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Effects of Polypropylene and Date Palm Fiber Reinforcements on High Performance Concrete at Elevated Temperatures and Their Impact on Spalling Phenomena

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Abstract

Concrete, a widely utilized construction material, faces challenges related to thermal instability when exposed to fire-induced temperature variations. To address the issue of explosive spalling, common concerns in concrete, polypropylene fibers, recommended by Eurocode 2, are added to the mix. This study aimed to evaluate alterations in physical and mechanical properties of high-performance concrete incorporating various fibers, including polypropylene and palm tree waste as an eco-friendly alternative to conventional fibers. The incorporation of palm fibers aligns with the promotion of local materials for their potential affordability due to local abundance. The assessment involved four high-performance concrete formulations tested under high-temperature conditions: SF (silica fume without fibers), SFPP (silica fume with polypropylene fibers), SFDF (date palm fibers with silica fume), and SFPPQS (polypropylene fibers with quarry sand, siliceous sand, and silica fume). Destructive and non-destructive evaluations encompassed compressive strength, flexural strength, ultrasonic pulse velocity, and mass loss. Experimental tests were conducted at room temperature (20°C) and elevated temperatures (250°C, 450°C, and 650°C). Results revealed a decline in both compressive and flexural strength for samples exposed to temperatures above 450°C. Notably, the inclusion of date palm fibers mitigated mass losses while exhibiting a lower compressive strength.

Keywords: High Performance Concrete. Polypropylene Fibers. Silica Fume. High Temperature. Spalling. Date palm fibers.

1. Introduction

The Performance and attributes of structures may degrade over time owing to exposure to numerous environmental variables. Fire is one of these variables that presents a very high risk to human safety. Liu *et al. (*2022) and Sogbossi (2020) found that when concrete is heated to 400 degrees Celsius, its strength significantly decreases. Nuruddin *et al*. (2014) and Guergah *et al*. (2021) found that if temperatures rise over a certain threshold, structural components suffer a substantial loss of strength and may even scale, reducing their load capacity. According to Abed and Brito (2020) and Ali (2012), the loss of concrete's strength when heated comes from the chemical breakdown of the bonding components. Increased interstitial water pressure, the breakdown of calcium-hydrate silicate gel (CSH), and thermal incompatibility between cement paste and granulates all play a role in concrete's weakening when it is subjected to fire.

In order to improve the strength and ductility of concrete, the development of fiber-reinforced concrete has been undertaken. The incorporation of fibers into concrete has been shown to have a substantial impact on the behavior of fiber-reinforced concrete when subjected to elevated loads and temperatures (Li *et al*., 2005). The materials often used for the purpose of reinforcing concrete include steel, glass, polymer, and basalt fibers (Savastano *et al.,* 2009; Arisoy *et al*., 2008). Various kinds of reinforcing fibers may impart distinct features (Wu *et al.,* 2020). The inclusion of steel fibers or basalt fibers has the potential to enhance several properties of concrete, including but not limited to its tensile strength, deformation capacity, strength, and energy absorption capacity (Ríos *et al*., 2019; Zheng *et al*., 2013). In contrast to conventional concrete, fiber-reinforced concrete exhibits elevated levels of compressive and tensile strength (Kang *et al*., 2016; Larisa *et al*., 2017), enhanced fracture toughness (Khan *et al*., 2016; Solhmirzaei *et al*., 2017), and exceptional resistance to impact (Yang *et al*., 2018; Ma *et al*., 2015). Fiber-reinforced concrete is extensively used in many engineering applications due to its exceptional material qualities.

At now, steel fiber is extensively used as a reinforcing material in concrete structures owing to its exceptional structural characteristics (Jyotsna and Srinivasa, 2015). Nevertheless, the durability properties, namely corrosion resistance, of fiber-reinforced concrete containing steel fibers are a significant disadvantage, emphasizing the need of exploring alternative fiber materials (Kazmi *et al.,* 2019). However, the use of polypropylene fibers in fiber-reinforced concrete is a potential solution to address the limitations associated with steel fiber-reinforced concrete. In recent years, there has been significant progress in the field of integrating polypropylene fibers into concrete, as shown by extensive study (Kazmi *et al*., 2018; Kaufmann., 2017).

Due to its cost-effectiveness, the use of polypropylene in concrete not only enhances its durability, but also renders polypropylene fiber-reinforced concrete a cheaper alternative compared to other types of fiber-reinforced concretes (Kazmi *et al.,* 2018). Additionally, it should be noted that polypropylene fiber has a very low melting point. Consequently, when integrated into concrete and exposed to elevated temperatures, the fiber will undergo a melting process, thus facilitating the formation of channels via which water vapor may escape. The aforementioned activity results in a decrease in the internal vapor pressure, hence safeguarding the microstructure of the concrete (Wu *et al*., 2020). Furthermore, it has been shown that the application of heat to polypropylene fiber might potentially enhance the concrete's resistance to scaling, as indicated by previous studies (Mindeguia *et al*., 2010). However, the production of these fibers necessitates the use of chemical compounds that do not meet the criteria of sustainable materials.

Several research projects have been conducted to investigate the viability of integrating plant waste into concrete, with the aim of substituting cement and aggregates, as well as reinforcing fibers (Mo *et al*., 2016). The use of natural fibers is increasingly being recognized as a viable option, presenting an alternative to traditional fibers in the composition of cement mixes and concrete.

The use of natural fibers in concrete is particularly relevant in developing nations and regions that need cost-efficient building techniques. Existing literature has shown that the use of natural fibers in concrete has the potential to enhance its resistance to cracking, strength, and performance after cracking. Nevertheless, the use of natural fibers in concrete has challenges in terms of durability when exposed to alkaline conditions (Claramunt *et al.,* 2011).

An oasis region of the Sahara cultivates date palms. Originating in North Africa, this plant is cultivated extensively throughout Arabia and the Persian Gulf, where it is characteristic of oasis vegetation. Additionally, the southern United States, the northern Mediterranean, and the Canary Islands are home to this species. This plant is tolerant of a wide range of soil conditions, as long as they are fruitful and well-drained. It is cultivated in sunny locations outdoors in temperate climates, primarily for its slender appearance and foliage (Kriker *et al*., 2005). Algeria's oases are home to more than 800 species of date palm. Local names for the most well-known varieties include deglelette Nour, Dokar (mal palm), elghaers, and deglabida (Kriker *et al.,* 2005).

In this study, polypropylene and date palm fiber-reinforced high-performance concrete (HPC) was developed, four different mixes were made for studying effects of polypropylene and date palm fiber reinforcements on high performance concrete at elevated temperatures and their impact on spalling phenomena.

2.Experimental program

2.1 Materials used

Portland cement (CPJ CEM II/A 42.5) was used as the cementitious material in this study. Table 1 shows the physical properties and chemistry proprieties of the particles that were used. Table 2 shows the chemicals and Physical Characteristics of the cement. The crushed limestone aggregate sources in Algeria's Annaba area, the gravel grain size between 5 and 12.5 mm, 04 mm maximum size of quarry sand. Siliceous dune sand 0/2mm size from Tebbesa Algeria Region.

Table 1. The physical characteristics of the Aggregates used.

Physical properties	Unit	Siliceous sand	Quarry sand	Gravel
Size	mm/mm	0/2	0/5	5/12.5
Density	g/m^3	2.60	2.75	2.57
Sand equivalent	%	87.45	83.96	-
Finesse modulus	-	2.31	3.1	-

Table 2, Chemical, Physical and Mechanical Characteristics of Cement used.

Chemical composition (%)		Physical Characteristics		
SiO_2	23.45	Apparent Density	g /cm^3	1.04
Al_2O_3	4.86	Absolute Density	g /cm^3	3.08
Fe_2O_3	3.20	Initial Setting	h/min	2/34
CaO	60.80	Final setting	h/min	3/36
MgO	1.00	Tensile Strength	MPa	7
SO_3	2.20	**Compressive Strength (MPa)**		
Na_2O	0.1	2 Days	MPa	19.04
K2O	0.45	7 Days	MPa	38.93
Cl-	0.05	14 Days	MPa	47.42
CaOl	0.9	28 Days	MPa	53.47

The TEMPO-12 super plasticizer was used in this study. It is a strong superplasticizer that gives concrete many useful features, such as longer rheology (over 2 hours), resistance to segregation, better surface quality, and high-water reduction. It's fabricated from the Algerian company Sika El-Djazair, and it is highly suggested for high-performance concrete (HPC). Key features of this superplasticizer are shown in Table 3. A rate of 1.8 kg/m^3 of polypropylene fibers were added to the SFPP and SFPPQS mixes, along with scientific information from the maker. According to NF EN 13263-1, silica fume is a mineral addition that is used in hydraulic concrete mixes. It makes the concrete structurally stronger and lasts longer. It is sold by the Algerian company Caracala Quartz Production Tebessa.

Table 3. Super plasticizer characteristics.

Properties	Unit	Value
Shape	-	Liquid
Color	-	light brown
PH	-	4.5 ± 1.0
Density	g/m^3	1.06 ± 0.01
Total chloride ion content	%	0.1
Sodium oxide	%	1.0

Table 4 shows what chemicals are in it and what its physical qualities are. The male date palm's skin was used to get the natural fibers used in this study. Naturally knitted, these date palm fibers on the outside can be removed from the trunk in the shape of a nearly rectangle mesh made up of layers on top of each other. In water, they are easy to split into their own fibers.

Table 4. Chemical composition and physical properties of silica fume.

Physical characteristics	Unit	Cement GPJ
Apparent density	g /cm^3	1.51
Absolute density	g /cm^3	2.64
Sand equivalent	%	87
Silica Content SiO_2	%	97.54
Iron Oxide Content FeO_3	%	0.21
Aluminum Oxide content Al_2O_3	%	0.10
Sand absorption SAb	%	3.86
Sand friability SF	%	18
loss on ignition	%	0.12

List of these fibers' physical and mechanical features can be found in Table 5. For SFDF mixes, 1.8 kg/m^3 of date palm fibers were added.

Table 5. Mechanical properties of date palm fibers.

Property	Lower-upper
Diameter(mm)	0.1 - 1
Tensile Strength (MPa)	285 ± 15
Apparent density (kg/m^3)	512.21-1088.81
Absolute density (kg/m^3)	1300-1450

2.2 Making and curing specimens

The various concretes are created in a laboratory setting. For four classes of concrete designated SF, SFPP, SFDF, SFPPQS, the concrete was cast in metal moulds of cubical form (10 x 10 x 10) cm^3 and (15x15x15) cm^3 accordingly. Table 6 shows the mix proportions for each concrete. To minimize evaporation, all specimens were covered immediately after being made. The specimens were taken from the moulds after 24 hours and kept in water for 28 days. After that, the various concretes were kept in excellent condition in the LAB for one year.

Table 6. Mix Proportion of Concrete.

MIX	SF	SFPP	SFDF	SFPPQS
W/L	0.27	0.27	0.27	0.27
Liant kg/ m^3	546	546	546	546
Cement kg/ m^3	490	490	490	490
Water kg/ m^3	150	150	150	150
Sand Siliceous kg/ m^3	369	369	369	184.5
Quarry Sand kg/m^3	369	369	369	553.5
Gravel kg/ m^3	1070	1070	1070	1070
SP kg/ m^3	7.34	7.34	7.34	7.34
PP Fiber kg/ m^3	-	1.8	-	1.8
DP fiber kg/ m^3			1.8	

SF: High performance concrete with Silica fumes.
SFPP: High performance concrete with Silica fume included the addition of polypropylene fibres.
SFDF: High performance concrete with Silica fume included the addition of Date Palm fibres
SFPPQS: High performance concrete with Silica fume and polypropylene fibres based on Quarry sand.

Three specimens from each mixture were subjected to thermal treatment in a furnace Figure 1, whereby the temperature was increased from the initial room temperature of (20±2) °C to three different levels: 250°C, 450°C, and 650°C. The heating process was conducted either for a duration of 1 hour or at an average rate of 7°C per minute. The peak temperatures were sustained for a duration of one hour. The Heating and Cooling curve for the oven is seen in Figure 2.

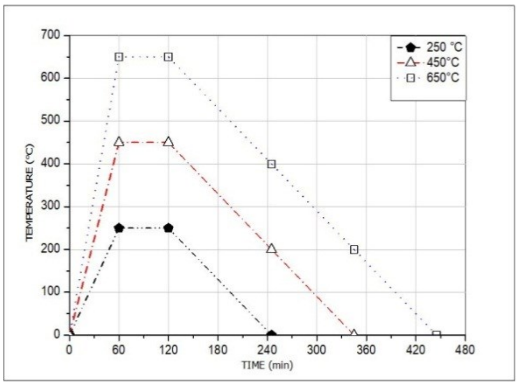

Figure 1. Curves of heating and cooling as a function of temperature.

Figure 2. B 180 Naberthen /furnace.

3. Results and discussion

3.1. Residual Compressive Strength

The impressive residual compressive strength of concretes at room temperatures (20+2) °C and even after heating to 250, 450, and 600°C are beautifully showcased in Figure 3, This figure effectively demonstrates the outcomes of residual compressive strength tests conducted at various temperatures, with the data succinctly compiled in Table 7.

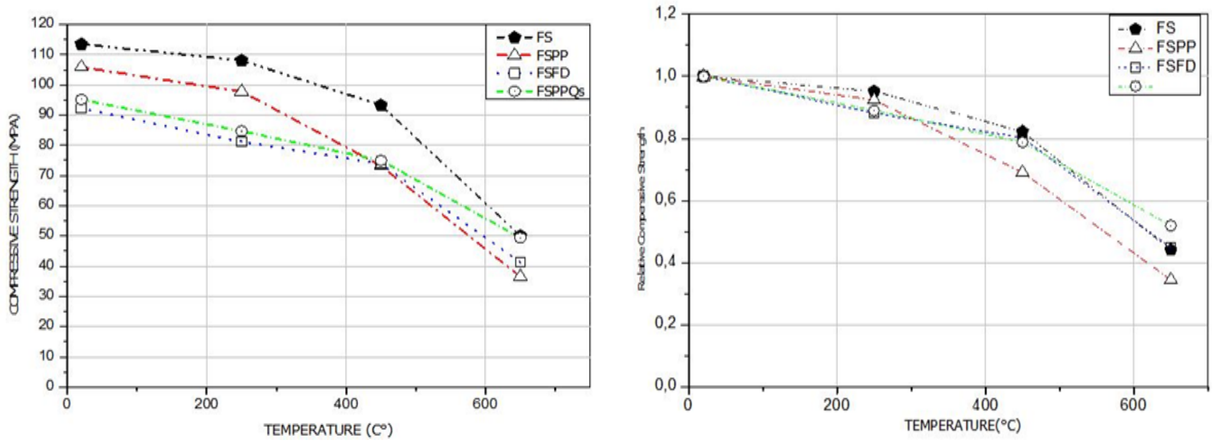

Figure 3. Residual Compressive Strength as Function of Temperature.

Table 7. Compressive Strength Test at Different Temperature.

	Compressive Strength (MPa)			
	20	**250**	**450**	**650**
FS	113.500 (100%)	108.100 (95.24%)	93.310 (82.21%)	50.060 (44.11%)
FSPP	105.920 (100%)	97.810 (92.34%)	73.210 (69.12%)	36.560 (34.52%)
FSFD	92.120 (100%)	81.260 (88.21%)	73.910 (80.23%)	41.300 (34.83%)
FSPPQs	95.170 (100%)	84.700 (89%)	75.010 (78.82%)	49.400 (51.91%)

Within the initial temperature range of 20 to 450°C, there was an observed decrease in the compressive strength of all concrete specimens, ranging from approximately 4-12% at 250°C, compared to the control specimens at 20°C. As indicated in Figure 3, within this specific temperature range, the mechanical performance of High-performance concrete with Silica fume (FS) and High-performance concrete with polypropylene (PP) fiber at elevated temperatures is markedly superior to that of High-performance concrete with date palm fiber (FD) and High-performance concrete with quarry sand (QS) dosage.

Various theories have been proposed in existing literature to elucidate the increase in compressive strength around the 250°C. The removal of moisture from the cement gel interlayer is thought to minimize disjoining pressure and enhance banding forces between hydration product particles, hence increasing concrete compressive strength (Ali *et al.,* 2009). The improvement in compressive strength of specimens exposed to 400°C might be attributed to a shorter time of high temperature exposure (Gai-Fei *et al*., 2006). Furthermore, the specimens' high temperature increased the hydration process (Benzaid & Benmarce, 2017).

The compressive strength of concrete steadily decreases as the temperature rises between 450°C and 650°C, highlighting the crucial significance of this temperature range in terms of the weakening of concrete's strength. The findings demonstrate that the initial compressive strength of the concrete at 20°C stays consistent at 77.60% when subjected to a temperature of 450°C. However, it declines to 43.83% when exposed to a temperature of 650°C. Various variables contribute to the decline in compressive strength. Initially, heightened temperatures cause a significant quantity of water to evaporate quickly, which is crucial for the hydration process of concrete. The early evaporation hinders further hydration and the subsequent growth of strength. Furthermore, the concrete samples experience substantial internal pressures due to the vapor generation. The application of high forces may lead to the deterioration of the internal structure of the concrete, causing the formation of microcracks. Consequently, this weakens the material and decreases its ability to withstand compression. (Benmarce *et al.,* 2005).

3.2. Residual Flexural Strength

In Figure 4, the relationship between temperature variation and residual flexural strength is systematically presented. The graph clearly shows a consistent and linear decline in the flexural strength of the materials as temperatures range from 250°C to 650°C. In the lower temperature spectrum, from 20 to 250°C, there is a discernible reduction in the structural integrity of concrete variants containing FSPP and FSFD. Notably, after a slight initial decrease, there is a significant drop, by approximately 58%, in the residual flexural strength at a heightened temperature of 650°C. This substantial incidence of micro and macro fractures within the specimens is presumably due to the thermal mismatch between the aggregates and the cementitious matrix, as detailed in the cited study (Hanaa *et al.,* 2009).

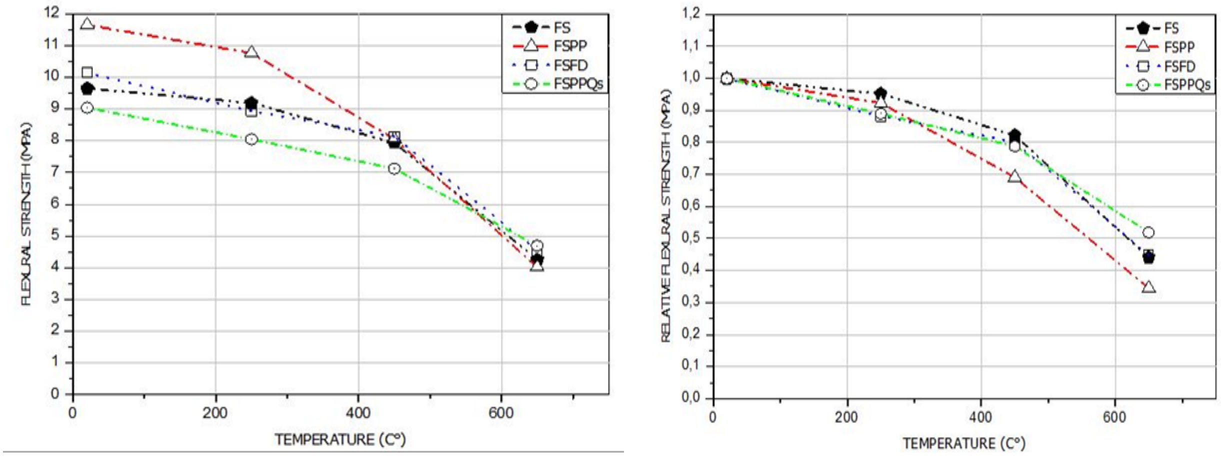

Figure 4. Residual Flexural Strength as Function of Temperature.

3.3. Ultrasonic Pulse Velocity (UPV)

Previously, the weakening of mechanical properties in heated concrete has been attributed to the development of cracks and fissures, caused by physicochemical transformations within the cement paste and a mismatch in thermal properties between the aggregate and the cement paste, as detailed by Sofren &Horiguchi, 2006). This study utilized the Ultrasonic Pulse Velocity (UPV) test to assess both the elastic modulus and the density of the material. Specifically, the UPV test was employed to ascertain the integrity of SF SFPP, SFDF, and SFPPQS specimens. Figure 5 illustrates the degradation of concrete as measured by ultrasonic pulse velocity. Notably, in the temperature range from 150°C to 650°C, there is a gradual reduction in UPV values, which might signify the incremental formation of microcracks within the concrete structure.

The ultrasonic pulse velocity of concrete specimens exhibits a reduction of 10% for FSPP specimens, and a reduction of 12% for SF specimens SFDF, and SFPPQS when exposed to a temperature of 250°C. Furthermore, all specimens experience a significant drop of 58.5% in ultrasonic pulse velocity when subjected to a temperature of 650°C. As previously mentioned, high performance concrete with different dosages demonstrates a consistent reduction in ultrasonic pulse velocity. The findings suggest that the attributes and properties of the specimen deteriorate when subjected to higher temperatures.

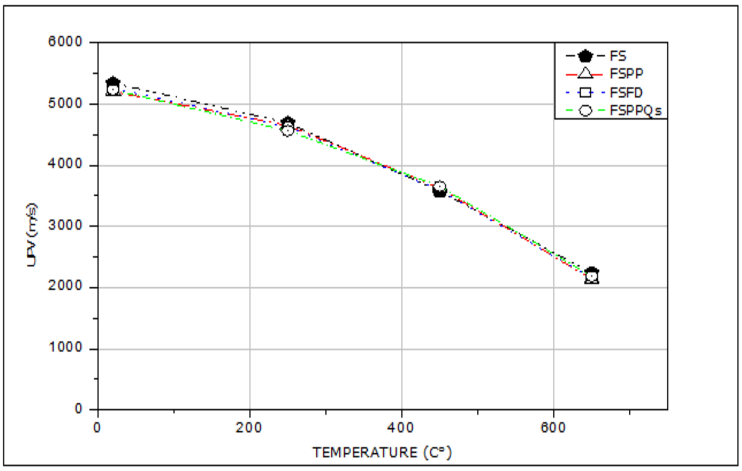

Figure 5. Ultrasonic Pulse Velocity as Function of Temperature.

3.4. Mass Loss

The masses of the cube specimens were measured both before and after being subjected to high temperatures in order to assess the extent of mass loss. Figure 6 illustrates the impact of increased temperature on the reduction in mass of concrete specimens. The image illustrates a strong correlation between the development of mass loss and temperature for the four concrete samples under investigation. This may be attributed to the sufficient duration provided for the water to dissipate from the concrete specimens. Across all examined specimens, there is a clear pattern of increasing mass reduction that corresponds to higher temperatures.

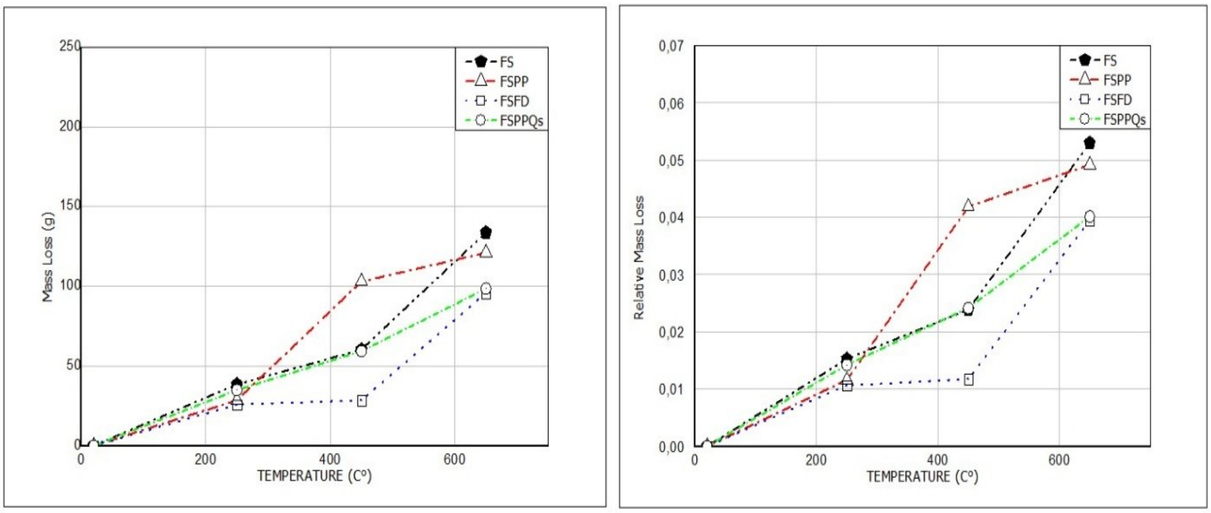

Figure 6. Residual Mass loss as Function of Temperature.

The relationship between mass loss and exposure temperature in the studied materials can be categorized into three distinct phases. In the initial phase, from ambient temperature up to 100°C, there is a minimal variation in mass, primarily attributed to the evaporation of free water from the capillary pores. As the temperature escalates to 450°C, there is a notable increase in mass loss, amounting to 4.2% for the FSPP specimens and 2.35% for both FSFD and FSPPQS specimens. This significant loss of mass in this temperature range is largely due to the expulsion of water from both the capillaries and the gel structure within the concrete (Mohammad *et al*., 2018). Above 600°C, there is another escalation in the rate of mass loss. This increase is likely attributable to several factors, including the decomposition of calcareous aggregates, the emission of CO_2, and the spalling or disintegration of the concrete surface, as indicated in studies by Jianzhuang *et al*. (2006) and Zhang *et al*. (2012). The FSFD mix experiences relatively less mass loss than the alternative mix, whereas the FS mix experiences greater mass loss than the others. At 650 C, a mass loos corresponding to 3.95 % for FSDF and FSPPQS and 5.02% for FS and FSPP of the initial mass was observed.

3.5. Spalling and cracking of concrete

A preliminary evaluation of probable damage resulting from exposure to high temperatures may be conducted by analyzing the exterior properties of the concrete surface. Thus, assessing fire-damaged concrete generally begins with a visual inspection of the concrete surface for color change, cracking, and spalling. Figure 7 depicts the concrete surfaces after being treated at high temperatures. The surface of the specimens heated to 250 °C showed no obvious change.

FS 250°C | FSPP 250°C | FSDF 250°C | FSPPQS 250°C

FS 450°C | FSPP 450°C | FSDF450°C | FSPPQS450°C

FS 650°C | FSPP 650°C | FSDF 650°C | FSPPQS 650°C

Figure 7. Concrete Surfaces after treatment at Elevated Temperatures.

Surface cracking in the concrete began to manifest at approximately 450 °C and progressively intensified with the increase in temperature up to 650 °C. Despite this, all types of concrete demonstrated effective resistance to spalling, with no visible spallation on the surfaces of the specimens even when heated to 650 °C. The failure of a heated concrete surface is most often caused by the growth of cracks parallel to the hot surface, the deterioration of concrete strength, and the decrease in the size of concrete pores (Sakr *et al*., 2005). Spalling may result in a significant impact on fire-exposed concrete, leading to a decrease in the load-bearing capability of a structure (Hertz & Sorensen, 2005). Furthermore, the phenomenon of explosive thermal spalling is defined as the sudden and forceful fragmentation of concrete, often occurring without any prior warning (Guergah *et al.,* 2018).

4. Conclusion

The following conclusions can be drawn from the experimental results:

- As the temperature rises, there is a continuous decrease in the compressive strength. At a temperature of 250 °C, the residual strength of SF and SFPP remains approximately 93.79%, while FSDF and FSPPQS retain 88.61% of the initial unheated value. Nevertheless, at 650 °C, the value decreases by 65.33% for SFPP and SFDF, and 55.69% for the SF mix. Conversely, the SFPPQS mix exhibits the lowest loss of compressive strength at 650 °C. This was in reference to the crucial QS aggregate present in its composition.
- The mass of the concrete specimens exhibited a notable decrease in correlation with the rise in temperature. The drop in mass gradually occurs until reaching a temperature of 650 °C, resulting in a comparable mass loss for all four types of concrete at 250 °C. At a temperature of 450 °C, there is a significant increase in mass loss of 4.2% for FSPP. The FSFD and FSPPQS components account for 2.35% of the original mass. At a temperature of 650°C, a reduction in mass of 3.95% was seen for both FSDF and FSPPQS, while FS and FSPP saw a reduction of 5.02% from their starting masses.
- The impact of elevated temperatures on the comparative durability of concrete was particularly noticeable for concrete mixes made with Quarry sand.
- Surface fractures were obvious in visual examination of concrete samples treated to extreme temperatures when the temperature reached 450 °C. At 650 °C, the fissures were fairly visible.
- No notable concrete spalling was observed on the concrete heated at 650°C after return to ambient temperature.
- Local material provides high mechanical and physical properties of high-performance concrete.
- Compared to polypropylene fibres, the use of date Palam fibers in concrete reduce mass losses while providing a lower compressive strength.
- The experimental results gained broadly align with the findings reported by the researchers in this study.

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