Hybrid Fiber Reinforced Cementitious Composites at Elevated Temperature: a Review

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Hybrid Fiber Reinforced Cementitious Composites at Elevated Temperature: A Review

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Abstract - Fire affects the concrete mechanical properties negatively and can significantly damage the microstructure. This can lead to considerable loss to the structure and deterioration of concrete, due to explosive exposure spalling of internal structure prone to fire, melting, burning, and thermal expansion of fibers at higher temperatures. The mechanical properties affected due to fire include compressive strength, mass loss, durability, flexural strength, internal microstructure, and tensile strength. The incorporation of fibers can counterbalance the drawbacks of concrete when subjected to higher temperatures. Different studies had been conducted on various several types of concrete when exposed to elevated temperatures. The main aim of this paper is to review the different properties of Hybrid fiber reinforced concrete (HFRC) at an elevated temperature of 800°C. Mainly the hybrid fibers reviewed include the incorporation of Polypropylene fiber and Steel Fiber. The objective of the present study is to examine the effect of elevated temperature on concrete mechanical properties. The properties reviewed include tensile strength, Mass loss, Microstructure of concrete, and Compressive strength. There was a direct correlation between the mass loss and the increase in temperature. The residual compressive strength of HFRC is increased with the incorporation of fibers like Steel and Polypropylene. The tensile strength is improved up to 300°C temperatures, but beyond 300°C, the tensile is affected negatively. The Microstructure is weakened due to heterogeneous expansion. The range of impacts of elevated temperature on the properties of HFRC has been discussed in detail in the present study.

Keywords - *Elevated Temperature, Hybrid Fiber Reinforced Concrete, Mechanical properties, Tensile strength, Mass Loss, Steel Fiber, Polypropylene Fiber, Basalt Fiber, $CaCO_3$ Whisker*

I. Introduction

Concrete should be sufficiently viable to resist long-lasting fires. Concrete behavior, when it is exposed to elevated temperature depends on mix proportions and constituents used in the cementitious matrix [1]. The surge of researchers on the research of different constituents in concrete reacting to elevated temperatures has been on the rise [2]–[7]. Civil protection is a critical issue especially against high-frequency-hazard I-e Fire. To get this into perspective, in Hengyang, China, an eight-story building collapsed after long exposure to fire [8].

Failure of concrete happens in progressive scaling: the microcracks upon exposure to elevated temperature scale up to micro cracks and the threat of building failure becomes more and more evident since the durability and mechanical properties change [9]–[12].

Various types of concrete have remained under study such as High strength concrete (HSC), Pulverized Fly ash concrete (PFAC) [13], and fiber-reinforced concrete (FRC)

[14] [15], and Hybrid fiber-reinforced concrete (HFRC) [16] [17]. The fire resistance (FR) of building materials is variable, but concrete, as compared to steel and wood, is excellent in fire resistance. There is no release of dangerous gases when concrete is subjected to elevated temperatures, but there is an appreciable irreversible change in the internal structure of concrete which is not detected without the help of standard tests, which can damage the structure performance and sometimes complete structural destruction. Various parameters for determining the performance of concrete are affected due to the impact of elevated temperatures, such as compressive strength, mass loss or weight loss, durability, internal structure, tensile strength, etc. Different specimens of different shapes and sizes are used to determine the performance at high temperatures [15]. Commonly in these tests, different sizes of rectangular prisms Cubes are used [18]. But it was found that the size of the specimen has significantly no impact on the concrete properties subjected to elevated temperature.

Several types of fibers are used in the HFRC in recent research, intended for improving the concrete properties including split tensile strength, impact response [19] [20], toughness, crack propagation prevention, plastic shrinkage, and drying shrinkage prevention [21]. Commonly used fibers are Polypropylene Fiber (PPF) and Steel Fiber (SF), Basalt fiber (BF), Coir fiber (CF), and Polyvinyl Alcohol fiber (PVA), Nylon fiber [22] [23] [24]. PPF improves split tensile strength, and flexural strength but not compressive strength while SF improves most of the concrete mechanical properties including tensile strength, impact resistance, flexural strength, ductility, and crack propagation prevention. Deterioration is examined in the concrete when exposed to elevated temperatures. In general, PPF has no effect on the residual compressive strength when elevated to elevated temperatures because of melting at 150°C. However, cracking is controlled, and tensile strength is improved because of incorporation of PPF length and better tensile strength, and better residual compressive strength is achieved by increasing the length of PPF fiber. The SF incorporation can enhance all the mechanical properties specifically an improvement in tensile and compressive strength of HFRC which is because higher thermal conductivity is offered by steel as compared to other cement constituents [25].

Various properties are reviewed in the present paper as these properties have much importance in the behavior of concrete. The properties that are reviewed in this paper include tensile strength, compressive strength, mass loss, and microstructure at elevated temperatures. The tensile strength of concrete is enhanced with the inclusion of fiber content or hybridization of fibers in the mix. The Compressive strength is also enhanced when hybrid fibers are added to the mix as compared to the control mix, however, the mass loss is higher in the mix containing the hybrid fibers because of melting or the creation of channels, for instance, the creation of channels due to the melting of concrete. The higher fibers volume fraction, the higher the mass loss at elevated temperature. There is minimum loss of mass when there are no fibers in the mix. The steel fiber remained effective in case of mass loss where there was a minimum mass loss at elevated temperature because of the reason that there is no melting in the case of steel fiber. There is a maximum mass loss in HFRC reinforced with short PPF when exposed to elevated temperature of 800°C [26].

The purpose of the present study is to review (HFRC) properties when subjected to elevated temperatures. The properties studied in this research include Tensile strength, Mass Loss, internal Microstructure and Compressive strength of HFRC when subjected to elevated temperature.

II. Tensile Strength of HFRC at elevated temperature

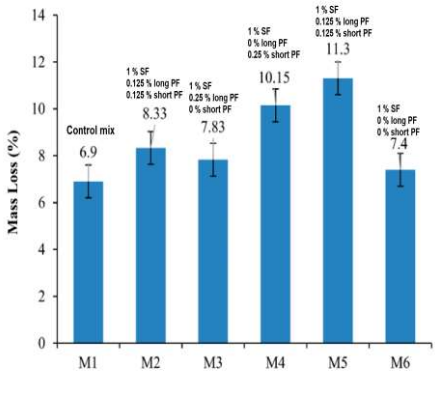
Tensile strength of concrete is of the utmost importance. Upon increase in temperature, PVA shows degrading tensile strength because when exposed to elevated temperature, it softens around 200°C and decomposes at 400°C. However, incorporation of steel fibers in the concrete hybrid mixture counter balances the tensile reduction by slowing down the rate of degradation [27]. [27] also discovered that addition of CaCO3 improves the tensile strength of HFRC at elevated temperature. [28] used steel fiber – polyvinyl alcohol hybrid combination and tested the tensile strength and concluded that the Hybrid Fiber Reinforced Concrete (HFRC) increases up till 200℃ mark but starts gradually decreasing up till 600℃. [29] discovered that the variations in tensile stress-strain curves mainly depend upon the macro fibers rather than the micro fibers. [30] found that by using steel and PPF fibers, the split tensile strength of HFRC decreases because of structure deterioration but the porosity of the HFRCC at elevated temperature increases. [31] took their sample, made of Steel and PPF fibers, up to 900℃ and concluded that the direct tensile strength and flexure strength has an inverse effect on temperature but in comparison with Ordinary Reinforced Concrete, the HFRCC shows much improved resistance capacity at elevated temperatures.

The Eurocode (EN 1992-1-2:2008/NA:2010P) [32] specifies that there is a linear decline in the concrete tensile strength when subjected to elevated temperatures from 100°C to about 600°C at which the concrete tensile strength is insignificantly lost at all, but not zero according to 600°C [33] [34]. A similar pattern for tensile strength after being subjected to elevated temperature has been observed in the compressive strength [35]. The decrease in tensile strength is much greater than the reduction in compressive strength [34] [36]. At an elevated temperature of 300°C, the tensile strength measured a 7% decrease for FRC. While in contrast to the Eurocode [32], there was a 31% residual tensile strength of FRC at 600 °C.

III. Mass Loss of HFRCC at elevated temperature

There is direct relation between mass loss, fiber content, and the temperature increase. With the increase in temperature, an increasing trend in the mass loss is observed with an increase of fiber content. This trend varies with the type of fiber used in the experimental study.

[26] examined the increase of mass loss with the temperature rise up to 800°C. The results for Mass loss (%) for beams showed that channels were formed in the concrete matrix due to the inclusion of PPF through which free water can be vaporized with ease. Increase in fiber content causes greater the mass loss which is illustrated in the *figure (1),* in which M5 mix shows highest mass loss of 11.3%. Mass loss affects the mechanical properties specifically the tensile strength because it is more susceptible to the voids. M1 which was control mix showed lowest mass loss of 6.9% as no channels were formed due to the absence of fibers. PPF with higher aspect ratio also showed lowest mass has with an increase of only 0.9% respective to M1.



PF: Polypropylene fiber, SF: Steel fiber

Figure 1: Mass of loss for beams [15]

However, PPF with shorter PPF caused channels linked to each other due to the melting of PPF which allows evaporation of capillary water and gel water due to which a greater mass loss of 3.25% respective to M1 was noted. Inclusion of only steel fibers also showed insignificant mass loss of 0.5% due to the reason that there is no melting of fibers at 800°C elevated temperatures.

With no spalling, the moisture loss leading to weight loss ratio of less than 10% was observed during the fire test. Whereas increased level of spalling was observed on the weight loss of above 15% [22].

[25] also compared the mass loss (%) in percentage as function of increasing temperature (T) is tabulated in the *table (1)*, which shows that there is higher mass loss in CSP3 mixes in comparison with the CS3 mixes.

Table 1: Mass loss (%) as a function of the temperature (T)

Temperature (°C)	*CS 3-30*	*CS 3-40*	*CSP 3-30 × 1*	*CSP 3-30 × 2*	*CSP 3-40 × 1*	*CSP 3-40 × 2*
300	4.1	4.4	4.7	4.6	4.7	4.9
600	6.8	7.1	6.8	6.7	7.2	7.4

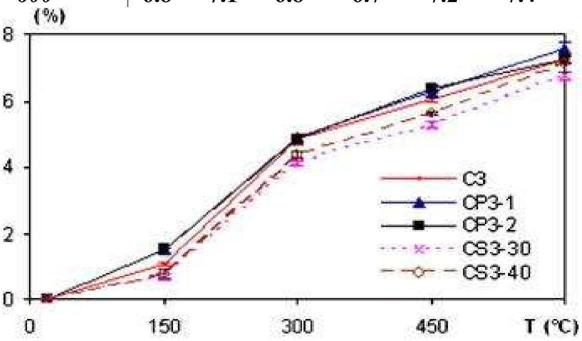


Figure 2: Mass loss of CS3 and CSP3 concretes as a function of temperature of 300°C and 600 °C [14]

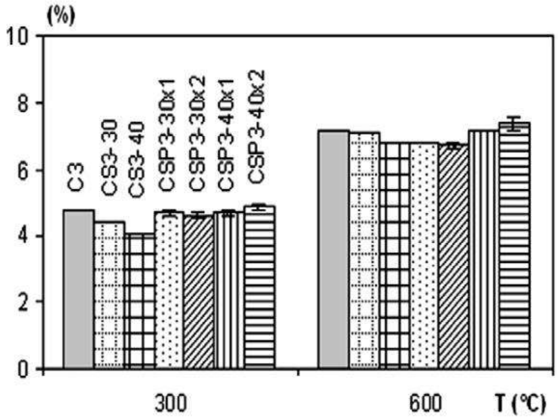


Figure 3: Mass loss of C3, CS3, and CSP3 concretes at elevated temperatures of 300°C and 600°C [14]

This is due to the propylene fiber which melts at elevated temperatures, but there are slight differences in the mass loss of both mixes. For instance, the mass loss in CS3-40 and CSP3-40 × 2 at 600°C is 7.1 and 7.4 respectively. The direct relationship of mass loss with time by increasing percentage of fibers in different mix is graphically illustrated in *figure (2)* and *figure (3)* respectively.

[37] studied the effect of mass loss due to the exposure of high temperatures and HC fluids and found that initially mass loss occurs because of free water evaporation at exposure to elevated temperatures. However lately, after the repeated exposure to HC fluids, the mass loss is due to the chemically bonded water evaporation, and the degradation of $Ca(OH)_2$ and C-S-H gel experimentally determined through XRD analysis and Thermogravimetric (TG) analysis.

IV. Microstructure of HFRCC at elevated temperature

Microstructure of concrete is quite intricate due to multi-phase heterogeneity present in the mix. It is constituted by the diverse amounts and different proportions of phases present in it [38]. The development of cracks in cementitious composites is a multi-level process. The micro crack in the beginning increases in size to macro level with time.

This is a serious threat to the durability [10] and mechanical properties of concrete [12]. The chemical changes in microstructure of concrete due to a small increase in temperature improves mechanical properties of concrete but further increase in temperature above specific threshold temperature will have detrimental consequence [1]. The bridging and reinforcing effect of whisker cease to exist when temperature is above 400℃ high (or elevated) temperature due to the weaker interface of CaCO3 whisker and the corresponding cement matrix [27]. [28] concluded that steel fiber, PVA fiber and CaCO3 whisker undergo chemical and physical changes upon inspection under SEM which effect the tensile and flexural properties of HFRC. [31] used Steel and PPF fibers in concrete, elevated it to 900℃ temperature, and concluded that the C-S-H gel is generated and hydration reactions speed up, making the microstructure of HRFC more densely packed. [39] found that Basalt Fibers (BF) in cause improvement in the mechanical properties up to 850°C by using BF of 50mm in combination with CaCO3 (22-30µm) whisker and Steel fibers of 35mm in their research. This is because of the strong bridging effect provided by the Basalt macro fibers. [40] also observed the creation of micro channels within the HFRC matrix under SEM which were preoccupied by Polymeric fiber which became empty due to melting caused by elevated temperature. This can be seen in the *Figure (4)*. Large tensile cracks (width about 5 µm) of PPF occur due to thermal expansion index (>21 10±5 /°C) which cause tensile strength depletion at elevated temperature of 180℃. [41] used PVA and Steel fibers in their mix and discovered that PVA melts at about 250℃ leaving voids in the HFRC matrix. This ultimately lowers the vapor pressure and as a result reduces spalling and mass loss. Better Thermostability of Steel fibers was also observed using SEM by [41]. [41] also factored that evaporation of water in capillary and gel pores due to increase in temperature (up till 200℃) does not negatively affect the internal microstructure of HFRC. The morphology of Reactive Powder Concrete (RPC) was tested by [42] at 400℃ and they discovered that a number of pores and meshy cracks appeared casing immense decrease in compressive strength.

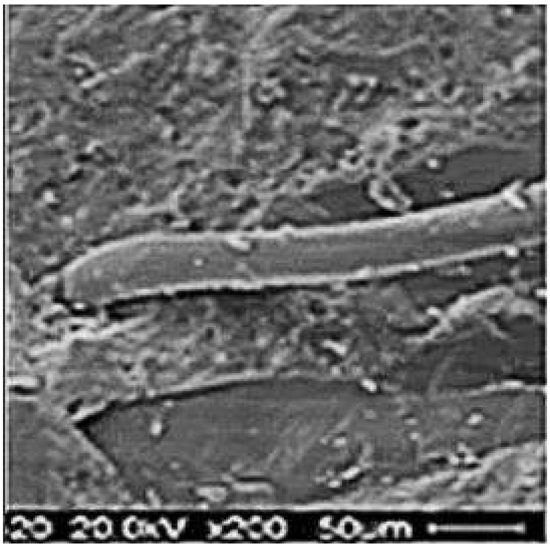


Figure 4: SEM Micrograph of Polypropylene Fiber at 20°C showing good behavior **[31]**

Figure 5: SEM Micrograph of signs microchannel creation of Polypropylene Fiber at 400°C **[31]**

As observed by the SEM figure in *Figure (5)* that the Polypropylene fiber holds its place shown in Figure 4 at normal temperature but when it is exposed to 400°C, the PPF fibers melt-creating a channel for water vapors to transit through shown in *figure (5)*.

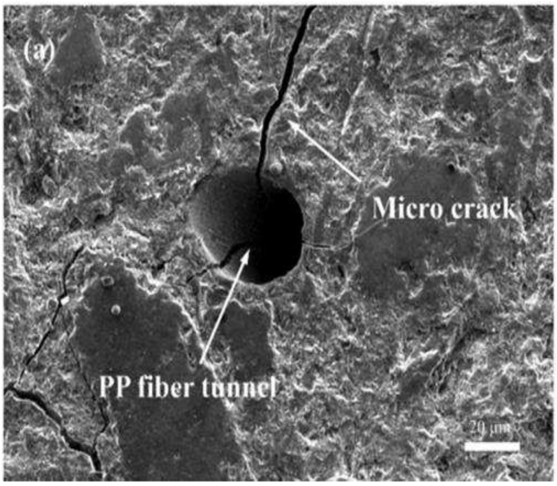


***Figure 6: Cross section of Ultra High Performance Reinforced Concrete sample having PPF fiber at 180°C* [40]**

This also results in lower internal pressure which in return lowers mass loss. *Figure (5)* also supports our argument and

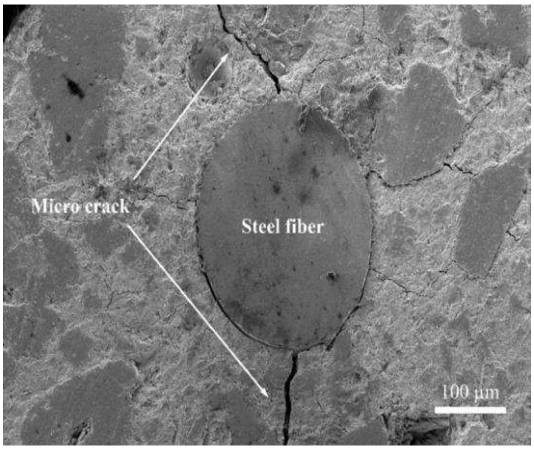


***Figure 7: Cross section of UHPFRC with steel fiber after exposure to 300°C* [40]**

[22] obtained the micrographs of SEM of specimen P2-N2-S5, which shows that coarsening is insignificant in the concrete inner structure although deterioration was observed near the surface, while internal cracks is the reason of reduction in the residual strength. This effect can be seen in the microstructure SEM micrograph in the *Figure (8)***.**

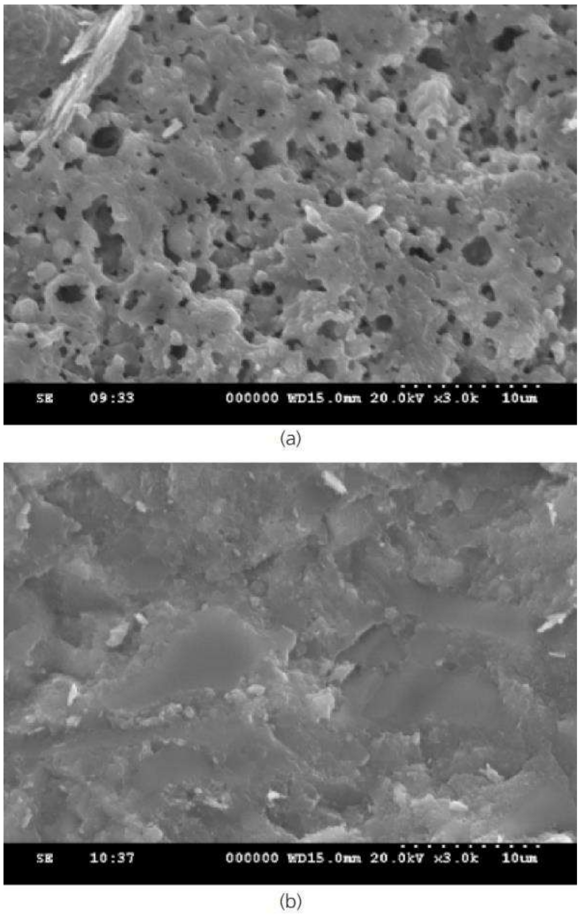


Figure 8: Micrograph obtained from Scanning Electron microscope (SEM) of concrete of specimen P2-N2-S5 after exposure to fire (a) exposed surface to fire near the surface of specimen (b) central part of the specimen [11]

V. Compressive Strength of HFRC at elevated temperature

The decrease in compressive strength of concrete is unavoidable at exposure to elevated temperature and certainly HFRC in which the incorporation of Hybrid fibers may reduce this decrease in the compressive strength. There are various stages seen in the residual compressive strength of HFRC[43]. The Eurocode (EN 1992-1-2:2008/NA:2010P) [32] specifies that there is an inverse relationship between elevated temperature and compressive strength which is in accordance with the results of [33] [34]. The concrete compressive strength decreases in the temperature ranging from 100-120°C which is then increased to the initial or sometimes above initial value of compressive strength at around 250°C [15]. At elevated temperature of 300°C, the compressive strength is increased as compared to the initial value observed at 20°C for FRC while further increase in temperature recorded a decline in the Compressive strength. The compressive strength of FRC was same as of Normal concrete at 450°C while 65% decline in strength as compared to the initial value was noted at 600°C [44].

The compressive strength of HPC, incorporating PPF decreased slightly as compared to the initial value, but after exposure to 800°C, there was an increase in heat resistance from the perspective of residual compressive strength [26]. The hybridization of normal concrete with steel and hybrid fibers can lessen the loss of compressive strength up to 40% as compared to the HSC which shows 60% loss at 400°C. Fibers used in the study was (PPF) and (SF). The loss in the residual compressive strength was greater in Polypropene and steel when used alone for instance for HSC when PPF was alone used, the compressive strength was 34.8 at 400°C as compared to the initial 89.8 MPa, while hybridization can mitigate this issue, as the compressive strength of HFRC incorporated with PFF and SF at 400°C was 50.4 MPa as compared to the initial 89.1 MPa. But using the SF alone had the same compressive strength as compared to the hybrid fibers incorporating SF and PPF [45].

Table 2: Effected Properties of HFRC due to elevated temperature [11]

ID of specimen	***Degree of spalling***	***Weight loss ratio (%)***	***Maximum spalling depth (mm)***	***Spalling area ratio (%)***	***Residual compressive strength ratio (%)***	***Compressive strength (MPa)***
P2-N2-S0	***Severe spalling***	***-***	***-***	***-***	***-***	***178.9***
P2-N2-S5	***No spalling***	***8.0***	***-***	***-***	***31.6***	***190.7***
P2-N4-S5	***No spalling***	***8.2***	***-***	***-***	***27.0***	***183.8***
P4-N2-S5	***No spalling***	***8.2***	***3.5***	***3.0***	***30.6***	***181.0***

The incorporation of SF and PVA in Hybrid Fiber reinforced strain hardening cementitious composite (HFR-SHCC) was done and was subjected to 800°C and the results showed that due to the ability of crack prevention and spalling, the compressive strength is retained closely relative to the initial value up to 400°C. While the conventional concrete lost its strength up to 67% of the initial value at the same temperature. The reason for this improvement in Compressive strength is that PVA fibers melts at elevated temperature leaving channels in the internal microstructure which ease the release of water with increased temperature, further increase in elevated temperature after 400°C causes the loss in compressive strength relative to temperature same as of all types of concrete and HFRC [29]. According to [22], there was no significant influence on the addition of different types of fiber types and their respective contents was observed due to the insufficient data consistent with the results of [25]. The reduction of compressive strength was observed between 20-55% of the original compressive strength after elevating at different higher temperatures shown in *figure (9)* and the results are tabulated in table (2), which shows that coarsening is insignificant in the concrete inner structure although deterioration was observed near the surface, while internal cracks is the reason of reduction in the residual strength.

The residual compressive strength of concrete incorporated with hybrid fibers decreases with the increase in temperature as shown in *Figure (10)* and *figure (11),* showing the relative residual compressive strength at two different temperatures of 300°C and 600°C.

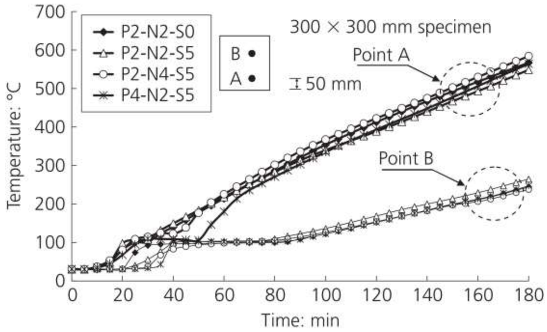


Figure 9:Temperature with time at different depths of concrete [11]

[25] compared the residual compressive strength loss of different types with the increasing temperature of mixes in which he used different proportions of fibers indicated as CS3 with SF only and CSP3 with hybrid fibers incorporating SF and PF. In CS3, two mixes were used namely CS3-30 (30 Kg/m^3 of steel fibers) and CS3-40 (40 Kg/m^3 of steel fibers) Similarly in CSP3, four different mixtures were used namely [n% (CSP3-a × b)] in which n% shows the volume fraction (%), a represents the SF quantity in Kg/m^3, whereas b represents the quantity of PF. The mixes were 0.49% (CSP3-30 × 1), 0.60% (CSP3-30 × 2), 0.62% (CSP3-40 × 1) and 0.73% (CSP3-40 × 2). The results showed at a temperature of 300°C, the behavior of CS3 and CSP3 was almost the same where the CSP3 showed 3% loss of relative residual compressive strength as compared to the CS3, which is due to the reason that polypropylene melts at higher temperatures, creating channels in concrete. There is negligible effect of changing volume fractions in both the mixes on the residual compressive strength. The residual compressive strength was not affected by changing the volume of two fiber types. The compressive strength loss of CSP3 between 300 and 600°C was than CS3 respectively as shown in the *Table (3)*. The relative residual compressive strength loss variation was always less than the conventional concretes. With the hybridization of steel fibers in the concrete, there was a little reduction in the degradation of concrete at elevated temperatures.

Table 3: Relative residual compressive strength loss rate in CS3 and CSP3 [14]

Temperature range	Rate of strength loss of concretes	
	CS3	CSP3
20-300°C	0.000	0.011
300-600°C	0.269	0.253

This is consistent with the results of [46], who noticed decrease of loss of compressive strength with hybridization of concretes in comparison with the control mix where there are earlier loss of compressive strength when exposed at elevated temperature of 800°C. The hybridization of SF and PPF results in improved mechanical properties including the increase of residual compressive strength when subjected to elevated temperature.

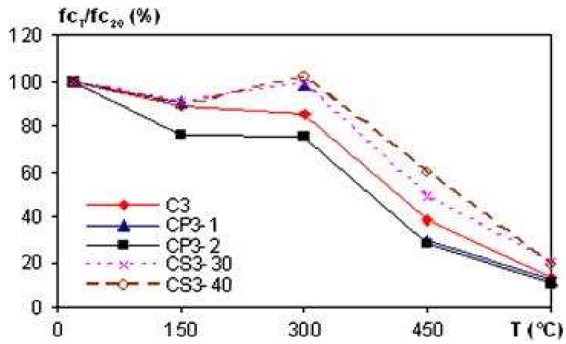


Figure 10: Relative residual compressive strength of CS3 and CSP3 as a function of temperature [14]

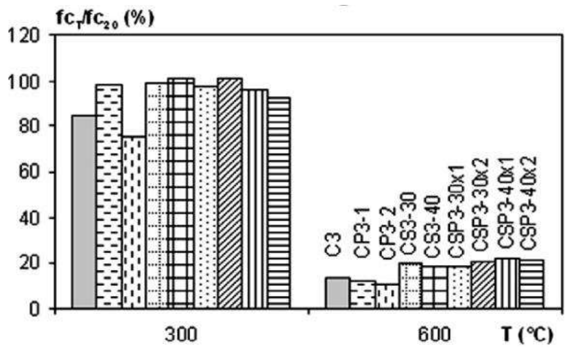


Figure 11: Relative residual compressive strength of concrete at 300°C and 600°C [14]

[37] found that the relative residual compressive strength is much better in case of HFRC than the SF and PF used alone. The loss of compressive strength was greater in specimens exposed to Hydrocarbons (HC) and elevated temperatures relative to exposure to elevated temperatures only such example can be practically found in airfield concrete pavements where the HC fluids can attack the pavement chemically while APU of jet engines can attack thermally. The effect can be seen in the *Figure (12).*

[26] used improved five dimensional-hooked SF of 60 mm length and PF in two proportions, one containing long PF of 54 mm and second containing short PF of 9 mm length, respectively. Six Mixes were formed with different volume fraction ranging from 0.125 to 0.25 in the mixes M2-M5 for PF and 1% for SF in the mixes from M2-M6 of each fiber in each mix, while M1 was control mix with no fiber inclusion.

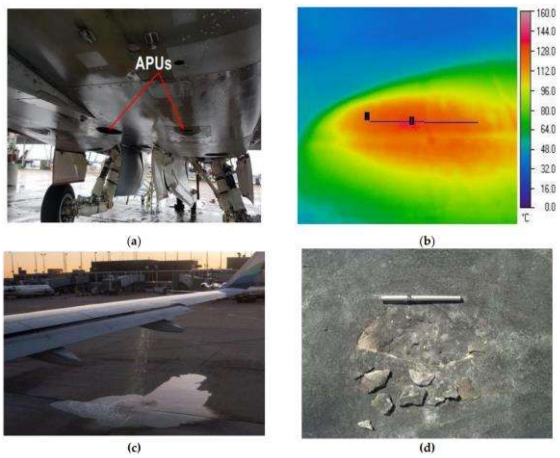
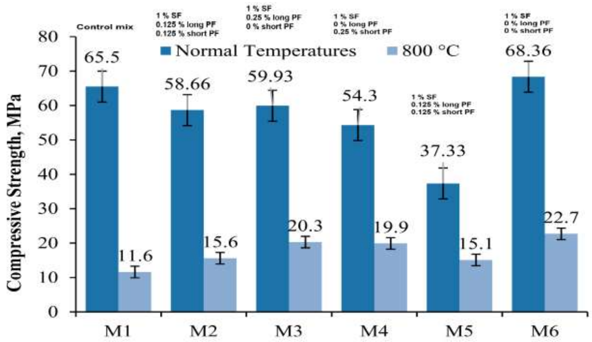


***Figure 12: (a) APU of a F/A-18 Hornet aircraft, (b) APU exhaust thermal profile of Military airfield pavement, (c) HC fluid leaks from an aircraft, (d) Deterioration of parking Apron* [37]**

All the mixes were subjected to elevated temperatures of 800°C. Results indicate that addition of PF has negligible impact on the compressive strength at normal temperatures. There was 4.2% increase in compressive strength was observed for M6 (68.36 MPa) as compared to M1 (65.5 MPa).



PF: Polypropylene fiber, SF: Steel fiber

Figure 13: Compressive strength at normal and elevated temperatures of 800°C [15]

Using long PF fibers as in M3 (59.93 MPa) in concrete mix yields greatest compressive strength of the mixes which include PF. All the data is illustrated in *Figure (13).*

Table (4) shows the effected properties of HFRC at elevated temperature of 800°C reviewed in this paper.

Table 4: Effected properties of HFRC at elevated temperature of 800°C.

Fiber type	*Compressive Strength*	*Tensile Strength*	*Mass loss effect*	*Microstructure effect*
PPF	+	+	+	-
SF	+	+	+	-
PPF + SF	+	+	+	+
$CaCO_3$ Whisker	*N/A*	*N/A*	*N/A*	+
BF	*N/A*	*N/A*	*N/A*	+

\+ denotes increase or positive impact.
\- denotes decrease or negative impact

VI. Conclusions

1. The tensile strength of HFRC at elevated temperature decreases. This is because various fibers used in the mix get either a. melted or b. disintegrate by burning.
2. The mass loss and fibers incorporation have a direct relation when subjected to higher

temperatures. Higher the incorporation of fibers, the higher the mass loss, this effect is seen in the M5 concrete which recorded greatest mass loss of as compared to the normal mix.

3. The Microstructure of HFRC at elevated temperature gets negatively impacted by the elevated temperatures. This is because fibers tend to leave microcracks upon their heterogenous contraction or expansion.
4. The inclusion of hybrid fibers improves the compressive strength of HFRC when subjected to elevated temperatures. The Concrete with Hybrid fiber loses less strength in comparison with the concrete without Hybrid fibers.

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