCCs, the FHSC samples linearly improved in the modulus of rupture.

3.3 Toughness

The toughness (energy absorption capabilities) of the FHSC samples without HCCs containing SF, PPF, and DPF was compared to the control sample. As the volume of fibre reinforcement in the concrete mixtures was increased, the toughness and load-bearing capacity improved (Hakeem et al., 2023).

The toughness of the FHSC samples without HCCs (curing for 28 days) and with HCCs (treatment for 270 days) are illustrated in Figure 5. According to the evaluation of the ruptured failure samples, the failure was caused by the crack-bridging interaction between the grout and fibres in the matrix (Abd et al., 2022; He et al., 2022; Ibrahim et al., 2022; Abd et al., 2023). As a result of the increased stiffness of the SF, its toughness in both circumstances, with and without HCCs, is greater than that of the PPF- and DPF-reinforced concrete samples. As a result, it is indicated that concrete containing SF is better suitable for hard weathering action than PPF and DPF concrete samples (Hakeem et al., 2023). Moreover, compared to the authors' previous study (Hakeem et al., 2023) at 180 days, there is a slight increase in toughness at 270 days, which is due to the effect of fibres.

3.4 Ultrasonic pulse velocity

Figure 6 presents the UPV of the HSC without HCCs (curing for 28 days) and with HCCs (treatment for 270 days) containing SF, PPF, and DPF. The SF, PPF, and DPF were introduced in increasing proportions to the HSC, which served to lessen ultrasonic wave pass-through further and more efficiently without the HCC (Hakeem et al., 2022b). HCCs had no effect on the FHSC as fibre amounts increased. This was to confirm that the FHSC was uniform and stable (Hakeem et al., 2023). Moreover, compared to the authors' previous study (Hakeem et al., 2023) at 180 days, there is a slight decrease in UPV at 270 days, which is due to the influence of thermal cycle exposure on the concrete.

Figures 7A–C illustrate the relationship between the volume of SF, PPF, and DPF and the UPV without HCCs (curing for 28 days) and with HCCs (treatment for 270 days).

3.5 Water sorptivity

The pore structure of concrete is widely known to have a significant impact on the material's durability. The quantity of water absorbed by immersion offers an estimate of the overall pore

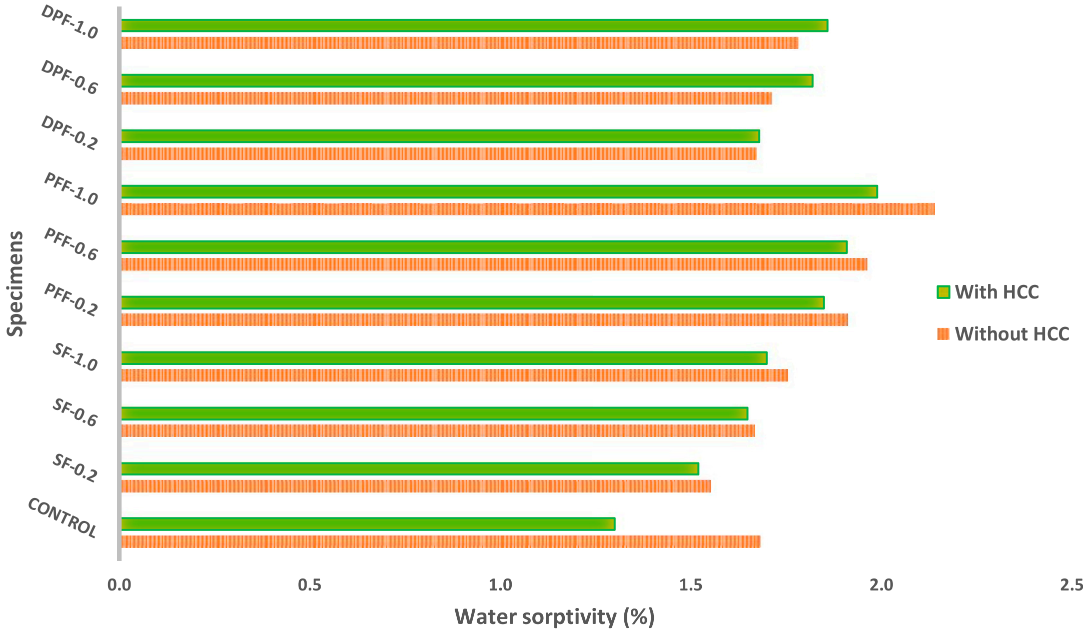


FIGURE 8
Variation of water sorptivity of FHSC.

volume of the concrete (De Schutter and Audenaert, 2004). In cases of applied HCC and without HCC, the water sorptivity of the FHSC samples was greater than that of the control concrete (Hakeem et al., 2023). Increasing the volume of fibre in the concrete increased the water sorptivity, as seen in Figure 8. Because the fibres flowed around the mortar and formed an interaction with it, they enhanced the micropores within the concrete. As a result, the water sorptivity of fibre reinforced was greatly enhanced as compared to the control sample. Nevertheless, the water sorptivity of FHSC was much lower, despite the fact that the water sorptivity of good-grade concrete should be less than 10 percent by weight (Neville, 1995; Hakeem et al., 2023). Moreover, compared to the authors' previous study (Hakeem et al., 2023) at 180 days, there is a slight decrease in water sorptivity at 270 days, which is due to influence of thermal cycle exposure on the concrete.

Figures 9A–C shows a substantial relationship between the water sorptivity and the volume of SF, PPF, and DPF content without HCCs (curing for 28 days) and with HCCs (treatment for 270 days).

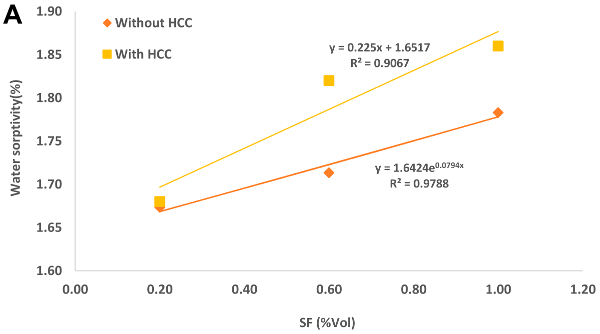
4 Conclusion

In continuation of the authors' project and the paper published in 28 and 180 days (Hakeem et al., 2023), the effect of HCC for 270 days on concrete comprising SF, PPF, and DPF was studied in order to develop HSC. For the production of FHSC, different percentages (0, 0.2, 0.6, and 1.0 percent) of SF, PPF, and DPF were used. Mechanical and durability properties comprising compressive strength, modulus of rupture, toughness, ultrasonic pulse velocity, and water sorptivity were investigated. Based on the laboratory findings, the following concluding observations can be made:

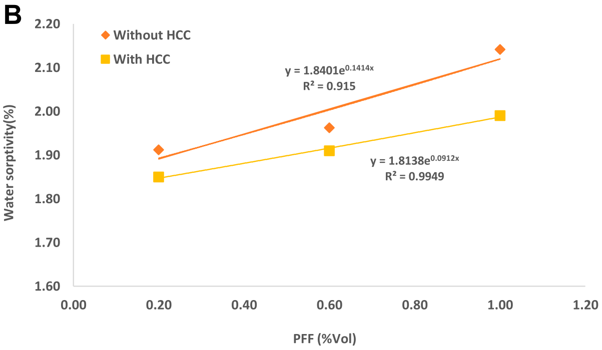
1. The compressive strength of FHSC was dramatically increased by increasing the quantity of fibre volume fraction without using HCC. In contrast, performing HCC on samples comprising PPF and DPF lowered their compressive strength. Nevertheless, the SF-encompassing samples demonstrated a significant improvement in this condition as well, owing to the fibres' higher compressive load-bearing capacity.
2. The modulus of rupture enhanced significantly when SF, PPF, and DPF were added to HSC without HCC (curing for 28 days) and with HCC (treatment for 270 days). As the percentages of SF, PPF, and DPF were increased from 0 to 1 percent, the modulus of rupture increased by up to 33, 2, and 1 percent, respectively, above the control samples when HCC was applied.
3. In all conditions, with and without the application of HCC, the introduction of SF, PPF, and DPF into HSC demonstrated a significant increase in toughness compared with the control sample.
4. The inclusion of SF, PPF, and DPF in HSC improved UPV when compared to the control sample without HCC. The application of HCC to the FHSC samples had no effect.
5. As a result, natural DPF can be used to make a sustainable FHSC that can resist harsh weather conditions.
6. Moreover, compared to the authors' previous study at 180 days, there is a slight increase in compressive strength and toughness and a slight decrease in the modulus of rupture, ultrasonic pulse velocity, and water sorptivity at 270 days.

5 Recommendations

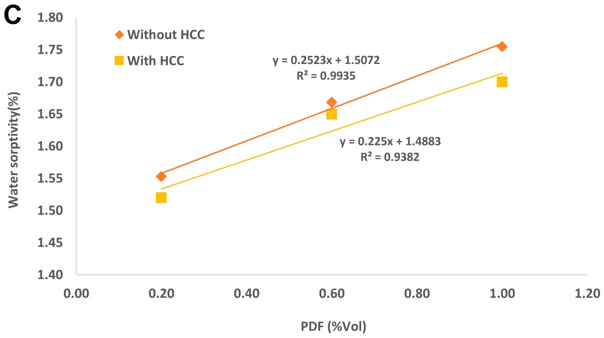
Further studies have to focus on the structural characteristics of SF-, PPF-, and DPF-comprising high-strength concrete, considering



Relationship between the volume of SF and water sorptivity



Relationship between the volume of PPFs and water sorptivity



Relationship between the volume of DPF and water sorptivity

FIGURE 9
Relationship between the volume and water sorptivity of SF, PPF, and DPF. **(A)** Relationship between the volume and water sorptivity of SF. **(B)** Relationship between the volume and water sorptivity of PPF. **(C)** Relationship between the volume and water sorptivity of DPF.

the full-scale structural elements under monotonic and fatigue loading.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

Conception and design of the study: MH, SQ, IH, MA, and AA; acquisition of data: YÖ, MoA; analysis and/or interpretation of data: MA, MoA, AA; drafting the manuscript: MH, SQ, IH, YÖ, MA, MoA and AA; revising the manuscript critically for important intellectual content: MA, MoA, AA; and approval of the version of the manuscript to be published: MH, SQ, IH, YÖ, MA, MoA and AA.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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