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Performance of Ultra-High Performance Fiber Reinforced Concrete at High Temperatures

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Abstract*— Ultra-high performance fiber reinforced concrete (UHPFRC) represents a new class of concretes. UHPFRC is typically very dense, has ultra-compressive strength in excess of 150 MPa and a low water to binder ratio. High Packing density results in very low permeability and superior durability over high performance concretes. The research on this composite materials with respect to fire is limited. In this investigation, the results of an experimental study carried out at high temperatures on UHPFRCs are presented. Also, the effects of elevated temperatures of 200, 300, 400, 600, and 800 ℃ for one hour on the main mechanical properties of ultra-high performance concrete were studied. Also, the effect of fibers type on spalling behavior of ultra-high performance concrete were studied. For this purpose, the testing was conducted on four ultra-high performance concrete mixes (UHPC): standard UHPC, steel fiber UHPC, polypropylene UHPC and hybrid steel fibers and polypropylene fibers. Compressive strength and tensile strength of UHPC are obtained after exposure to elevated temperatures. The results indicated that, the strength, heat resistance and spalling resistance of the UHPFRC have increased with the use of hybrid steel and polypropylene fibers. The results have shown the effectiveness of adding polypropylene fibers for UHPC in reducing the spalling risk.

***Index Terms*— Ultra-high performance concrete, Temperature, Fiber reinforcement.**

I. INTRODUCTION

Ultra-high performance concrete (UHPC) is a relatively new class of concretes which has been developed in the past several decades. UHPC typically have compressive strengths of at least 150 MPa with significant ductile behavior [1]. Ultra-high performance fiber reinforced concrete (UHPFRC) is a fiber reinforced concrete that has significantly improved properties of strength and durability. UHPFRC is typically very dense, has very high compressive strength and a low water to cementitious ratio (w/cm) blew 0.2. In order to achieve high compressive strengths, the particle packing density of the material has been optimized to reduce the porosity [2]. It is well established that there exists an inverse relationship between the porosity and compressive strength of concrete [3,4].

UHPC falls in the larger category of high performance concrete (HPC). HPC exhibit high-strength, high workability and high durability [4]. In the early 1990s, Richard and Cheyrezy were the first researchers working to develop reactive powder concrete (RPC) at Bouygues company in France [5]. Examples of commercialized products based on this concept are Ductal and CeraCem , which were introduced in the late 1990s. RPC reflect further refinements of the mixture proportioning and curing conditions (either standard, steam or autoclave curing). The elimination of the coarse aggregate allows for improved homogeneity of the mixture. In order to reduce the extremely brittle matrix of RPC, steel fibers were introduced to increase the tensile strength and ductility [5].

UHPC are made using fine aggregates, high amounts of cement, silica fume, and quartz powder. The workability properties are attained through optimization of the ‘granular packing’ and the use of high-range water-reducing admixtures[6,7].The fibers increase the ductility and mechanical strength of concrete, reduce its plastic shrinkage, and increase its resistance to impact at room temperature [8].

Human safety in the event of fire is one of the considerations in the design of residential, public and industrial buildings. Concrete has a good service record in this respect [3]. Sudden exposure to high temperatures strongly modifies the behavior of concrete. To increase the level of safety for concrete structures in the event of fire, design calculation have to take the dependence of the thermo-mechanical properties with temperature into account. Furthermore, a lot of researches have shown that concrete can present a risk of thermal instability with fast increases in temperatures. This phenomenon is commonly called spalling. Moreover, high-strength concretes seem to have an increased susceptibility to this instability [8]. The low porosity of UHPFRC may result in failure by explosive spalling at high temperatures. The use of steel and polypropylene fibers has shown to mitigate the problem of spalling at high temperatures. Heating causes different changes of its properties and, in particular, changes in microstructure accompanied by the loss of mechanical strength. Polypropylene fibers have a melting point at about 170°C. When concrete heats up past this point, the fibers themselves melt and disperse into the surrounding matrix [9,10]. This leaves artificial pores apace roughly the size of fiber. This newly introduced void space helps reduce the vapor pressure from evaporating water and the dehydration of concrete. This reduces the tendency of dense concretes to spall when heated quickly [11,12]. In low density concrete, the pressure build up is generally not as severe due to the high pore volume in the concrete.

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A great deal of work has been done on the strength of normal and high strength concrete with regards to temperature [11,12]. However, due to relatively new nature of UHPC the amount of research done on residual strength is limited. Additional investigations are needed to increase the knowledge on the effects of high temperatures on the performance of ultra-high performance fiber reinforced concrete.

Research significance

The aim of this research is to investigate the residual mechanical properties of ultra-high performance fiber reinforced concrete at high temperatures. Also, the present study targets to study the spalling behavior of UHPFRC when exposed to elevated temperatures up to 800 ℃ using different types of fibers (steel fibers (S), polypropylene fibers (PP), and polypropylene fibers in combination with steel fibers(S+PP).

II. EXPERIMENTAL PROGRAM

A. Materials

The main constituents of UHPC are: Portland cement, silica fume, quartz powder, fine sand, fine aggregate, superplasticizer and fibers. The type of cement used in all of the concrete mixtures was Portland cement type CEM I 52.5 N. It was supplied by El-Suez Cement Company and complied with the requirements of ES 4756-1/2013 and BS EN 197-1/2011. The fine sand was graded quartz sand with grain size of 0.125/2 mm with specific gravity 2.64. t/m^3. Natural crushed dolomite with the fractions of 2/8 mm from Attaka quarry in Suez City in Egypt was used in this study. Fig. 1 shows the grading of the used fine sand and fine aggregates. Locally produced quartz powder with a particle size ranging from 1to 7µm with a SiO_2 content of 97% was used. It acts as an effective filler to occupy the spaces between the larger cement particles and the finer sand particles. The sand particles finer than 0.125 mm were excluded to avoid the interference with the coarse cement particles (100 um) as recommended by Richard and Cheyrezy [5]. The used silica fume was locally produced in Egypt.. It is a waste by-product of silicon and silicon alloys industry consisting mainly of non-combustible amorphous silica (SiO_2) particles, a specific gravity of 2.20 and a specific surface area of 170,000 cm²/gm.

The high-range water-reducing (HRWR) admixtures, often referred to as super plasticizers, it is essential in UHPC help in increasing the workability of concrete without adding water and helping the fine particles to fill the void spaces and to decrease the amount of water in the mix. In this study a superplasticizer namely Viscocrete 3425 locally produced was used. It is an aqueous solution of modified polycarboxylate and complies with ASTM C494-Type F. Steel fibers are used to increase the tensile capacity and improve the ductility of the UHPC. Polypropylene fibers with a specific gravity of 0.91 t/m^3, length of 12 mm and the diameter of fibers used are 18 µm. Tap water was used throughout the mixing and curing procedures for the concrete in this study.

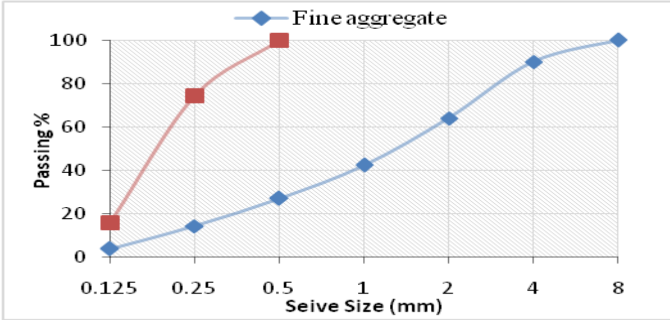

Fig. 1 Grading curves of fine sand and fine aggregates

B. Mixing procedure

The constituents of each mixture were mixed for 15 to 20 minutes using laboratory pan mixer of 15 liters. the dry constituents were mixed for 3 minutes and then 75% of the mixing water was added. After thorough mixing, the superplasticizer was added and the remaining 25% of the water was added to the mixture. Fibers were added at the end. This process of mixing seemed to improve the action of the superplasticizer [13].

C. Mix proportions

The mix was designed in order to produce an ultra-high performance fiber reinforced concrete without the need for elaborate curing conditions which are not readily producible in the field. The water/binder ratio was fixed at 0.18 for all UHPC mixes. Polypropylene fibers were used to improve fire spalling. The amount of polypropylene fibers was 1.82 kg/m^3. One control UHPC mixture without fibers and three UHPFRC mixtures were prepared in this study. Four batches of UHPC mixtures were made as follows: UHPC(plain UHPC, UHPC-St (UHPC with steel fibers), UHPC-PP (UHPC with polypropylene fibers) and UHPC-St+PP (UHPC with hybrid of steel and polypropylene fibers). The concrete mixture of these mixtures are given in Table 1.

Table1: The proportions of the concrete mixtures (kg/m^3)

Mix No.	C	SF	Q	FA	SP	W	St	PP
UHPC	900	225	270	826	36	162	0	0
UHPC-St	900	225	270	773	36	162	156	0
UHPC-PP	900	225	270	813	36	162	0	1.82
UHPC-St+PP	900	225	270	800	36	162	78	0.91

C: Cement, Q: Quartz powder, FA: Fine Aggregate, SP: Super plasticizer, W: Water, St: Steel Fiber, PP: Polypropylene Fiber

D. Specimen preparation

Casting process

All specimens were consolidated in the same manner using a high frequency vibrating table. Due to the relatively high flowability of the batches, the duration of the fresh specimens on the vibratory table were kept to a minimum to avoid over-consolidation and separation of the steel fibers from the fresh concrete. Each mold was filled with concrete in three layers. For each of the concrete mixtures, cubic specimens (50 mm), cylindrical specimens (diameter 50 mm, height 100 mm) and prismatic specimens (40x40x160 mm) were cast. After casting, the specimens were covered in a heavy plastic sheet and left to set for 48 hours before they were demolded. The demolded specimens were cured in water bath at 21±2ºC until the age of testing. Tests were carried out on specimens after 56 days.

Heat testing

The samples were subjected to an elevated temperature in an electric furnace. Samples were heated at a rate of 5°C/min until the following temperatures: 200°C, 300°C, 400°C, 600°C and 800°C. Once the test temperatures was reached, samples were maintained at this temperature for one hour in order to ensure a good homogeneity of the thermal field in the sample. At the end of each interval, the power was shut off and the oven returned to room temperature. Mechanical tests were performed on heated and non-heated specimens in order to determine initial and residual properties.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Compressive Strength

The residual compressive strength is considered to be the maximum compressive strength obtained following heating to the prescribed temperature and retuning to ambient temperature. Evolution of the residual compressive strength versus temperature for the UHPCs are presented in Fig.2 and corresponding data can be found in Table2. The value presented is the average of three tests heated to a given temperature. It can be seen from the Table2, the residual compressive strength of UHPC slightly increased during early periods of heating (up to 200°C), but compressive strength of specimens significantly decreased as heating proceeded. Relative compressive strength is defined as the ratio between the value obtained at the test temperature and the initial value at room temperatures (25 ºC). Relative residual compressive strength of UHPCs mixes are given in Table3.

Table 2. The Compressive strength of UHPC mixtures with increasing temperature

Mix No.	Compressive strength (MPa) at temperature					
	20 ºC	200 ºC	300 ºC	400 ºC	600 ºC	800 ºC
UHPC	145	162	122			
UHPC-St	170	184	174	119		
UHPC-PP	143	154	146	112	62	36
UHPC-St+PP	159	169	161	120	66	41

Table 3. Relative compressive strength of UHPC mixes with increasing temperature.

Mix No.	% of compressive strength with increasing temperature					
	25 ºC	200 ºC	300 ºC	400 ºC	600 ºC	800 ºC
UHPC	1	1.12	0.84	-	-	-
UHPC-St	1	1.08	1.02	0.70	-	-
UHPC-PP	1	1.08	1.02	0.78	0.43	0.25
UHPC-St+PP	1	1.06	1.01	0.75	0.44	0.26

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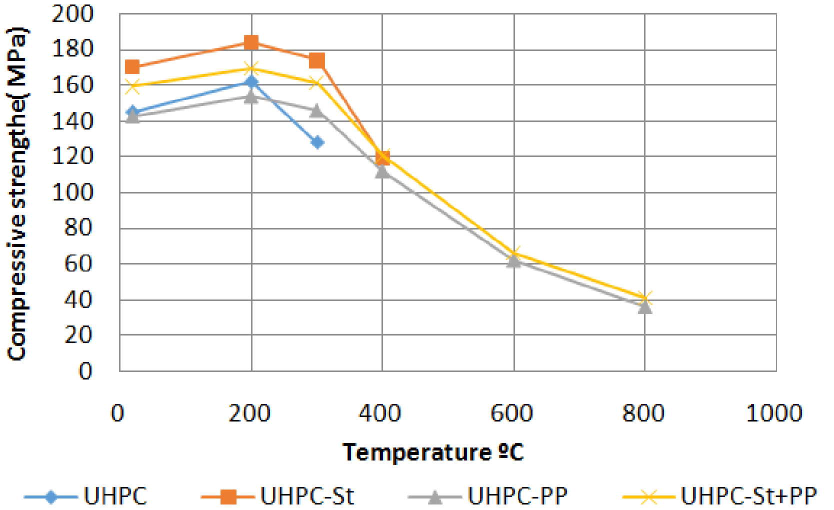

Fig.2. Residual compressive strength of UHPC mixes with increasing temperature

The plain UHPC exhibited explosive spalling at oven temperatures in the range of 300°C and 400°C. The specimens of UHPC with steel fibers (UHPC-St) spalled at oven temperatures in the range of 400°C and 500°C.

As it can be seen from Fig. 2, the performance of two UHPFRCs (UHPC-PP and UHPC-St+PP) were relatively close. The evolution of strength can be divided into two phases. During the first stage, between 25–200°C, compressive strength did not decrease and even presented a slight increase of about 7%. This can be explained by the migration of water from material. The lower water permeability of UHPFRC could explain its delayed strength increase. This could be related with water removal which induces shrinkage of concrete while making the micro structure of concrete more porous. The increase of strength is attributed to the fact high temperature accelerate the pozzolanic reaction, increase the hydration products, and reduce the pore size. According to Cheyrezy et al. [5] the pozzolanic reaction of RPC specimens that underwent heat curing of 250°C could reach 100%; the compressive strength increased as well. The compressive strength of concrete during the second stage of heating, between about 200-800°C compressive strength decreases with the rise in temperature. This is can be mainly explained by the cracks generated because of the thermal incompatibilities between the cement paste and the aggregates and decomposition of hydration products such as calcium silicate hydrate (C-S-H) and calcium hydroxide (CH).

At 600 °C two UHPFRCs (UHPC-PP and UHPC-St+PP) lost about 43% of its initial compressive strength. These observations are in good agreement with measured evolution of strength in prepackaged, high-cost, commercially available products such as Ductal-AF and BSI-fire [15, 16].

At 800 °C the compressive strength of UHPC-PP and UHPC-St+PP dropped about 75%, retaining only about 25% of its original compressive strength. These Hybrid fibers appear to offer a good compromise: polypropylene fibers reduce internal pressure that causes cracking during heat exposure, and steel fibers limit cracking during heat exposure and subsequent mechanical loading.

Polypropylene fibers melt at 170 °C thus creating a porosity which limits pore pressure due to the evaporation of pore water that occurs during heat exposure. Consequently, the spalling is prevented during exposure to heat. Fig. 3 shows a Scanning Electron Microscopy image of the residual melt material and void left by the melted fiber. This newly introduced void space helps reduce the vapor pressure from the dehydrating concrete and evaporating water. This reduces the tendency of dense concretes to spall or explode when heated quickly [17,18]. In low density concrete, the pressure built up is generally not as severe due to the high pore volume in the concrete.

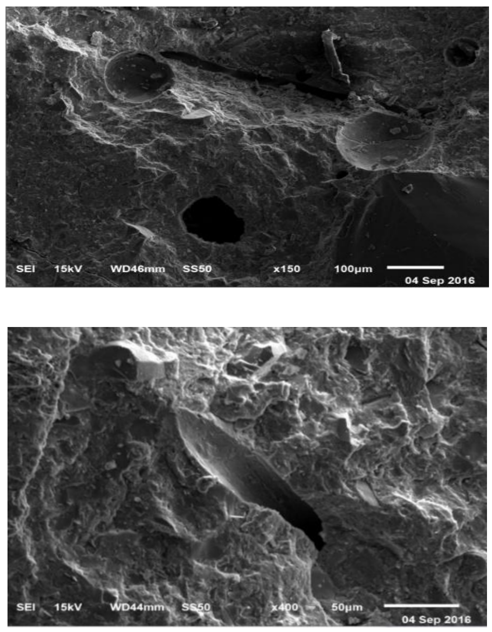

Fig.3 Void left by melting Polypropylene fiber in UHPC-PP Matrix

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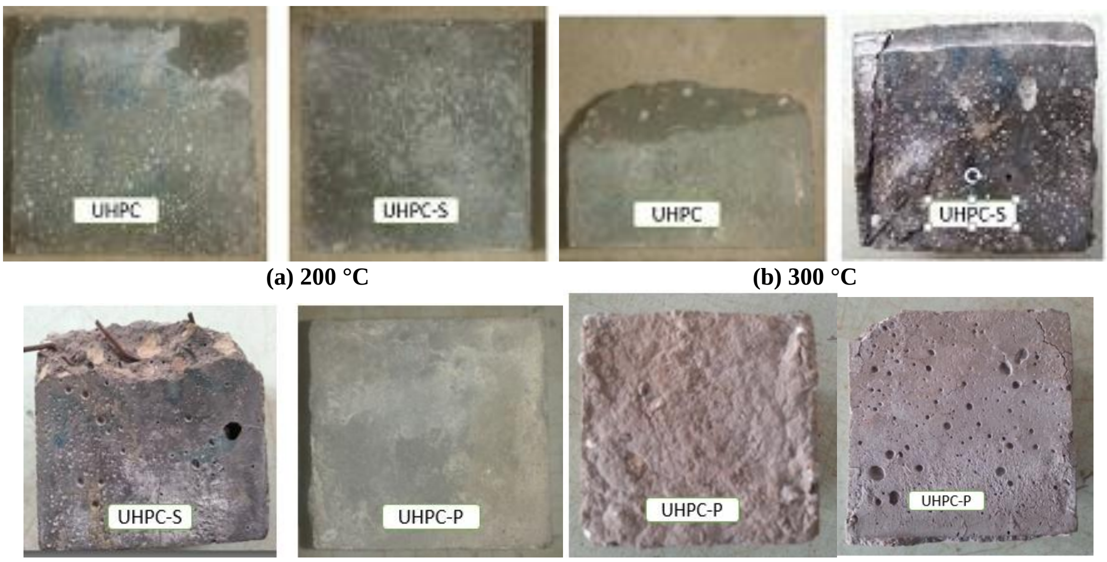
B. Spalling

The very high compressive strengths and durability characteristics of UHPC arise mainly from its increased packing density. This increased packing density results in an increased susceptibility to explosive spalling due to reduced porosity. The standard mixture of UHPC exhibited explosive spalling at oven temperatures in the range of 300°C and 400°C (Fig.4b). The addition of steel fibers to a concrete increases the thermal diffusivity by 50 to 100% when compared to a standard concrete mix [17]. Steel fibers are used to increase the resistance to spalling. They accomplish this by increasing the tensile resistance of concrete. Depending on its porosity, steel fibers are only useful in preventing spalling below 500°C. The specimens of UHPC with steel fibers (UHPC-St) spalled at oven temperatures in the range of 400°C and 500°C (Fig.4c). The test results indicated that the inclusion of steel fibers was not effective to reduce spalling risk. There was no spalling observed for specimens with PP fibers (UHPC-PP and (UHPC-St+PP). This demonstrates that incorporation of 0.2% PP fibers prevents the occurrence of explosive spalling in UHPFRC at high temperatures up to 800 °C. The results indicated that heat resistance and spalling resistance of the UHPFRC have increased with the use of hybrid steel and polypropylene fibers (0.5% S +0.1% PP). Hybrid fibers appear to offer a good compromise: polypropylene fibers reduce internal pressure that causes cracking during heat exposure, and steel fibers limit cracking during heat exposure and subsequent mechanical loading.

Fig.4e shows the surface character of UHPC-PP samples at 800 °C. Only a small amount of spalling was seen at the edges and the corners of some specimens at 800 °C. When the PP fibers are added to UHPC, they allow for the creation of a pore structure when the fibers begin to melt at 170°C. This will vent the pressure before explosive spalling can occur, thus they prevent concrete from cracking and exploding. When temperature reached 800 °C, the specimen surface contained more pores and large cracks (Fig.4e).

C. Flexural Strength

The tensile strength of concrete is important because it determines the ability of concrete to resist cracking. Flexural strength was measured on 40x40x160 mm prismatic specimens . Evolution of the residual Flexural strength versus temperature for the UHPCs are presented in Fig.5 and corresponding data can be found in Table 4. The remaining flexural strength of specimens after a high temperatures, divided by their flexural strength at room temperatures are given in Table 5. It is evident that, the flexural strength of UHPC with fibers (UHPC-St and UHPC-St+PP) was greater than that of the plain UHPC by 23.4 % and 15.8 % respectively. A significant effect of steel fibers on the flexural strength of UHPC was observed. According to Fig.5, After UHPFRC specimens were heated to 200°C, there flexural strength increased about 3%. Following heating of UHPC-PP and UHPC-St+PP to 600 °C, the flexural strength decreased about 93% and 89% respectively. This loss of flexural strength due to many micro and macro-cracks were produced in the specimens due to the thermal incompatibility between aggregates and cement paste. This behavior may be due to the melting of PP fibers which creates some pores in the matrix. In most cases, Polypropylene fibers are not added to concrete in order to increase the tensile strength, but to act as a sacrificial material. They are typically added to increase the fire resistance of high density or low permeability concretes [9].



(a) 200 °C (b) 300 °C

(c) 400 °C (d) 600 °C (e) 800 °C

Fig.4 Spalling and Surface character of UHPC and UHPFRCs at elevated temperatures

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Table 4. The flexural strength of UHPC mixtures with increasing temperatures

Mix No.	Flexural Strength (MPa) at temperature					
	25 ºC	200 ºC	300 ºC	400 ºC	600 ºC	800 ºC
UHPC	30.4	29.4	22.6			
UHPC-St	37.5	38.3	30.8	16.4		
UHPC-PP	32.2	31.5	20.4	12.3	2.1	0
UHPC-St+PP	35.2	36.3	27.5	14.2	4.1	2.0

Table 5. Percentages of flexural strength of UHPC mixes with increasing temperatures.

Mix No.	% of flexural strength (MPa) with increasing temperatures					
	25 ºC	200 ºC	300 ºC	400 ºC	600 ºC	800 ºC
UHPC	1	0.97	0.74			
UHPC-St	1	1.02	0.82	0.44		
UHPC-PP	1	0.98	0.64	0.38	0.07	0
UHPC-St+PP	1	1.03	0.78	0.40	0.11	0.06

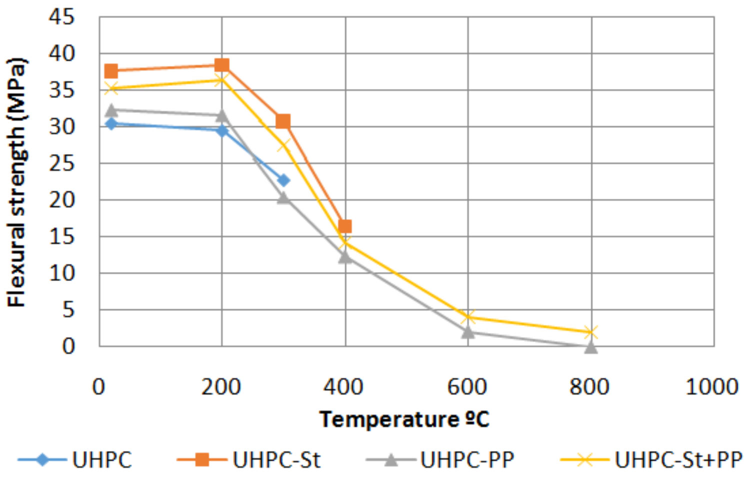

Fig. 5. Residual flexural strength of UHPC mixes with increasing temperatures

IV. CONCLUSIONS

The following conclusions were drawn from this work:

1-UHPC with compressive strength of more than 145 MPa can be produced using locally available materials using simple process techniques.

2-The performance of UHPCs produced with local materials at elevated temperatures were similar to those provided by prepackaged, high-cost, commercially available products such as Ductal-AF and BSI-fire.

3-The compressive strength of UHPFRC gradually increases when specimens are heated to 200 °C, but starts to decrease as temperatures increase continuously.

4- Explosive spalling was observed when temperature of the plain UHPC specimens was in the range of 300°C and 400°C.

5-The addition of polypropylene fibers proved to be a good mechanism for reducing the explosive spalling of UHPC when exposed to high temperature.

6-The incorporation of steel fibers was not effective to prevent spalling for the UHPC even with dosage of 2% by volume. Spalling was observed when temperature of the UHPC with steel fibers was in the range of 400°C and 500°C. The steel fibers enhance the mechanical properties of UHPC at room temperature up to 400°C.

7-Hybridization both steel and PP fiber yields the best results with regard to fire resistance. The steel fibers being responsible for increasing the tensile strength to limit cracking due to the thermal stresses and the PP fibers to reduce the vapor pressure build up inside the matrix.

Recommendation for future work, to improve sustainability of UHPC, Rice Husk Ash and Ground Granulated blast furnace Slag should be considered for use as a partial replacement for silica fume and cement.

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