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The Impact of Natural Fibers on Thermal Resistance and Spalling in High-performance Concrete

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Abstract

This article presents an experimental approach to evaluate the effectiveness of palm fibers as a natural innovative solution to enhance the thermal resistance of high-performance concrete (HPC) under fire conditions. The utilization of palm fibers aims to promote local materials, since locally sourced materials may be more affordable due to their abundance. Four different high-performance concrete formulations were tested. The first, called HPCSF, which is composed of fibreless silica fumes, served as a reference mix. The second, HPCPSF, included the addition of polypropylene fibers to silica fume. The third, HPCDFSF, integrates date palm fibers with silica fume. Finally, the fourth, HPCPQSSF, combined polypropylene fibers with varying amounts of quarry sand and silica sand, in addition to silica fume. The results of the fire resistance tests show that the incorporation of palm fibers into the concrete mixture improves structural strength, reduces spalling, prevents crack formation under high-temperature conditions, and increases fire resistance in HPC.

Keywords

local materials, palm fibers, fire resistance, spalling, high-performance concrete

1 Introduction

In the event of a fire, Civil engineering and high-rise buildings are susceptible to fire both during the building process and during the duration of their lives. Fires may threaten property and human lives, as historical events all across the globe have shown [1, 2]. Concrete constructions' mechanical qualities and structural integrity may be seriously jeopardized under such harsh conditions. This may cause the building to crack, or even collapse. Among these damages, a phenomenon called (spalling) constitutes a major risk that must be assessed for concrete structures when they present a risk of exposure to fires, particularly those with rapid development. This predominant physical phenomenon is responsible for the ejection of concrete during a fire, which exposes the reinforcement closest to the surface to high temperature and thus accelerates the reduction in strength. This can eventually lead to premature failure of the structure.

Several studies have been carried out to understand the spalling mechanism and the strength of concrete. Some of these works estimate that the main causes of this phenomenon include the low permeability of concrete, its dimensions, temperature, the migration of water vapor into concrete at high temperatures, the heating rate, and the moisture content [3, 4].

However, concrete types currently used in construction are broadly divided into several categories, with the most significant being ordinary concrete (OC), high performance concrete (HPC), and ultra-high-performance concrete (UHPC), classified according to their range of compressive strength. High performance concrete (HPC) is considered as a promising material for structural protective design [5]. Compared to ordinary concrete, high performance concrete (HPC) is more susceptible to explosive spalling than ordinary concrete in fire conditions [6].

Furthermore, according to several recent studies, structural elements made from higher-strength concretes, such as high-performance concrete (HPC) [7], exhibit lower fire resistance compared to ordinary concretes (OC) [8].

2 Fire-induced spalling phenomena

Spalling caused by fire is a complex phenomenon that is affected by several parameters such as temperature, moisture, chemical reactions, and mechanical stress. It significantly weakens the structural integrity of concrete,

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and in severe cases, may lead to the complete collapse of the building [9, 10]. This problem may occur soon after a fire starts, causing the underlying reinforcements to be exposed. This accelerates the weakening process and may lead to the premature collapse of the building. Usually, this happens within a temperature range of 250 to 400 °C, which is readily reached during a fire [2, 11]. Spalling in High-Performance Concrete (HPC) is mostly seen at temperatures ranging from 300 to 650 °C, as documented in [12], with a more precise range of 250 to 400 °C, as stated in [2]. Furthermore, rapid increases in temperature are recognized to exacerbate the spalling of concrete. According to [13], a temperature rise of 5 °C per minute is sufficient to start the spalling of concrete. Spalling may present itself in many forms and degrees of severity, depending on its precise geographical location.

Corner spalling refers to the occurrence of spalling in the lower corners of a concrete structure, which becomes noticeable during the latter stages of a fire. Concrete is degraded when it experiences tensile strains at its edges and corners [14].

Aggregate Spalling: This phenomenon is closely linked to the type of aggregate used and causes surface damage. It results from the thermal expansion of aggregates close to the surface due to the increase in temperature.

Surface Spalling: Commonly referred to as spalling, this type is characterized by the expulsion of small fragments from the fire-exposed facing surface. It exhibits lesser violence compared to explosive bursting [13, 15].

Explosive Spalling: This manifestation is marked by sudden and forceful disintegration, ejecting either small or large concrete fragments accompanied by a loud noise. This type of event can occur within the initial thirty minutes of a fire [16]. Observations of explosive spalling in concrete have been made in concrete in both controlled laboratory environments and under actual fire conditions [12, 17].

To increase the spalling resistance of high-performance concrete (HPC) when exposed to fire, fiber-reinforced concrete has been developed. Steel, glass, polymer, and basalt fibers are commonly used materials for reinforcing concrete and increasing its resistance to spalling at high temperatures. Varied kinds of reinforcing fibers may have varied properties; Khaliq and Kodur [6] and Xiong and Richard Liew [18] propose the use of polypropylene and/or steel fibers as a feasible approach to decrease spalling under such circumstances.

3 Research context

Recent investigations [4, 6, 19] have highlighted the potential of polypropylene fibers to improve the thermal stability of concrete mixtures. These fibers, which melt at temperatures around 165–170 °C, facilitate the formation of channels that allow vapor to escape, thereby mitigating internal pressure and reducing the risk of spalling due to the enhanced porosity and pathways created by the melting process [12].

Incorporating polypropylene into concrete not only augments its durability but also provides a cost-effective alternative to other fiber-reinforcement strategies [20, 21]. It's important to recognize the low melting point of polypropylene fibers, which, when exposed to high temperatures within concrete, melt to create conduits for water vapor release. This mechanism effectively lowers vapor pressure within the concrete, preserving its microstructural integrity [22]. Additionally, heating polypropylene fibers has been suggested to increase concrete's resistance to scaling, reinforcing the material's durability under thermal stress [22]. Nonetheless, the production of polypropylene fibers involves chemical processes that may not align with environmental sustainability criteria.

Numerous studies have explored the potential of integrating plant debris into concrete as a substitute for traditional components like cement, aggregates, and reinforcing fibers [7, 23]. The adoption of natural fibers in concrete and cement mixtures is gaining recognition as a viable alternative to synthetic fibers, particularly in regions seeking affordable construction methods [24, 25]. Previous investigations have shown that natural fibers can enhance concrete by increasing its resistance to cracking, improving strength, and maintaining performance post-cracking. However, the durability of these fibers in alkaline conditions poses challenges [26].

In Algeria, despite being abundantly available, date palm fiber (*Phoenix dactylifera*) is not extensively utilized. It is crucial to highlight the distinctive properties of these fibers [27].

Date palm trees are central to the agricultural practices within oasis regions in the Sahara's core. Originating from North Africa, these trees are widely cultivated in the Arabian and Persian Gulf regions, contributing significantly to the oasis vegetation. Their ability to thrive in diverse soil conditions, as long as the soil is nutrient-rich and well-drained, allows for their cultivation in temperate zones outdoors, where they are valued for their aesthetic appeal and foliage [27].

Algeria's oases host approximately 800 date palm varieties, known by local names such as Deglet Nour, Dokar (Mal-Palme), Elghaers, and Deglabida [27].

4 Materials and methods

In our research, we focused on analyzing high performance concrete (HPC) that was reinforced using a combination of polypropylene and date palm fibers. To assess the impact of these fiber reinforcements on the properties of HPC when subjected to elevated temperatures and their effect on spalling behavior, we developed four distinct concrete formulations.

These high-performance concrete mixes were designed to investigate the roles of polypropylene and date palm fibers in HPC. The baseline mix, referred to as HPCSF, contained silica fume without any fiber addition and acted as the control sample. The second formulation, named HPCPSF, was enhanced with polypropylene fibers alongside the silica fume. The third mix, HPCDFSF, integrated date palm fibers with silica fume, exploring the effect of natural fibers. The final formulation, HPCPQSSF, was a composite mix that included polypropylene fibers and a combination of quarry sand and dune sand, in addition to silica fume, to explore the synergistic effects of synthetic and natural materials in HPC.

4.1 Utilized materials

This study employed Portland cement (CPJ CEM II/A 42.5). Table 1 summarizes the chemical and physical features of this cement, whereas Table 2 shows the physical qualities of the aggregates utilized. The crushed limestone aggregates were found in Algeria's Annaba area, and consisted of gravels ranging in size from 8 to 15 mm and quarry sand with a maximum size of 3 mm. The dune sand, which has a grain size of 0/3 mm, was taken from Algeria's Tebessa region.

Table 1 Mechanical, physical, and chemical features of the cement

Chemical composition (%)		Physical and mechanical characteristics		
Al_2O_3	4.45	Absolute density	g/cm^3	3.08
SiO_2	17.41	Apparent density	g/cm^3	1.06
CaO	62.33	Final setting	h:min	3h02min
MgO	1.22	Initial setting	h:min	2h00min
SO_3	2.93	Compressive strength (MPa)		
Na_2O	0.41	2 Days	24.70	
K_2O	0.71	7 Days	37.30	
CaOl	0.93	28 Days	45.25	
Cl^-	0.017	Flexural strength (MPa)		
FeO_3	3.42	2 Days	5.30	
Residus insolubles	1.31	14 Days	6.92	
P.A.F.	7.35	28 Days	7.62	

Table 2 Physical properties of the utilized aggregates

Physical properties	Unit	Quarry sand	Dune sand	Gravel
Density	g/cm^3	2.60	2.62	2.69
Size	mm/mm	0/3	0/3	8/15
Sand equivalent	%	83.96	87.45	–
Finesse modulus	–	2.98	2.28	–

During this study, we used the superplasticizer TEMPO-12. This strong superplasticizer provides many benefits to concrete, including extended rheology (more than 2 hours), resistance to segregation, improved surface quality, and a significant reduction in the amount of water required. This product is manufactured by the Algerian company Sika El-Djazair and is especially recommended for high-performance concrete.

The HPCSF and HPCPQSSF mixtures included 1.85 kg/m^3 of polypropylene fiber, The PP used in our study are marketed by the Algerian company GRANITEX Their technical characteristics are given by the manufacturer Table 3.

Fumed silica is a mineral ingredient used in hydraulic concrete mixes to enhance structural robustness and longevity, as per the specifications outlined in BS EN 13263-1:2005+A1:2009 [28]. The fumed silica used in this investigation was procured from Caracala Quartz Production Tebessa, an Algerian corporation.

The chemical composition and physical properties of the substance are detailed in Table 4 [29]. Utilizing the outermost layer of the male date palm, the natural fibers utilized in this investigation were extracted. Extraction of the outer date palm fibers from the trunk results in a nearly rectangular weave composed of layered layers, which are

Table 3 Polypropylene fibers characteristics

Physical characteristics	Unit	Cement CPJ
Apparent density	kg/m^3	1500
Absolute density	kg/m^3	2650
Sand equivalent	%	87.00
Silica content SiO_2	%	97.54
Iron oxide content FeO_3	%	0.22
Aluminum oxide content Al_2O_3	%	0.11
Sand absorption SAb	%	3.87
Sand friability SF	%	18.05
Loss on ignition	%	0.11

Table 4 Chemical and physical characteristics of silica fume [29]

Physical characteristics	Unit	Cement CPJ
Apparent density	kg/m^3	1500
Absolute density	kg/m^3	2650
Sand equivalent	%	87.00
Silica content SiO_2	%	97.54
Iron oxide content FeO_3	%	0.22
Aluminum oxide content Al_2O_3	%	0.11
Sand absorption SAb	%	3.87
Sand friability SF	%	18.05
Loss on ignition	%	0.11

interwoven naturally. These materials easily disintegrate into individual fibers when submerged in water.

4.1.1 Palm fiber

In this investigation, the focus was on fibers of the Dokar variety, sourced from the date palm plant, as depicted in Fig. 1. Drawing from the research conducted by Kriker et al. [30], which examined four types of fibers harvested from the exteriors of the date palm varieties Dokar, Deglette-Nour, Degla-Bida, and Elguers (using their local nomenclatures), Dokar fibers were identified to possess superior tensile strength. Consequently, Dokar fibers were selected for inclusion in our study. The physical and mechanical properties of Dokar fibers are delineated in Table 5 [31]. Within the HPCDFSF mixtures, Date palm fibers, with a length of 30 mm and a diameter of 0.30 mm, were added at a rate of 1.85 kg/m^3. These fibers begin to thermally degrade at around 250 °C and usually fully decompose between 450 °C and 500 °C.

Fig. 1 Illustrations of palm fibers

4.2 Fabrication and curing of concrete specimens

Concrete samples were produced in the LCEH laboratory, catering to the four distinct concrete formulations: HPCSF, HPCPSF, HPCDFSF, and HPCPQSSF. These mixes were cast into cubic metal molds measuring 10 × 10 × 10 cm^3 and 15 × 15 × 15 cm^3, respectively. The specific mix ratios for each type of concrete are detailed in Table 6. To prevent the loss of moisture, the surfaces of all specimens were immediately covered post-casting. After a period of 24 hours, the specimens were demolded and submerged in

Table 5 Physical and mechanical properties of the palm fibers used [31]

Physical characteristics	Lower-Upper	Coefficient of variation CV (%)
Length (mm)	20–100	–
Diameter (mm)	0.1–1	0.45–54.43
Tensile strength (MPa)	285 ± 15	–
Apparent density (kg/m^3)	512.20–1088.80	900–17.64
Absolute density (kg/m^3)	1300–1455	1383–5.52
Natural water content (%)	9.50–10.50	10–5.00
Ultimate strain (%)	11.00–16.00	–
Modulus of elasticity (GPa)	4.74–5.25	–
Water absorption (%)	96.84–202.65	–

Table 6 Batches quantities in kg/m^3

MIX	HPCSF	HPCPSF	HPCDFSF	HPCPQSSF
W/B	0.275	0.275	0.275	0.275
Cement kg/m^3	489.20	489.20	489.20	489.20
Water kg/m^3	150	150	150	150
Dune sand kg/m^3	368.970	368.970	368.970	184.485
Quarry sand kg/m^3	368.970	368.970	368.970	553.455
Gravel kg/m^3	1070	1070	1070	1070
Superplasticizer kg/m^3	7.338	7.338	7.338	7.338
Silica fume kg/m^3	48.920	48.920	48.920	48.920
PP fiber kg/m^3	–	1.85	–	1.85
DP fiber kg/m^3			1.85	

water for a duration of 28 days for curing. Following this phase, the specimens were maintained in controlled conditions at the LCEH Laboratory for a period of one year.

4.3 Test conditions and procedure

Fire resistance tests were performed on the four samples by exposing them to fire on all sides after a severe fire scenario. The temperature gradually increased from the starting ambient temperature of 20 °C to three unique levels: 250 °C, 450 °C, and 650 °C. The heating procedure took 60 minutes at an average rate of 8 °C per minute, with maximum temperatures held for one hour. Following that, the examined samples were subjected to cooling settings designed to imitate ordinary building fires. The outcome of each test is the average of three cubic concrete specimens. Fig. 2 depicts the furnace's heating and cooling curve. The Fig. 3 shows the furnace that was used during the experimentation process.

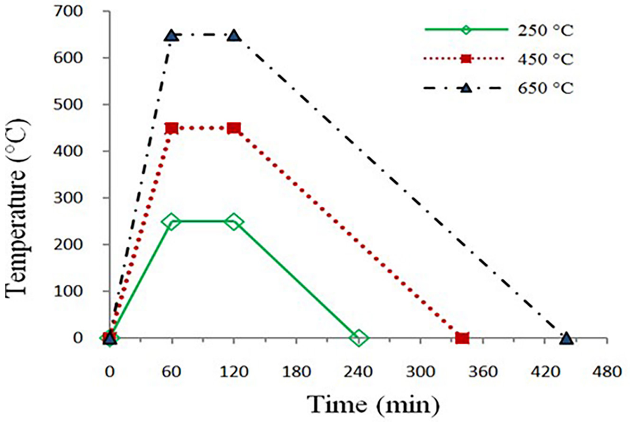


Fig. 2 Curves of heating and cooling according to temperature

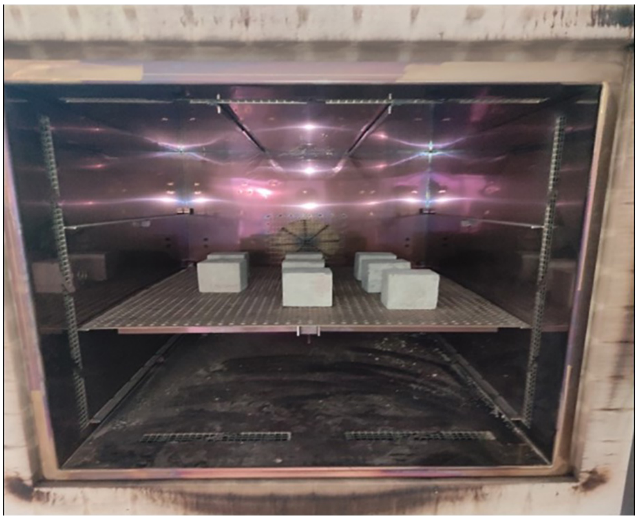


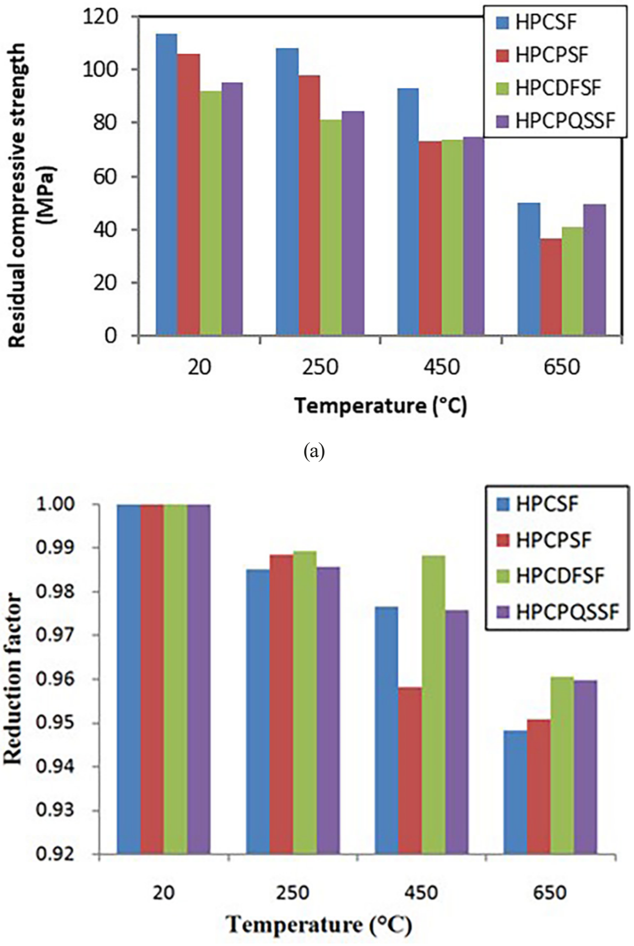
Fig. 3 Naberthen furnace

5 Results and analysis

Different concretes' fire performance is evaluated by comparing their residual compressive strength, residual flexural strength, ultrasonic pulse propagation velocity (UPV), mass loss, and spalling progression.

5.1 Residual compressive strength

According to literature reviews [19, 32], the properties of concrete subjected to high temperatures are influenced by various factors, including initial strength, composition of materials, age of the concrete, moisture content, among others. It is widely acknowledged that both standard-strength and high-performance concrete exhibit a marked reduction in compressive strength when exposed to rapid temperature increases, typical of fire conditions [33]. This study involved analyzing and comparing samples from different concrete formulations, as illustrated in Fig. 4.



(a)

(b)

Fig. 4 (a) Compressive strength of all concrete types as a function of temperature, (b) Compressive strength reduction factors of all concrete types as a function of temperature

The findings related to the residual compressive strength at ambient temperature (20 ± 2 °C) and following exposure to temperatures of 250, 450, and 600 °C are documented in Table 7, with each entry representing the mean of three specimens. Table 6 clearly demonstrates a decline in the compressive strength of concrete as the temperature rises. The average residual compressive strengths, in comparison to those at room temperature, were observed to be between 88% to 95% at 250 °C, 69% to 82% at 450 °C, and 35% to 52% at 650 °C. The visual appearance of the samples after exposure to 450 °C, prior to compressive strength testing, is presented in Fig. 5.

The study's analysis up to 650 °C, showcased in Fig. 4 (a), reveals a consistent decrease in compressive strength with escalating temperatures, underscoring the significant impact of thermal exposure on this property. The reduction in compressive strength relative to room temperature was approximately 5% to 12% at 250 °C, 18% to 31% at 450 °C, and 48% to 65% at 650 °C, as determined in this investigation.

The comparative analysis indicates that the mechanical performance of high-performance concrete with silica fume (HPCSF) and high-performance concrete with polypropylene fibers (HPCPSF) under high temperatures significantly surpasses that of high-performance concrete with date palm fibers (HPCDFSF) and high-performance concrete with quarry sand (HPCPQSSF) within the studied temperature spectrum.

Table 7 Reduction in residual compressive strength as a function of temperature

Temperature	Room temp.	250 °C	450 °C	650 °C
	Compressive strength (MPa)			
HPCSF	113.50	108.10	93.31	50.06
HPCPSF	105.92	97.81	73.21	36.56
HPCDFSF	92.12	81.26	73.91	41.30
HPCPQSSF	95.17	84.70	75.01	49.40

This research emphasizes the beneficial effect of integrating palm fibers as an alternative to polypropylene in enhancing the fire resistance of high-performance concrete (HPC). Notably, Fig. 4 (b) reveals that after three hours of exposure to elevated temperatures, a 65% reduction in concrete strength was recorded, mirroring the loss observed with polypropylene fibers. These encouraging outcomes underscore the potential of palm fibers as an effective replacement for polypropylene in improving the fire resilience of HPC.

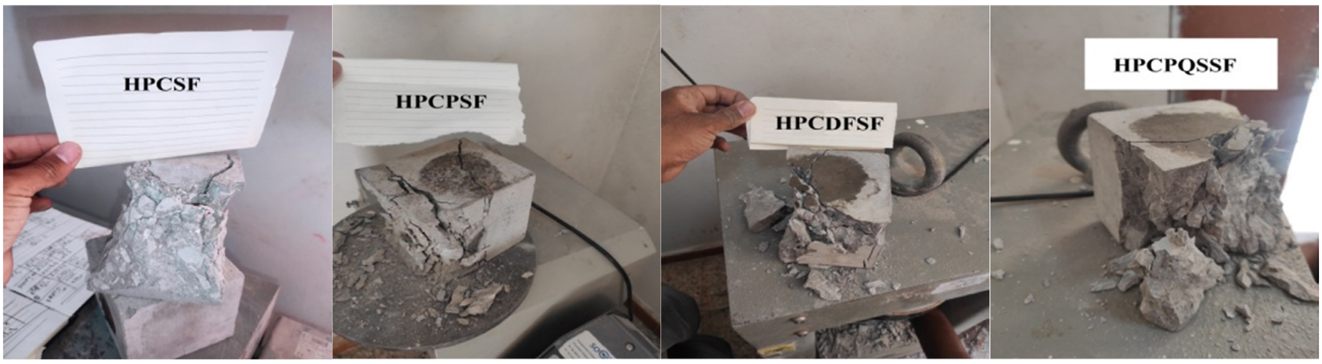
To examine the results of this study, the strength reduction factor recommended by Eurocode 2 [34], which depends on the exposure temperature, was used according to the following formula:

$$R_{ck} = \frac{f_{c(\theta)}}{f_{ck(20\ °\mathrm{C})}} . \tag{1}$$

Where:

- R_{ck}: is the strength reduction factor,
- $f_{ck(20\,°\mathrm{C})}$: is the compressive strength at room temperature,
- $f_{c(\theta)}$: is the compressive strength at elevated temperature.

Equation (1) has been validated as a suitable method to evaluate the decrease in the strength of concrete exposed to elevated temperatures. The strength reduction factors, obtained from Eq. (1), are summarized in Table 8. It is notable that the strength reduction factor of palm fiber concrete presents an accepted value and is very close to other types of concrete such as HPCSF, HPCPSF, and HPCDFSF.



(a) (b) (c) (d)

Fig. 5 The condition of the samples after testing their compressive strength after exposure at 450 °C: (a) HPCSF 450 °C, (b) HPCPSF 450 °C, (c) HPCDFSF 450 °C, (d) HPCPQSSF 450 °C

Table 8 Reduction factors of compressive strength (R_{ck})

T °C	CEN EN 1992-1-2: 2004 [34]	HPCSF	HPCPSF	HPCDFSF	HPCPQSSF
Room temp.	1.00	1.00	1.00	1.00	1.00
250	0.90	0.95	0.92	0.88	0.89
450	0.68	0.82	0.69	0.80	0.79
650	0.38	0.44	0.35	0.35	0.52

The compressive strength reduction factor determined in this study can be compared with those suggested by Eurocode 2 [34], which recommends the reduction factor for normal weight concrete with silica aggregates. However, all samples exhibit values slightly higher than those recommended by the Eurocodes standards, especially within the temperature range of 250 to 450 degrees Fig. 4 (b).

5.2 Modulus of elasticity in compression

The modulus of elasticity of concrete is consistently related to its initial compressive strength. However, as shown in Fig. 6, the series of curves for all types of concrete studied show performance superior to those recommended by Eurocode 2 [34], with differences varying between 12% and 24% over a temperature range of 250 °C to 650 °C. The largest differences occur at a temperature of 450 °C. Additionally, palm fiber concrete HPCDFSF and polypropylene concrete HPCPSF showed significant degradation beyond 450 °C compared to other types of concrete. This seems logical because fibers generally have a negative effect on the elastic modulus; this has been demonstrated by research conducted by Hager and Pimienta [35]. The elastic modulus reduction factors are summarized in Table 9.

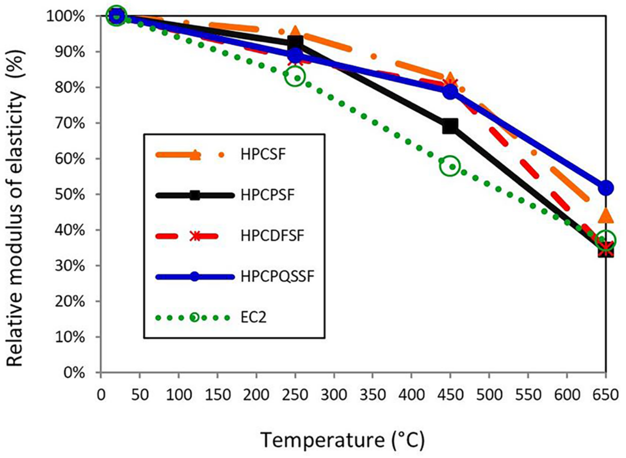


Fig. 6 Relative modulus of elasticity of all types of concrete as a function of temperature

Table 9 Elastic modulus reduction factors

T °C	CEN EN 1992-1-2: 2004 [34]	HPCSF	HPCPSF	HPCDFSF	HPCPQSSF
20	1	1	1	1	1
250	0.9	0.95	0.92	0.88	0.89
450	0.68	0.82	0.69	0.8	0.79
650	0.38	0.44	0.35	0.35	0.52

5.3 Residual flexural strength

Fig. 7 clearly illustrates a continuous and linear drop in flexural strength up to 450 °C for all concrete samples. The curves describe the change in residual tensile strength as a function of temperature for various kinds of concrete. However, a notable loss in strength is shown in every instance as the temperature above this 450 °C threshold. In particular, concrete that incorporates palm fibers shows a relatively acceptable flexural strength compared to other types of concrete, exhibiting only a 55%

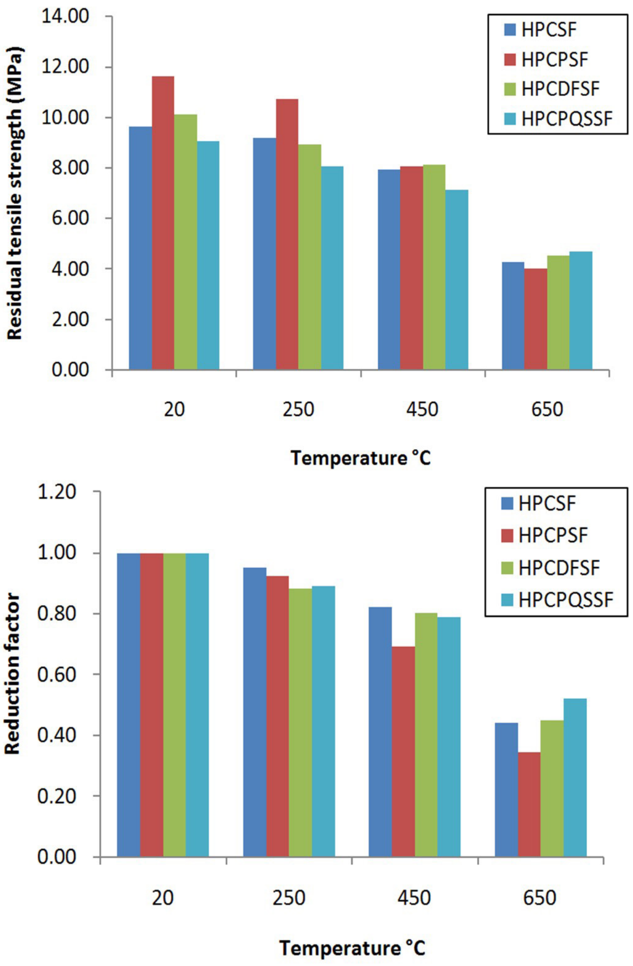


Fig. 7 Residual tensile strength of all concrete types as a function of temperature

reduction, similar to the outcome observed with polypropylene-based concrete.

This result arises from the ductile nature of the internal structure of these fibers, which enhances the flexibility of the concrete and prevents the formation of cracks, thus improving its flexural resistance [27, 36, 37].

Consequently, it can be inferred that replacing polypropylene (PP) with palm fibers (PF) is a viable option to improve the tensile strength of high-performance concrete under fire conditions.

5.4 Observations of spalling behavior

An important aspect of this study involves the examination of the impact of palm fibers on the resistance of HPC to spalling. Following exposure to different elevated temperatures, we recorded observations related to physical characteristics, including spalling frequency, color alterations, and crack formation, to assess their behavior under high-temperature conditions. Figs. 8–10 illustrate the concrete surfaces after being treated at high temperatures. An initial assessment of the potential damage due to high temperature exposure can be carried out by examining the external properties of the concrete surface. It is evident that the surface of the samples heated to 250 °C shows no noticeable changes (Fig. 8). However, the cracks in the concrete surface began to manifest at approximately 450 °C (Fig. 9) and continued to worsen as the temperature increased, reaching their peak at 650 °C. After exposure to temperatures exceeding 600 °C, HPCPQSSF concrete, which includes polypropylene fibers along with varying proportions of quarry sand and siliceous sand, exhibited light brown discoloration, accompanied by the development of numerous cracks and surface bumps as shown in Fig. 10 (d). Furthermore, Fig. 10 illustrates a color change, providing a visual indication of a notable alteration in the properties of concrete for all types of concrete.

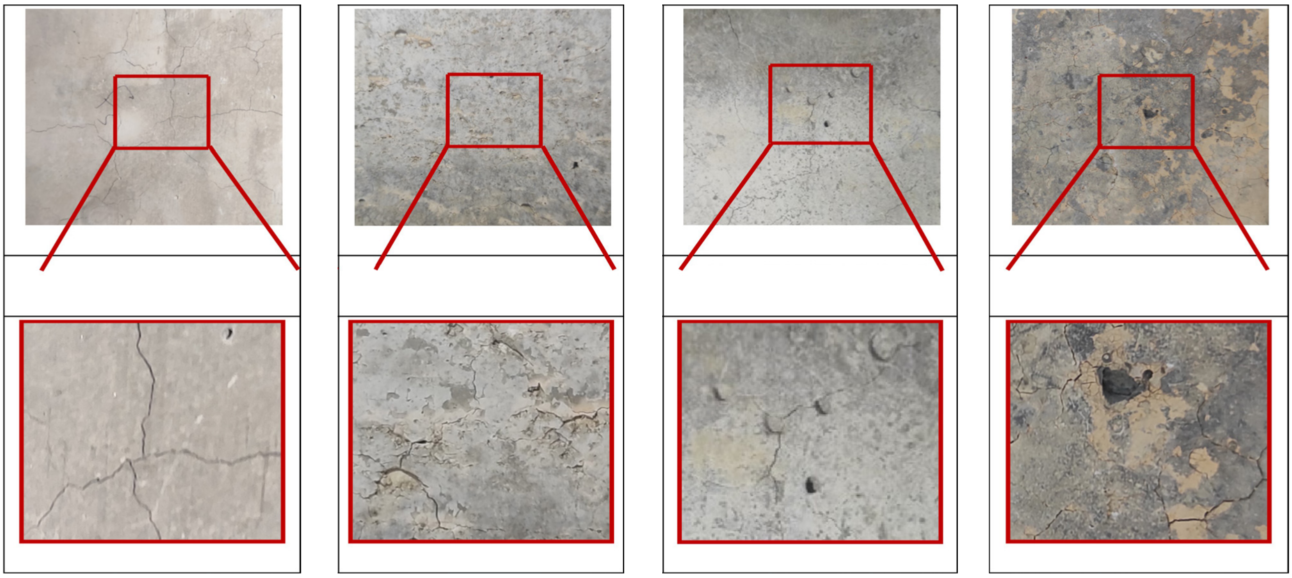
However, it is crucial to emphasize that all types of concrete showed robust resistance to spalling. Despite the presence of several raised bumps on the surface, severe concrete spalling was not observed in these samples, even when exposed to temperatures as high as 650 °C. Fig. 10 illustrates the state of these specimens after exposure to a temperature of 650 °C. When analyzing concrete samples with palm fibers (Fig. 10 (c)), it becomes evident that the spalling phenomenon is entirely absent. Furthermore, this type of concrete shows no cracks up to 450 °C, and its surface remains intact up to 650 °C, at which point we observed the appearance of some surface cracks. This clearly illustrates the positive impact of using palm fibers to prevent concrete spalling at high temperatures. This observation has significant economic value by reducing potential costs associated with the use of polypropylene fibers to mitigate spalling in concrete. The utilization of palm fibers proves to be effective not only in terms


(a) (b) (c) (d)

Fig. 8 Condition of the concrete surface at 250 °C: (a) HPCSF 250 °C, (b) HPCPSF 250 °C, (c) HPCDFSF 250 °C, (d) HPCPQSSF 250 °C


(a) (b) (c) (d)

Fig. 9 Condition of the concrete surface at 450 °C: (a) HPCSF 450 °C, (b) HPCPSF 450 °C, (c) HPCDFSF 450 °C, (d) HPCPQSSF 450 °C



(a) (b) (c) (d)

Fig. 10 Condition of the concrete surface at 650 °C: (a) HPCSF 650 °C, (b) HPCPSF 650 °C, (c) HPCDFSF 650 °C, (d) HPCPQSSF 650 °C

of performance, but also economically advantageous by preserving the structural integrity of concrete elements exposed to elevated temperatures. This solution offers economic and environmental benefits.

5.5 Mass loss

To assess mass loss, we measured the weight of the cubic samples before and after their exposure to elevated temperatures, as shown in Fig. 11. This representation highlights how the increase of temperature influences the reduction of the concrete mass samples. The correlation between variation in mass loss and temperature is clear for all four types of concrete examined, as noted by several authors [37–39]. They found that the variation in mass loss as a function of temperature exposure is linked to the presence of water in the concrete in free, bound, or adsorbed form, which gradually escapes and represents the main cause of the loss of concrete mass. These authors identified three phases in the evolution of mass loss.

- In the first phase, from room temperature to 150 °C, a slight loss of approximately 3% was observed, corresponding to the release of water contained in the capillary pores.
- Between 150 and 300 °C, a significant increase in mass loss is observed.
- Above 300 °C, a slowdown in mass loss is observed. The main physicochemical transformation undergone by the heated concrete between 150 and 300 °C is the dehydration of CSH.

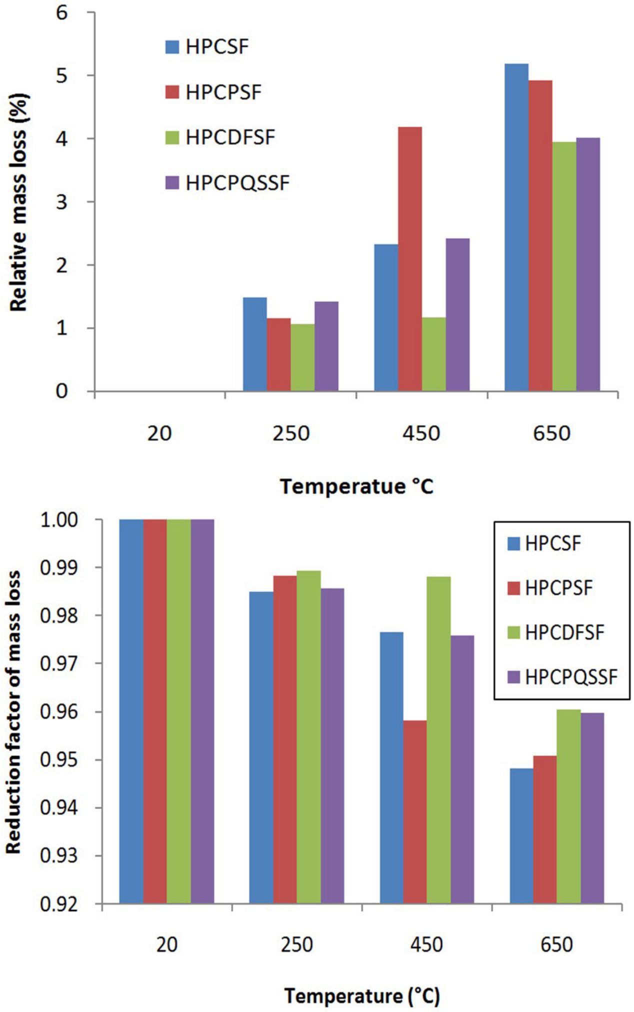


Fig. 11 Residual mass loss as a function of temperature

However, all concrete samples examined in the present study exhibited a significant mass loss from room temperature to 650 °C. At 250 °C, the samples (HPCSF, HPCPSF, HPCDFSF, and HPCPQSSF) recorded a mass loss of approximately 3%, 5%, 7% and 10%, respectively. This trend continues with increasing temperature, reaching approximately 3%, 5%, 7%, and 10% at 450 °C. On the contrary, mix having palm fibers experiences minimal mass loss between 250 °C and 450 °C, unlike other types of concrete. This difference can be attributed to the fact that palm fibers only melt at very high temperatures, around 1170 °C [40], thus preserving their internal structure and improving the properties of this type of concrete. Above 600 °C, a significant increase in the rate of mass loss is observed. According to research conducted by Xiao et al. [40] and Zhang [41], the phenomena of splitting or degradation of the concrete surface may be linked to many reasons, including the breakdown of limestone particles and CO_2 emissions. When compared to other mixes, HPCDFSF mixes exhibit comparatively less mass loss, but HPCSF mixes exhibit a more noticeable mass loss than the others. The HPCDFSF and HPCPQSSF blends showed a mass loss of 3.95% at 650 °C, but the HPCSF and HPCPSF blends showed a mass loss of 5.02% at that temperature.

5.6 Ultrasonic Pulse Velocity (UPV)

The evaluation of the elastic modulus and material density was performed utilizing an ultrasonic pulse velocity (UPV) test, aimed at examining the structural integrity of the HPCSF, HPCPSF, HPCDFSF, and HPCPQSSF specimens. Fig. 12 graphically depicts the degradation of concrete integrity as determined by ultrasonic pulse measurements. A discernible decline in UPV values across the temperature spectrum from 250 °C to 650 °C suggests an incremental formation of microcracks within the concrete matrix. At 250 °C, the velocity of ultrasonic pulses saw a reduction of 11% in HPCPSF specimens and 12% in the HPCSF, HPCDFSF, and HPCPQSSF specimens. Moreover, a notable decrease of 58% in ultrasonic pulse velocity was observed at 650 °C for all specimens, as illustrated in Fig. 12.

The observed trends indicate a uniform decrease in ultrasonic pulse velocity across the board for specimens of high-performance concrete at elevated temperatures, signaling a deterioration in their physical properties and structural integrity.

Additionally, the findings from the UPV test further establish that concrete reinforced with palm fibers exhibits comparable outcomes to other tested concrete variants. This parallel in performance serves as a robust affirmation of the effectiveness and dependability of palm fibers as a reinforcing agent in high-performance concrete (HPC).

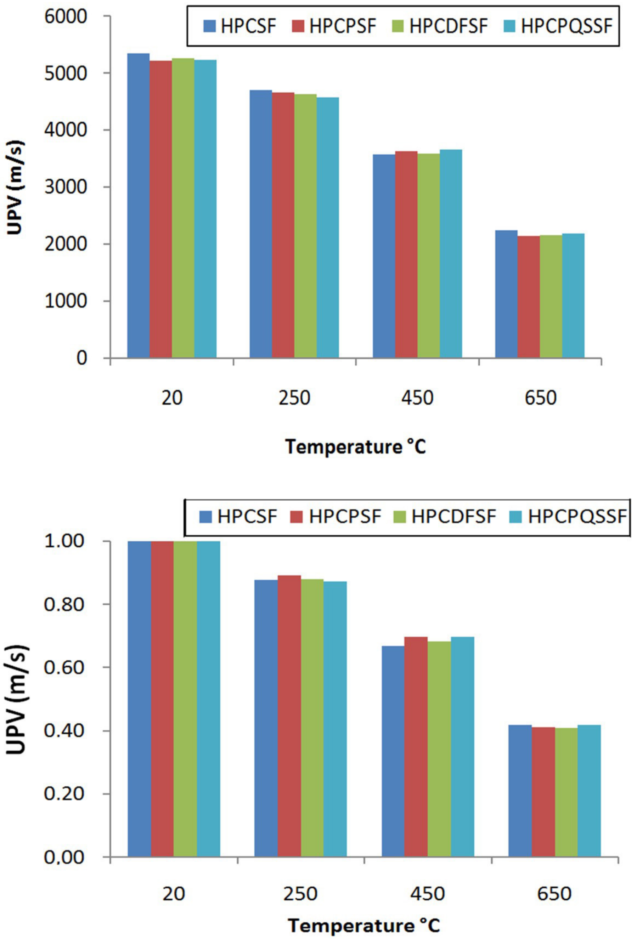


Fig. 12 Temperature-dependent ultrasonic pulse velocity

6 Discussion

In recent decades, there has been a global trend towards the utilization of eco-friendly and cost-effective natural resources, which has gained momentum. Among these resources are palm fibers, which are readily abundant in desert countries such as Algeria. These regions often have significant amounts of natural fibers, which frequently remain unexploited. This is the reason behind our choice of this topic. Their use is supported by their affordability, low density, biodegradability, availability, ease of processing, recyclability, nontoxicity, and their renewable nature in the environment. However, the approach that we have adopted aims to promote palm fibers to improve the thermal resistance and the spalling phenomenon of HPC under fire conditions.

The current study has confirmed when concrete is exposed to high temperatures, palm fibers absorb the internal water vapor pressure resulting from the evaporation of free water and physically bound water. This ability arises from their excellent properties and porous structure, rich in empty spaces [29, 36, 37]. This beneficial feature helps reduce existing thermal stresses, thereby preventing concrete spalling.

Furthermore, a study conducted by Zhang et al. [7] on the Influence of natural fibers on the thermal spalling resistance of ultra-high-performance concrete, demonstrated that these fibers shrink at elevated temperatures, thereby increasing permeability. This enhanced permeability helps resist thermal spalling in the UHPC. On the contrary, in the case of UHPC with polypropylene fibers, a notable increase in permeability is observed with increasing temperature, which promotes increased porosity, and contributes to the reduction of tensile stresses caused by pore pressure [6]. This is due to the formation of an interconnected network of cracks resulting from thermal incompatibility between the PP fibers and the cementitious matrix.

7 Conclusions

This paper examined the important mechanical properties of HPC under high temperature conditions, including compressive strength, tensile strength, mass loss, elastic modulus, and spalling phenomenon. Nevertheless, we acknowledge that this study does not include all other mechanical properties, such as thermal conductivity, gas permeability, specific heat, and thermal expansion, which would require further work. However, due to this research, we have been able to highlight the positive properties of these palm fibers. Abundant in desert regions, environmentally friendly and easy to use, they offer significant benefits. On the one hand, they contribute to the preservation of the environment and, on the other hand, improve the properties of concrete under fire conditions.

Experiments were conducted to evaluate these properties, and the following conclusions can be drawn:

- As previously demonstrated, a 65% reduction in the compressive strength of palm fiber concrete was observed after three consecutive hours of exposure to high temperatures. This percentage is similar to that observed with polypropylene-based concrete. These encouraging findings demonstrate how well-suited palm fibers are for replacing polypropylene.
- The impact of elevated temperatures on the durability of concrete was especially significant for mixtures incorporating quarry sand.
- Interestingly, palm fiber concrete has a flexural strength that is only marginally lower than other types of concrete, showing only a reduction of 55% lower than what is seen with polypropylene-based concrete. This outcome is due to the internal ductile structure of these fibers, which improves the flexural resistance of the concrete by increasing its flexibility and preventing crack formation.
- Unlike other types of concrete, concrete containing palm fibers lost very little mass between 250 °C and 450 °C. This disparity is explained by the thermal behavior of date palm fibers, which begin to degrade thermally at around 250 °C, with complete decomposition typically observed at temperatures around 450 °C to 500 °C. The fibers do not melt but degrade, contributing to the concrete's resistance to mass loss under high temperatures.
- Integrating palm fibers into the concrete mix significantly augments its permeability under elevated temperature conditions, thereby enhancing the thermal spalling resistance of high-performance concrete (HPC). In contrast, the presence of polypropylene fibers in HPC is associated with a notable enhancement in permeability. This enhanced permeability facilitates the emergence of an extensive network of interconnected cracks, a consequence of the thermal disparity between the polypropylene fibers and the cementitious framework.
- Adding palm fibers to the concrete mix has a double advantage: On one hand, they absorb water pressure due to increased temperature, allowing water vapor to escape, thus minimizing the risk of spalling. On the other hand, they preserve the strength of the concrete, because they only melt at extremely high temperatures.
- The experimental data obtained in this investigation align closely with the results presented by researchers as part of this study's framework.
- Finally, the initial results appear to confirm that the inclusion of palm fibers significantly enhances the thermal resistance of high-performance concrete. However, further experimental tests will be required to validate and comprehensively assess the other mechanical properties of HPC that incorporate palm fibers.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Authorship contribution statement

M. Hamda: Investigation, Writing, Performing laboratory tests, Analysis, Validation. C. Guergah: Conceptualization, Writing, Formal Analysis, Validation. A. Benmarce: Supervision, Review and Editing. All authors have read and agreed to the final version of the manuscript as published

Nomenclature

HPCSF	High-performance concrete with silica fume and without fibers
HPCPSF	High-performance concrete with Silica fume included the addition of polypropylene fibers
HPCDFSF	High-performance concrete with Silica fume included the addition of Date Palm fibers
HPCPQSSF	High-performance concrete with Silica fume and polypropylene fibers based on quarry sand
PP	Polypropylene
PF	Palm fibers
HPC	High-performance concrete
UHPC	Ultra high-performance concrete
LCEH	Laboratory of Civil Engineering and Hydraulics (Guelma University, Algeria)

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