EFFECTS OF POLYPROPYLENE FIBERS ON ULTRA HIGH PERFORMANCE CONCRETE AT ELEVATED TEMPERATURE

  

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This paper presents an experimental study to evaluate the influence of polypropylene on fire resistance of ultra-high performance concrete (UHPC). Concrete mixtures are prepared by using different percentages of polypropylene fibres 0%, 0.75% and 1.5%, by volume. Samples are heated to 250 or 500 °C, for exposures 2.5 or 5 hours, and tested after cooling for compressive strength and flexural tensile strength. The research includes the use of mineral admixture of a recognized, polypropylene fibre, quartz sand, superplasticizers and without using any type of aggregates other than the quartz sand.

The effect on subjected samples to elevated temperature up to 250 ºC and 500 ºC for durations 2.5 hours and 5 hours was studied for each mix and comparing the results of compressive strength and tensile strength among the mixes.

Results obtained, showed that adding 0.75% of polypropylenes fibres only to a concrete mixture, improved the fire resistance of the concrete by 27% and 72% when the samples exposed to 250 ºC and 500 ºC for 2.5 hours respectively, compared with concrete mixes without fibres. In addition, the residual strength was improved by 39% and 14% when the samples exposed to 250 ºC and 500 ºC for 5 hours, respectively.

Keywords: concrete, fibres, polypropylene, UHPC, FRC, fire, elevated temperature

1. INTRODUCTION

Reinforced concrete is the most commonly used construction material worldwide. High performance concrete (HPC) is a novel material with improved properties like higher strength, longer durability and higher workability, than conventional concretes (Aïtcin 1998). Concrete with high strength and durability has been primarily used in special constructions such as military buildings, nuclear power plants, infrastructures and high rise buildings since it became commercially available (Akca and Zihnioğlu 2013).

Ultra high performance concrete (UHPC) is a newly developed material that has gained more interest in the concrete construction industry. Fibres added to concrete improve its mechanical properties, reduce its plastic shrinkage, improves its resistance to fire, to abrasion and to impact and decrease its permeability. With such material, engineers are able to design new structures, original in their design or their ability to resist severe conditions.

Since the strength development, mechanical properties and durability characteristics of high-performance concrete may be different from ordinary concrete, moreover high-performance concrete is a relatively new class of concrete, so additional research is needed to understand more fully the factors affecting the development of its physical and mechanical characteristics, it follows that actual performance of ultra-high performance concrete (UHPC) under elevated temperature is also different and it should be studied.

1.1 Statement of the problem

The damage caused by fire is one of the most serious problems that face civil engineers, especially in countries that are susceptible to wars and enemy fighting such as Gaza Strip. During the last war (2014) perpetrated by the Israelis on Gaza Strip, large number of buildings were subjected to fires lasting for long periods of time. Some of these buildings were repairable, while others are beyond repair and need to be demolished and reconstructed. The activity of concrete rehabilitation or reconstruction usually takes place in areas which are more exposed to fire risk. In these cases, special types of concrete should be used.

The usage of ultra-high strength concrete with high compressive strength in construction applications has been increasing worldwide and it will make an impact construction industry due to the limited land area available and the fast growing population. High-rise multistory buildings have increasingly used, where the large loads in high rise buildings lead to the design of large sections when ordinary concretes are used. But when ultra-high performance concrete is used small cross sections can be designed. Also, this type of concrete will be used in rehabilitation techniques.

1.2 Research objectives

The main goal of this research is to study the effect of polypropylene fibres on improving fire resistance of Ultra High Performance Concrete and to produce Ultra High Performance

Fire Resistant Concrete (UHPFRC) using available materials. This will open new possibilities for the production of a new material.

2. LITERATURE REVIEW

Shihada S. (2011) investigated the effects of using polypropylene fibres (PP) on fire resistance of normal strength concrete. Concrete mixtures were prepared by using different percentages of polypropylene fibres (PP) 0%, 0.5% and 1%, by volume. Samples subjected to elevated temperatures 200 °C, 400 °C and 600 °C, for exposures duration up to 2, 4 and 6 hours, and tested for compressive strength. Results showed that, the relative compressive strengths of concretes containing polypropylene fibres were higher than those of concretes without polypropylene fibres. Furthermore, the researcher concluded that concrete mixes which are prepared using 0.5% polypropylene fibres, by volume, can significantly promote the residual compressive strength during the heating, lower and higher contents of fibres generally showed worse performance due to the more deterioration and higher volumes of voids, respectively.

Dharan and Lal (2016) studied the effects of adding polypropylene fibres of 0.5%, 1%, 1.5%, and 2% to concrete. Tests on workability, modulus of elasticity, compressive strength, split tensile strength and flexural resistance were conducted on specimens obtained that compressive strength of concrete contains 1.5% of polypropylene fibre was increased by 17% of the strength of conventional concrete. Moreover, strength enhancement in split tensile strength is 22%, flexural strength is 24% and modulus of elasticity is 11% compared to that of conventional concrete.

Tanyildizi and Çevik (2009) studied the effect of using polypropylene fibre and silica fume on the mechanical properties of lightweight concrete exposed to high temperatures. Mixes containing polypropylene fibres with 0%, 0.5%, 1% and 2% and silica fumes with 0% and 10% were prepared. The flexural and compressive strength for lightweight concrete samples were determined after being exposed to high temperatures (400 °C, 600 °C and 800 °C). Three control factors (silica fume percentage, polypropylene fibre percentage and high temperature degree) were used for this study. They demonstrated that the compressive and flexural strength of polypropylene fibre reinforced lightweight concrete drops with temperature starting from 400 °C. The test results indicated that each temperature range had a distinct pattern of strength loss.

Sohaib et. al. (2018) studied the using polypropylene fibres in concrete to achieve maximum strength, and they observed the significant improvement in ultimate compressive strength, and the inclusion of polypropylene fibres increases the compressive strength by 20% after 7 days and 16 % after 28 days, compared to the control samples, moreover, 11% and 17% increment was observed in split tensile strength after 7 days and 28 days respectively. They have been concluded that the optimum percentage of polypropylene fibres was obtained both in compressive and split tensile strength as 1.5% of cement contents.

Komonen and Penttala (2003) investigated the effect of high temperature on the residual properties of plain and polypropylene fibre reinforced Portland cement paste. Plain Portland cement paste with w/c ratio of 0.32 exposed to elevated temperatures up to 1000 °C. Paste with polypropylene fibres was exposed to elevated temperatures up to 700 °C. The residual flexural and compressive strengths were measured. The gradual heating coarsened the pore structure. At 600 °C, the residual compressive capacity ($fc_{600°C}/fc_{20°C}$) was still over 50% of the original. Strength loss due to increasing of temperature was not linear. Polypropylene fibres produced a finer residual capillary pore structure, decreased compressive strengths, and improved residual flexural strengths at low temperatures. According to the tests, it seems that exposure temperatures from 50 °C to 120 °C can be influence as exposure temperatures 400–500 °C to the residual strength of cement paste produced by a low water cement ratio.

3. CONSTITUENT MATERIALS & EXPERIMENTAL PROGRAM

3.1 General overview

The experimental program and the constituent materials used to produce ultra-high performance fire resistant concrete associated with this research work.

The laboratory investigation consisted of tests on hardened concrete. The tests for hardened concrete included compressive and flexural strengths.

The influence of the polypropylene fibres "PP" was studied in order to obtain the optimum percentage for the mix and to reduce the loss in compressive strength due to high temperature by preparing different mixes with different percentages of "PP".

The influence of silica fume dosages, cement/ultra-fine ratio, superplasticizer, steel fibres and polypropylene fibres amounts on the compressive strength concrete that's subjected to high temperatures together with the workability and density of UHPFRC were studied by preparing several concrete mixes.

The properties of the different constituent materials used to produce UHPFRC were also discussed such as moisture content, unit weight, specific gravity and the grain size distribution. The test procedures, details and equipment used to assess concrete properties are also shown.

3.2 Characterizations of constituent materials

Constituent materials used in this research included ordinary Portland cement, silica fume, quartz sand, polypropylene fibres. In addition, superplasticizer was used to ensure suitable workability. Proportions of these constituent materials have been chosen carefully in order to optimize the packing density of the mixture.

Cement paste is the binder in UHPFRC, it holds the aggregate (fine, micron fine) together and reacts with mineral materials in hardened mass. The property of UHPFRC depends on the quantities and the quality of its constituents. Because cement is the most active component of UHPFRC and usually has the greatest unit cost, its selection and proper use is important in obtaining most economically the balance of properties desired of UHPFRC mixture.

The cement used throughout the experiments is ordinary Portland cement (OPC) 52.5. The results of mechanical and physical tests of the cements are summarized in *Table 1.* along with the requirements of ASTM C150 specifications for comparison purposes.

Table 1: Cement characteristics according to manufacturer data sheet

Test type		Ordinary Portland Cement	
		Results	ASTM C 150
Setting time (Vicat test) [min]	Initial	90 min.	>60 min.
	Final	192 min.	<375 min.
Mortar comp. strength [MPa]	3 days	18 MPa	min. 12 MPa
	7 days	34 MPa	min. 19 MPa
	28 days	52 MPa	no limits
Fineness (cm^2/g)		3390	> 2800
Water demand		27.5 %	no limits

Silica fume is a by-product resulting from the reduction of high-purity quartz with coke or coal and wood chips in an electric furnace during the production of silicon metal or ferrosilicon alloys. The silica fume, which condenses from the gases escaping from the furnaces, has a very high content of amorphous silicon dioxide and consists of very fine spherical particles (ACI 548.6R-96). Silica fume is extremely fine with particle size of 0.1 μm. It exists in grey powder. The dry bulk density is 0.65 ±0.1 kg. The silica fume was supplied by SIKA Company.

Aggregate is relatively inexpensive and strong making material for concrete. It is treated customarily as inert filler. The primary concerns of aggregate in mix design for Ultra High Performance Fibre Reinforced Concrete are grain size distribution, maximum size and strength. Providing that concrete is workable, the large particles of aggregate are undesirable for producing UHPFRC. For producing UHPFRC, the nominal size ranges from 0.15 to 0.6 mm for quartz sand (fine aggregate) which are locally available in Gaza. In addition, it is important to ensure that the aggregates are clean, since a layer of mud or clay will reduce the cement aggregate bond strength, in addition to increasing the water demand.

Tap water of the laboratory at Islamic University of Gaza was used in all concrete mixtures and in the curing all of the tests specimens. Polypropylene is a plastic polymer that was developed in the middle of the 20th century.

Polypropylene fibres (PP) were first suggested for use in 1965 as an admixture in concrete material for blast resistant buildings at USA.

Subsequently, the polypropylene fibre has been improved further and now, used as short discontinuous fibrillated material for production of fibre reinforced concrete or as a continuous mat for production of thin sheet components. Moreover, the application of using PP fibres in construction was largely increased because addition of fibres in concrete mix improves the flexural strength, tensile strength, toughness, impact strength and the failure mode of concrete.

Micro cracks develop in concrete with curing and these cracks propagate rapidly under applied stress resulting in low tensile strength of concrete. Hence addition of fibres improves the strength of concrete and these problems can be overcome by use of polypropylene fibres in concrete (Madhavi et al. 2014).

Application of polypropylene fibres provides strength to the concrete while the matrix protects the fibres. The primary role of fibres in a cementitious composite is to control cracks, increase the tensile strength, toughness and to improve the deformation characteristics of the composite, recently become widely used in the construction industry in order to enhance fire resistance of concrete. *Table 2.* shows property of the used polypropylene in this research work.

Table 2: Polypropylene fibres properties

Property	Polypropylene
Density (g/cm^3)	0.9 – 0.91
Reaction with water	hydrophobic
Tensile strength (MPa)	300 – 400
Elongation at break (%)	100 – 600
Melting point (°C)	175
Thermal conductivity (W/mK)	0.12
Length of fibres (mm)	15

The chemical admixture used is superplasticizer which is manufactured to conform to ASTM-C-494 specification types G and F. This plasticizing effect can be used to increase the workability of fresh concrete, extremely powerful water reduction, excellent flowability, reduced placing and compacting efforts, reduce energy cost for steam cured precast elements, improve shrinkage and creep behaviour, also it reduces the rate of carbonatisation of the concrete and finally improves water impermeability. This type is known as Sika ViscoCrete-10, some technical data shown in *Table 3*.

Table 3: The technical data for the superplasticizer

Type	Property
Appearance	Turbid liquid
Density	1.08 kg/l ±0.005
PH value	7.5
Basis	Aqueous solution of modified polycarboxylate
Toxicity	Non-Toxic under relevant health and safety codes

In all trial mixtures, where the w/c was constant and equal to 0.24, no segregation was observed and all mixtures were homogenous and fibres were well distributed through every batch.

3.3 Preparation of UHPFRC

After selection of all needed constituent materials and amounts to be used (mix designs); all materials are weighed properly. Then mixing with a power-driven tilting revolving drum mixer, started to ensure that all particles are surrounded with cement paste, silica fume and all other materials furthermore fibres should be distributed homogeneously in the concrete mass.

All mixes and tests were conducted in Soil & Materials Laboratory at the Islamic University of Gaza, Palestine.

Mixing procedure was carried out according following steps: (Arafa et.al. 2010)

1. Placing all dry materials (cement, silica fume, quartz sand and polypropylene fibres) in the mixer pan, and mixing for 2 minutes.
2. Adding 40% of superplasticizer to the mixing water.
3. Adding water (with 40% of superplasticizer) to the dry materials, slowly for 2 minutes.
4. Waiting 1 minute then adding the remaining superplasticizer to the dry materials for 30 seconds.
5. Continuation of mixing as the UHPFRC changes from a dry powder to a thick paste.
6. After final mixing, the mixer is stopped, turned up with its end right down, and the fresh homogeneous concrete is poured into a clean plastic pan.

The casting of all UHPFRC specimens used in this research was completed within 20 minutes after being mixed. All specimens were cast, cured and covered to prevent evaporation.

All mixtures were subjected to hardened concrete tests in order to be classified as UHPFRC. Some mixing ingredients were fixed and the others were variable. *Table 4.* summarizes the different mix proportions. The percentage of silica fume, quartz sand, superplasticizer and water was used was the same percentage obtained by Madhoun A. (2013) in his research at Islamic University.

Each result listed in the search is an average of three examined specimens with the same properties and under the same conditions at least.

Table 4: Different mix proportions of UHPFRC by weight of cement

Mix No.	Mix-1	Mix-2	Mix-3
Cement	1	1	1
Silica fume	15%	15%	15%
Quartz sand	125%	125%	125%
Superplasticizer	3%	3%	3%
PP fibre	0%	0.75%	1.50%
Water	24%	24%	24%

4. RESULTS AND DISCUSSION

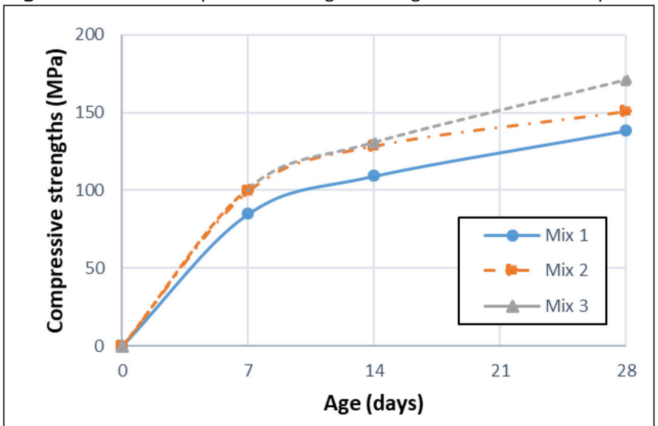
4.1 Hardened properties results

Laboratory tests were conducted to evaluate and study the hardened properties of UHPFRC. Results are the unit weight, compressive strength and tensile strength tests. Mean results for concrete mixtures at several ages are summarized in *Table 5* and *Figures 1 through 3*. These results are the base line in comparing the strength reduction of the samples after being subjected to the heating tests.

Table 5: Compressive and tensile strengths for samples without heating

Mix No.	Density kg/m^3	Compressive strengths MPa			Flexural strengths at 28 days, MPa
		7 days	14 days	28 days	
Mix1	2335	84.8	109.1	138.2	14.2
Mix2	2320	99.2	128.5	150.6	16.7
Mix3	2315	101.5	130.9	171.4	19.2

Figure 1: Mean compressive strengths vs. age for unheated samples



Results shown in *Table 5* and *Figure 1* demonstrate that it is possible to develop UHPFRC with different polypropylene amounts.

It can be observed that increasing the polypropylene content from 0.75% to 1.5% effectively increases the compressive strength of concrete when it was used alone.

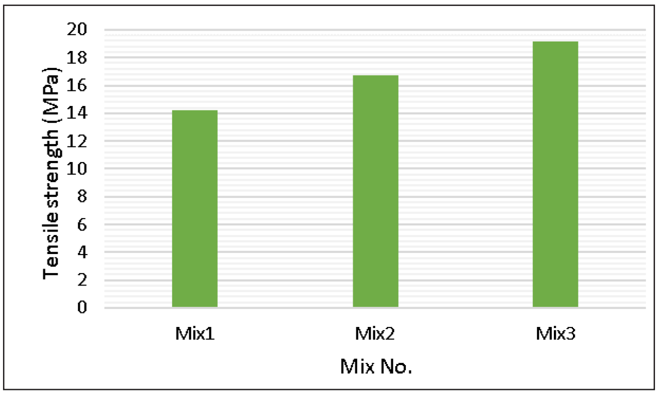


Figure 2: Mean tensile strengths for unheated samples

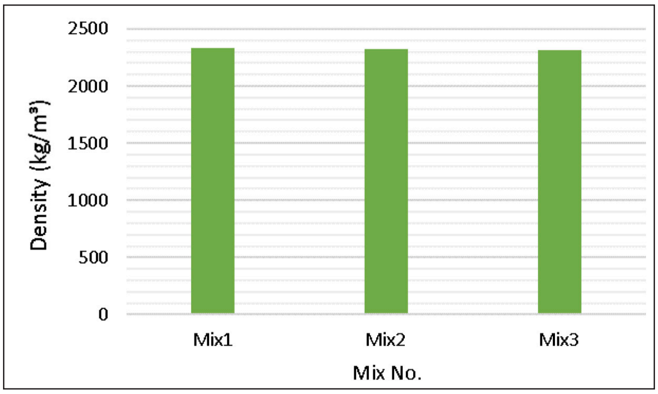


Figure 3: Mean density for unheated samples

4.2 Compressive strength test results of heated samples

Results of the compressive strength tests are shown in Table 6, Table 6 and Figures 5 through 6 for different percentages of polypropylene (0%, 0.75% and 1.5%), different heating temperatures (room temperature, 250 °C and 500 °C) and heating durations (0, 2.5 and 5 hours).

Table 6: Compressive strengths for heated samples

2.5-hour heating				
Mix No.		**Mix-1**	**Mix-2**	**Mix-3**
% of PP fibre		0.00%	0.75%	1.50%
Average compressive strength (MPa)	room temp.	138.2	150.6	171.4
	250 °C	113.3	145.0	168.7
	500 °C	40.1	69.3	63.6

Table 7: Compressive strengths for heated samples

5-hour heating				
Mix No.		**Mix-1**	**Mix-2**	**Mix-3**
% of PP fibre		0.00%	0.75%	1.50%
Average compressive strength (MPa)	room temp.	138.2	150.6	171.4
	250 °C	92.6	128.7	140.9
	500 °C	21.8	34.9	37.8

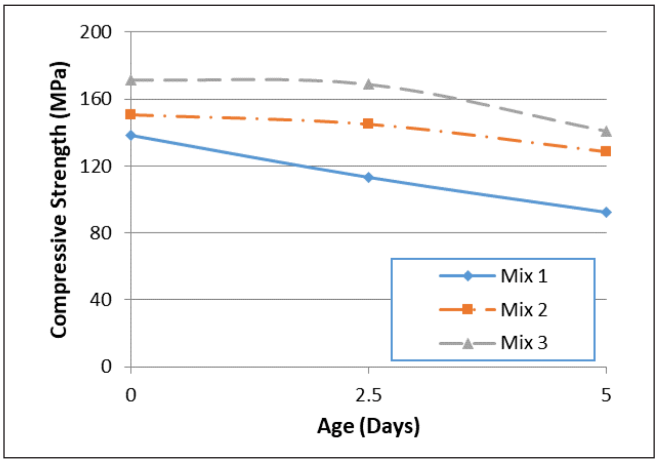


Figure 4: Compressive strength results for samples heated to 250 °C

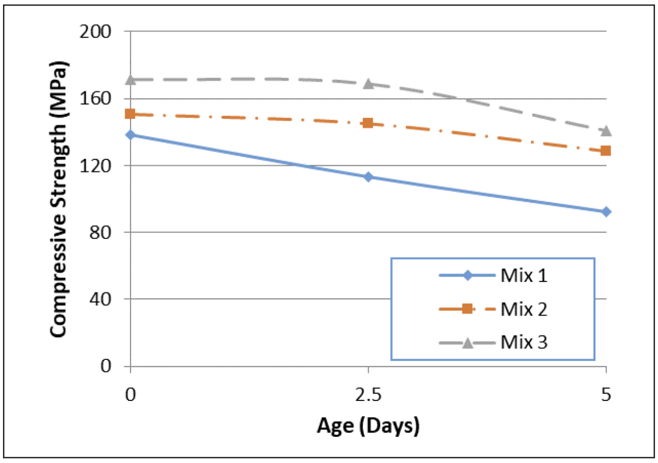


Figure 5: Compressive strength results for samples heated at 500 °C

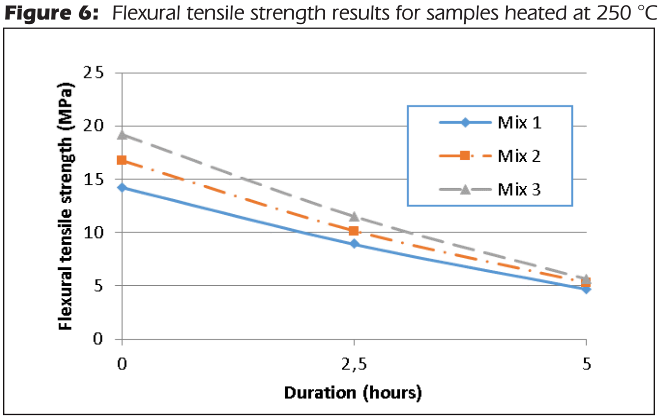
4.3 Flexural strengths test results after heating tests

Results of the flexural tensile strength tests are shown in Table 8 and Figures 6, for different percentages of PP (0%, 0.75% and 1.5%), different heating temperatures (room temperature and 250 °C) and heating durations (0, 2.5 and 5 hours).

Table 8: Flexural tensile strength for heated samples

Mix No.	% of PP fibre	Average flexural tensile strength, MPa		
		0 hour	2.5 hours	5 hours
Mix-1	0.00%	14.2	8.9	4.7
Mix-2	0.75%	16.7	10.1	5.3
Mix-3	1.50%	19.2	11.5	5.7

Figure 6: Flexural tensile strength results for samples heated at 250 °C



From Table 8 and Figure 6, it is noticed that for samples without polypropylene, the reductions in flexural tensile strengths are larger than at those with polypropylene. For example, the percentage of strength losses for samples without PP fibres heated at 250 °C for 2.5 hours was 37.7%, and when heated to 5 hours at the same temperature was 66.8%. On the other hand, the loss in tensile strength for samples with 0.75% PP fibres heated at 250 °C for 5 hours the loss was 68.5%. So from these results, one may conclude that the addition of polypropylene is highly decreasing the loss of concrete tensile strength when it was heated up to 2.5 hours at 250 °C but its not significant when the samples heating to 250 °C for 5 hours.

4.4 Results discussion

It is noticed that PP fibres not only improve the concrete resistance at elevated temperatures, but also improve samples initial strength before heating.

Results showed that the optimum percentage of polypropylene fibre is 1.5%, and this percentage complies with both Sohaib et. al. (2018) and Dharan and Lal (2016) they conclude that the optimum percentage of polypropylene fibres to improve the strength of concrete is 1.5%, and after 1.5% the decrease is gradual. The optimum percentage of polypropylene fibres was changed in other researchers, whose studying different type of concrete, fibres or additional materials in the concrete mix, for example 1.5% PP was not comply with the optimum percentage of Shihada (2011), Komonen and Penttala (2003); the different results comes from the difference of the type of concrete, in ultra-high performance concrete we have a high density mix without aggregate so the polypropylene fibres working as an internal reinforcement to confine the structural core of concrete, in addition the difference of polypropylene length, shape and diameter will lead to difference behaviour of the concrete mixture.

To conclude, all of researchers agreed that adding polypropylene fibres to the concrete mix improves their performance and increases strength, but in different proportions depending on the type of concrete mixture.

The masses of the different groups of concretes decrease with temperature. An additional mass decrease is noticed with the concrete incorporating polypropylene fibres, after the heating at 250 ºC and 500 ºC, the mass loss of fibres (PP fibres) concretes is lower than that of concretes with polypropylene fibres,

5. CONCLUSION

In this research, specimens of various concrete compositions were made and subjected to different heating periods. Three concrete groups were formulated without or with polypropylene fibres. Concrete mass loss and residual mechanical properties were studied. The following conclusions can be drawn from the experimental results:

1. All of concrete mixes prepared in this research achieved high workability and flowability, and may be used it as a self-compacting concrete the compressive strength of reference mixture was higher than 138 MPa.
2. The masses of the different groups of concretes decrease with temperature. An additional mass decrease is noticed with the concrete incorporating polypropylene fibres. After the heating at 250 ºC and 500 ºC, the mass loss of fibres (PP fibres) concretes is lower than that of concretes with PP fibres.

3. The 0.75 and 1.5% of PP fibre addition increased the compressive and the flexural tensile strength, too. The compressive strength for mix without fibres (Mix 1) was increased by 34.8% when polypropylene fibres were added as in (Mix 3).
4. The residual compressive strength of fibre reinforced concrete was relative and absolute higher than reference mixture. Comparing with concretes without fibres (Mix 1), reduction of relative residual strength was observed at 250 °C for 5 hours was 33%, and when heated at 500 °C for 5 hours was 84.2%. On the other hand, for concrete (Mix 2) heated at 250 °C for 5 hours, the loss was 14.5% and when heated to 500 °C for 5 hours the loss was 76.8%.
5. The relative residual flexural strength of mixtures with fibres are lower than the reference mixture, but the flexural strength increasing in room temperature were so high, than the absolute value of flexural strength is higher after heating. Comparing with concrete without fibres (Mix 1), it is noticed that the reductions in flexural tensile strengths are larger than at those with polypropylene fibres. The percentage of strength losses for Mix 1 heated at 250 °C for 2.5 hours was 37.7%, and when heated to 5 hours at the same temperature was 66.8%.

The optimum amount of polypropylene fibres on Ultra High Performance Concrete (UHPC) improves the fire resistance properties, by decreasing the rate of compressive strength loss as well as increasing the time of exposure before occurrence of failure.

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