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Effect of Polypropylene Fibers on the Behavior of Dune Sand Concrete Subjected to Elevated Temperatures

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Abstract

In the field of civil engineering, concrete is one of the most used materials. Above a particular temperature, concrete can exhibit thermal instability during fire events. Improving the safety of buildings and structures is an important issue of this study. This paper investigates the effects of adding polypropylene fibers to dune sand concrete at high temperatures. Prismatic specimens (4 x 4 x 16 cm^3) are produced, and stored until the concrete is hardened. The samples are then subjected to a heating-cooling cycle, starting from room temperature and increasing by 0.1 °C/min until reaching 600 °C. The length and the rate of polypropylene fibers are examined to determine their impact on compressive strength, porosity, and weight loss at temperatures of 80, 150, 300, 450, and 600 °C. Also, the partial replacement of dune sand (DS) with river sand (RS) is investigated. The results show that, for temperatures below 450 °C, the strengths of dune sand concretes varied from 29 to 39% compared to those obtained with concretes subjected to an ambient temperature (20 °C). However, it should be noted that residual compressive strength values decrease at most temperatures with the addition of polypropylene fibers. Furthermore, sand concrete with 50% DS and 50% RS shows an increase in compressive strength of 43.77% compared to that obtained by 100% DS concrete.

Keywords

dune sand concrete, polypropylene fibers, high temperatures, compressive strength, porosity

1 Introduction

The valorization of local materials has become a necessary alternative for economic development. Algeria has a vast desert area, characterized by enormous quantity of dune sand; and almost zero cost of extraction [1, 2]. The exceptional geotechnical properties of dune sand and the issue of the availability of georesources habitually employed in the manufacture of concrete can be resolved [3]. Several investigations have explored the utilization of this superabundant material in the construction sector [4–11]. These previous works have demonstrated that adding dune sand to concrete enhances its workability, and that the use of dune sand varies depending on its physical characteristics, and that dune sand concrete can reach mechanical strengths comparable to the strengths of ordinary concretes without replacing conventional concretes, because concretes based on dune sand have certain disadvantages related to their high porosity.

Recently; several researches have indicated that the real fire resistance of fire-prone building elements can be lower than the fire resistance rating specified in the regulations [12–14]. When concrete is exposed to elevated temperatures, the imposed convection leads to heat and water transfer processes inside the concrete structure causing water evaporation, and increased pressure in the pores. When concrete is subjected to high temperatures, these mechanisms are frequently regarded as one of the most common causes of spalling and cracking [13, 15].

Polypropylene fibers are commonly utilized for reinforcing concrete due to their excellent characteristics, including high tensile strength, durability, and resistance to chemical attack. However, polypropylene fibers can effectively reduce the spalling damage to fiber-reinforced concrete and increase its residual compressive strength when exposed to elevated temperatures.

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Kalifa et al. [16], found that the strength of the concrete reinforced by PP fibers and subjected to high temperatures is influenced by various factors including gel rehydration, cement grain hydration, and calcium oxide carbonation. It was noted by Xiao and König [17] that the compressive strength of concrete initially decreases somewhat and then increases slightly as the temperature rises from room temperature to 400 °C. The temperature begins to reduce significantly when it exceeds 400 °C. Compressive strength decreases to less than 20% at 800 °C compared to ambient temperature.

Behnood and Ghandehari [18] concluded that the relative compressive strengths were improved by the addition of PP fibers and that the residual mechanical characteristics after heating could be significantly improved by adding 2 kg/m^3 of PP fibers. Furthermore, above 200 °C when using PP fibers, the compressive strength was more effective than splitting tensile strength.

According to Sideris et al. [19] the fibers had a negative impact on the residual compressive and tensile strengths of concrete. However, Rodriguez et al. [20] concluded that the fibers melt at about 170 °C and form a network of microchannels in the concrete through which water vapor is released into the atmosphere, thereby preventing the type above failure. Adding PP fibers to the mixture increases the spalling resistance of mortar and concrete.

Shihada [21] examined mixtures with varying percentages of fibers (0%, 0.5%, and 1%) which are prepared and subjected to heating for 6 hours at temperatures: 200, 400, and 600 °C. The results show that concrete with PF has higher relative compressive strengths than concrete without fibers. Nonetheless, an excessive fiber content could potentially degrade performance due to increased deterioration and void volume.

Khaliq and Kodur [22] observed a decline in both compressive and tensile strength as temperatures increase. According to Murahari et al [23], a fiber content of 0.5% by weight of cement was identified as optimal, leading to notable enhancements in concrete's flexural and compressive strength. Mehul et al. [24] found that the inclusion of PP fibers resulted in increased compressive strength in high-strength concrete.

Al-Qadi and Al Zaidyeen [25] investigated the effects of sample form and fiber volume of polypropylene fibers (PF) self-compacting concrete on residual strength at elevated temperatures ranging from 20 °C to 600 °C. The study varied the PF content from 0.5% to 2.5% by volume. It was found that PF can enhance the concrete's residual strength and fracture energy when exposed to thermal shock during the cooling process from elevated temperatures up to 600 °C to ambient temperature.

Patel et al. [26] studied concrete reinforced by polypropylene fiber (PFRC), with granite aggregates; cylindrical samples of 150 × 300 mm and 100 × 200 mm using dosage fiber of 0.5%, subjected to temperatures of 400 °C and 600 °C. The results show no notable improvement in flexural and compressive strengths. They conclude that PFRC can be used effectively in applications where exposure to high temperatures is expected, such as in the construction of fire-resistant structures.

Al-Ameri et al. [27] studied the compressive and flexural strengths of concrete with PF. They indicate that increasing the PF percentage from 0 to 0.2% leads to an increase in compressive strength, and when the PF approached 0.3%, this increase began to disappear. Likewise, the flexural strength increases when the PF percentage is from 0% to 0.3%. With an increase of 0.5% in PF, concrete's compressive and flexural strengths began to decrease considerably compared to the control mixture.

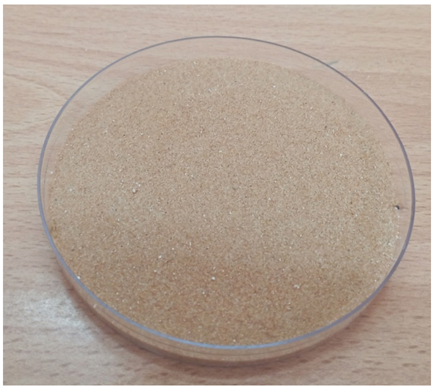
The results obtained by Meena and Ramana [28] show that the compressive strength of polypropylene fiber-reinforced concrete increased by 15.58% compared to the control concrete. Concrete mixes with polypropylene fiber dosages of 0.20%, 0.35%, and 0.50% tested at a temperature of 200 °C exhibited higher compressive strength, whereas higher fiber content led to a decrease in strength.

The usage of polypropylene fibers and their impact on the fire resistance of normal, self-compacting, and high-strength concretes remains a topic of debate. Limited research has been conducted on how polypropylene fibers affect the comportment of dune sand concrete at high temperatures [29]. This study, therefore, aimed to investigate how elevated temperatures affect the compressive strength, residual compressive strength, weight loss, and porosity of concrete incorporating dune sand (DS) and polypropylene fibers (PF). The experiments involved subjecting samples to 5 heating-cooling cycles: 80, 150, 300, 450, and 600 °C.

2 Material used and methods

2.1 Material

Two types of sand were utilized in this research. The first type is dune sand (DS), sourced from Ain El-Beida in the Ouargla region (South-East of Algeria). The second type, is a river sand (RS), obtained from the Hassi Sayah quarry located 30 km from Ouargla, as illustrated in Figs. 1 (a) and (b). Observations of sand grains under a binocular optical

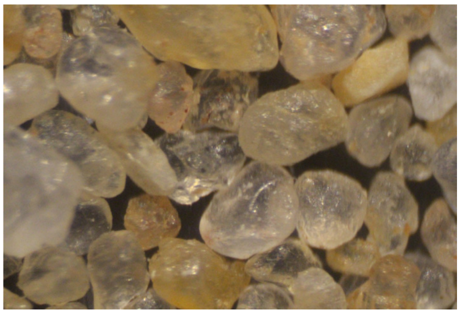


(a)

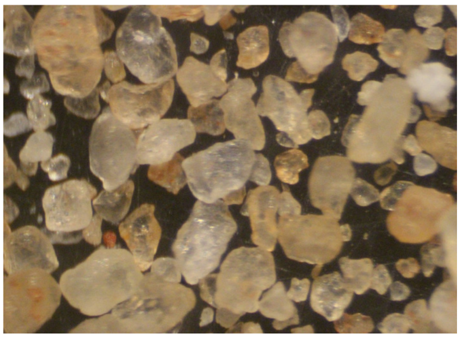
(b)

Fig. 1 Sands used: (a) Dune sand, (b) River sand

microscope are shown in Figs. 2 (a) and (b). Dune sand grains exhibit a round and isometric shape, while river sand grains are irregular in shape and vary in size. The grain size distribution of the sands was determined in accordance with the norm P 18-560 [30], as shown in Fig. 3. Tables 1 and 2 present the physical characteristics and chemical analysis of the different sands used, respectively. The dune sand curve deviates from the range required by the NF EN 1097-6 [31] for ordinary concrete, and 50% river sand needs to be added for granular correction. The high sand equivalent value obtained (97%) confirms the cleanliness of the dune sand. The mineralogical composition of sand used in concrete production was analyzed using X-ray diffraction (XRD) in the 2θ range [10°–90°]. Fig. 4 shows significant diffraction peaks indicating that the dune sand is composed of more than 95% quartz with a small amount of calcite.



(a)



(b)

Fig. 2 Examination of quartz sand grains with binoculars: (a) Dune sand, (b) River sand

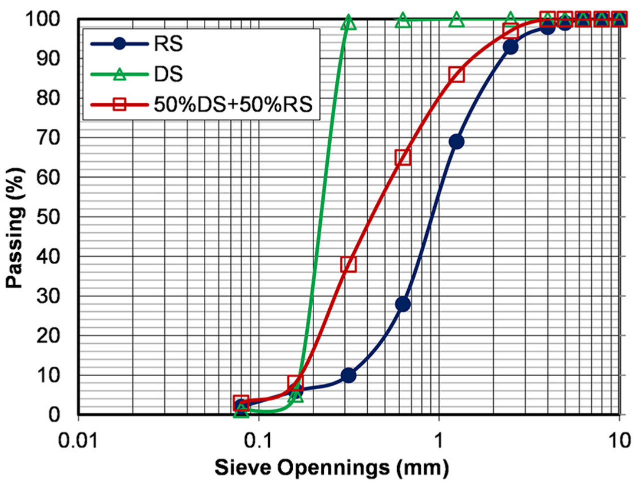


Fig. 3 Granular curve of the sands used

Polypropylene fiber (PF) used are Fibertek PP fibers (Fig. 5), which can be used for various applications. The standard lengths used are 18 and 12 mm for F1 and F2

Table 1 Physical characteristics of sands used

Test	Apparent density (kg/m^3)	Absorption (%)	Fineness modulus (%)	Sand equivalent (%)
Standard	NF EN 1097-6 [31]	NF EN 1097-6 [31]	P 18-560 [30]	NF EN 933-8 [32]
Dune sand (DS)	1450	1.04	0.91	97.11
River sand (RS)	1610	0.56	2.49	74.28

Table 2 Analysis of the chemical composition of the sands

Elements	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	K_2O	Na_2O	P_2O_5
Dune sand (DS) (%)	89.704	0.522	0.778	0.203	0.404	0.472	0.240	0.097	0.013
River sand (RS) (%)	90.476	0.510	0.909	0.265	0.037	0.304	0.235	0.081	0.012

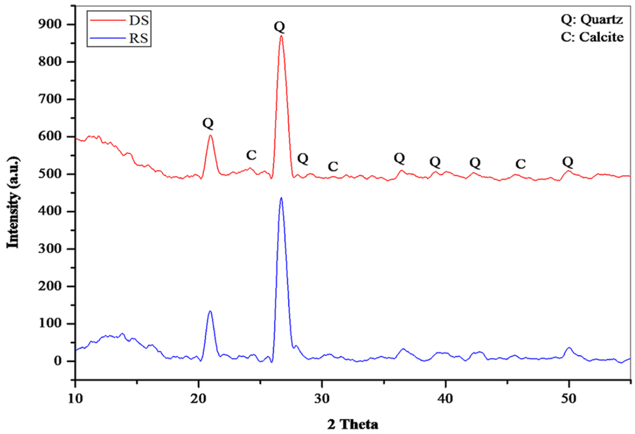


Fig. 4 X-ray diffraction (XRD) of dune sand and river sand

Fig. 5 Polypropylene fibers

fibers respectively. Table 3 summarizes the physical and mechanical characteristics of the fibers utilized.

Table 4 presents the chemical properties of the Portland cement CEM II/A-L 42.5N (MATINE) utilized in this research.

Table 3 Characteristics of polypropylene fibers [33]

Fiber	Length (mm)	Diameter (µm)	Specific gravity (g/cm^3)	Melting point (°C)
F1	18	32	0.91	160
F2	12			
Fiber	Elongation at failure (%)	Tensile strength (MPa)	Modulus of elasticity (MPa)	
F1	40	450	3700	
F2				

Table 4 Chemical characteristics of cement used [34]

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO
(%)	18.88	4.36	3.10	62.23
Element	MgO	SO_3	K_2O	LOI
(%)	1.43	2.7	0.58	6.02

To facilitate the blending of concrete, especially when incorporating fibers, the water-reducing plasticizer Medafluid 40 is used, having respectively a density, pH, and chlorine content of 1.19, 8–9, and < 1 g/l [35].

2.2 Samples preparation and test methods

To prepare the sand concrete composition, we followed the standard EN 196-1 [36] using a cement-to-sand ratio of 1:3, similar to that of standardized mortar. The amount of water required for the plastic concrete was determined using the VeBe test according to standard NF P18-452 [37], resulting in water-to-cement ratios (W/C) of 0.58 and 0.47 for dune sand and river sand blinders, respectively. To examine the impact of polypropylene fiber on sand concrete, two dune sand concrete mixtures were prepared: DSC (100% dune sand concrete) and DRSC (50% dune sand + 50% river sand). Polypropylene fiber-reinforced sand concretes were created using these base mixtures with varying fiber volumes (0.10% and 0.15%) of the volume of concrete, and fiber types (F1 and F2). The labeling of these mixtures follows a specific pattern: first, the notation of the plain concrete mixture, followed by a dosage of fibers (0.10% or 0.15%), and finally, the letter F1 or F2 indicates the type of fiber. For instance, DRSC_0.10%F1 denotes a mixture with DRSC concrete, 0.10% fiber volume, and F1 fiber. The specific proportions of the sand concrete mixture are detailed in Table 5.

Samples were then placed in the designed molds (4 × 4 × 16) cm^3. They were air-dried for 24 h in the laboratory, before demolding. Following removal, the hardened concretes were then cured for the recommended period in water, as shown in Fig. 6, before testing.

Following a 28-day curing period, the samples were exposed to elevated temperatures by the fire standard (ISO-834) [38]. Five heating-cooling cycles were employed, starting from 20 °C and reaching various temperatures: 80, 150, 300, 450, and 600 °C in a programmable electric oven

Table 5 Dune sand concretes mix (1 m³)

Mixtures	Sand (Kg)		Cement (Kg)	Water (l)	Fibers (Kg)	Plasticizer (Kg)	E/C (%)
	DS	RS					
DSC	1388.65	0			0	0	
DSC_0.10%F1	1385.98	0			1	1.7	
DSC_0.15%F1	1384.64	0	462.88	268.47	1.5	2.5	0.58
DSC_0.10%F2	1385.98	0			1	1.7	
DSC_0.15%F2	1384.64	0			1.5	2.5	
DRSC	711.40	711.41			0	0	
DRSC_0.10%F1	710.07	710.09			1	1.7	
DRSC_0.15%F1	709.41	709.44	474.27	222.91	1.5	2.5	0.47
DRSC_0.10%F2	710.07	710.09			1	1.7	
DRSC_0.15%F2	709.41	709.44			1.5	2.5	

Fig. 6 Conserved samples

(Oyten Thermotechnik gmbh D-2806- A3741), a voltage of 9.9 kV and a maximum temperature of 1200 °C (Fig. 7). The temperature was raised by 1 °C/min, followed by a one-hour stabilization phase at the desired temperature, and then cooled in the closed oven until room temperature at a rate of around 1 °C/min. The heating cycle is shown in Fig. 8. The arrangement of the samples in the oven is made in such a way as to have a uniform heat distribution.

Fig. 7 Oven used for heating samples

An analysis using a scanning electron microscope (SEM) was conducted on a DRSC_0.15%F2 sample to investigate the impact of fibers on concrete cracking and strength at varying temperatures. Additionally, this study aimed to confirm alterations in the microstructure of the samples following exposure to high temperatures. SEM micrographs were conducted on an SEM FEI (Quanta FEG 250) using an accelerating voltage of 200 V–30 kV and a magnification of 30 X–300 Kx. For compressive strength, 180 specimens after heating-cooling cycles were tested according to the standard NF EN12390-3 [39].

The water porosity of dune sand concretes was assessed following the guidelines outlined in European standards NF EN 12390-7 [40]. For each mixture and temperature cycle, three specimens were analyzed. The testing

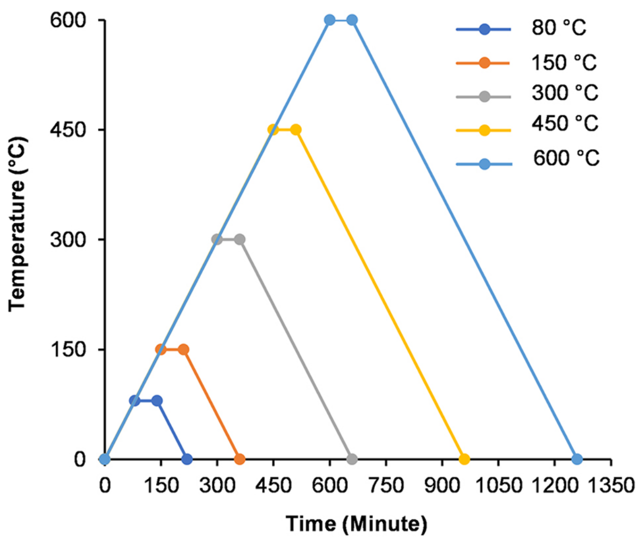


Fig. 8 Characteristics of heating-cooling cycles

procedure involved immersing the samples in a water tank for a minimum of 48 hours until a consistent wet weight (W_{wet}) was achieved. Subsequently, the specimens were dried in an oven at 105 °C ± 3 for at least 72 h until a stable dry weight (W_{dry}) was reached. The porosity was then determined through hydrostatic weighing (W_{hyd}) measurements, with calculations based on the provided formula.

$$P(\%) = \left[(W_{wet} - W_{dry}) / (W_{wet} - W_{hyd}) \right] \times 100 . \quad (1)$$

Change in mass of specimens heated from 20 to 600 °C, allows us to estimate the amount of free water in the tested materials. Additionally, this method enables the observation of the drying and dehydration rates of the samples.

3 Results and discussion

3.1 SEM micrographs

The results from the examination of samples DRSC_0.15% F2 using scanning electron microscopy (SEM) at different temperatures are shown in Fig. 9. Samples at 20 °C and 150 °C are shown in Figs. 9 (a), (b), (c) and (d) respectively. The fibers are embedded in the cement paste, forming connecting bridges that indicate the existence of hydration products like CSH gel and portlandite. The microstructure of the sample at 150 °C illustrates a dense arrangement of hydrated products, indicating stability under heat treatment and a rise in compressive strength during this phase. Following exposure to 450 °C, Fig. 9 (e) and (f) indicates the sample's porous nature, attributed to the release of free water, a portion of the bound water in the CSH, and the primary structural water of ettringite and portlandite. In Fig. 9 (g) and (h), the SEM micrograph of the samples treated at 600 °C reveals the formation of microcracks. The increased porosity of the sample structure is a result of the complete disappearance of portlandite and the gradual dehydration of the CSH. Additionally, cracks are observed traversing the siliceous aggregate, with the disintegration of the siliceous aggregate occurring at 573 °C due to the alpha-beta conversion of quartz sourced from dune sand.

3.2 Compressive strength

The results of tests conducted on concrete samples made from dune sand, comparing those with polypropylene reinforcement to those without, will be presented and discussed. Following exposure to identical temperatures, the impact of fibers on the compressive strength of the concrete was examined.

3.2.1 Impact of granular correction of dune sand

Fig. 10 shows the results of the compressive strength of concrete DSC made with 100 % DS and DRSC made with 50% DS mixed with 50% RS without fibers as a function of different temperatures: 20, 80, 150, 300, 450, and 600 °C. For all temperatures, the results of the compressive strength of mix DRSC exceeded that of mix DSC. The increase in recorded strength for mixture DRSC compared to mixture DSC at the same temperature (20, 80, 150, 300, 450, and 600 °C) is 30.76, 39.64, 40.65, 43.77, 43.22, and 36.44% respectively. The rise in strength is attributed to the granulometric correction, resulting in a decrease in the specific surface area. This reduction lowers the fine content and enhances the dynamic of water penetration, facilitating the even distribution of water within the concrete. Consequently, this promotes effective cement hydration [4, 5, 6]. However, the best compressive strength results for concrete DSC and DRSC are observed when they are exposed to a temperature of 80 °C. The compressive strength of dune sand concrete DSC at this temperature is 18.70 MPa, with strength increases of 15.51%, 2.24%, 8.50%, 14.22%, and 25.67% compared to all the mixtures subjected to temperatures of 20, 150, 300, 450, and 600 °C, respectively. Similarly, for DRSC at each temperature, the increases are 26.34%, 0.58%, 2.07%, 8.81%, and 29.41%, respectively. The improvement in compressive strength from room temperature to 300 °C in the majority of samples can be attributed to two main factors. Firstly, it is due to the rehydration of calcium hydrates (CSH) during water migration and condensation to the colder areas of the specimen. SEM micrographs (Figs. 9 (a), (b), (c) and (d)) reveal a compact structure of the mixtures, suggesting that the samples remain stable under the heat treatment and experience a boost in compressive strength during this stage. Secondly, the formation of siloxane (Si-O-Si) bonds, which help remove the paste and increase the strength [41, 42, 43]. At a temperature of 600 °C, we observed a decrease in compressive strength in both mixtures, with reductions of 12.03% and 4.16% for DSC and DRSC, respectively. This decline is attributed to the chemical and physical alterations that take place in the aggregates beyond 450 °C, resulting in the formation of microcracks in the grains. Hager [15] demonstrated that siliceous aggregates undergo destabilization between 500 °C and 600 °C, leading to physical and chemical transformations affecting their shape and surface, as depicted in the SEM micrographs (Fig. 9 (g) and (h)). These microcracks contribute to the decrease in compressive strength.

3.2.2 Effect of fiber percentage and length

The compressive strength results of concrete DSC and DRSC with different percentages of 0.1% and 0.15% polypropylene fibers F1 and F2, exposed at different

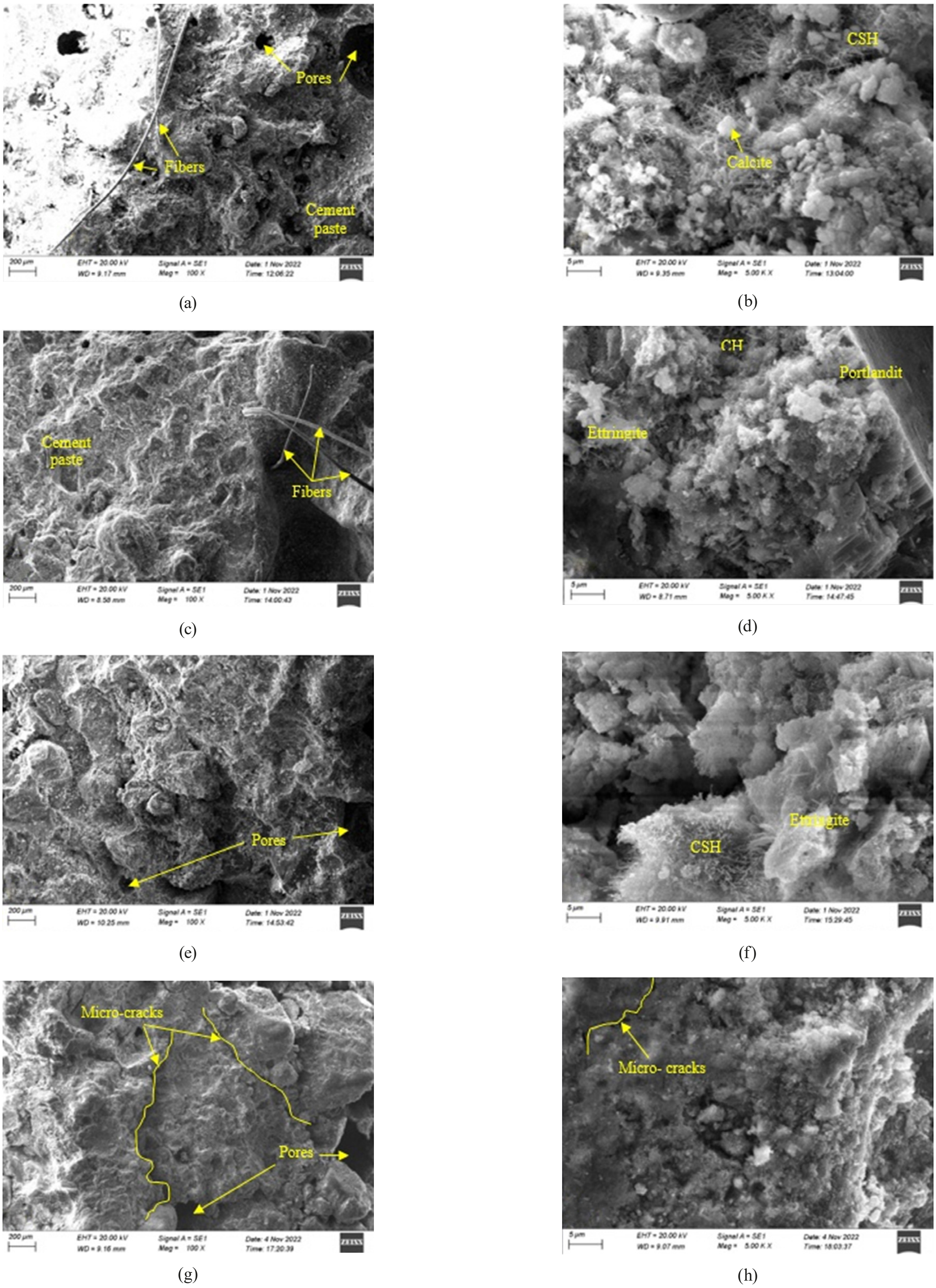


Fig. 9 SEM micrographs of mixture DRSC_0.15%F2 at different temperatures: (a), (b) at 20 °C, (c), (d) at 150 °C, (e), (f) at 450 °C, (g), (h) at 600 °C

temperatures (20, 150, 300, 450, and 600 °C) are illustrated in Figs. 11 (a) and (b). It can be observed that the concretes made with F1 and F2 fibers, with a percentage of 0.15%, show higher strength compared to those made with a fiber volume of 0.10%. At 80 °C, this increase is 6.77%, 5.29%, 4.78%, and 3.87% for the mixtures DSC_F1, DSC_F2, DRSC_F1 and DRSC_F2 respectively. In addition, concretes reinforced with F2 (12 mm) fibers

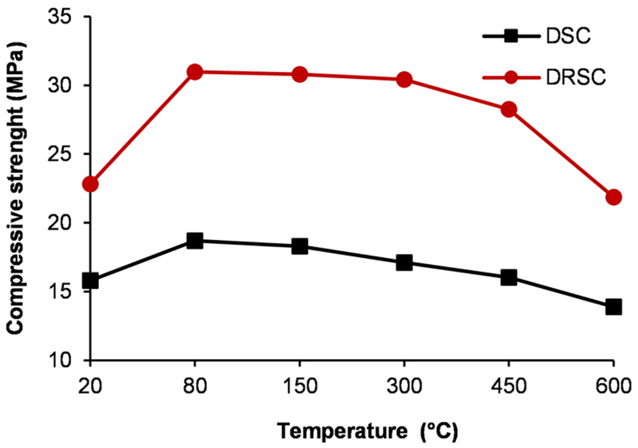
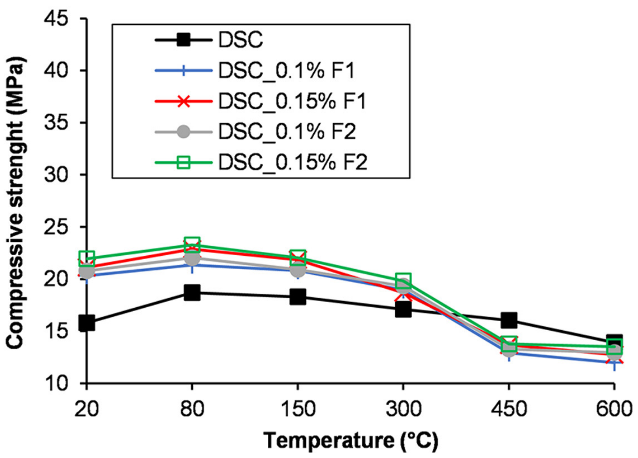
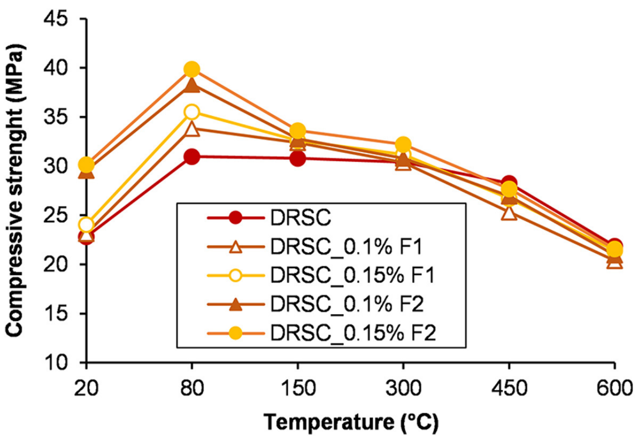


Fig. 10 Compressive strength of concrete DSC and DRSC without fibers as a function of different temperatures



(a)



(b)

Fig. 11 Compressive strength of sand concrete with and without fibers as a function of different temperatures: (a) Sand concrete DSC, (b) Sand concrete DRSC

have higher compressive strengths than concretes with F1 (18 mm) fibers at 80 °C. This increase is 3.22% and 1.67% for the DSC mixtures and 10.74% and 10.89% for the DRSC mixtures, with a fiber volume of 0.10% and 0.15% respectively, which is in accordance with the studies realized by Eidan et al. [44] and Lublóy [45], attesting that short polypropylene fibers give a relatively higher compressive strength at temperatures below 300 °C. However, some studies realized by Memon et al. [46] and Yermak [43] in ordinary or high-performance concrete show that the longer the polypropylene fibers, the higher the compressive strength.

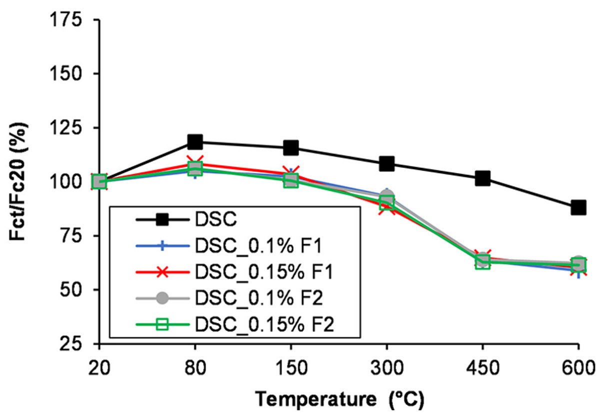
The results achieved display that dune sand concrete (DSC) containing PF may be used in applications subjected to elevated temperatures. Also, between 20 and 300 °C, for all mixtures containing fibers, there is no significant decrease in the mechanical characteristics. The compressive strength shows an increasing trend with rising temperatures up to 150 °C and 300 °C for DSC and DRSC mixtures, respectively. Subsequently, there is a slight decrease between 150 °C and 300 °C for the DSC mixture and between 300 °C and 450 °C for the DRSC mixture, followed by a rapid decrease when the temperature exceeds 450 °C. Reduction in compressive strength recorded at 450 °C compared to ambient temperature is 36.45%, 35.30%, 36.01%, 37.30%, 3.46%, 1.54%, 12.18%, and 11.53% for the mixtures DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2, DSC_0.15%F2, DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, and DRSC_0.15%F2, respectively. However, an increase in the compressive strength of concretes without fibers exposed to a temperature up to 450 °C was observed. A reduction in strength is recorded at 600 °C compared to the ambient temperature with 12.03%, 41.07%, 39.66%, 37.65%, 38.52%, 4.16%, 11.92%, 11.09%, 29.06%, and 29.41% respectively for mixtures DSC, DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2, DSC_0.15%F2, DRSC, DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, and DRSC_0.15%F2. With the same percentage of fibers, the shorter the length of the fiber, the greater its number, which will cause an increase in the void surface after melting. Kalifa et al. [16] show that the fusion of the PF occurs at 160 to 171 °C, where they are either fully or partially absorbed by the porous structure of the cementitious matrix. This absorption creates a vacuum space in place of the fibers, providing additional space for water vapor to circulate. Thus, the risk of spalling decreases as vapor pressure within the material decreases, reducing the stress on the sand and thereby enhancing the physical and mechanical properties of dune sand concrete. These findings align with the studies conducted by Rodriguez et al. [20] and Hager [41].

3.3 Residual compressive strength

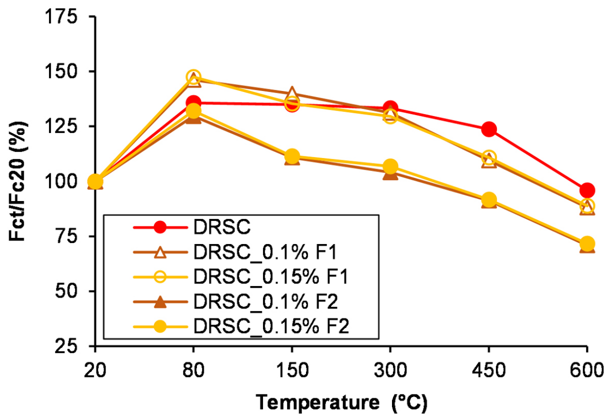
Figs. 12 (a) and (b) illustrates the residual compressive strength of mixtures DSC and DRSC with and without polypropylene fibers after exposure to 80, 150, 300, 450, and 600 °C, as well as at ambient temperature. It can be noted that the addition of polypropylene fibers, decreases the residual compressive strength for DSC and DRSC concretes, which has already been observed and discussed several times in the literature. Hager [41], Pliya [42], Yermak [43] and Karahan [29] concluded that this decrease can be linked to the degradation of the microstructure of the cement paste and aggregates as well as that of water. Moreover, DSC exhibits a greater decrease in strength compared to DRSC, regardless of the presence of PF. The influence of the length and the rate of PF on the decrease of compressive strength becomes more marked at 600 °C.

The residual mechanical strengths of the two mixtures, DSC and DRSC, are equivalent. In terms of the relative resistance to compression, two broad types of behavior for concrete have been distinguished. Fig. 12 illustrates the presence of two distinct stages in the correlation between residual strength and temperature. In the first stage, which has a temperature range between ambient temperature and 150 °C, then up to 300 °C, a slight rise in residual resistance was detected for DSC and DRSC concretes with and without fibers. For 80 °C, the increase in residual strength for concretes DSC, DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2, DSC_0.15%F2 was 18.35%, 4.92%, 8.28%, 6.12%, and 5.97% respectively, and for concretes DRSC, DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, DRSC_0.15%F2 were respectively 35.76%, 46.13%, 47.55%, 29.67%, and 32.15%. This rise in strength can be explained by the evaporation of free pore water before 150 °C, the rehydration of CSH (calcium hydrates) during water migration and condensation towards cooler regions of the specimens, and the formation of siloxane (Si-O-Si) bonds. These factors contribute to the extraction of the paste and the enhancement of resistance [27, 41–43, 47]. For DSC with fibers, the melting of fibers after 160 °C creates an additional vacuum for the circulation of water vapor, thus decreasing the vapor pressures inside the material and affecting the improved performance of dune sand concrete [27, 43]. In the second stage, which ranges from 450 to 600 °C, all mixtures with fibers lose more than 35% and 10% of their initial strength for DSC and DRSC respectively. At temperature 450 °C, the decrease in the relative compressive strength of concretes with fibers DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2, DSC_0.15%F2, DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, and DRSC_0.15%F2 is respectively 36.45%, 35.31%, 36.01%, 37.30%, 3.46%, 1.54%, 12.18%, and 11.53%. While concretes without fibers DSC and DRSC present an increase of 1.53% and 23.79% respectively. Also, at 600 °C, the decrease in the relative compressive strength of concretes DSC, DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2, and DSC_0.15%F2 is respectively 12.03, 41.07 %, 39.66 %, 37.65 %, and 38.53 %, while for DRSC, DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, and DRSC_0.15%F2 it is respectively 4.16 %, 11.92 %, 11.09 %, 29.06 %, and 28.41 %.

This decrease in resistance is due to the appearance of cracks [29, 42, 47]. Additionally, this decrease is explained by the decomposition of portlandite into free lime according to the reaction: $Ca(OH)_2 \rightarrow CaO + H_2O$ [29, 41, 43, 48]. Research has established a temperature range for the degradation of portlandite between 450 °C and 550 °C. It is important to mention that in the context of siliceous concrete (utilizing siliceous aggregates), the conversion of α quartz to β quartz is observed within the temperature range of 573 °C to 579 °C, resulting in a decrease in concrete strength [41].



(a)



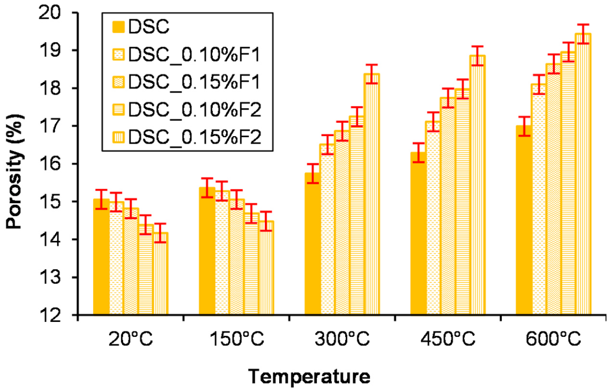
(b)

Fig. 12 Residual compressive strength of sand concrete with different fiber volumes at different temperatures (a) Sand concrete DSC, (b) Sand concrete DRSC

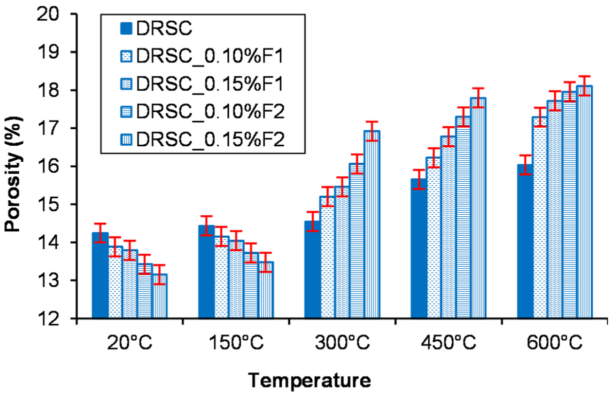
3.4 Porosity

Figs. 13 and 14 display the porosity results of dune sand concrete (DSC) samples before and after being subjected to high temperatures. The data illustrates a direct correlation between the rise in temperature and the increase in concrete porosity.

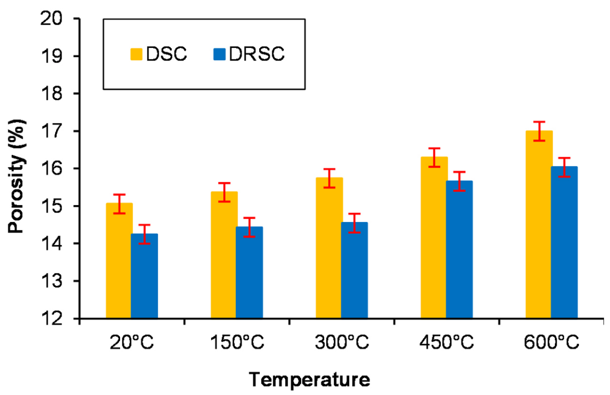
Figs. 13 (a), (b), and (c) shows that the porosity of concrete DRSC (50% DS + 50% RS) with and without fibers is lesser than that of concrete DSC (100% DS) in the same conditions. A low level of porosity serves as the most effective protection for concrete against various harmful agents, confirming the impact of the granulometric correction to dune sand on the granular composition of the DRSC mixture, where the number of large pores has been decreased and, consequently, the porosity also decreased and the compactness of the internal structure of concrete increased. Fig. 13 (c) presents the improvement in porosity of mixture DSC without fibers compared to mixture DRSC which is 5.38%, 6.06%, 7.58%, 3.91%, and 5.64% for each of the temperatures 20, 150, 300, 450, and 600 °C respectively. Between 20 °C and 150 °C, very little change in the porosity accessible to water is observed. For concrete with fibers, the porosity varies little compared to concrete without fibers. This small variation can also be linked to the dehydration of hydrated calcium silicates. According to Figs. 14 (a) and (b), the length of polypropylene fibers used in concrete can affect the material's porosity. It can be noticed that fibers have a positive effect on the porosity of concrete, especially short ones. The concretes reinforced by 0.15%F2 recorded the largest reduction, with 5.89% and 5.77% for DSC, and 7.66% and 6.61% for DRSC at 20 °C and 150 °C respectively. This is because shorter fibers have a higher surface area per unit volume compared to longer fibers. This increased surface area can lead to more inter-contact with the cement paste, which can help reduce the porosity of the concrete. These findings align with Pliya's research [42] on the impact of fiber type and quantity in heated concrete. Pliya used three different amounts of polypropylene fibers (1, 1.5, and 2 kg/m^3) and found that adding polypropylene fibers did not alter the porosity evolution curves. A decrease in porosity was observed between 50 °C and 150 °C with fiber volumes of 1 and 1.5 kg/m^3, while an increase in porosity was noted with 2 kg/m^3 of fibers. Several researchers have noticed that incorporating polypropylene fibers into ordinary concrete leads to an increase in porosity [41, 42]. Above 300 °C, a significant rise in porosity is evident in all concrete samples, regardless of the presence of polypropylene fibers (Figs. 14 (c) and (d)). At 600 °C (Fig. 14 (e)) the increase in porosity for DSC and DRSC with 0.15%F2 was of 14.37% and 12.95% respectively. Between 573 and 575 °C, the changes in texture and mineralogy of quartz sands are observed showing either an increase in porosity or a loss in strength [43, 49]. This rapid increase in porosity can be due as well to the decomposition of the portlandite in cement, and the allotropic changes of quartz α to quartz β in dune and river sands, which contain more than 90% silica. Moreover, at this stage, the effect of fibers becomes negative in terms of porosity; the higher the percentage of fibers or the shorter their length, the greater the porosity, this is due



(a)



(b)



(c)

Fig. 13 Porosity of dune sand concretes at different temperatures: (a) DSC with and without fibers, (b) DRSC with and without fibers, (c) DSC and DRSC without fibers

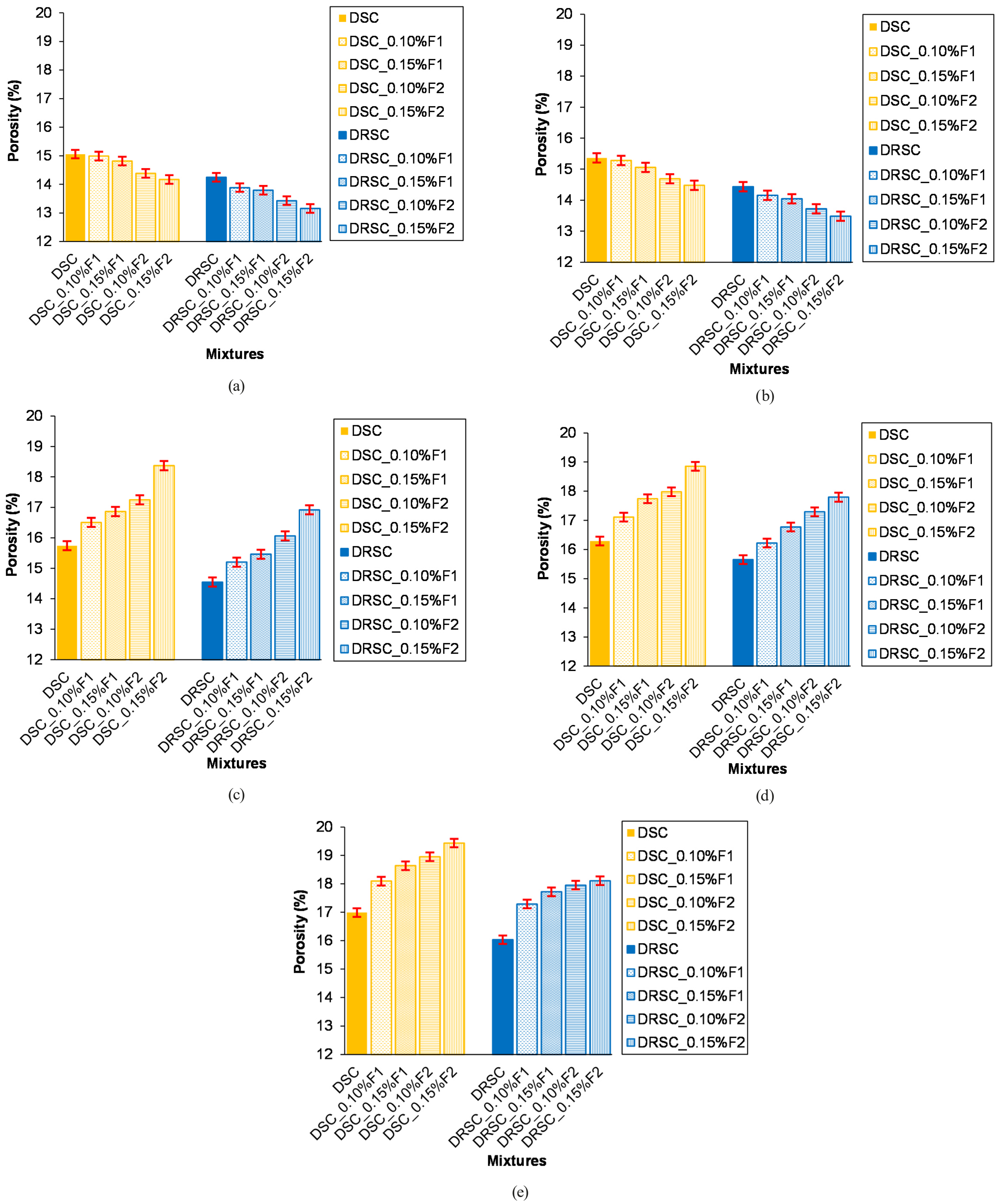


Fig. 14 Porosity of dune sand concretes DSC and DRSC with and without fibers at different temperatures: (a) 20 °C, (b) 150 °C, (c) 300 °C, (d) 450 °C, (e) 600 °C

to the short fibers having a larger surface area compared to the same percentage of longer fibers, and thus when melting, they leave more voids.

3.5 Weight loss

The results of the weight loss of dune sand concrete (DSC) specimens are plotted in Fig. 15. For temperatures below 80 °C, it is observed that all mixtures DSC experience higher weight loss compared to mixtures DRSC under the same conditions (fiber length, fiber volume, and heating temperatures). According to Figs. 15 (a), (b), and (c), the difference in mass loss between mixtures DSC and DRSC is 64.77%, 70.12%, 67.55%, 68.53%, and 65.66%, for fiber percentages 0%F, 0.10%F1, 0.15%F1, 0.10%F2, and 0.15%F2 respectively. This may be due to the nature of the concrete, made with only dune sand, and it is known that it requires a large amount of mixing water compared to river sand, which was used for granular correction in the mixture DRSC. At temperatures above 150 °C up to 600 °C, both mixtures DSC and DRSC take the same shape of the curve and are close, which is due to the free water and bound water present in the samples being completely removed at 150 °C. Several authors [15, 41, 43, 47, 50] confirm that beyond 120 °C free water is completely removed from the concrete specimen. The weight loss is more significant in the DSC reinforced with PF compared to those without fibers. Figs. 15 (b), (c), (d), and (e) also show that the weight loss is greater in dune sand concrete with 0.15% PF compared to those with 0.10% PF. It was also found that DSC mixtures reinforced with F1 fibers exhibit lower weight loss for most temperatures, compared to mixtures containing F2 fibers with fiber volume fractions of 0.10% and 0.15%. Figs. 15 (d) and (e) shows concretes DSC and DRSC with and without fibers, the difference in weight loss between fiber-reinforced concretes and concrete without fibers (control) at 600 °C, is 12.64%, 19%, 52%, 10.07%, and 11.43% respectively for the mixtures DSC_0.10%F1, DSC_0.15%F1, DSC_0.10%F2 and DSC_0.15%F2, while for the mixtures DRSC_0.10%F1, DRSC_0.15%F1, DRSC_0.10%F2, and DRSC_0.15%F2, the results are 8.27%, 19.39%, 6.78%, and 19.59% respectively. The inclusion of fibers in the concrete has resulted in the formation of preferential channels that enhance the water elimination process, a phenomenon that becomes more pronounced as the fiber percentage increases. These findings align with those documented by Hager [41] and Pliya [42].

4 Conclusions

This study investigates how polypropylene fibers impact the performance of dune sand concrete under high temperatures. From the experimental results, we concluded the following:

- Incorporating 50% river sand into the dune sand concrete mixture (composition DRSC) resulted in improved compressive strength at all heating temperatures and reduced porosity;
- The performance of polypropylene fibers at high temperatures is influenced by various factors including fiber length, dosage, and duration of exposure;
- The compressive strength of concrete reinforced with 0.15% polypropylene fibers was higher than that of concrete reinforced with 0.10%;
- For DSC and DRSC concrete mixes, the length of polypropylene fibers has a notable impact on compressive strength. Shorter F2 fibers enhance the fire resistance of concrete better than longer F1 fibers. The strength remained superior to the control sample without fibers at temperatures ranging from 20 °C to 300 °C. However, a decrease of 38% and 28% was observed for DSC_0.15%F2 and DRSC_0.15%F2, respectively, after exposure to 600 °C;
- Up to 300 °C, fiber-reinforced dune sand concrete has good mechanical resistance. This is caused by an increase in internal pressure in the concrete, which can play a prestressing role;
- Dehydration is one of the main phenomena caused by increasing temperature. The dehydration reaction gradually involves various aqueous products that form concrete, such as portlandite ($CaOH_2$) and calcite ($CaCO_3$). The decomposition of these mineral phases, after overheating, is among the important reasons which are at the origin of the decrease in the mechanical strength of concrete;
- The presence of fibers in dune sand concrete has a positive role before melting because it reduces porosity. However, after melting, their presence becomes negative due to increased voids in the mixture, leading to increased cracking;
- The impact of polypropylene fibers on porosity is positive within the temperature range of 20 to 150 °C. This positive trend is consistent for both short fibers (F2) and fiber dosages (F1 and F2) at 0.15%. However, beyond 150 °C, the effect changes direction, leading to an improvement in porosity with increasing temperatures;
- The main cause of deterioration and damage to the building is the loss of water. Weight loss is higher for fiber-reinforced dune sand concrete compared to concrete without fibers. The quantity of fibers appears to be the most crucial factor in weight loss.

This study focuses on the valorization of dune sand, used in the formulation of sand concrete at a rate of 50%. It highlights the importance of incorporating polypropylene fibers in dune sand concrete. The results provide valuable information for the development of more durable and fire-resistant concrete structures.

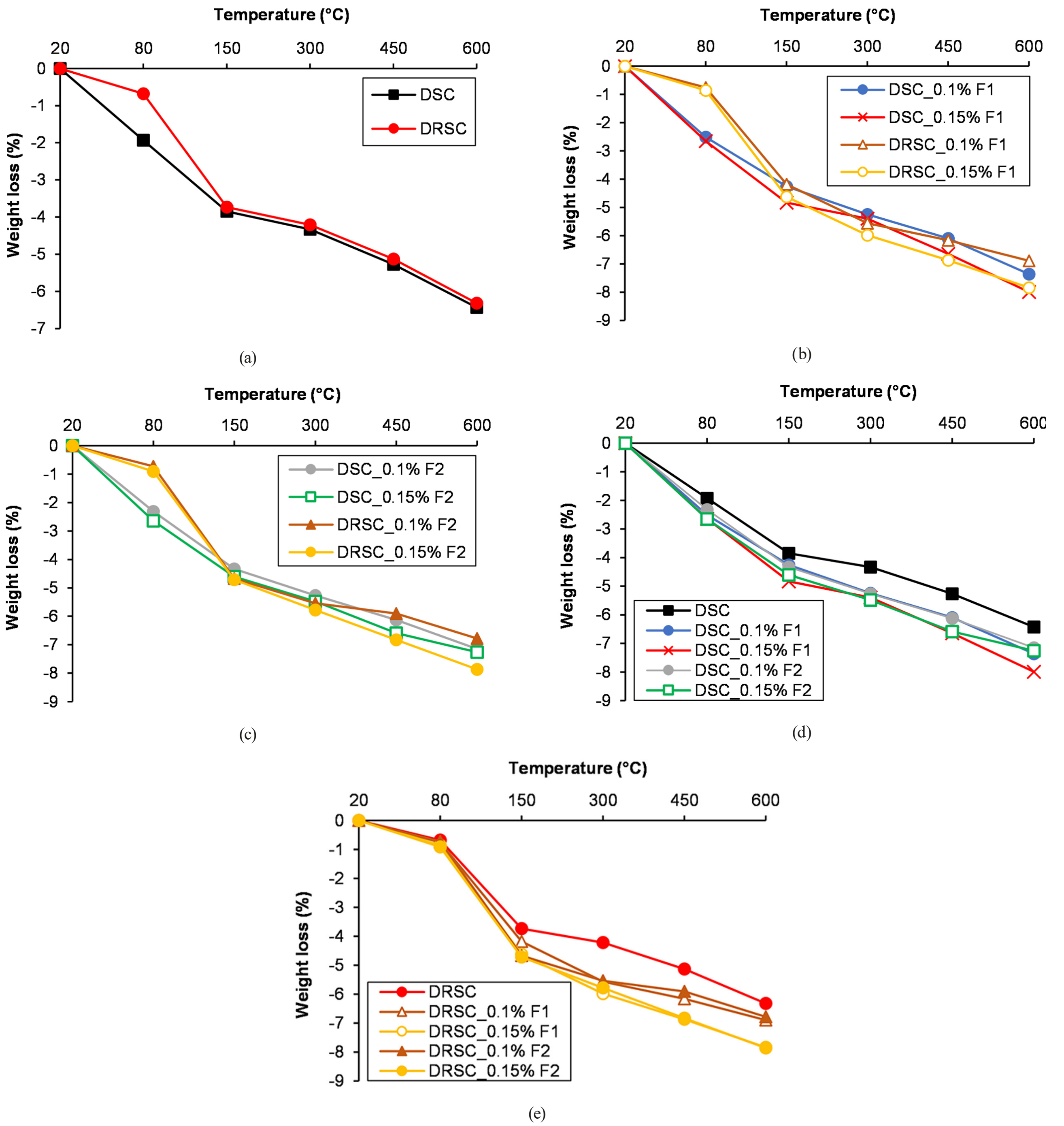


Fig. 15 Weight loss at different temperatures: (a) SDC DSC and DRSC without fibers, (b) SDC DSC and DRSC with fibers F1, (c) SDC DSC and DRSC with fibers F2, (d) SDC DSC with and without fibers, (e) SDC DRSC with and without fibers

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