Evaluating Residual Mechanical and Physical Properties of Concrete at Elevated Temperatures

S. Hachemi, A. Ounis, S. Chabi

***Abstract*—**This paper presents the results of an experimental study on the effects of elevated temperature on compressive and flexural strength of Normal Strength Concrete (NSC), High Strength Concrete (HSC) and High Performance Concrete (HPC). In addition, the specimen mass and volume were measured before and after heating in order to determine the loss of mass and volume during the test. In terms of non-destructive measurement, ultrasonic pulse velocity test was proposed as a promising initial inspection method for fire damaged concrete structure. 100 Cube specimens for three grades of concrete were prepared and heated at a rate of 3°C/min up to different temperatures (150, 250, 400, 600, and 900°C). The results show a loss of compressive and flexural strength for all the concretes heated to temperature exceeding 400°C. The results also revealed that mass and density of the specimen significantly reduced with an increase in temperature.

***Keywords*—**High temperature, Compressive strength, Mass loss, Ultrasonic pulse velocity.

I. Introduction

CONCRETE is the most widely used construction material in the world. Although concrete engineering is more than one hundred years old and concrete is thought to be a well-understood construction material. In recent years, high performance concrete (HPC) is becoming an attractive to traditional normal strength concrete (NSC). HPC exhibits significantly higher mechanical strengths as well as superior performances under severe conditions in comparison with normal strength concrete (NSC). The alleged HPC is generally defined as high fluidity and high durability concrete, moreover, high performance water reducer and superfine mineral admixtures are absolutely necessary ingredients. The dense microstructure of HPC ensures a high strength and a very low permeability, which is essential to obtain good durability in severe exposure conditions where there are aggressive agents. However, the dense microstructure of HPC seems to be a disadvantage, when compared to NSC, in the situation where concrete is exposed to fire.

Fire represents one of most sever risks to buildings and structures. Being a primary construction material, the properties of concrete after exposure to high temperatures have gained a great deal of attention since the 1940s [1]–[3]. The behavior of NSC under elevated temperatures has been clearly understood [4]–[6]. In recent years, there have been many research studies to determine the thermal behavioral differences between HSC and NSC [7]–[16].

The mechanical properties of concrete at high temperature degrade mainly because of two relevant mechanisms: mechanical and physic-chemical damage [17]–[23]. In the case of elevated heating conditions, the dehydration of CSH gel, the thermal incompatibility between the aggregate and cement paste and the pore pressure within the cement paste are the main detrimental factors. To investigate the effect of high temperature and to obtain necessary information for evaluating the structural safety and establishing reparation methods, the residual strength and properties of concrete that has been exposed to high temperatures should be determined.

In this experimental investigation, the effect of elevated temperatures on the physical and mechanical properties of concrete mixtures produced by different water/cement (w/c) ratios and different types of aggregates were extensively examined. In the tests, temperatures of 20, 150, 250, 400, 600 and 900°C were chosen for ease of observation of the test results.

II. Experimental Study

The cement used in this study was Portland cement (CPJ CEM II/A 42.5). Its chemical composition is presented in Table I. Natural siliceous river sand with a maximum grain size of 5mm was used as a fine aggregate (fineness modulus of 2.65). Coarse aggregate was crushed calcareous (diameter ranging from 5mm to 20mm). The specific gravity of the aggregate was 2600 kg/m^3.

TABLE I
CHEMICAL, PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT USED

Chemical composition (%)		Physical properties	
CaO	60.41	Specific gravity (kg/m^3)	3000
Al_2O_3	5.19	Initial setting (h:mn)	2 h : 06’
SiO_2	21.91	Final setting (h:mn)	3 h : 03’
Fe_2O_3	2.94	Compressive strength (MPa)	
MgO	1.60		
Na_2O	0.16	2 days	19.03
K_2O	0.54	7 days	44.93
Cl^-	0.02	28 days	53.41
SO_3	2.19		

100mm cube specimens were prepared for three grades of concrete named NSC, HSC and HPC, respectively. The mix proportions of each concrete are given in Table II. The concretes specimens were cast in the moulds for 24h at room temperature of (20±2)°C. After demolding, specimens were

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cured in water at (20±2)°C until 28-day age.

TABLE II
MIX PROPORTION OF CONCRETE

Mix	w/c	Cement (Kg/m3)	Water (Kg/m3)	Sand (Kg/m3)	Aggregate (Kg/m3)		SP (L/m3)
					20 mm	10 mm	
NSC	0.60	329	199	715	646	390	-
HSC	0.42	475	199	715	646	390	2.78
HPC	0.27	610	168	715	646	390	8.81

Three specimens from each mix were placed in an oven and heated from room temperature (20±2)°C to 150, 250, 400, 600 and 900°C at an average rate of 3°C/min. The peak temperature was maintained for 1h. The time temperature curve for the oven is given in Fig. 1. Specimens were allowed to cool-down inside the oven in order to prevent thermal shock. The average cooling rate was about 1°C/min. After the cooling, the residual compressive and flexural strength, ultrasonic pulse velocity, mass loss, volume and density were determined.

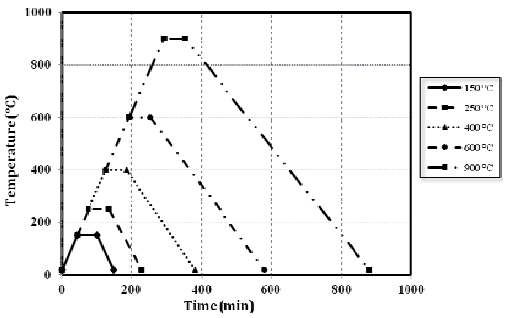

Fig. 1 Heating and cooling curves

III. RESULTS AND DISCUSSION

A. Residual Compressive Strength

The residual compressive strength of concretes at room temperature (20±2)°C and after heating to 150, 250, 400, 600 and 900°C are presented in Fig. 2. This figure shows the results of residual compressive strength tests at different temperature, they are also presented in Table III. Fig. 2 shows that the compressive strength drops with temperature starting from 400°C. Two temperature ranges are observed, 20 to 400°C and 400 to 900°C.

TABLE III
RESULTS OF COMPRESSIVE STRENGTH TEST AT DIFFERENT TEMPERATURE

T (°C)	Compressive strength (MPa)		
	NSC	HSC	HPC
20	27.68 (100.0%)	49.43 (100.0%)	76.85 (100.0%)
150	24.77 (89.49%)	47.90 (96.90%)	70.90 (92.26%)
250	23.54 (85.04%)	44.73 (90.49%)	74.18 (96.53%)
400	26.95 (97.36%)	51.70 (104.6%)	75.44 (98.17%)
600	22.93 (82.84%)	43.00 (86.99%)	49.93 (64.97%)
900	05.22 (18.86%)	03.47 (07.02%)	12.33 (16.04%)

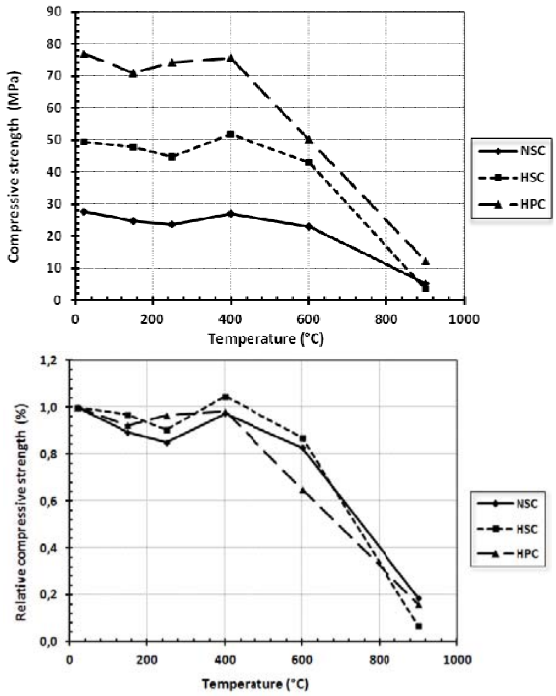

Fig. 2 Residual compressive strength as function of the temperature

In the first temperature range (20 to 400°C), the compressive strength of all concrete specimens decreased by about 3-10% at 150°C in comparison with the control specimens (20°C). Then, around 400°C, it goes up a little.

It clearly shows from Fig. 2 that the mechanical behavior of High performance concrete HPC and High strength concrete HSC at elevate temperature is batter that of Normal strength concrete NSC in this temperature range. Several hypotheses have been proposed in the literature to explain the increase in compressive strength between around 400°C. It's supposed that the removal of moisture from the interlayer of cement gel would reduce the disjoining pressure and increase the banding forces between the particles of hydration products and thus the compressive strength of concrete [24]–[26]. The increase in compressive strength of specimen's exposure to 400°C might be due to a shorter duration of exposure to high temperature [27]. Furthermore, the high temperature of the specimens accelerated the hydration reaction [25].

In the second temperature range (400 to 900°C), the compressive strength is gradually decreased with the increase in temperature. This temperature range may be regarded as critical to the strength loss of concrete. It can be seen from Fig. 2 that an average of 78% of the original compressive strength (20°C) was retained after exposure to 600°C, and was further reduced to 14 % after exposure to 900°C [28]. There are several possible reasons that can be given to explain why the compressive strength of concrete decrease with the increase in temperature. Firstly, at higher temperatures, a large amount of water, which would have been used in the hydration of concrete, is rapidly lost and further hydration of the concrete and therefore, gain in strength is inhibited. Secondly, high pressures may be caused inside the specimens as steam is generated. This pressure may damage the internal structure of the concrete, in the form of micro cracking, and result in a weakened concrete structure and therefore a decrease in compressive strength [29].

B. Residual Flexural Strength

Fig. 3 presents the variation of the residual flexural strength as a function of the temperature. The residual flexural strength decreases continuously from 150°C up to 900°C. We can observe stabilization decrease for NSC and HSC between 150 and 250°C. After this moderate decrease in residual flexural strength, an important decrease (about 90 %) is observed at 600°C. This is because many micro and macro cracks were produced in the specimens due to the thermal incompatibility between aggregates and cement past [30].

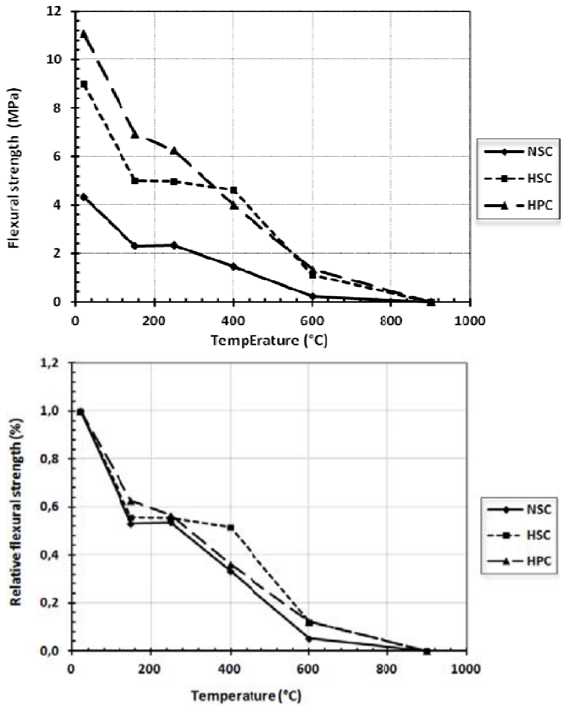

Fig. 3 Residual flexural strength as a function of elevated temperature

C. Ultrasonic Pulse Velocity

Generation of pores and cracks resulting from physicochemical changes in cement paste and thermal incompatibility between aggregate and cement paste was believed to be responsible for the deterioration in mechanical properties of heated concrete [31]. The UPV test can be used to determine the elastic modulus and also the density of materials. In this study, the UPV test only used to determine the quality of concrete specimen for NSC, HSC and HPC. Fig. 4 shows the concrete deterioration through ultrasonic pulse velocity measurements. The UPV values decrease gradually between 150 and 900°C which could be the result of gradual increase of micro cracks in the structure of the concrete.

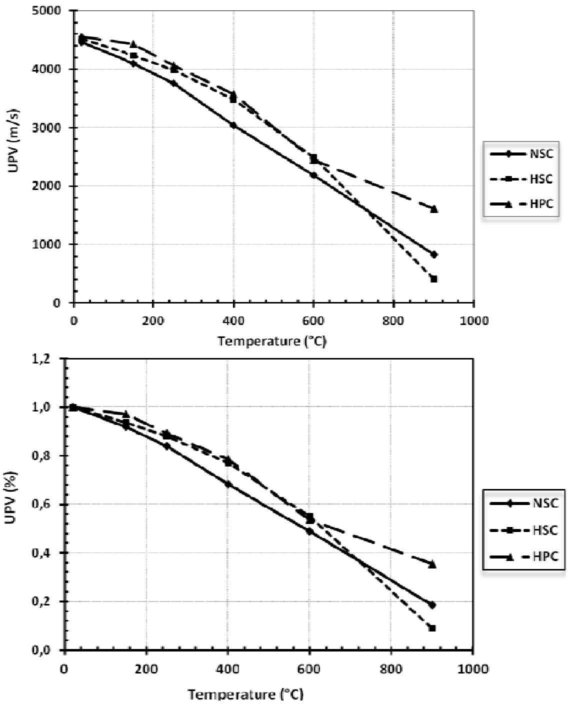

Fig. 4 Ultrasonic pulse velocity as a function of elevated temperature

When the specimens are exposed to 250°C, the ultrasonic pulse velocity of concretes shows a decrease of 16%, 12%, and 11% for NSC, HSC and HPC, respectively, while in 900°C, the decrease is 81%, 91%, and 64% for NSC, HSC and HPC, respectively. As stated above, high performance concrete shows a decrease in the ultrasonic pulse velocity lower than that NSC and HSC. The conclusion can be made that the characteristic and quality of specimen become weaker after exposed to the elevated temperature.

D. Mass Loss

The masses of the cube specimens before and after exposure to high temperature were determined, respectively, for the mass loss evaluation. Fig. 5 presents the effect of elevated temperature on the mass loss of concrete specimens. It can be seen from this figure that the evolution of mass loss versus temperature is very close for the three studied concretes; because, the heating rate was low (3°C/min) and water had time to escape from the concretes. We can observe, for all the specimens, an increase in mass loss with the increase of temperature.

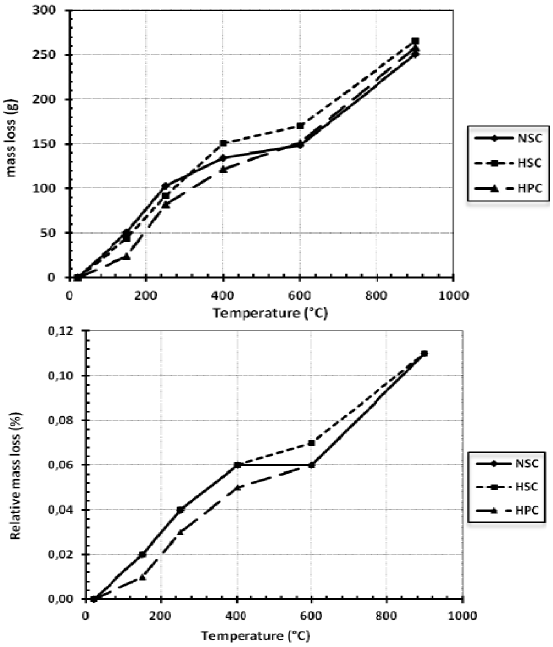

Fig. 5 Mass loss of the concrete specimens subjected to elevated temperature

The variation of mass loss versus exposure temperature can be divided into four phases. Between the ambient temperature and 100°C, the variation of mass is rather weak. The loss of mass in this domain corresponds to the departure of free water contained in the capillary pores. When temperature rises from 100 to 400°C, an important increase in mass loss corresponding to 5.5% of the initial mass can be observed for all concretes. The mass loss in this domain is owing to the release of both capillary water and gel water [8]. Between 300 and 600°C, the rate of mass loss comparatively slows down. Beyond 600°C, the mass loss rate increases again. This could be the consequence of the decomposition of calcareous aggregates, the release of CO_2 and the sloughing off of the concrete surface [32]. At 900°C, a mass loss corresponding to 11% of the initial mass was observed.

E. Effect of High Temperature on Volume and Density

Fig. 6 gives the relative changes in volume of the material as function of elevated temperature. Dimensional changes directly affect the volume of the material. After fire exposure, the volume of HSC increases with the increase in temperature. While the volume of the NSC and HPC gradually decreases between 150 and 400°C for NSC and between 150 and 250°C for HPC. It is 0.995 at 150°C. The reason of the increase in volume, especially approximately above 400°C, is mainly the result of gradual increase of micro cracks developing in the structure of the material due to the thermal expansion of the material [33]. Table IV shows the value of volume before and after specimen exposed to elevated temperature.

Fig. 7 gives the evolution of apparent density as a function of elevated temperature. We noted that whatever the mix, the density decreased between 150 and 900°C.

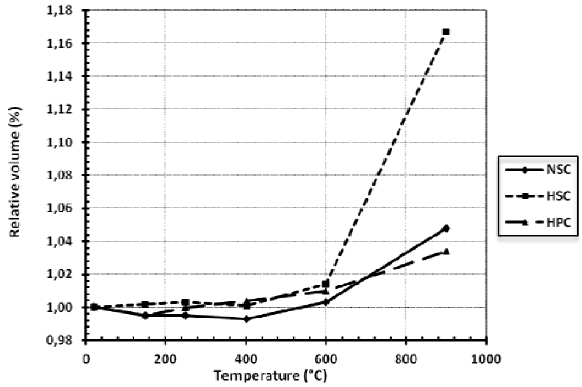

Fig. 6 Relative volume of concrete as a function of elevated temperature

TABLE IV
VOLUME OF NSC, HSC AND HPC AT DIFFERENT TEMPERATURE

T (C°)	Volume (cm^3)								
	NSC			HSC			HPC		
	Before	After	%	Before	After	%	Before	After	%
20	1006,6	1006,6	1.00	1005	1005	1.00	1005	1005	1.00
150	1019,1	1013,7	0.99	1004	1006	1.00	1020	1015	0.99
250	1009,9	1004,9	0.99	989,8	993,2	1.00	1005	1005	1.00
400	1018,4	1011,7	0.99	998,8	999,9	1.00	1005	1009	1.00
600	1017,8	1020,5	1.00	1003	1017	1.01	999,9	1010	1.01
900	1007,6	1056,3	1.05	991,5	1157	1.17	999,6	1034	1.03

Between 20 and 400°C, the overall decrease was around 8% for NSC, 6% for HSC and 5% for HPC. At 900°C, the overall decrease in apparent density was 15% for NSC, 14% for HPC and 26% for HSC. Table V shows the value of apparent density before and after specimen exposed to elevated temperature. The decrease in density is due to the departure of water during heating (dehydration of hydrates like the CSH and portlandite CH) [30].

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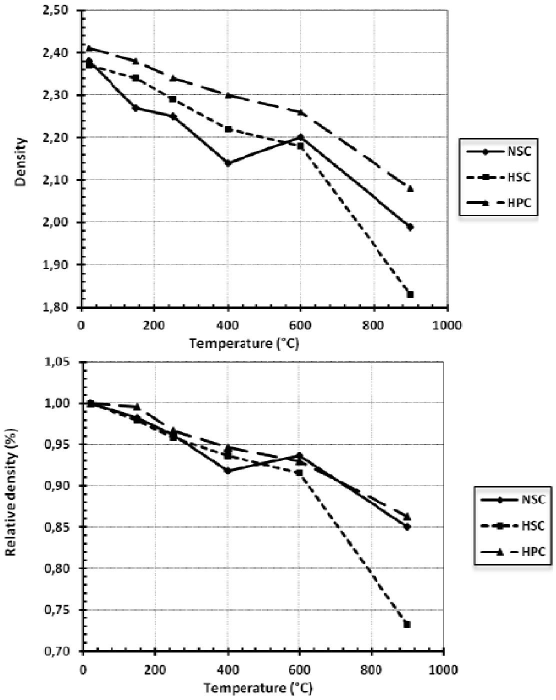

Fig. 7 Concrete density as a function of temperature

TABLE V
APPARENT DENSITY OF NSC, HSC AND HPC AT DIFFERENT TEMPERATURE

T (C°)	Apparent density								
	NSC			HSC			HPC		
	Before	After	%	Before	After	%	Before	After	%
20	2,38	2,38	1,00	2,37	2,37	1,00	2,41	2,41	1,00
150	2,31	2,27	0,98	2,39	2,34	0,97	2,39	2,38	0,99
250	2,34	2,25	0,96	2,37	2,29	0,95	2,42	2,34	0,96
400	2,33	2,14	0,91	2,38	2,22	0,93	2,43	2,30	0,94
600	2,35	2,20	0,93	2,40	2,18	0,91	2,43	2,26	0,93
900	2,34	1,99	0,85	2,37	1,83	0,73	2,41	2,08	0,86

F. Cracking of Concrete

The surface cracks started to appear at around 400°C and continued to grow till the final rise in temperature up to 900°C. Immediately after cooling, the crack widths were measured using a microscope (MPB-2 Magnit 24^x) that can measure the surface crack widths up to 0.05 mm. The crack widths are reported in Table VI. Fig. 8 shows typical crack patterns observed in different concretes at 400, 600 and 900°C.

TABLE VI
CRACK WIDTH OF NSC, HSC AND HPC SPECIMENS AT DIFFERENT TEMPERATURE

Concretes mixes	Crack widths (mm)					
	400°C		600°C		900°C	
	min	max	min	max	min	max
NSC	< 0.05	0,08	< 0.05	0,25	< 0.05	0,70
HSC	< 0.05	0,05	< 0.05	0,10	< 0.05	0,50
HPC	< 0.05	0,05	< 0.05	0,08	< 0.05	0,35

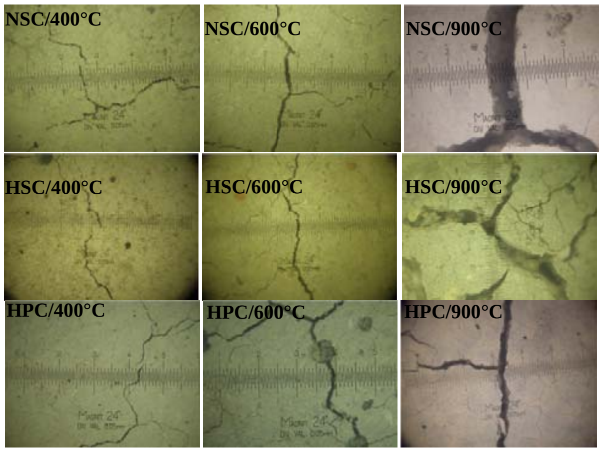

Fig. 8 Typical crack patterns observed in NSC, HSC and HPC at 400, 600 and 900°C

The crack widths increased with the increase of temperature. From Fig. 8, it can be seen that the surface cracking of concrete become significant when the exposure temperatures were higher than 400°C, the internal cracks commenced after 600°C. This was attributed to the thermal incompatibility of the cement past and aggregates and dehydration of cement past due to heating [34].

IV. CONCLUSION

In this paper, the results of elevated temperature on the compressive and flexural strength, ultrasonic pulse velocity, mass loss, volume and density of Normal Strength Concrete (NSC), High Strength Concrete (HSC) and High Performance Concrete (HPC) were presented. The mechanical strength of the tested concretes generally decreased with the increase of temperature. The compressive and flexural strength of HPC decreased in a similar manner to that of HCS and NCS when subjected to high temperature up to 900°C. High temperature can be divided into two ranges. In the first range, between 20°C and 400°C, a little increase in compressive strength for all concretes specimens at 400°C was observed. In the second range, beyond 400°C, the compressive strength of all tested concretes decreased quickly.

The mass and density of the concrete specimens reduced significantly as the temperature increased. This reduction was gradual up to 900°C. As the heating rate was low (3°C/min), water (free water and bound water) had time to escape from the concretes, so, the mass loss for the three concretes is therefore very similar. After fire exposure, the increase of volume specimens is due to the thermal expansion of the material. No explosive spalling is observed, with an average rate of 3°C/min, during the high temperature tests.

Further research is needed to find out the effects of high temperature on the mechanical and physical properties of ultra high performance concrete and also the reinforced concrete structural behaviors after exposed to high temperature.

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