Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (39) No. (4) October, 2017

Mechanical Properties of Ultra-High Performance Concrete under Elevated Temperature with different exposure time and different Cooling regimes

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ملخص البحث

تهدف هذه الدراسة التجريبية لدراسة تأثير درجات الحرارة المرتفعة على الخواص الميكانيكية للخرسانة فائقة الأداء (UHPC) مع أنظمة تبريد مختلفة وعلي فترات مختلفة. حيث تم تسخين العينات الخرسانية في فرن كهربائي بدرجات حرارة متفاوتة تصل إلى 400 درجة مئوية وكانت أوقات التعريض (ساعة، ساعتين ،أربع ساعات) وأنظمة التبريد كانت (تبريد الهواء والغمر بالمياه). حيث تعرضت العينات الساخنة للتبريد المفاجئ بالمياه و التبريد البطي في الهواء. وكانت خصائص المدروسة هي قوة ضغط المتبقية وقوة الشد ونسبة فقدان الوزن وامتصاص الماء. حيث تم تحديد التغير في قوة الانضغاط والشد والوزن. وتم عرض نتائج التحقيق التجريبي في تأثير درجات الحرارة المرتفعة على قوة الضغط المتبقية ومقاومة الشد للخرسانة فائقة الأداء المصنوعة من الأسمنت البورتلاندي العادي، وغبار السيليكا، ومسحوق الكوارتز، والرمل، والألياف الفولاذية.

ABSTRACT

The aim of the experimental study was to evaluate the effect of Elevated temperatures on Mechanical Properties of Ultra-High Performance Concrete (UHPC) with different cooling regimes and different times of exposure. The temperatures were (room temperature, 100 °C, 200 °C, 300 °C, and 400 °C) and were exposure times (1, 2hr, 4hr) and cooling regimes were (air cooling and water quenching). The properties of the study were residual compressive strength, tensile strength, mass loss ratio and water absorption. The results of the experimental investigation are presented in Elevated temperature effects on the residual compression strength and tensile strength of the Ultra-High performance concrete made of ordinary Portland cement, silica fume, quartz powder, and steel fiber. Concrete specimens were heated in an electric furnace at varying temperatures up to 400 ° C. The change in compressive strength, tensile strength, weight was determined. The heated specimens were subjected to sudden cooling in water quenching and slow cooling down in the air.

Keywords: Ultra-High performance concrete, compression strength, tensile strength, ultrasonic pulse velocity, Elevated temperature, exposure time, weight loss, cooling regimes.

1. Introduction

In recent years, the use of Ultra-High performance concrete (UHPC) has increased significantly owing in infrastructures applications such as bridges, large roof structures, containers for hazardous liquids or nuclear waste due to UHPC exhibits superior properties in terms of compressive behaviors, tensile behaviors, and durability. Ultra-High-performance concrete acceptance by the construction industry has contributed to the economic construction of high-rise buildings and long spans the bridges. The use of High Water Reducing Admixtures (HRWRA) and silica fume in the production of workable high strength concrete, having a compressive strength of more than 100 MPa [1]. Ultra-High Performance Concrete (UHPC) is a very dense and with a compressive strength of about 150 to 200 MPa with a large ductile behavior [2]. Ultra-High Performance Concrete Reinforced Fiber (UHPFRC) is a reinforced fiber that has significantly improved the properties of strength and durability. The UHPFRC compound is usually very dense, with very high compressive strength and low water to cement (w / cm) ratio of 0.2. In order to achieve high compressive strength, the particle density of the material has been improved to reduce porosity [3] The elimination of coarse aggregate allows for better homogenization of the mixture. In order to reduce the extremely brittle matrix of UHPC, steel fibers were introduced to increase tensile strength and ductility [4]. The risk of Ultra-high-performance concrete structures being exposed to high temperatures increases with the use of Ultra-high performance concrete in the construction industry [5]. The use of steel fibers and polypropylene has been shown to mitigate the problem of spalling at elevated temperatures. Heating causes different changes in its properties, and in particular, changes in the microstructure accompanied by loss of mechanical strength. Polypropylene fibers have a melting point at about 170 ° C. When the concrete is heated up to this point, the fibers themselves melt and disperse into the surrounding matrix [6]. This pore leaves artificial pores almost the size of the fiber. This newly introduced void space helps reduce vapor pressure from evaporation of water and dry concrete. This reduces the tendency of dense concrete to spills when heated rapidly [7, 8] Therefore, it becomes necessary that Ultra-high performance concrete properties subject to Elevated temperatures are clearly understood. Fire resistance of concrete is affected primarily by factors such as temperature, duration and fire condition. On the other hand, the type of cooling, dry cooling (in the air) and wet cooling (in water) affect the compressive strength [9].

2. Research Significance

The objective of this study is to investigate ability to produce UHPC by using the local material in Egypt and then evaluate the influence of elevated temperatures, cooling regimes, and exposure times on the properties of Ultra-high performance concrete, having a compressive strength above 102 MPa. The parameters studied were the maximum temperature up to 400^{o}C, and different cooling regimes and different exposure times. The following characteristics of concrete were identified before and after heating: Mass Loss Ratio, Water absorption, compressive strength, and indirect tensile strength.

3. Methodology

In general, the following methodology should be followed:

1. Selection of appropriate local materials suitable for the production of UHPC, including cement, silica fumes, super plasticizer, aggregate, crushed quartz powder, and steel fibers.
2. Determination of the mixture ratios for the production of UHPC.

3. Arrange, heated and cooled the samples as the requirement of the procedure of testing the specimens.
4. Conduct physical and mechanical laboratory tests on UHPC samples.
5. Analyzing the results and drawing conclusions.

4. Experimental Investigations

4.1 Material Preparation and Characterization

4.1.1 Portland Cement

The Ordinary Portland Cement (OPC) CEM I 52.5 N was used in this research to produce of UHPC Mix, which provided from Al Arish Cement Company and their physical properties and chemical analysis as follows in table 1 and table 2.

Table 1 Physical and mechanical properties of used cement CEM I 52.5N

Property	Specific surface area (cm^2/gm)	Setting Time (min)		Compressive strength (MPa)	
		Initial	Final	2 days	28 days
Test result	3750	85	210	22	55.8
Limits*	Not less than 2750	Not less than 45	-	Not less than	Not less than 52.5

*The limits are according to Egyptian Standard ES 4756-1/2013.

Table 2 Chemical composition of the used cement (OPC)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	L.O.I
Content (%)	21.58	4.94	3.56	61.09	0.50	0.18	1.65	3.22	2.60
ES 4756-1/2013*	-	-	-	-	-	-	-	≤ 4%	≤ 5%

*Egyptian Standard Specification (ES 4756-1/2013)

4.1.2 Silica Fume

The physical properties and chemical analysis as follows in table 3 and table 4

Table 3 Physical Properties of the silica fume*

Property	Specific surface area (m^2/kg)	Particle size (µm)	Specific gravity	Bulk density (t/m^3)	Color
Test results	17,000	8.0	2.2	0.25	Light gray

* According to data sheet of the manufacturer.

Table 4 Chemical composition of the used silica fume (SF)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3
Content (%)	96.02	1.01	0.52	---	0.14	0.35	0.18	0.26

* According to data sheet of the manufacturer.

4.1.3 Super Plasticizer

High-range water reducing admixtures (HWRA) are used to increase the ability of the ultra-fine particles to fill the void spaces. The use of super-plasticizers further reduces the need for water in the mixture [10]. A commercially available type of high range water reducing superplastisizer was use in this research was used **ViscoCrete 3425** is a third generation superplastisizer as High Range Water Reduces (HRWR), as recommended by Christian [11], and the physical properties as follows in table 5. It complies with BS EN 934 part 2: 2001 and (ASTM C494) type G and F.

Table 5: Physical properties of the used admixture

Property	Density	Colure	PH value	Solid content by wt.
Value	1.08	Clear liquid	4	40%

* According to data sheet of the manufacturer.

4.1.4 Crushed Quartz Powder

Locally produced quartz powder added in a percentage of 30% by weight of cement. With the maximum particle 150 µm and with 97.0% of SiO_2 provided from EGY SAND Company.

4.1.5 Aggregate

The fine aggregate used was fine quartz sand, which ranged in size from 600 µm to 125 µm [12, 4], the gravity of 2.61 tons / m3, the apparent density of 1.820 tons / m 3, Table 6 and Table 7 shows Physical properties and Grading of the fine quartz sand used as Coarse aggregate [13]. The sand particles finer 125 µm were excluded to avoid interference with coarse cement particles (100 µm) as recommended by Richard and M. Cheyrezy [4]**.** The maximum aggregate size of 600 µm was used as the coarse aggregate and Powder Quartz sand as fine aggregate (specific gravity of 2.62).

Table 6: Physical properties of used quartz sand

Tests	Used sand physical properties			
	Specific weight (t/m^3)	Bulk density (t/m^3)	Fineness modulus	Material finer than No 200 sieve %
Sand	2.62	1.810	2.95	2.6
Limits *	-	-	-	Less than 3%

*The limits according to Egyptian Specification No (**1109/2008**).

Table 7: Grading of the fine quartz sand used

Sieve size (mm)	0.85	0.6	0.25	0.125	0.09
Fine quartz sand passing (%)	100	87	56	25	2

4.1.6 Steel Fibers

The steel fiber (SF) is used to improve the tensile capacity the ductility of the UHPC. The steel fibers used is hooked steel wire fibers (25 mm length) and diameter (1 mm ± 0.02 mm) and discrete length steel fibers bars having an aspect ratio from 20 to 25 and its comply with (ACI 544.1R. 1999) [14] and density of 7.85 g/cm3.

4.1.7 Concrete Mixtures

The constituent material proportions were used fine sand as coarse aggregate largest particle is the fine quartz sand from 600 µm to 125 µm [12], then the cement with an average diameter of approximately 10 µm. The smallest particle is the silica fume, has a diameter small enough to fill the interstitial voids between the cement and the crushed quartz particles [15]. Mixture proportions used in preparing concrete for one cubic meter for mixes of UHPC are shown in table 8.

Table 8: Mix. Design

Materials	ingredient/cement content	Proportion (kg/m^3)
Cement CEM I 52.5N	1	900
Water cement ratio (w/c)	0.18	162
Silica fume /cement	0.25	225
Fine aggregate /cement	0.86	774
Quartz powder /cement	0.3	270
Superplastisizer /cement	0.06	36
Steel fibers	0.17	157
Water binder ratio (w/b)	0.14	--

To investigate the effect of Elevated temperature at UHPC, the cooling regimes, and exposure times it as case to resist the elevated temperature.

The investigated parameters can be summarized as follows:

- The effect of elevated temperature.
- The effect of cooling regimes.
- The effect of exposure times.

The required specimens were included 100 × 200 mm cylinders, 50 × 50 ×50 mm cubes. The specimens were cast in two layers; a table vibrator was used for compaction. After casting, all the molded specimens were covered with plastic sheets and were left in the casting room for 24 hours. Afterwards, they were remolded and transferred to the moisture curing room at 100% relative humidity until required for testing and stored in water at 20^{o}C till the age of 28 days.

4.2 Heating Equipment

An electric heating furnace was used to heat the concrete samples to a temperature of up to 400 ° C. Heating rate was maintained at 400 ^{o}C/hr. the Figure 1 shows the Time – Temperature furnace characteristics during heating. The oven is heated by exposed heating Elements were placed on the thermal walls of the inside of the room, which were about 150 x 150 x 300 mm in dimension. The test samples were stacked with enough space between two adjacent samples to obtain uniform heating in each sample. Since the room was limited size concrete samples were heated in batches.

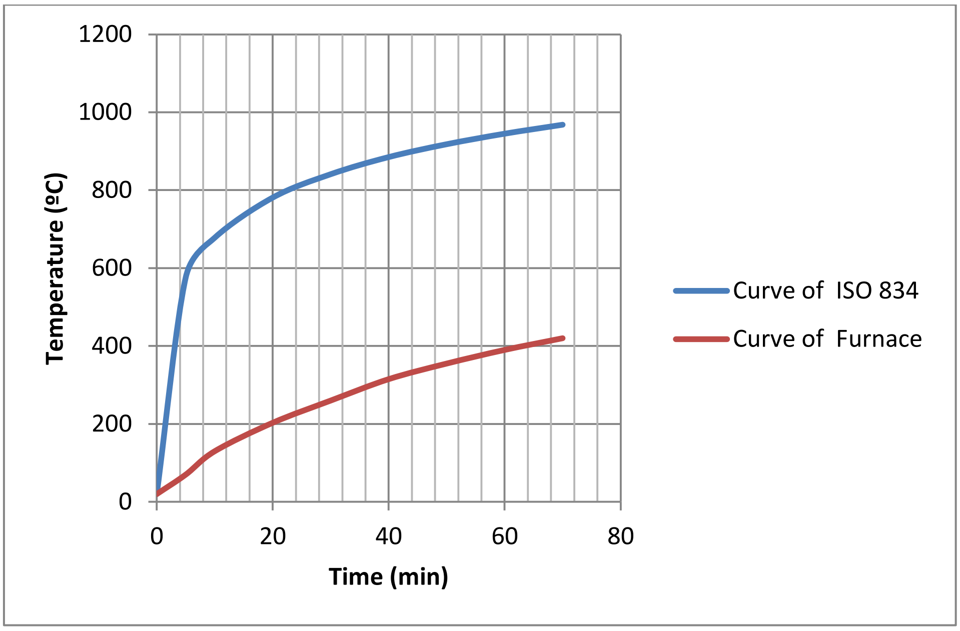

Figure 1: Time–Temperature furnace characteristics during heating

4.3 Procedures of Testing the Specimens

At the age of 28 days, concrete samples were removed from water and dried in air for 24 hours in laboratory conditions with average relative humidity and temperature of 64% and 25^{o}C, respectively. The samples are then placed in a ventilated furnace at 80^{o}C for 48hrs before being subjected to Elevated temperatures in the electric furnace. It was found that this step is necessary to avoid the explosion of concrete samples in the furnace due to the formation of steam. Heating rate was maintained at 400 $^{\circ}$C/hr. Once the target oven temperature is reached, the temperature is maintained until for 1 hr., 2 hr. and 4 hr. samples are before removed. For all concrete samples, the exposure temperature of the furnace was divided for three exposure times (1, 2, and 4) hours and each time divide for two cooling regimes (Air cooling, Water quenching cooling). The maximum furnace temperatures were 100, 200, 300, 400 $^{\circ}$C.

4.4 Cooling Regimes of Specimens

Two cooling regimes were used for hot concrete samples. At the end of continuous periods at the corresponding maximum temperatures, the samples were removed from the furnace. Some hot samples were submerged in water at 20 ° C in a very large water tank and kept in water for 24 hours and 24 hours for air dry after removed from the tank before the compression test. The remaining samples were cooled into the air in laboratory conditions for 48 hours, before the force test. Both irrigated water and air-cooled concrete samples were tested either in compression or indirect tension. Samples were weighted at different stages of heating and cooling.

5. Tests Results and Discussion

5.1 Residual Strength in Compressive after Heating

The compressive strength tests according to ASTM C109 (2004) and BS EN 12390-4: 2002 standard test method for cubes. The residual compressive strength is the maximum compressive strength obtained after heating to the prescribed temperature and the initial value at ambient temperature control. The displayed value is the average of three tests heated to a certain temperature for certain periods and cooled. It can be seen from Table 9, and Figure 2 shows the evolution of the compressive strength for the UHPCs versus the temperature. Table 10 shows the relative residual compressive strength of UHPs mixes and Figure 3 shows the evolution of the residual compressive strength. And the compression strength can be classified in two phases of strength loss, 23-200 ºC and 200-400 ºC. Temperatures of up to 200 °C seem to help increase compressive strength up to 132% for two-hour exposure with air cooling but decrease to 124% by water cooling regimes and if the exposure period increased to four-hour lead to decrease the compressive strength to 122% with air cooling and 120% with water cooling. After 200 ° C, the compression strength decreased to 67% at 400 ° C for four-hour exposure time with air cooling but the cooling regime by quenching in water general helps compression strength and hardness recovery before 200 ºC for 2 hour exposure time and 100 ºC for 4 hour exposure time. But Exposure time in general affected the compression strength with 4 hours exposure time. The residual compressive strength of the UHPC increases slightly during early periods of heating (up to 400 ° C) and with water quenching cooling and with exposure times, but the compressive strength of the samples increased significantly with heating up to 200 ° C, but after it trends to decrease. Increasing the actives temperatures of the reaction chain in cement hardness paste, the complete drying of the pore system followed by decomposition of hydration products and destroys the gel structure in wet cement paste.

Table 9: The Compressive strength of UHPC Mix with elevated temperature

Exposure Times	Cooling Regime	Compressive strengths at Elevated Temperature (MPa)				
		Temperature ^{0}C				
		23 ^{0}C	100 ^{0}C	200 ^{0}C	300 ^{0}C	400 ^{0}C
1	Air	120	117.3	138.7	133.3	114.67
	Water	120	142.7	146.7	116	97.6
2	Air	120	106.7	158.7	142.7	93.33
	Water	120	128	149.3	113.3	123.07
4	Air	120	162.7	146.7	128	80.267
	Water	120	120	144	104	132

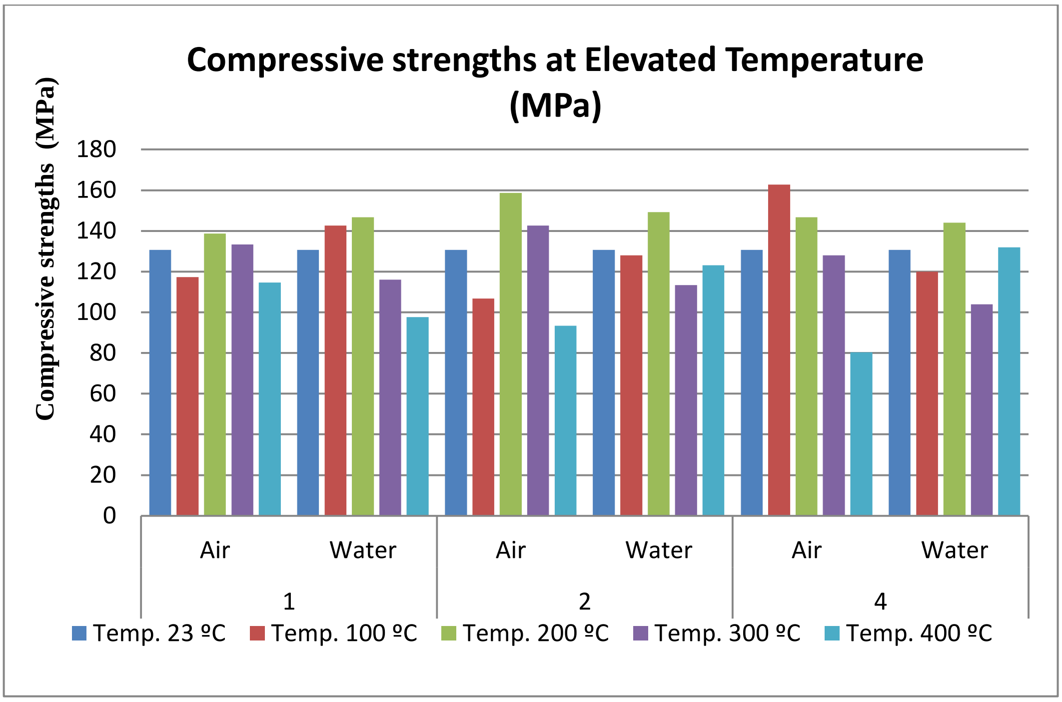

Figure 2: Relationship between temperatures and Compressive Strength and cooling regimes and exposure time

Table 10: The Relative Residual Compressive strength of UHPC Mix with elevated temperature

Exposure Times	Cooling Regime	Relative Residual Compressive strengths at Elevated Temperature (MPa)				
		Temperature ^{0}C				
		23 ^{0}C	100 ^{0}C	200 ^{0}C	300 ^{0}C	400 ^{0}C
1	Air	1.00	0.98	1.16	1.11	0.96
	Water	1.00	1.19	1.22	0.97	0.81
2	Air	1.00	0.89	1.32	1.19	0.78
	Water	1.00	1.07	1.24	0.94	1.03
4	Air	1.00	1.36	1.22	1.07	0.67
	Water	1.00	1.00	1.20	0.87	1.10

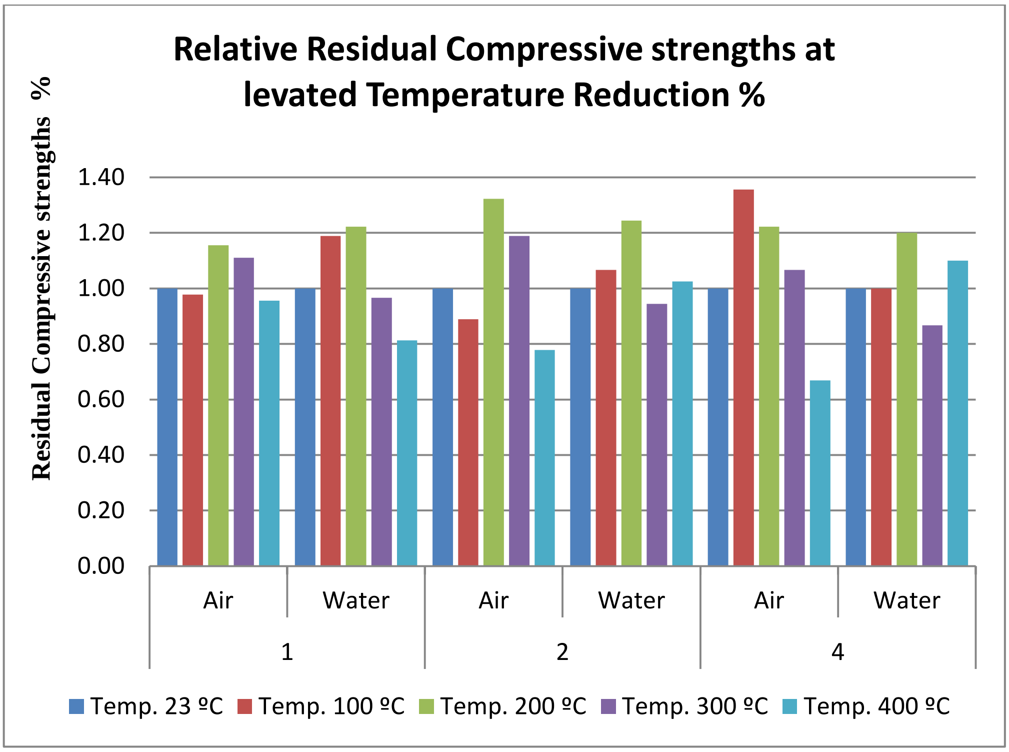

Figure 3: Relationship between temperatures and Residual Compressive Strength and cooling regimes and exposure time

5.2 Residual Strength in Tensile after Heating

The splitting tensile strength of UHPC was measured according to ASTM C496 (2004) and BS EN 12390-6: 2009. The residual tensile strength was increased up to 400 ° C 109% for two-hour exposure time with two different cooling regimes. But the maximum residual tensile strength was 142% at 200 for one-hour exposure time with water quenching cooling regime. But in general the tensile strength is not getting more deterioration, due to using the steel fibers in the matrix concrete but it do not resist spalling due to steam pressure. The water quenching cooling regime show better performance to healing the deterioration up to 400 for two-hour exposure time. The Tensile Strength of UHPC Mix with elevated temperature was seen in table 11, The Residual Tensile strength of UHPC Mix with elevated temperature seen in Table 12. Figure 4 show the relationship between temperatures and Tensile Strength and cooling regimes and exposure time. Figure 5: Relationship between temperatures and Residual Tensile Strength and cooling regimes and exposure time.

Table 11: The Tensile Strength of UHPC Mix with elevated temperature

Exposure Times	**Cooling Regime**	**Tensile Strengths at Elevated Temperature (MPa)**				
		Temperature ^{0}C				
		23 ^{0}C	**100 ^{0}C**	**200 ^{0}C**	**300 ^{0}C**	**400 ^{0}C**
1	**Air**	14.01	14.1	17.49	14.78	15.35
	Water	14.01	15.8	19.96	14.78	17.49
2	**Air**	14.01	14.69	15.46	13.67	14.86
	Water	14.01	16.01	15.2	14.35	15.29
4	**Air**	14.01	17.37	15.71	14.01	12.74
	Water	14.01	15.92	16.6	15.37	11.63

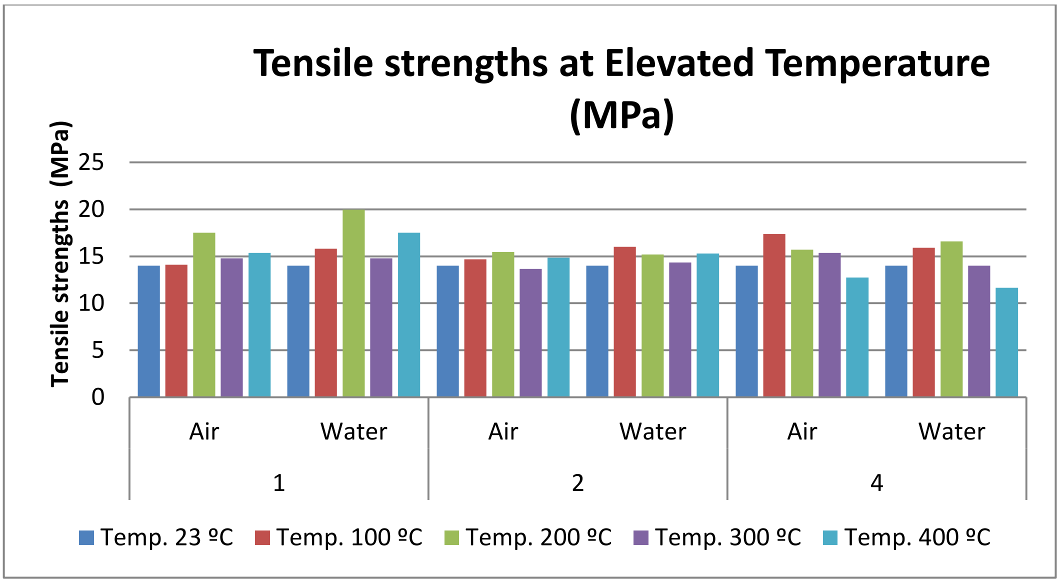

Figure 4: Relationship between temperatures and Tensile Strength and cooling regimes and exposure time

Table 12: The Residual Tensile strength of UHPC Mix with elevated temperature

Exposure Times	Cooling Regime	Residual Tensile Strengths at Elevated Temperature (%)				
		Temperature ^{0}C				
		23 ^{0}C	100 ^{0}C	200 ^{0}C	300 ^{0}C	400 ^{0}C
1	**Air**	1.00	1.01	1.25	1.05	1.10
	Water	1.00	1.13	1.42	1.05	1.25
2	**Air**	1.00	1.05	1.10	0.98	1.06
	Water	1.00	1.14	1.08	1.02	1.09
4	**Air**	1.00	1.24	1.12	1.00	0.91
	Water	1.00	1.14	1.18	1.10	0.83

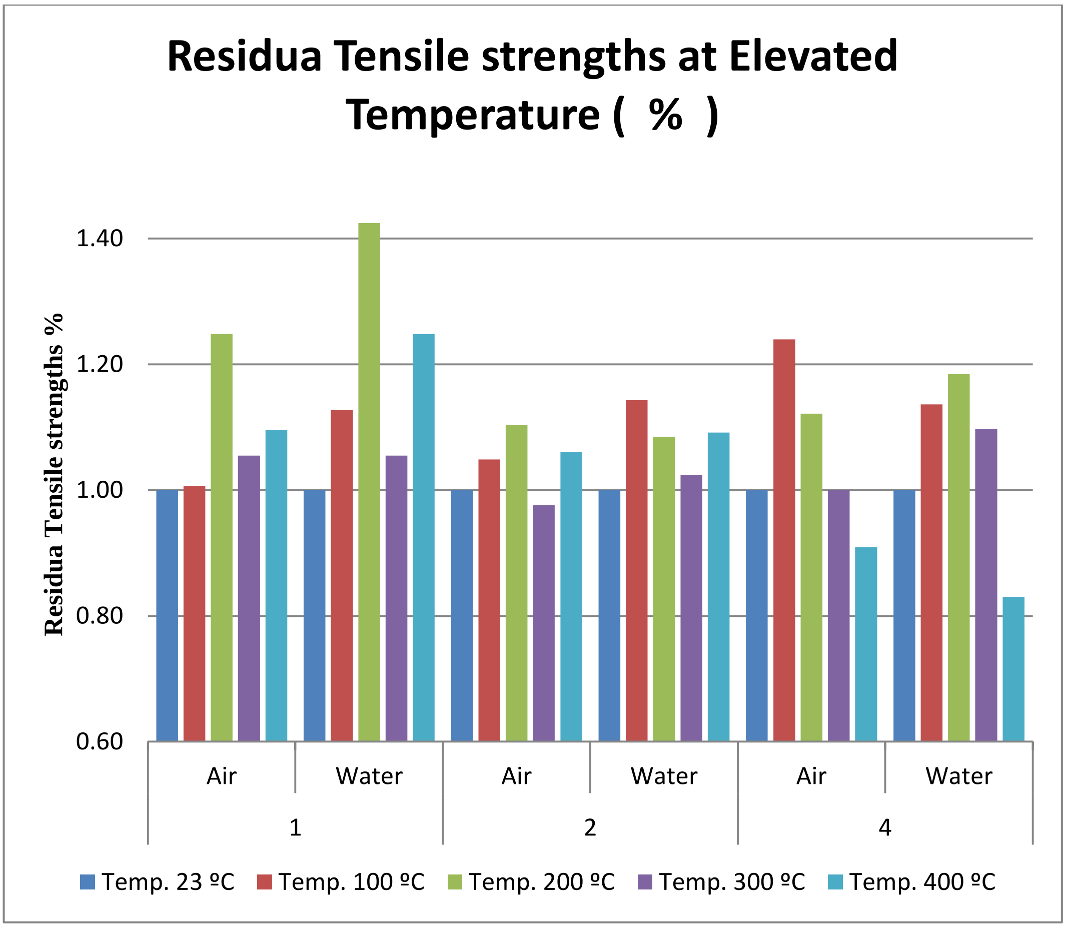

Figure 5: Relationship between temperatures and Residual Tensile Strength and cooling regimes and exposure time

5.3 Mass Loss for Ultra-High Performance Concrete on Heating

When concrete is exposed to elevated temperatures, a mass reduction is expected due to loss of free and chemical water. To determine the percentage of Mass loss of the concrete due to elevated temperatures the weight of all specimens were recorded weight the specimens before and after exposure to the elevated temperature. The weight loss from Ultra-high performance Concrete with an increase in extreme temperature exposed due to accelerated drying. Figure 6 shows the relationship between temperatures and Mass Loss and cooling regimes and exposure time. The results showed that the loss of mass increases with increased the temperature and the exposure time and shows to extremealy at 300 °C with 4 hour expsoure time and 400 °C with 2 and 4 exposure time.

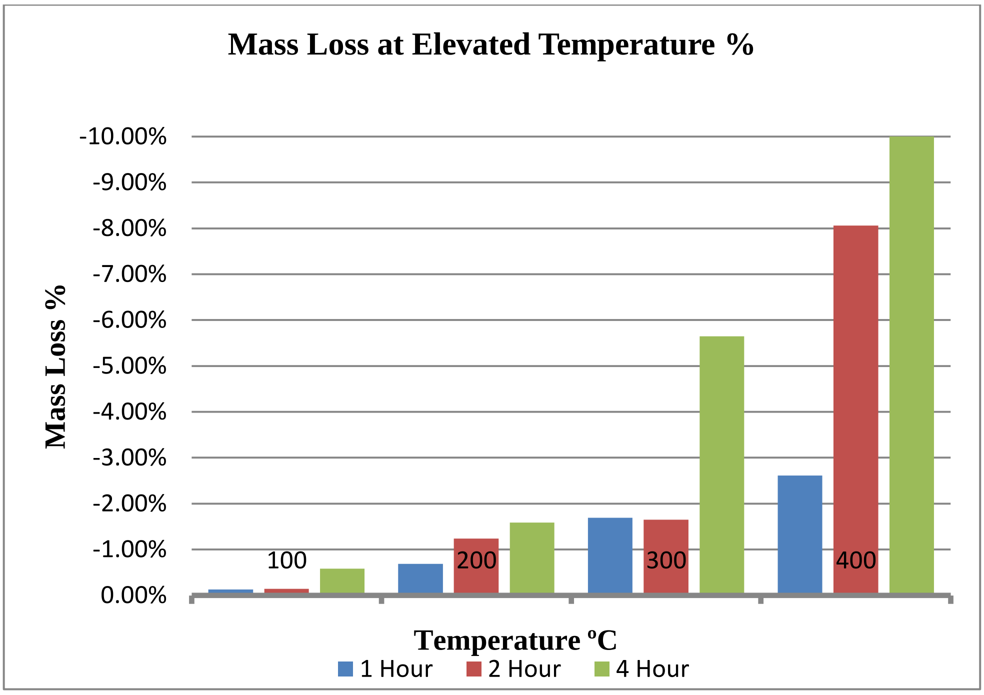

Figure 6: Relationship between temperatures and Mass Loss and cooling regimes and exposure time

5.4 Water Absorption of Ultra-High Performance Concrete on Heating

Determine the percentage of water absorption by weight the specimens before and after quenching in water for cooling after subjected to various elevated temperature. The weights of concrete samples were taken for up to 24 hours after being placed in water. The samples were cooled for 24 hours in water for 24 hours. Water-fed samples were kept for 48 hours. Figure 7: Relationship between temperatures and Water Absorption and cooling regimes and exposure time. The results showed that the water absorption increases with increased the temperature and the exposure time and shows to extremealy water absorption at 400 °C with 4 hour expsoure time.

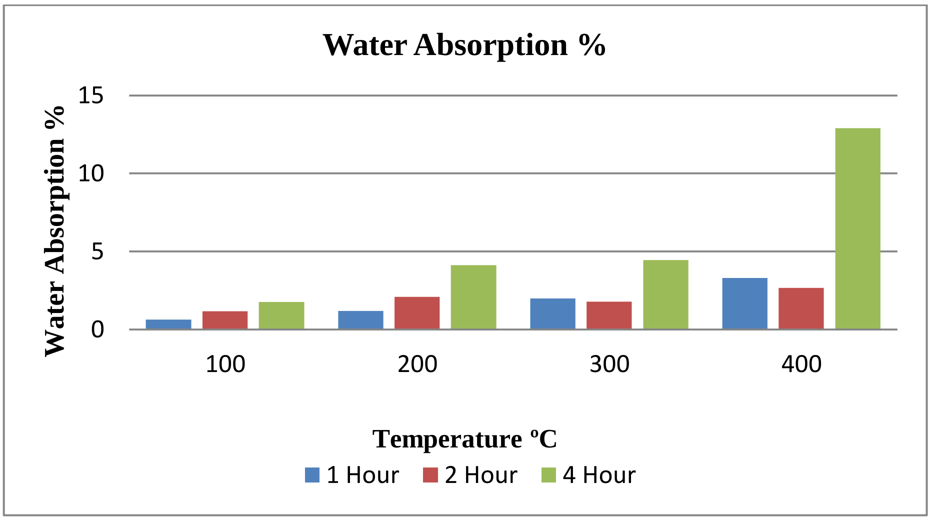

Figure 7: Relationship between temperatures and Water Absorption and cooling regimes and exposure time

6. Conclusion

The objective of this work was to investigate the effect of cooling regimes and time exposure on the mechanical properties of UHPCs samples subject to elevated temperatures. Based on this study, the following conclusions can be drawn:

1. UHPC with more than 150 compressive strength can be produced using locally available materials and by using simple process techniques as heating treatment.
2. The Compression strength the temperatures of up to 200 ° C seem to help increase strength for one-hour exposure with air cooling. After 200 ° C the compression strength decreased from the first-hour exposure time with quenching water cooling.
3. The cooling regime of quenching in water helps compression strength and hardness recovery before 200 ºC till two-hour exposure time but after that is defect the strength.
4. The Tensile strength increase with the temperature up to 400 ° C with two-hour exposure time and cooling by quenching in water. But after that the strength defected. The Steel fibers are responsible for reduce cracking due to thermal pressures up to 400 ° C till two- hours exposure time but they do not resist spalling due to steam pressure which were observed when the temperature range from 300 ° C to 400 ° C.
5. The mass loss has increased by increasing the exposure temperature, a result mainly related to the liberalization of free and material water. At temperatures higher than 200 ºC and 400 ºC, weight loss was caused of UHPCs due to dehydration of the paste. During the heating treatment up to 400 ºC, the extremely spalling happens and also had an effect on mass loss.
6. The water absorption is effect of elevated temperature lead to absorb of water by increase the elevated temperature and exposure time. It will be extremely more than 12% at 400 ºC with 4 hours exposure time. The color of UHPCs specimens changed from gray at 20 ° C to light yellow at 400 ° C and the flow of specimens in water turned to dark gray. The capillary cracks were observed above 300 ºC and the cooling in the water may help heal the crack surface due to further hydration.

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