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EFFECT OF ELEVATED FIRE TEMPRATURE AND COOLING REGIME ON THE FIRE RESISTANCE OF NORMAL AND SELF-COMPACTING CONCRETES

A. M. K. ABDELALIM*, G. E. ABDEL-AZIZ, M.A.K. EL-MOHR*** and G. A. SALAMA******

*Professor & Dean of the Faculty of Eng. Shoubra, Benha University, Egypt.

**Associate Professor, Faculty of Eng. Shoubra, Benha University, Egypt.

***Assistance Professor, Faculty of Eng. Shoubra, Benha University, Egypt.

****Master student, Faculty of Eng. Shoubra, Benha University, Egypt.

ABSTRACT

The current research studied the effect of elevated fire temperature and cooling regime on the fire resistance of self-compacting concrete (SCC) and normal concrete (NC). Both concretes were exposed to elevated degrees of fire temperature of 200, 400, 600 and 800 °C. In addition, the temperature was maintained at 800 °C while the exposure durations have been increased to 15, 30, 60 and 120 minutes. After that the samples were cooled to room temperature using three different cooling regimes namely; air cooling, CO_2 powder cooling and water cooling. Reductions in both compressive and tensile strength results along with the extent of spalling were examined. The effect of fire and cooling regime on both porosity and absorption capacity of SCC and NC were also investigated.

The results indicated that residual compressive and tensile strengths of SCC are generally higher than those of NC. In other words, elevated fire temperature is more damaging to the NC compared with SCC. Same has been confirmed by the obtained results of spalling which were found to be higher for NC compared with those of SCC. The results also indicated that adopting CO_2 powder as a cooling regime provided the least extent of damage to both NC and SCC concretes while water cooling regime provided the greatest damage. It is worth mentioning that the incorporation of polypropylene fibre improved the fire resistance of concrete regardless of the concrete type and cooling regime. Increasing the dosage of self-compacting admixture did not significantly affect the mechanical properties and fire resistance of SCC.

Key words: Elevated fire temperature, self compacting concrete, spalling, cooling regime, porosity, absorption.

1. INTRODUCTION

During the past 20 years, concrete mix design and manufacturing have been progressed quite rapidly and the concrete ingredients have been tailored to provide better performance that suites different types of environments. This has been carried out by selecting the concrete mix ingredients that produce concrete suitable for certain exposure conditions. The change occurred in the concrete mix design includes reducing the w/c ratio, using high range water reducers (super-plasticizers), optimizing the grain size distribution of concrete constituent materials, employing cement replacement materials with pozzolanic activity, incorporation of certain types of fibres, etc [1]. This has led to striking improvements in the concrete properties such as rheology of fresh concrete and strength development, ductility, compactness and durability of hardened concrete. In spite of such improvements, most of the produced concrete was found to exhibit brittle behaviour when exposed to fire conditions [2]. To overcome this problem, self-compacting concrete (SCC) which is a new category of high performance concrete [3] has been utilized. Such concrete is resulted from the technological advancements in the area of under-water concrete technology, where mixture of normal concrete ingredients and polycarboxylate type of super-plasticizer are proportioned to provide concrete with high workability and flowability but without segregation [3, 4].

Elevating the concrete temperature as a result of exposure to fire conditions causes a major reduction to the concrete strength and its ability to resist deformation. Also concrete may lose its stiffness as well as its mass in the form of surface spalling. It has been reported that normal concrete loses about 30% of its compressive strength when heated up to 300 °C and about 70% when heated up to 800°C [5, 6]. The reduction in the concrete compressive strength depends on many factors such as the original compressive strength of the concrete prior to the exposure to fire, modulus of elasticity, coefficient of thermal expansion and creep of the structural members [7] as well as aggregate type and water/cement ratio [8].

Many studies in the literature have dealt with the influence of heating rates as well as the degree of fire temperature on the behaviour of NC and SCC. However, the effect of cooling regimes on the behaviour of both NC and SCC after exposure to fire was not fully covered, despite the fact that cooling regime is a very important factor especially when fire is extinguished by water in a real situation. Xin et al [9] studied the effect of water cooling and the in-furnace cooling regimes (air cooling) on the behaviour of both NC after exposure to elevated temperatures up to 1100 °C. The results showed that water cooling caused significant thermal shocks to the hot concrete and as a result, severe deterioration has taken place. On the other hand, less deterioration has occurred to the in-furnace cooled concrete.

In spite of the above studies, the effect of cooling regime (water, CO_2 and air cooling) and the elevated degrees of temperature on the mechanical properties of NC and SCC was not fully covered specially on the locally produced concrete. Therefore the objectives of this study are carefully selected to study the effect of both cooling regime and elevated degrees of temperature on the fire resistance of NC and SCC in terms of mechanical properties (compressive and tensile strength), spalling as well as porosity and absorption capacity of NC and SCC . This is outlined as follows:

1. Studying the effect of elevated fire temperature on the mechanical and microstructure properties of NC and SCC in terms of compressive strength, indirect tensile strength, spalling, porosity and absorpativity. The elevated degrees of temperature studied in this research were 200, 400, 600 and 800 °C.

2. Fire temperature was maintained at 800 °C and the concrete samples were exposed to different time durations of 15, 30, 60 and 120 minutes.

3. Concrete samples exposed to the above conditions were cooled to room temperature using three different cooling regimes namely; air cooling, CO_2 powder cooling and water cooling.

4. Based on the above exposure conditions, reductions in both compressive and indirect tensile strength (residual strength) results along with the extent of spalling were examined. Same was evaluated for both porosity and absorption capacity of SCC and NC.

2. EXPERIMENTAL

2.1 Materials and Concrete Mix Proportions.

Ordinary Portland Cement (OPC) complying with the Egyptian Standard Specifications ESS, 1658/ 1988 with a content of 400 kg/m^3 was used in all concrete mixes. Natural siliceous sand with a fineness modulus of 2.75 and natural gravel with maximum aggregate size of 20 mm are also used in the preparation of concrete mixes. Polypropylene fibres with a constant content of 0.5% of the cement weight was used wherever applicable as presented in Table

1. Limestone powder and self-compacting admixtures (Sica-viscocrete- 5400) with a weight percentage of 0.62, 0.75, and 0.87 % of the cement mass were used in the preparation of SCC mixes. Clean tap water with a constant free w/c ratio of 0.45 was used in concrete mixing. The values of slump of NC and slump flow of SCC were measured and the results are listed in Table 1.

As presented in Table 1, six concrete mixes were used to cover the research outlines. Three mixes were assigned for SCC with different dozes of Sica-viscocrete of 0.62, 0.75, and 0.87 % of the cement mass. These dozes were selected as per the manufacture recommendations. In addition, one mix for SCC with fibres and 2 mixes for NC one with fibres and the other is without fibres were also used.

Table 1, details of concrete mix proportions.

Mix Code	Cement Content, kg/m^3	Water Content kg/m^3	Sand Content kg/m^3	Coarse Aggregate Content kg/m^3		Limestone Powder content kg/m^3	% of Sica-viscocrete as wt of OPC	Slump mm	Slump Flow mm
				5-10 Mm	10-20 Mm				
NC	400	180	660	690	690	—	—	28	—
SCC1	400	180	750	525	525	80	0.62%	—	600
SCC2	400	180	750	525	525	80	0.75%	—	650
SCC3	400	180	750	525	525	80	0.87%	—	700
PF NC	400	180	660	790	790	—	—	28	—
PF SCC2	400	180	750	525	525	80	0.75%	—	630

2.2 Test Techniques and Procedures

2.2.1 Compressive Strength

Cubic concrete specimens of 100 mm in side length were prepared for measuring compressive strength according to the Egyptian Specifications. The specimens were stored in water curing tanks at 21±2°C until testing age of 3, 7, 14 and 28 days. The samples were exposed to a varying degree of temperature of 200, 400, 600 and 800 °C. The samples were then left to cool according to the specified cooling regimes (air cooling, CO_2 powder cooling and water cooling) and then tested. The average compressive strength was calculated using triplicate specimens.

2.2.2 Indirect Tensile Strength

Indirect tensile strength test was carried out according to the E.S.S 1658/1988 on hardened concrete cylinders of 100 mm in diameter and 200 mm high at an age of 28 days before and after exposure to fire. As given by Equation 1, Residual indirect tensile strength % = T_1/T_2 …………………………... (EQ. 1).

Where: T_1 = splitting tensile strength after exposure to fire in kg/cm^2,

T_2 = splitting tensile strength before exposure to fire in kg/cm^2.

2.2.3 Sorpativity

Water absorption by capillary action (sorpativity) was measured before and after exposure to fire to evaluate the degradation of concrete surface layer. When concrete is subjected to water, some water can be absorbed by the capillary action through a specified area of the tested specimen. [7].The amount of the absorbed water depends on the characteristic of the concrete surface layer. This test was carried out on concrete cubes at an age of 28 days, before and after exposure to fire using a plastic container filled with water to a depth of 20 mm. Steel bars of 18 mm diameter were placed at the bottom of container such that, the water level was maintained to just above the top surface of the steel bars. The specimens were weighed after greasing the four surrounding sides and put in the container over the steel bars such that the water level in the container was not more than 5.0 mm above the tested surface. The specimen was taken out from water and the surface water was removed using a damp cloth. The weight of the specimen was then recorded. After that the specimen was returned back to the water for another 15 minutes, and the whole process was then repeated every 15 minutes for a period of 2 hours and the average was taken. Finally the sorpativity of the tested specimens was calculated using equation 2, [7].

$i = A + S\,t^{1/2}$ ………………………………………..……..............(EQ.2)

Where, A is a constant, i is the increase in mass of the tested specimen in g/mm^2, t is the time at which the weight is determined in minutes and S is the sorpativity of the tested specimen in mm/min$^{1/2}$.

2.2.4 Capillary and Total Porosity

This test is used to evaluate the degradation and the changes in pore structure of the concrete specimens. The test was carried out on 100 mm concrete cubes at an age of 28 days, before and after exposure to fire. The specimens were removed from their curing tanks and weighed in saturated-surface–dry (SSD) condition (W_1). The specimen was then exposed to an environment with a 90.7 % relative humidity (RH) at 21±2°C until constant weight (W_2) has been achieved. This high humidity environment has been maintained using a saturated barium chloride solution in an air tight plastic container [7]. Then the capillary porosity was then calculated using Equation 3:

Capillary porosity, % = $[(W_1 - W_2) / V]*100$ ………………………….. (EQ. 3)

Where, V is the volume of the concrete specimen. The capillary porosity is usually used to estimate the pores with an approximate size of greater than 30 nm [9]. The specimen was finally oven dried at 105°C for 24 hours and the weight (W_3) was recorded. The total porosity is calculated using equation 4:

Total porosity, % = $[W_1 - W_3) / V]*100$. …………………….………….. (EQ. 4)

2.3 Firing Steps

The aim of this research is to study the concrete resistance to fire through an exposure to elevated degree of temperatures of 200, 400, 600 and 800 °C. It also studies the concrete resistance to an elevated constant degree of temperature of 800°C with exposure durations of 15, 30, 60, and 120 minutes. The concrete specimens were placed in the furnace and the degree of temperature was set on 200°C. Upon reaching the assigned degree of temperature using the normal heating rate of 8.8 degree/minute, the oven was switched off and samples were left to cool using the considered cooling regimes which are air cooling in the furnace, water cooling and CO_2 powder cooling. Same procedures have been repeated with other degrees of temperature of 400 °C and 600 °C. However for the degree of temperature of 800 °C, the oven was left on and the degree of temperature of 800 °C was maintained for 120 minutes.

3. RESULTS AND DISCUSSION

3.1. Assessment of compressive strength of SCC and NC prior to exposure to fire

Compressive strength development of SCC containing different percentage of Sica-viscocrete admixture of 0.62, 0.75 and 0.87% by weight of cement (selected percentages are based on the manufacturer recommendations) at different ages of 3, 7, 14, and 28 days is presented in Figure 1, while strength of NC and SCC2 is presented in Figure 2. As shown in Figure 1, increasing the percentage of self compacting concrete admixture (Sica-viscocrete) does not affect the obtained values of compressive strength of SCC at the considered ages however it increased the slump flow of fresh concrete as presented in Table 1. For this reason SCC2 mix was taken to represent SCC in rest of the research. As illustrated in Figure 2, SCC2 provided higher values of compressive strength compared with that of NC at all ages. This may be attributed to the imperviousness achieved with SCC as a result of using fine particles that fill and block the concrete pores at same w/c [8]. The difference in the obtained strength values decreases at early ages and increases after that. However it ranges from 5 to 10%.

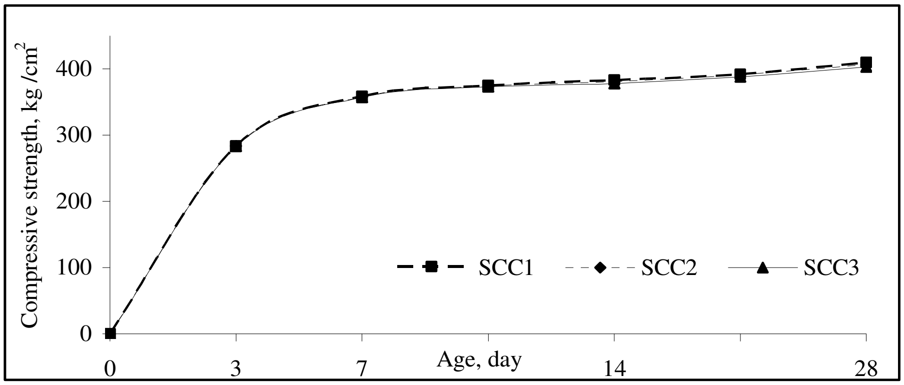

Figure 1 Compressive strength development of SCCs containing different percentage of Sica-viscocrete of 0.62, 0.75 and 0.87% by weight of cement.

3.2 Assessment of Mechanical Properties of Concrete after Exposure to Fire

3.2.1 Compressive Strength

The losses in compressive strength values of SCC's and NC (control) along with their fibre mixes after exposure to elevated fire temperatures of 200, 400, 600 and 800 °C are presented in Figure 3. It can be noticed that, at room temperature (before exposure to fire) the compressive strength is 410 kg/cm^2 for SCC and 360 kg/cm^2 for NC while at 800 °C the compressive strength values have been decreased to 201kg/cm^2 and 80 kg/cm^2 for SCC and NC respectively. On other words, the residual compressive strength is 49% and 25% for SCC and NC respectively.

At low fire temperature, i.e. at 200 ^{o}C the compressive strength decreased by about 3 to 4% compared with the original compressive strength at room temperature. While increasing the exposure temperature from 200°C to 400°C caused a slight increase in the compressive strength of SCC. This could be attributed to the general stiffening of the cement gel or the increase in surface forces between gel particles as a result of removal of the adsorbed moisture which in turn depends on the porosity of concrete [4]. Increasing the exposure temperature from 400°C to 600 °C, caused a dramatic reduction in the compressive strength values by about 30%. Finally, increasing temperature from 600°C to 800°C, the values of compressive strength have been reduced by about 51 % for SCC. A similar behaviour was obtained with the NC.

In view of the above, it can be concluded that SCC is more resistant to fire exposure up to 800°C compared with NC. Since a reduction percentage of 51% has been obtained for SCC compared with 75% of the NC after exposure to same fire temperature of 800 °C. In addition, no signs of explosive spalling have been noticed with SCC.

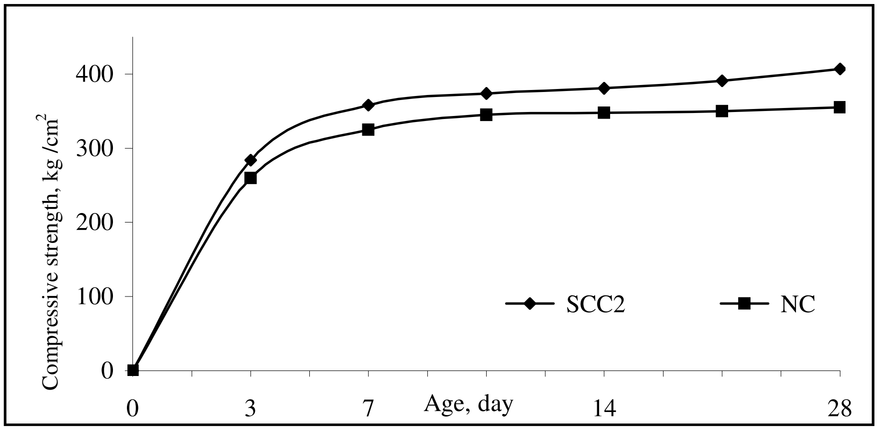

Figure 2 Compressive strength developments of SCC2 and NC

Figure 3 also shows that the incorporation of polypropylene fibres caused a slight improvement in the performance of both SCC and NC. This could be attributed to the increase in the tensile strength inside the concrete core and thereby retard the initiation of internal cracking inside concrete [11].

On the other hand, Figures 4 and 5, show the effect of cooling regimes on the compressive strength values of NC and SCC respectively after exposure to constant fire temperature of 800°C for time durations of 15, 30, 60 and 120 minutes. As shown in the Figures, increasing the exposure duration from 15 to 120 minutes caused a dramatic reduction in the value of compressive strength for both NC and SCC regardless of the used cooling regime. However for same time duration, cooling regime plays an important role in the obtained percentages of the residual compressive strength for both NC and SCC. Water cooling regime provided the least percentage of the residual compressive strength while CO_2 cooling regime (chemical) provided the highest percentage of residual compressive strength. In other words, CO_2 cooling has the least damaging effect on the residual compressive strength of concrete. This could be attributed to the fact that CO_2 powder provide a carbonated solid surface that covers the concrete specimens and thereby close near-surface cracks. While, sudden water cooling regime caused a negative thermal shock for the concrete specimens and thereby increasing the near-surface cracks. As a result the compressive strength decreases [12]. This agrees with the results of previous findings by Xin et al [9].

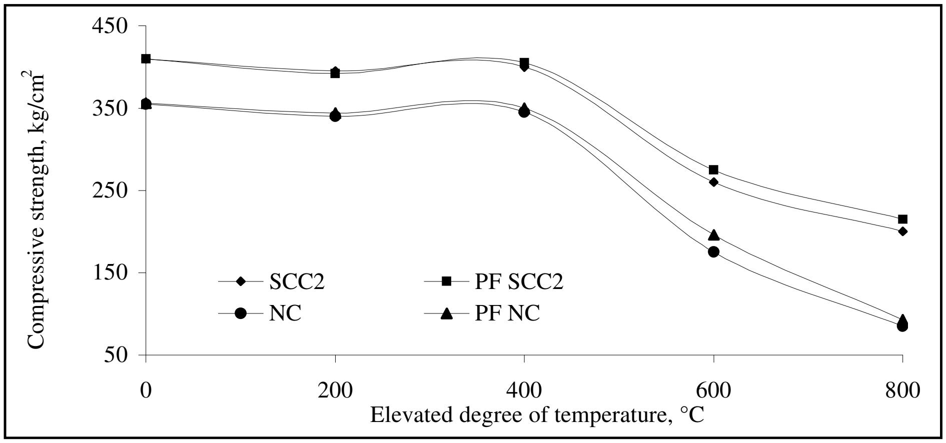

Figure 3 Effect of elevated degree of temperature on compressive strength of SCC & NC and their corresponding fibre concrete mixes.

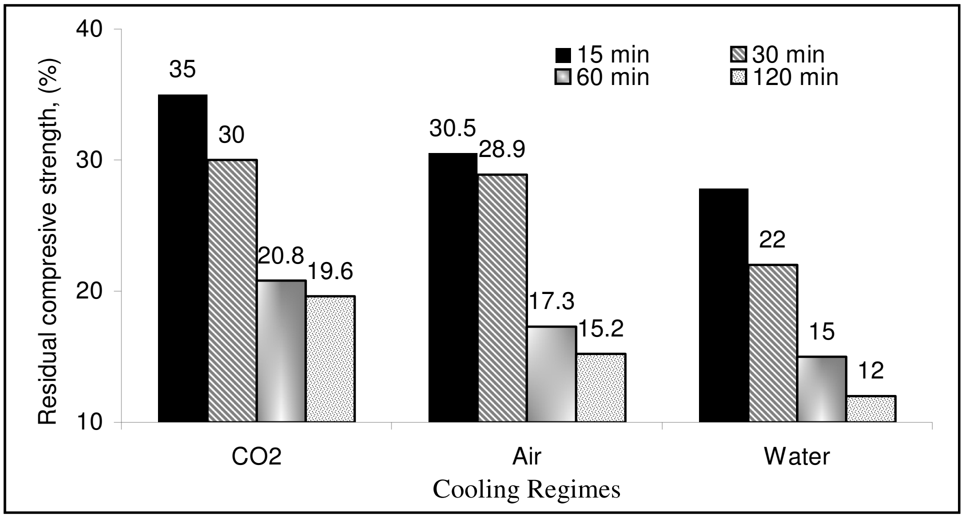

Figure 4 % of residual compressive strength of NC after exposed to fire temperature of 800 °C with different time durations and cooling regimes.

3.2.2 Indirect tensile strength

Figure 6 shows the reduction in the percentage of tensile strength of SCC and NC along with their fibre mixes when exposed to elevated degree of temperature up to 800 °C. As shown in the figure, the performance of SCC is better than that of the NC at elevated degree of temperature up to 600 °C. Beyond that the performances of both SCC and NC are getting closer.

The incorporation of polypropylene fibres improved the residual tensile strength by about 8 to 10%. This is due to bridging-effect that limits the propagation of cracks and thereby retards cracks initiation [11].

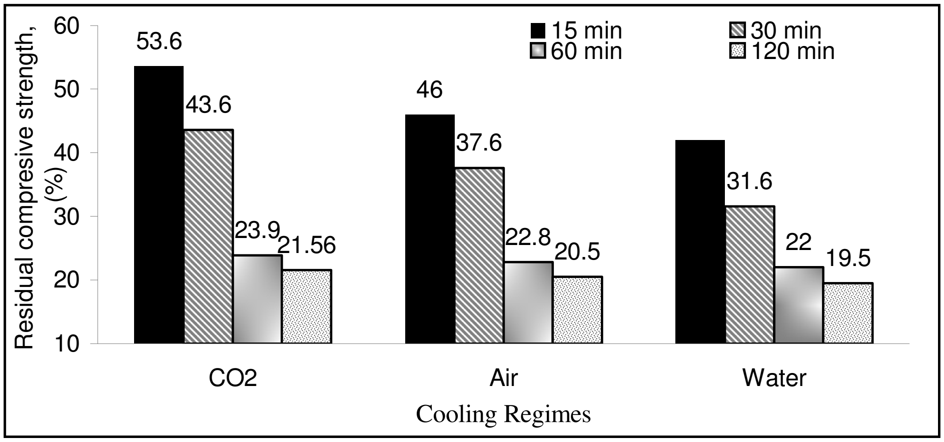

Figure 5 % of residual compressive strength of SCC after exposed to fire temperature of 800 °C with different time durations and cooling regimes.

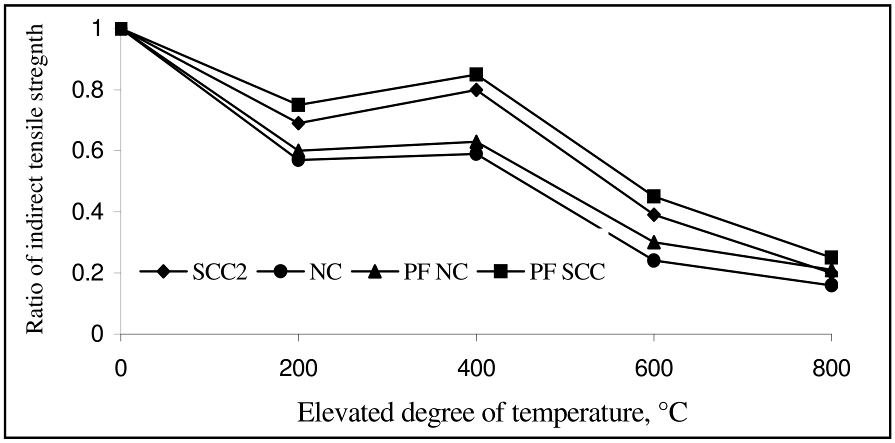

Figure 6 Effect of elevated degree of temperature on the values of indirect tensile strength of SCCs & NC and their corresponding fibre concrete mixes

Figures 7 shows the effect of cooling regime on the indirect tensile strength values of NC and SCC along with their fibre mixes respectively after exposure to time duration of 15 minutes at constant fire temperature of 800 °C. As shown in the Figure, cooling regime plays an important role in the obtained percentage of the residual tensile strength for both NC and SCC. Water cooling regime provided the least percentage of the residual tensile strength while CO_2 cooling regime (chemical) provided highest percentage. As previously advised CO_2 cooling regime has a less damaging effect on the residual tensile strength of concrete. Regardless of the cooling regime, the incorporation of polypropylene fibre to both NC and SCC increased the percentage of residual tensile strength. It is worth mentioning that, residual tensile strength was evaluated only at a time duration of 15 minutes since most of concrete specimens failed at longer exposure duration to a constant degree of temperature of 800°C.

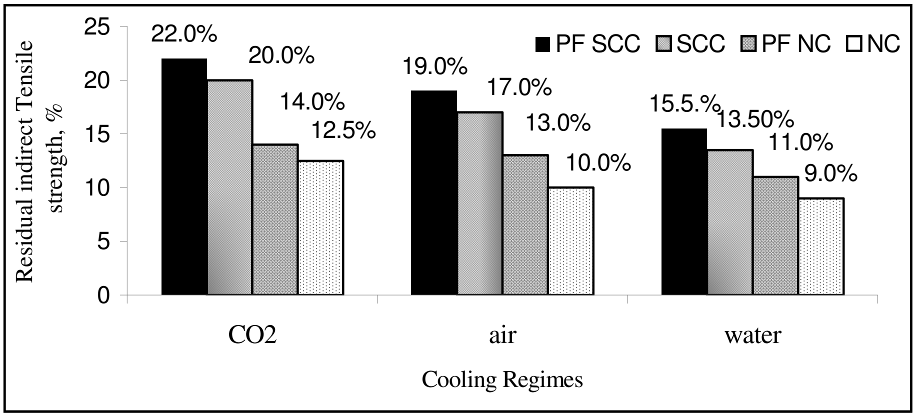

Figure 7 Effect of cooling regimes on the % of residual tensile strength of SCC and NC after exposed to fire temperature of 800 °C for a time duration of 15 minutes .

3.3 Porosity

Figure 8 shows the variation in the porosity of SCC, NC and their corresponding fibre concrete when exposed to elevated degree of temperature. As shown in the Figure, increasing the degree of temperature caused an increase in the total porosity of concrete. The slope was not steep at the first stage of heating up to 200°C and become steeper after that. Increasing the exposure temperature to 200 °C caused an increase in the concrete porosity by about 4%. This could be attributed to the material property of the cement paste that begins to lose its stability due to a weak physical-chemical reaction, particularly for the first heating cycle. In this temperature range, the evaporable moisture plays a dominant role in reducing cohesive forces between C-S-H layers and their gel surface energy [13]. It is conceivable that the partial loss of the chemically bonded water at 100°C contributes to shrinkage and strength reduction. Both chemical decomposition and loss of bonded water cause significant changes to the microstructure of cement paste. They affect the primary chemical bonds, secondary cohesive force (Van der Wall forces), porosity, and pore size distribution [13].

Increasing the exposure temperature from 400°C to 600°C and then to 800°C, the porosity of SCC increased from about 12.5 % to 17% and then to 25 % respectively. Such increase in the porosity could be attributed to the increase in the permeability of SCC due to losses and burning of fine and organic material [4] which changes the SCC from impermeable to permeable material. In addition, SCC has changed from dense to porous material by the effect of high temperature

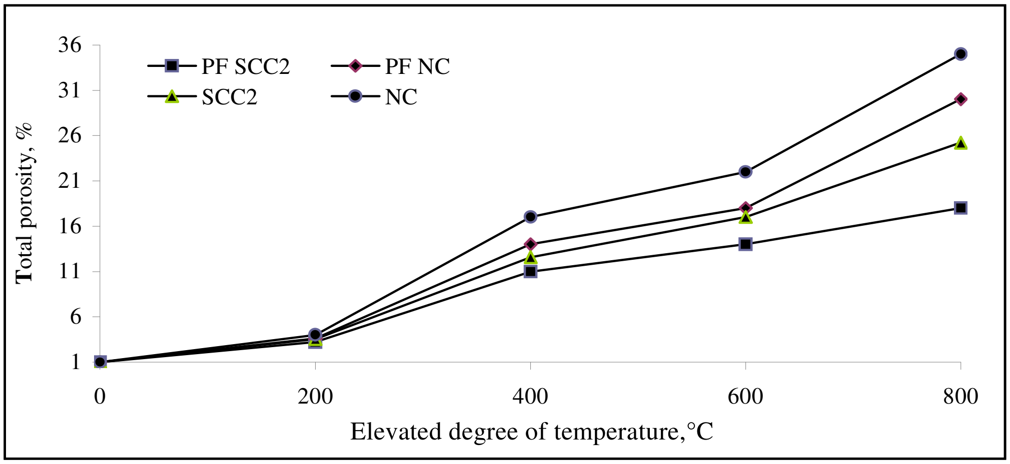

Figure 8 Effect of elevated degree of temperatures on the percentage of Total Porosity of NC and SCC and their corresponding fibre concrete mixes

Similar behaviour was obtained with NC subjected to similar degree of temperatures; however the increasing in the values of NC porosity is greater than those of SCC. Increasing the exposure temperature from 400°C to 600°C and then to 800°C caused an increase in the porosity of NC by 18%, 22% and 36% respectively. These values are corresponding to12.5%, 16 %, 25% respectively in case of SCC exposed to the same conditions. This could be attributed to the large quantity of fine and superfine material with a high surface area included in SCC. These materials consume mixing water during hydration process, and thereby forming stable chemical compound like tri- calcium silicate hydrate C_3S. This compound acts as a gelling material that fills the concrete pores and thereby increasing the impermeability of SCC. Due to the exposure to high temperature, these compounds lose a high percentage of its chemical composition and as a result the concrete porosity decreases [4]. Therefore it is recommended to paint the structural element after exposure to high temperature to prevent moisture penetration through the concrete cover due to the increased porosity.

On the other hand and as shown in the Figure 8, the incorporation of fibre in both SCC and NC caused a reduction in the value of porosity. The obtained percentages of reduction are 4%, 5% and 6% for NC, and 2%, 4% and 7 % for SCC when the exposure temperature increased from 400°C to 600°C and then to 800°C respectively. This is due to the improvement achieved in the values of tensile strength inside core of the concrete specimen.

Figures 9 and 10 are showing the effect of cooling regimes on the percentage of porosity of NC and SCC_2 respectively. As the degree of exposure temperature increase, the percentage of porosity increases for all cooling regimes and/or concrete type. From the cooling regime standpoint, chemical cooling (CO_2 powder) regime provided the least increase in the resulting porosity for both NC and SCC_2 while water cooling regime provided the highest increase in the corresponding porosity. This indicates that CO_2 cooling regime is having less damaging effect to the concrete elements compared with other types of cooling regimes. This is because CO_2 powder covers the surface of the concrete specimen and provided carbonated surface that closes surface cracks and thereby reduce the degradation of the concrete porosity [12]. While, water cooling regime causes thermal shocks to the concrete specimen and thereby creating more cracks to the surface layer [12] which leads to more porosity. Lin et al [13] returned the cracks development to the separation between aggregates and the cement paste that usually takes place during cooling. They added that when concrete is exposed to fire in the range of 500 °C, spreading cooling water to the concrete will generally develop cracks in the order of 1- mm width and 10~20-mm length. In addition, it was advised that water cooling creates temperature gradients that induces thermal stresses which are likely to cause severe cracks after the first heating [13].

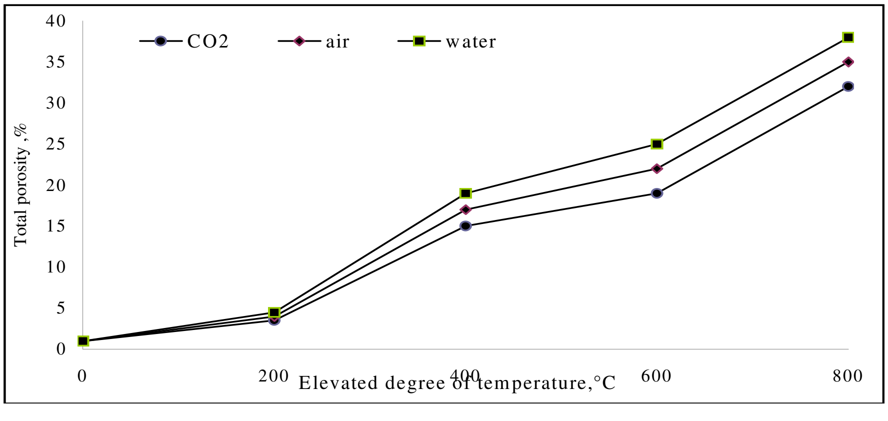

Figure 9 Effect of cooling regime on the % of Total Porosity of NC after exposure to elevated degree of temperature.

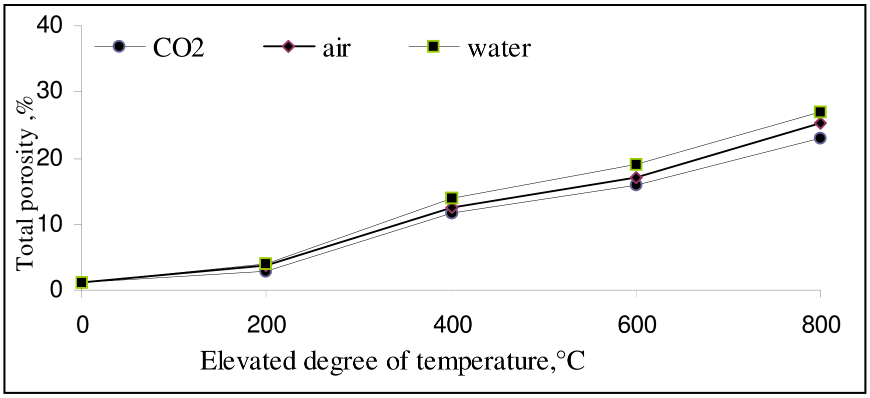

Figure 10 Effect of cooling regime on the % of Total Porosity of SCC2 after exposure to elevated degree of temperature.

3.4 Absorpativity

Figure11 shows the effect of exposure to elevated temperature on the obtained absorpativity of SCC, NC and corresponding fibre concrete mixes. It is clear from the Figure that, the values of absorpativity do not change when the concrete is exposed to elevated degree of temperature up to 200°C. While, increasing the exposure temperature from 200 ^{o}C to 800 °C through 400 °C and 600°C, the absorpativity of SCC increased by about 5.5 %, 7.4 % and 11% respectively. Such increase is very similar to that obtained with the porosity when SCC is exposed to similar conditions. Similar behaviour was obtained with NC and fibre concrete but with slightly low values.

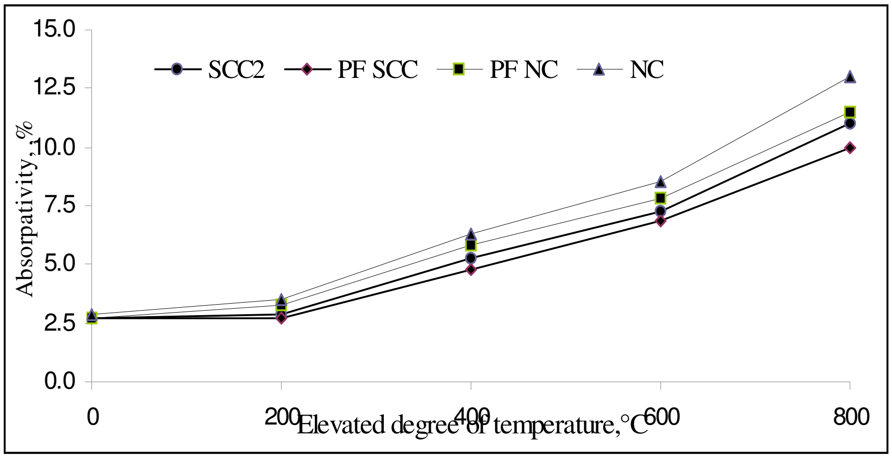

Figure 11 Effect of elevated degree of temperature on the value of Absorpativity of NC and SCC and their corresponding fibre concrete mixes

Figure12 shows the effect of cooling regimes on the value of absorpativity for NC and SCC2 and their corresponding fibre concrete after exposure to an elevated degree of temperature of 800 °C for time duration of 15 minutes. It can be noticed that, in case of chemical cooling (CO_2 powder), the percentage of absorpativity of SCC and NC are 1.5, 1.57 which are usually less than those obtained with air cooling which are 1.6, 1.65. This represents reduction values of 10% and 8% for both SCC and NC respectively. But the corresponding values of water cooling (1.62 and 1.71) are higher than those obtained in case of CO_2 cooling by 12%, 14%. This means that CO_2 cooling regime is the best regime having less damaging effect on the absorpativity of concrete elements.

On the other hand and as presented in the same Figure, the incorporation of fibre to both SCC and NC caused a reduction in the values of absorpativity. The extent of reduction ranges from 3 to 4% for SCC and from 2 to 3% for NC. This is due to the fibre bridging effect and corresponding increase in the values of tensile stresses inside core of the concrete specimens. Similar results are obtained at fire duration of 30 minutes.

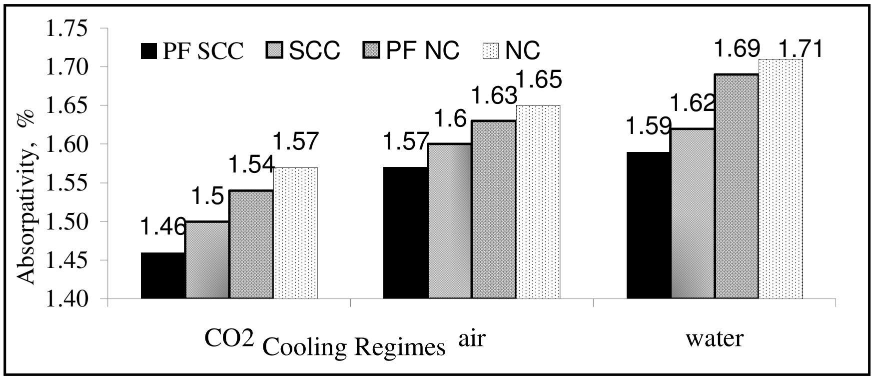

Figure 12 Effect of cooling regime on the absorpativity of NC and SCC and their corresponding

3.5 Effect of exposure to elevated fire temperature up to 800 °C and cooling regime of the extent of Spalling

The extent of spalling of SCC and NC and their corresponding fibre concrete after exposure to an elevated degree of temperature of 800 °C with time durations of 15, 30, 60 and 120 minutes is presented in Figure 13. It can be noticed that, the percentage of losses in the concrete mass of SCC are 0, 1, 7.5, 8 % and 1, 1.5, 8, 8.5 % for NC at fire durations of 15, 30, 60, 120 minutes respectively. This means that, at all fire durations the extent of spalling of SCC is slightly less than those of NC which reflects a better performance of SCC over NC. Previous studies advised that spalling of HSC may occur due to the dense internal microstructure, which hinders the transport and release of water vapour in concrete [2] However in case of SCC, the extent of spalling decreases due to the increase in the tensile strength as a result of the gelling material effect that fills the concrete pores and causing SCC impermeably as well as it increases surface forces between gel particles due to the removal of adsorbed moisture [4]. The obtained value of tensile strength is higher than that of the pore water pressure and therefore the extent of spalling decreases in SCC [4].

Moreover, as illustrated in Figure 13, the rate of spalling between time duration of 30, 60 minutes increases and reduces after that. This could be attributed to the accumulation of excessive pore pressure inside the concrete to a level that overcomes the tensile strength of concrete. As a result, local failure accompanied by a release of high energy takes place. This may lead to a chain of concrete microstructure failure in the adjacent parts and as a result violent explosion of concrete takes place [4]. This pore pressure results from the evaporation of free and combined water inside the concrete and it increases at the beginning and decreases after that due to the water consumption. As also shown in Figure 13, the presence of fibres causes a large reduction in the percentage of spalling as it retards the initiation of spalling from 15 min to 30 min for both SCC and NC.

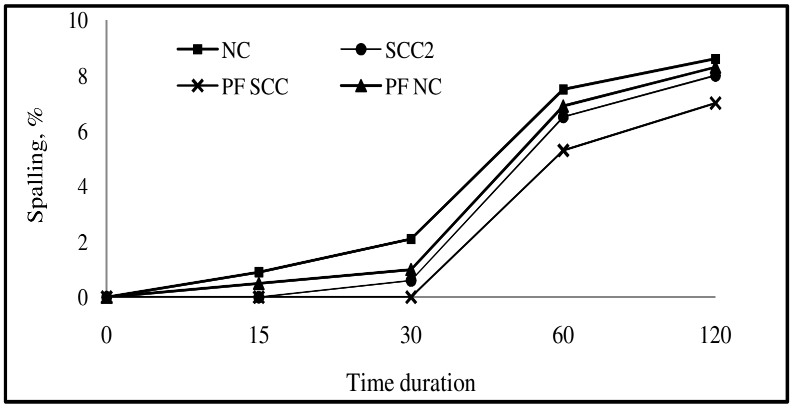

Figure 13 Effect of time duration on the extent of spalling of SCC and NC and their corresponding fibre concrete after exposure to elevated degree of temperature of 800 °C.

Figure14 and 15 show the effect of cooling regimes on the extent of spalling for NC and SCC with and without polypropylene fibres after exposure to an elevated degree of temperature of 800 °C for time durations of 60 and 120 minutes respectively. As illustrated in these Figures, the trend of spalling for both NC and SCC seems to be similar for the used cooling regimes. As previously advised CO_2 cooling regime provided the least value of spalling while water cooling provided highest value of spalling for both SCC and NC at the studied time durations. Similarly the incorporation of fibres increases the value of tensile strength and thereby decreases the extent of spalling of both SCC and NC for the used cooling regimes at the studied time durations.

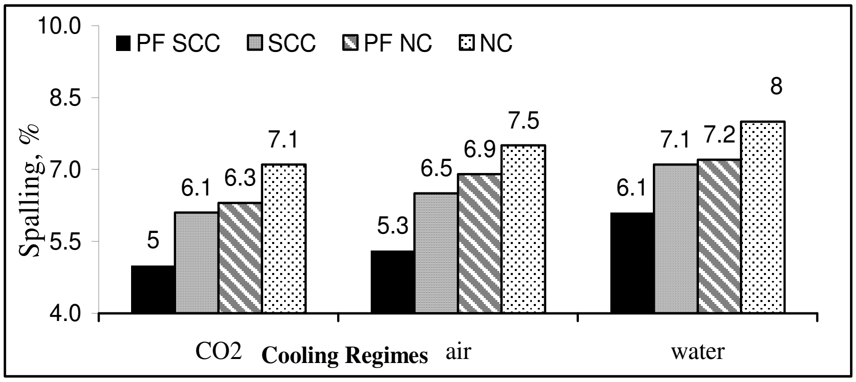

Figure14 Effect of cooling regimes on spalling of NC and SCC with and without of fibres after exposure to an elevated degree of temperature of 800 °C for a time duration of 60 minutes.

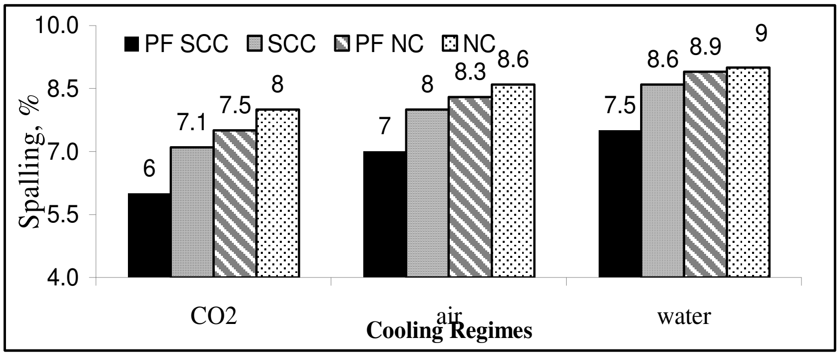

Figure15 Effect of cooling regimes on spalling of NC and SCC with and without of fibres after exposure to an elevated degree of temperature of 800 °C for a time durations of 120 minute

CONCLUSIONS

The following conclusions can be drawn from this research program.

1- Residual compressive and tensile strength of SCC are higher than those of NC for the studied degree of temperatures and time durations. In other words, the effect of exposure to elevated degree of temperatures is more damaging to mechanical properties of NC compared with that of SCC.

2- Exposure to fire caused more damage to the concrete microstructure of NC compared with SCC. This is reflected in the porosity and absorption properties of NC and SCC.

3- Spalling of SCC is less than that of NC regardless of the exposure temperature and cooling regimes.

4- CO_2 powder cooling regime provided the least damage to the concrete after exposure to fire while water cooling regime was the worst of the studied cooling regimes.

5- Spalling of concrete increases with increasing the exposure duration to fire temperature.

6- Incorporation of polypropylene fibres improved the tensile strength and accordingly fire resistance of both SCC and NC under all exposure conditions and cooling regimes.

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