Coupled Effect of High Temperature and Heating Time on the Residual Strength of Normal and High-Strength Concretes

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ABSTRACT

This paper is part of a present research that leads to estimate the level of concrete degradation properties altered by high temperatures, especially by using the maturity concept. In order to evaluate the coupled effect of high temperature and heating time on the residual strength of concrete, a series of compressive and indirect tensile tests was performed on normal and high strength concretes. The effect of incorporating polypropylene fibers in high strength concretes was also investigated. Cubical concrete specimens were exposed to different target high temperatures (100, 300, 500 and 700 ºC) for 3, 6 and 9 hours and then cooled in air. Compressive and flexural strengths of these concrete samples were compared with each other and with the unheated samples. Experimental results indicate that concrete strength decreases with increasing temperature and heating time. The grade of concrete affects the residual compressive and flexural strength; the decrease in the strength of ordinary concrete is more than that in High Performance Concrete (HPC), the effect being more pronounced as the heating time increases. Polypropylene fibers were found to have a beneficial effect on residual strength of HPC at least at high temperatures over their melting and vaporization.

KEYWORDS: HPC, Effect of heat, Concrete strength, Temperature, Fibers, Fire.

INTRODUCTION

Concrete structures could be exposed to elevated temperature conditions. Examples of such conditions are concrete foundations for launching rockets carrying spaceships, concrete structures in nuclear power stations or those accidentally exposed to fire as the case of many tunnels registered in many countries. The last one was in the tunnel between Lakhdaria and Ammal (Algeria) in February 28, 2008. Following the collision of two trains in this tunnel, 750m^3 of gas oil were burnt. The temperature has reached 1200°C. Intervention to extinct the fire was impossible and the duration of the fire was 48 hours. Dramatic damages were observed and the tunnel is closed until nowadays.

Normal strength concrete and high-strength concrete structures subject to fire have been studied in various aspects. Various experimental parameters have been examined such as maximum temperature, heating rate, types of aggregates used and various binding materials. Many test methods are used to determine the resistance of concrete samples exposed to high temperature. Three test methods are basically used (Phan, 1996). These are named as stressed, unstressed and unstressed residual

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strength tests. More and more attention has been paid to the unstressed residual properties of concrete after exposure to elevated temperatures (Bazant et al., 1996; Noumowe et al., 1995). It represents the lowest limit of residual strength. When concrete is subjected to elevated temperatures, various physical (e.g., evaporation, condensation, water and vapor advection, vapor diffusion, heat conduction and advection, phase expansion), chemical (e.g., dehydration, thermo-chemical damage) and mechanical (e.g., thermo- mechanical damage, cracking, spalling) processes take place, resulting in the deterioration of the concrete (Heikal, 2000; Xu et al., 2001). The spalling of concrete exposed to fire has been observed under laboratory and real fire conditions (Diederichset et al., 1995; Bilodeau et al., 2004; Kodur et al., 2003). Adding polypropylene fibers to concrete mix is much more effective in minimizing spalling in HSC under fire exposure and enhances fire endurance (Bilodeau et al., 2004). Therefore, the effects of high temperatures are generally visible in the form of surface cracking (Ali et al., 2004; Kalifa et al., 2000). Omer (2007) has noticed that the surface cracks became visible when the temperature reached 600 °C. The cracks were very pronounced at 800 °C and increased extremely when the temperature increased to 1000°C. The alterations produced by high temperatures are more evident when the temperature surpasses 500°C. Most changes experienced by concrete at this temperature level are considered irreversible (Luccioni et al., 2003). According to Chan et al. (1999), the range between 400 and 800°C was critical to the strength loss. Savva et al. (2005) observed that at a temperature over 600°C, all tested concretes suffered deterioration and only a small part of the initial strength was left, ranging from 7% to 25% for all mixtures.

To decrease the explosive spalling of high strength concrete at high temperatures, Nishida et al. (1995) and Atkinson (2004) have revealed that the application of polypropylene fibers in concrete may considerably reduce the amount of spalling for HPC at high temperatures. Polypropylene fibers melt and create channels through which the water vapor pressure built-up within HPC as temperature rises is released. This release of the vapor pressure significantly reduces the spalling tendency of HPC under fire conditions (Consolazio et al., 1998; Dale, 2000; Kalifa et al., 2001). Poon et al. (2004) have concluded that inclusion of PP fibers results in a quicker loss of the compressive strength after exposure to elevated temperatures up to 800°C. However, they also have found that the residual compressive strength of HPC with ordinary Portland cement containing PP fibers increases 4.6% after exposure to 600 °C, while it decreases 3.2% after exposure to 800 °C, compared with that for HPC without PP fibers.

Jianzhuang et al. (2006) concluded that except for the mass loss, the addition of PP fibers in HPCs has no negative effects on the residual compressive and flexural strengths of HPCs after exposure to high temperatures. However, the influences of higher content of PP fibers on the residual mechanical behavior are still unclear. This deserves a further investigation.

Previous experimental studies on concrete under high temperatures have mainly concentrated on the reduction of stiffness and strength properties. Only few studies (Mohamedbhai, 1986; Resheidat et al., 1999) have evoked the combined effect of high temperature and heating time on residual strength of concrete. This subject needs more investigation that will be beneficial in engineering practice. Although the assessment of the degree of deterioration of the concrete structure after exposure to high temperatures can help engineers decide how a structure can be repaired, aesthetic damage is generally easy to repair while functional impairments are more profound and may require partial or total repair or replacement, depending on their severity.

EXPERIMENTAL PROGRAM

Materials Used

Aggregates used were of crushed limestone. Their properties are given in Tables (1) and (2). Commercial Portland cement of 42.5 MPa grade, produced in Jordan as CEM I cement was employed. The chemical composition and physical properties of the cement are given in Tables (3) and (4). Silica fume (ASTM C-494 F type) and polypropylene fiber (PP fiber) were used. Physical properties of PP fibers are given in Table (5).

Table (1): Sieve Analysis of Aggregates.

Grain size mm	Sieve opening (mm)						
	0.25	0.5	1	2	4	8	12.5
0 – 4	29	41	69	82	97	100	100
4 – 12.5	0	0	0	1	2	46	99

Table (2): Physical Properties of Aggregates.

Grain size mm	Specific gravity	Unit weight (kg/m^3)	Water absorption ratio 24 h (%)
0 – 4	2.46	1705	1.62
4 – 12.5	2.75	1617	1.05

Table (3): Physical Characteristics of Cement.

Physical test results	
Initial setting time (minutes)	145
Final setting time (minutes)	260
Specific surface (cm^2/gr)	2810
Specific gravity	3150
Residue on 200 µm (%)	1.00

Mix Proportioning

The gradation of aggregates used to obtain the three types of concretes designated by Normal Strength Concrete (NSC), High Strength Concrete (HSC) and High Strength Concrete incorporating Polypropylene fibers (HSC-PP) was the same. In the mixture proportioning of normal strength and high strength concretes, water to cement ratios of 0.45 and 0.30 were used, respectively. In the production of high strength concrete, silica fume was added (10% of weight of cement) and superplasticizer admixture was used. The detailed mixture proportion of these concretes is given in Table (6).

Table (4): Characteristics of Cement.

Physical Results		Chemical %	
Initial setting time	2:25	CaO	58.80
Final setting time	4:20	SiO_2	21.70
Specific surface, cm^2/gr	2810	Al_2O_3	6.10
Specific gravity	3.15	Fe_2O_3	3.60
Residue on 200 µm,%	1.0	MgO	3.60
Composition %		SO_3	3.00
C_3S	61.19	K_2O	0.72
C_2S	11.09	NaO	0.44
C_3A	7.92		
C_4AF	10.39	LOI*	1.50

* Loss of Ignition.

Table (5): Physical and Mechanical Properties of Fibers.

Diameter, µm	50
Length, mm	20
Aspect ratio	1000
Relative density, g/cm^3	0.91
Ignition temperature, ºC	600
Melting temperature, ºC	165

Mixing and Casting Procedure

In mixing concrete, a concrete mixer having 80 l capacity and inclined axes was used. The course and fine aggregates were weighed and placed into the concrete mixer, moistened in advance and mixed for 3 minutes with the addition of saturation water, for 3 minutes with the addition of cement and silica fume. The superplasticizer was then mixed thoroughly with the mixing water and added to the mixer. Fibers were dispersed by hand in the mixture to achieve a uniform distribution throughout the concrete, which was mixed for a total of 3 minutes. Fresh concrete was cast in steel moulds and compacted on a vibrating table. Cube specimens of 100 mm size were used for strength determination, and beams of 100 mm x 100 mm x 300 mm, were used for flexural tensile strength determination. After demolding at one day, the specimens were cured in water at 20 until 28-day age and then cured in air with a temperature of 20 °C and 50% R.H.

Table (6): Concrete Mixture Proportion/m³.

Composition	NSC	HSC	HSC-PP
Cement, kg	500	500	500
Sand, kg	1125	1220	1220
Gravel, kg	1470	1450	1450
Silicate fume, kg	-	50	50
Polypropylene Fibers, kg	-	-	1.5
Water, liter	250	204	204
Superplasticizer	-	3 %	3 %
Water/Binder	0.50	0.37	0.37

After the feeding operation, each of the specimens was allowed to stand for 24 hours before demolding, stored in lime water at 22 ± 2 °C for 21 days, and then removed and kept at room temperature and 65% relative humidity until the time of the experiment. The specimens were 28 days old at the time of the tests.

Testing Methodology

At 28 days, a control set of unheated samples was tested for compressive and tensile flexural strength. Other specimens were heated in an electric furnace (Carbolite gpc, Figure 1) at a heating rate of 10ºC/min to target temperature. Three target temperatures; namely, 300, 500 and 700ºC were used. At each target temperature, the specimens were maintained at the target temperature for the duration of 3, 6 and 9 hours so that the temperature in the middle of the specimen is close to the target temperature, as measured by a Type K thermocouple.

Figure (1): Specimens inside the Furnace.

The elevated temperature exposure cycle compared with the standard curve in ISO 834 is illustrated in Figure (2). After each exposure cycle, the specimens were allowed to cool to laboratory room temperature for 24 hours and were then tested to assess the residual strength. For each data point of test, three identical specimens were used to guarantee repeatability in all tests.

DISCUSSION OF RESULTS

Compressive Strength

The residual concrete compressive strengths for NSC, HSC and HSC-PP are given in Figures (3-a, 3-b and 3-c).

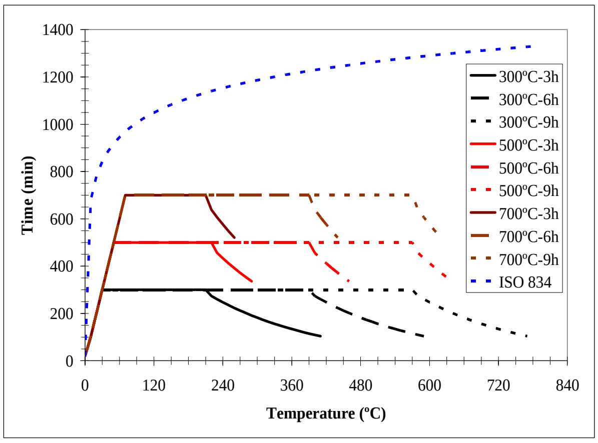

Figure (2): Experimental Time-Temperature Curve Compared with the ISO 834 Curve.

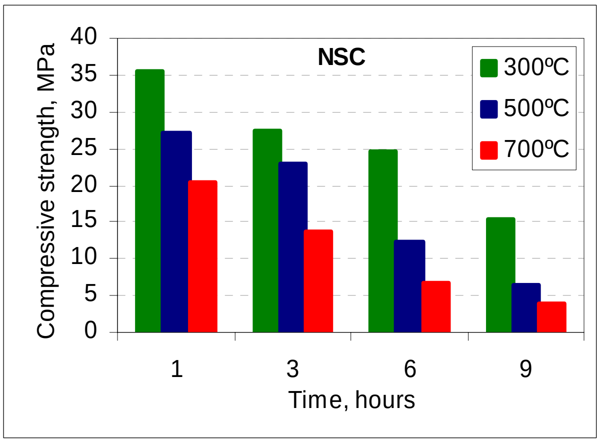

Figure (3-a): Residual Compressive Strengths of NSC Heated Concretes.

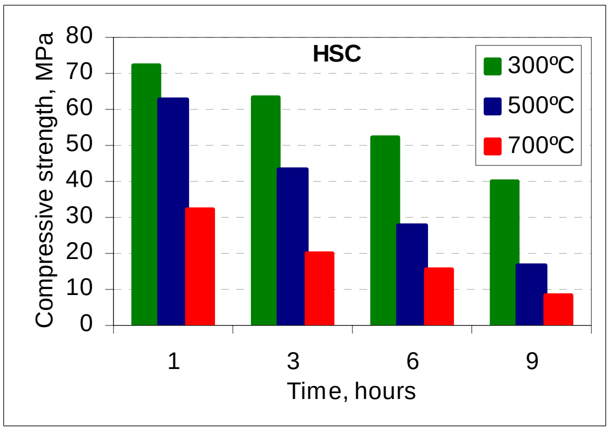

Figure (3-b): Residual Compressive Strengths of HSC Heated Concretes.

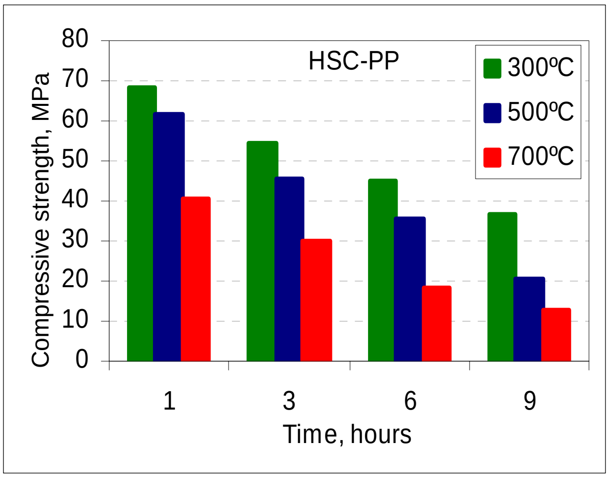

Figure (3-c): Residual Compressive Strengths of HSC-PP Heated Concretes.

Influence of Temperature and Heating Time

Figure (3) shows that the compressive strength of concrete drops with target temperature and heating time starting from 300°C in this research. According to these results, when the temperature was increased up to 300 °C and for 1 hour heating time, there was a little increase of compressive strength of 2%, 3% and 5% for NSC, HSC and HSC-PP, respectively. For this heating time and for the temperatures of 500-700°C, compressive strength loss is 22-42% for NSC, 10-54% for HSC and 6-38% for HSC-PP. Former studies indicated that the increase is caused by evaporation of free water and removal of water of crystallization from the cement paste (Husem, 2006). As shown in Table (7), for a heating time of 3, 6 and 9 hours at 500°C, all tested concretes have revealed a compressive strength loss. The largest value of strength loss was 56% for NSC (9 hours) and the smallest value was 10% for HSC (3 hours). At 700°C, the largest and smallest straight values were, respectively, 89% for NSC (9 hours) and 54% for HSC-PP (3 hours).

Compressive strength loss of heated concretes results mainly from the change that occurs in the concrete microstructure during the heating process. Some complicated processes of shrinkage, decomposition, expansion and crystal destruction occur during fire.

According to Min et al., (2004), crystal shape transformation of SiO_2 results in the increase of volume up to 0.85%. Dehydration, followed by the hydroscopic process of $Ca(OH)_2$, also makes volume expansive. Moreover, expansion caused by temperature rise and shrinkage caused by dehydration of cement paste ultimately result in a volume change of 0.5% (Min et al., 2004).

Effect of Strength Grade

As can be seen from Figures (4-a, 4-b, 4-c and 4-d), generally the strength loss of HSC surpasses that of NSC for a heating time less than 6 hours. This difference is notable, especially in the range of 25-300°C. For 9 hours of heating, HSC retained 24% of compressive strength at 500°C and 12% at 700°C, while for NSC the values were 18% at 500°C and 11% at 700°C. According to (Phan, 1996; Ali, 2002; Phan et al., 2001), explosive spalling of HSC when it occurs, the temperature range is between 300 and 650°C. Many factors were identified as affecting explosive spalling. These factors include age, moisture content, type of gravel and sand used, curing method and rate of heating. In this study, no explosive spalling was observed.

Effect of Polypropylene Fibers

Overall, residual compressive strength of HSC was found less important than HSC-PP mainly beyond 300°C and for all heating times. This confirms that the PP fibers can markedly improve resistance of HSC subject to elevated temperature by reducing its explosive spalling and its surface cracking and deterioration as shown in Figures (5-a, 5-b and 5-c).

Figure (5) illustrates the surface character of NSC, HSC and HSC-PP heated at 700°C for 3 hours. After exposure to high temperature, many surface cracks occur on HSC. However, few cracks take place on NSC and HSC-PP. This is because free water has been transgressed a great deal at about 105°C, and then cement particles combine more tightly and vapor transgress becomes more difficult as reported by Min et al. (2004).

Table (7): Loss of Compressive Strength as Function of Temperature and Heating Time.

Concrete Type	Heating Time, h	Heating temperature °C		
		300	500	700
NSC	1	+0.02	-0.22	-0.42
	3	-0.21	-0.34	-0.61
	6	-0.30	-0.65	-0.81
	9	-0.56	-0.82	-0.89
HSC	1	+0.03	-0.10	-0.54
	3	-0.10	-0.38	-0.71
	6	-0.25	-0.60	-0.78
	9	-0.43	-0.76	-0.88
HSC-PP	1	+0.05	-0.06	-0.38
	3	-0.16	-0.30	-0.54
	6	-0.31	-0.46	-0.71
	9	-0.44	-0.68	-0.80
- Loss of strength, + Gain of strength.				

The residual flexural tensile strengths for NSC, HSC and HSC-PP are given in Figures (6-a, 6-b and 6-c).

From Figure (6), it can be seen that as like as compressive strength, the flexural tensile strength was reduced after elevated temperature. After 9 hours at700 °C, the retained flexural tensile strength was only 22%, 8% and 15% for NSC, HSC and HSC-PP, respectively. For the HSC concrete, the dense structure induces thermal stress that results in many micro-cracks (Figure 5) that reduce the valid area of cross-sections. As a result, the effect of cracks on the flexural tensile strength is more noticeable than on the compressive strength as was also reported by Min et al. (2004).

The flexural tensile strength loss as function of temperature and heating time is reported in Table (8).

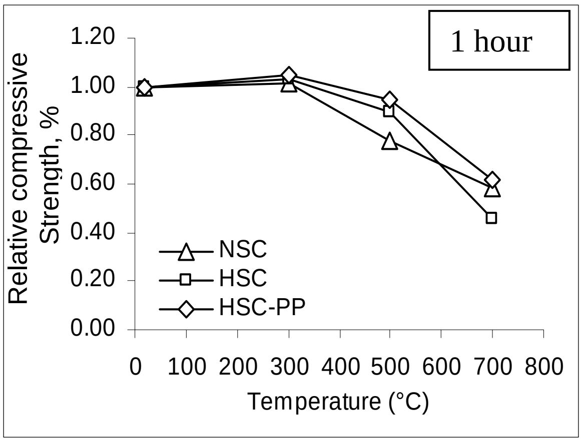

Figure (4-a): Relative Residual Compressive Strength of Heated Concretes for 1 Hour.

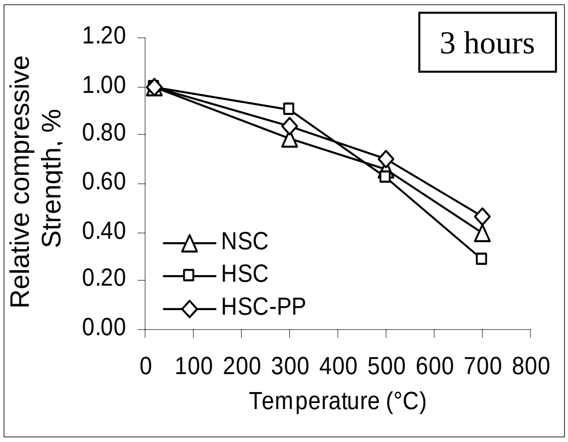

Figure (4-b): Relative Residual Compressive Strength of Heated Concretes for 3 Hours.

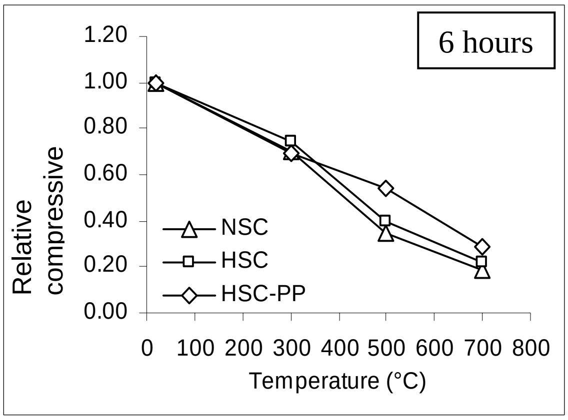

Figure (4-c): Relative Residual Compressive Strengths of Heated Concretes for 6 Hours.

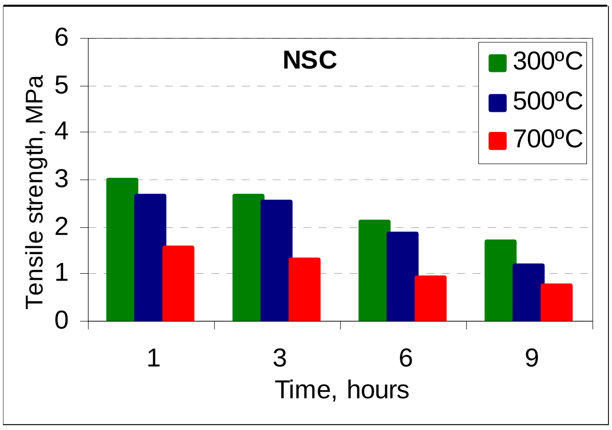

Figure (6-a): Residual Flexural Tensile Strength of NSC Heated Concretes.

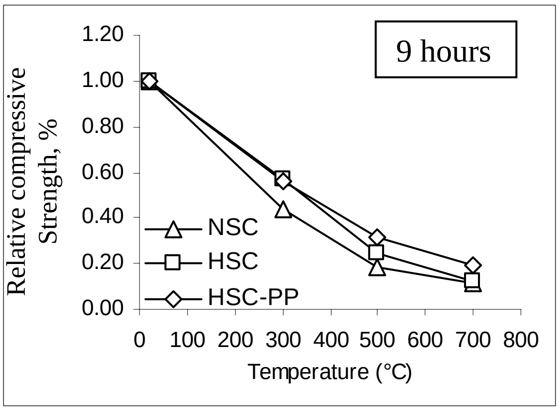

Figure (4-d): Relative Residual Compressive Strengths of Heated Concretes for 9 Hours.

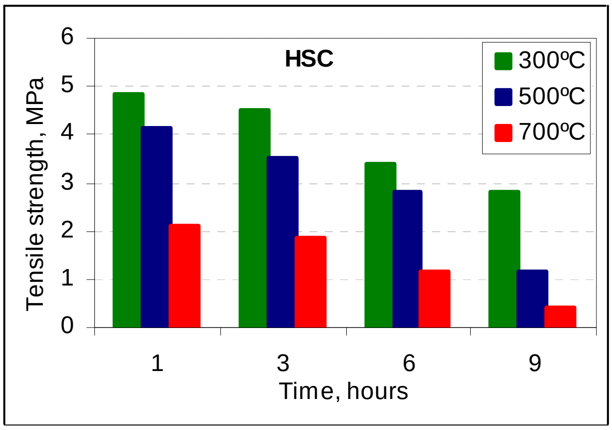

Figure (6-b): Residual Flexural Tensile Strength of HSC Heated Concretes.

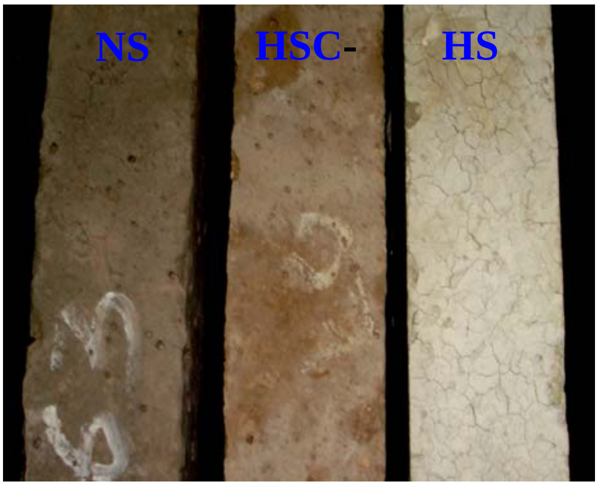

Figure (5): Surface Character of NSC, HSC and HSC-PP Heated at 700°C for 3 Hours.

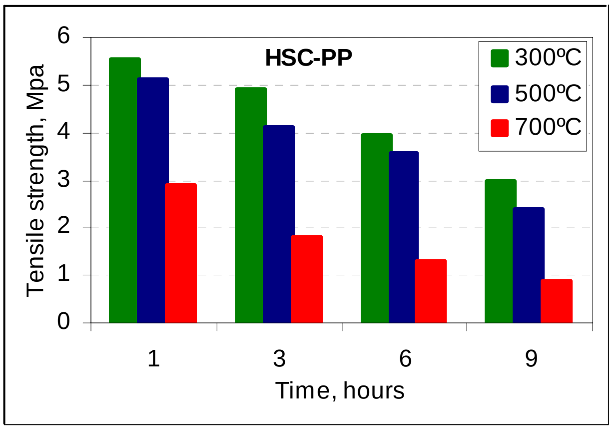

Figure (6-c): Residual Flexural Tensile Strength of HSC-PP Heated Concretes.

Table (8): Percentage of Flexural Tensile Strength Loss as Function of Temperature and Heating Time.

Type of Concrete	**Heating time (h)**	**Heating temperature (°C)**		
		300	**500**	**700**
NSC	1	-11	-21	-53
	3	-21	-25	-61
	6	-38	-45	-72
	9	-50	-64	-78
HSC	1	-8	-21	-60
	3	-14	-33	-64
	6	-35	-46	-78
	9	-47	-78	-92
HSC-PP	1	-06	-13	-51
	3	-16	-30	-69
	6	-33	-40	-78
	9	-49	-59	-85

- Loss of strength, + Gain of strength.

Tensile Flexural Strength

Contrarily to compressive strength, when the temperature was increased up to 300°C and for 1 hour heating time, there was no increase of flexural tensile strength. It decreases for all heating times and temperatures. Similar to compressive strength loss, flexural tensile strength loss results mainly from cracking, the change that occurs in the concrete specimens during the heating process and shrinkage caused by dehydration of cement paste. The lowest values of retained flexural tensile strength were observed for HSC and the highest ones for the NSC and HSC-PP. Consequently, adding polypropylene fibers to HSC improves also its residual tensile strength.

CONCLUSIONS

In this paper, a series of experiments was performed to investigate the residual strength of NSC, HSC and HSC-PP subjected to elevated temperatures ranging from 300 to 700°C for a heating duration between 1 hour and 9 hours. Based on the experimental results presented in this paper, the following conclusions may be drawn from this study:

1. The residual strength of concrete decreases as the exposure temperature increases, and prolonging the heating time decreases also the residual concrete strength. The strength degradation of heated concretes comes mainly from the peak temperature and the increase of exposure time.
2. Adding polypropylene fibers to HSC mixtures improves their residual compressive and tensile strengths.
3. Contrasting the residual compressive strength, the residual flexural strength of HSCs without and with polypropylene fibers always drops continuously under rising temperatures.
4. The polypropylene fibers melt at high temperatures (e.g. fire) providing voids that help reduce explosive characteristics of concrete.

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