International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/

Print ISSN 2785-9509   *Online ISSN 2812-5142*

Special Issue for ICASGE’19

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ASGE Vol. 04 (01), pp. 87-103, 2020

International Conference on Advances in Structural and Geotechnical Engineering

ICASGE'19

25-28 March 2019, Hurghada, Egypt

FIRE ENDURANCE OF FIBER REINFORCED CONCRETE SUBJECTED TO DIFFERENT COOLING REGIMES

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ABSTRACT

Fiber reinforced concrete (FRC) has become a very famous material due to its improved performances under both static and dynamic loads. On the other hand, Fire represent one of the most severe environmental conditions, and therefore, should be properly accounted for in the design of FRC. In addition, there is an urgent need to study and understand the behavior of FRC after exposure to fire. Therefore, this paper investigates the effect of using different types of aggregates and the effect of different cooling regimes on the mechanical properties; compressive strength, splitting tensile strength and flexural strength of FRC after exposure to fire flame. Two types of local aggregates crushed limestone and gravel were used. FRC were produced by addition of steel and polypropylene fibers in the mixtures at a constant content of 0.5% by volume. A total of seven concrete mixtures were produced and fibers were added in five of them. At the age of 28 days. Specimens were subjected to fire flame temperature ranging between (400-800°C). Three temperature levels (400, 600 and 800°C) where chosen with exposure period of 2 hours after reaching the target temperature. After burning, the concrete specimens were allowed to different cooling regimes namely; air cooling, CO_2 powder cooling, 15min spraying water and quenching water cooling.

The results obtained from this study indicated that cooling regimes significantly influences residual properties of concrete, such as compressive strength, tensile splitting strength, and flexure strength. The fact that the impact of spraying water for 15 min or more on mechanical properties was almost the same as that of water quenching, indicates that spraying water for 15 min or more could cause thermal shock to a similar degree to water quenching. For each type of concrete under identical target temperature, among the four cooling regimes, CO_2 powder cooling maintained a relatively higher value of residual compressive strength. Similar results were also obtained on splitting tensile and flexural strengths. The incorporation of fiber improved the fire resistance and splitting tensile strength of concrete as shown in concrete specimens containing steel fiber. Hybrid fiber (steel fiber and PP fiber) and steel fiber can enhance both residual strength of concrete subjected to thermal shock induced by rapid cooling from elevated temperature up to 800°C.

Keywords: Fiber reinforced concrete, fire, coarse aggregate, fibers, cooling regimes, residual strength

INTRODUCTION

Fiber reinforced concrete is a composite material essentially consisting of concrete reinforced by random placement of short, discontinuous and discrete fine fibers of specific geometry [1]. Fibers have extensively been used to improve the ductility of concrete. Recently, it has been found that a number of fibers can improve residual properties of concrete after exposure to elevated temperatures [2]. In buildings, the used construction materials are usually subjected to different kind of stresses as well as different environmental exposure conditions. Fire represents one of the most severe environmental conditions. Even though concrete is good against fire loads, concrete subjected to temperature above 500°C significantly loses the strength and affects the durability of structures[3]. It is therefore important to study the thermal and structural behavior of the concrete exposed to high temperature. On the other hand, the effect of cooling regimes on mechanical properties of concrete is of great concern, especially after a fire case could lead to a collapse of the building [4].

Spalling is one of the major problems facing concrete structures subjected to elevated degrees of temperature. During exposure to fire, free and combined water inside the concrete start to evaporate and form pore pressure. This pressure builds up and induces stresses on the internal structure of the concrete elements [5]. On the other hand, aggregate type plays an important role on the concrete spalling under fire conditions. Concrete made with carbonate aggregate (dolomite aggregate) provides better spalling resistance compared with natural siliceous aggregate concrete. This is because carbonate aggregate has a substantially higher heat capacity which is beneficial in preventing spalling [6]. Extent of spalling is found to be much greater when lightweight aggregate is used. This is mainly because the lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures [7].

Abdelalim et al [5], studied the influence of coarse aggregate type and incorporation of polypropylene fibers on the mechanical properties of normal concrete (NC) and self-compacting concrete (SCC) such as compressive strength, tensile strength, porosity, near surface absorption and Spalling before and after exposure to elevated degrees of temperature. They used three types of coarse aggregates natural gravel, dolomite, and basalt. And subjected samples to different temperatures (200-400-600-800°C) during periods of exposure (15-30-60-120) minutes. The results showed that, Increase the temperature of the fire caused significant reduction of compressive strength values and indirect tensile strength values of NC and SCC regardless of the type of aggregate used. Residual compressive strength of dolomite aggregate was higher than basalt and natural aggregates of NC and SCC. The conclusions were similar to those presented by Hager et al [8]. The mechanical degradation is found to be more severe for gravel concrete than for basalt concrete. This is due to the fact that basalt aggregate thermally is a more stable material than gravel [4].

Savva et al [9], tested limestone and siliceous ordinary concrete. They noticed that up to 300 °C, the type of aggregate does not affect compressive strength significantly. In the range between 100 and 300 °C, compressive strength increases. In the case of siliceous concrete, the increase is higher than for the limestone one. Above 300 °C, a reduction of strength is observed for both types of aggregates; however, for siliceous aggregate concrete, the reduction is higher. Opposite conclusions have been reached as a result of testing the modulus of elasticity. A decrease of Young’s modulus was observed at the whole range of temperature and it was the most prominent in the case of limestone concrete. Xing et al. [10], Investigated HPC made of siliceous and calcareous aggregate and showed that using siliceous aggregate results in better performance of the concrete subjected to high temperature than using the calcareous one as far as compressive strength is concerned. Similar relationship has been demonstrated for tensile strength.

The addition of fibers in concrete has been proven to improve the mechanical properties of concrete, particularly the tensile strength, flexural strength, ductility performance and fire resistance. Furthermore, incorporation of fibers in concrete results in reductions in the shrinkage, creep deformations of concrete. However, it has been shown that fibers may also have negative effects on some properties of concrete, such as the workability, which get reduced with the addition of steel fibers. The addition of fibers, particularly steel fibers, due to their conductivity leads to a significant reduction in the electrical resistivity of the concrete, and it also results in some reductions in the chloride penetration resistance of the concrete [11]. When concrete is exposed to high temperatures, it loses its strength and stiffness. The key factors which affect the performance of fiber reinforced concrete at desired temperature; strength of concrete, type of fibers, percentage of fibers, type of aggregates and spalling resistance [16].

The inclusion of steel fibers in concrete cannot reduce the risk of spalling, but they can affect the spread of cracking, and potentially improve the performance of concrete, after exposure to high temperatures [12, 13]. Steel-fiber-reinforced concrete also showed the highest energy absorption capacity after the high-temperature exposure, although they suffered a quick loss of this capacity after exposure to 800°C [14]. Inclusion of steel fiber in the concrete mix leads to an improvement in mechanical properties and a better resistance to heating effects [12]. Steel fiber reinforced HPC mixture with silica fume and fly ash decreased loss of compressive strength, splitting tensile strength and modulus of elasticity at low temperatures [15]. Polypropylene (PP) fibers are very useful in preventing HPC from spalling [17, 18]. PP fibers melt and vaporize due to their lower melting point (about 165°C), which results in many micro-channels in HPC, which may be the reason for no explosive spalling in HPC with PP fibers [17-20].

Covidarajan et al [21], conducted an experimental work on concrete cubes cast with glass fibers of size 150×150×150 mm and the specimens were tested at 7 and 28 days. The results showed that; adding 1% of glass fibers on concrete improvement of performance of concrete and the compressive strength, tensile strength and flexural strength. The high percentage increase of glass fibers would reduce the strength of concrete. Mugume et al [22], studied the development of pore pressure in fiber reinforced concrete at high temperatures. Concrete samples were made using polypropylene fibers, steel fibers and hybrid fibers. Polypropylene fibers reduce pore pressure within the concrete. Rapid heating rate is one of the reasons for increased pore pressure in concrete. Steel fibers increase the bond between the free space inside the concrete and the pressure of the pores inside the concrete. Arabi et al [23], studied the behavior of self-compacting concrete with polypropylene fibers at high temperatures up to 600 m. Concrete samples were treated for 90 days and tested at (200-400-600 °C) for two hours and 4 hours. 0.05 % polypropylene fibers give better results in the case of exposure to heat for two hours, and 0.1% gives more residual strength at exposure to heat for a period of 4 hours in the case of cubes test. However, in the case of cylinder compressive test, 0.05% of the polypropylene fibers give better results.

Behnood et al [24] studied the behavior of high strength concrete with and without polypropylene fibers at high temperatures (200 - 400 - 600 - 800 - 1000°C) at an average heating rate of 3°C / min within 3 hours. The addition of 2 kg/m^3 of polypropylene fiber to concrete improve its mechanical properties. There is no variation in the residual strength at exposure to temperature 100°C, but higher than 200°C polypropylene fibers melt and create holes and holes in the concrete, which increases the free space inside the concrete and thus reduces pore pressure and increases the ability to absorb heat shocks in the concrete samples.

As the various ways of cooling the structure affects the mechanical strength of FRC, the effect of cooling regimes on mechanical properties of concrete is of great concern. Thermal shock produced by water cooling or quenching produces a more deterioration in strength than in the case of furnace cooling [25-27]. Quenching of concrete specimens could cause internal cracks, due to stresses that developed when temperature difference between the core and the surface of a specimen [25-27]. Water spraying for duration of 30 minutes or more is in consistency with quenching in water which has a same effect as a water curing [28]. Under thermal shock hybrid fiber (steel fiber and polypropylene fiber) can enhance residual strength and fracture energy of concrete subjected to high temperatures up to 800°C [28].

Xin et al [4] 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. Abdelalim et al [29] studied the effect of cooling regime (water, CO_2 and air cooling) and the elevated degrees of temperature up to 800°C on the mechanical properties of NC and SCC. The results showed 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.

In spite of the above studies, the influence of coarse aggregate type, the effect of fire flame exposure and cooling regime on the mechanical properties of fiber reinforced concrete was not fully covered specially on the locally produced concrete. Therefore the objectives of this study are carefully selected to study the effect of aggregate type, types of different cooling regimes and elevated degrees of temperature on the fire resistance of fiber reinforced concrete in terms of mechanical properties (compressive, splitting tensile and flexural strengths).

EXPERIMENTAL WORK

Materials and Concrete Mix Proportions

The experimental work includes seven concrete mixes containing the same cement. Portland Cement (PC) ((CEM I 42.5N)) complying with the Egyptian Standard Specifications [ESS 4756-1/2006] with a content of 450 kg/m^3 was used in all concrete mixes. Siliceous well graded sand with a specific gravity of 2.55 and a fineness modulus of 2.48 was used. Two coarse aggregates gravel (G) and crushed limestone (D) with maximum aggregate size of 14mm were considered. The physical properties of the used coarse aggregates are presented in **Table 1**. Polypropylene and steel fibers with a constant content of 0.5% of the volume were used. The properties of the investigated fibers according to the manufacturer are presented in **Table 2**. Tap water with a constant free w/c ratio of 0.3 was used in concrete mixing. Silica fume with a content of 10% of cement weight was used. In order to obtain an adequate workability of the fresh mix, water reducing agent (superplasticizers (Sika visco-crete-3425)) for high workability was used.

For each mix, the ingredients were placed into a mechanical concrete mixer with 100 L total capacity. First, the water in addition to water reducing agent and powder were mixed for one minute to ensure the uniformity of the constituents. Secondly, coarse aggregate was simultaneously charged into the mixer and was mixed for another one minute and then sand was added and mixed at least for two minutes. Thirdly, fiber was manually dispersed into HPC and mixing process was continued for 5 minutes to assure the uniformity of the mixture, then after mixing, the mixed concrete was discharged from the mixer for next processes. After mixing, the concrete was poured into the moulds, compacted using a vibrating table till no air bubbles emerged from the surface of the concrete and kept for 24 h. Finally, the specimens were demoulded and cured in an ambient controlled room (25 ± 2) °C and 50% RH until an age of 28 days. For each mix, 39 cubic specimens of 100 mm side length were cast for measuring the compressive strength before and after fire and the extent of spalling. While 39 cylindrical specimens of 100 mm diameter and 200 mm depth were also cast to evaluate the indirect tensile strength (splitting tensile strength) of concrete before and after exposure to fire. 39 prism with a square section of the 100 mm side length 400 mm total length and the clear span 300 mm were used to determine the flexural strength before and after exposure to fire. The concrete mix proportions were designed by using absolute volume method. The mix design proportioning for all mixes are detailed in **Table 3**.

Table 1: properties of the used aggregates

Property	Dolomite	Gravel	Sand
Specific gravity	2.6	2.67	2.55
Unit weight (t/m^3)	1.84	1.79	1.65
Fineness modulus	5.18	5.26	2.48
Water absorption, %	1	0.72	1.7
Crushing value, %	22	14.7	-
Clay and fine dust content, %	0.96	0.58	1.86

Table 2: Properties of the investigated fibers described in the product data sheet

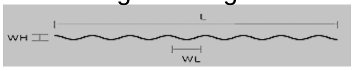
Properties/types of fibers	Steel	Polypropylene
Length [mm]	25	Gradient of (6-18 mm)
Diameter [µm]	-	18
Thickness[mm]	2	-
Specific gravity	7.86	0.91
Shape	Corrugated Segment 	Fiber mesh
Tensile strength [Mpa]	700	300-400
Elastic modulus [GPa]	210	3.6
Melting point [°C]	-	169

Table 3: details of concrete mix proportions

Mix ID	Fiber %		W/C	kg/m^3					SP	
	steel	**pp**		**C**	**SF**	**CA**	**S**	**W**	**%**	**kg/m^3**
D-0	0	0	0.3	450	45	1080	720	149	1	4.95
G-0	0	0	0.3	450	45	1080	720	149	1	4.95
D-S0.5	0.5	0	0.3	450	45	1067	711	149	1	4.95
G-S0.5	0.5	0	0.3	450	45	1070	713	149	1	4.95
D-P0.5	0	0.5	0.3	450	45	1067	711	149	1	4.95
G-P0.5	0	0.5	0.3	450	45	1070	713	149	1	4.95
D-PS1	0.5	0.5	0.3	450	45	1067	711	149	1	4.95

Where,

C: Cement content ($\mathrm{kg/m^3}$),
CA: Coarse aggregate content ($\mathrm{kg/m^3}$),
W: Water content ($\mathrm{kg/m^3}$),
P0.5: 0.5% Polypropylene fiber,
PS1: 0.5% Polypropylene fiber + 0.5% steel fiber.
SF: Silica fume content ($\mathrm{kg/m^3}$),
S: Fine aggregate content ($\mathrm{kg/m^3}$),
SP: Super plasticizer ($\mathrm{kg/m^3}$).
S0.5: 0.5% steel fiber,

Test Techniques and Procedures

Compressive Strength Test

The compressive strength test was carried out according to BS EN 12390-3:2009. For each mixture the test was performed on 100 mm cubes. The compressive strength was obtained at the ages of 28 days by using a compressive strength testing machine of capacity 1500 KN. The specimens were exposed to a varying degree of fire flame temperature of (400, 600 and 800 °C). Heating rate of 9.6°C/min was applied to reach the desired degree of temperature. The specimens were then left to cool according to the specified cooling regimes (air cooling, CO_2 powder cooling, 15 min spraying water cooling and water cooling) and then tested. The average compressive strength (f_c) was calculated using triplicate specimens.

Splitting Tensile Strength Test

The splitting tensile strength test was carried out according to BS EN 12390-6:2009. For each mixture, Splitting tensile strength test was performed on cylinders test specimens of size of 100 mm diameter and 200 mm length. The test specimens were tested for tensile splitting strength at an age of 28 days. The splitting tensile strength (f_t) was calculated using triplicate specimens.

Flexural Strength test

The Flexural Strength test was carried out according to BS EN 12390-5:2009. For each mixture, the flexural test was performed on specimens of size 100×100×400 mm at 28 days using three points loading test. The effective span length of the beams was 300 mm. the tests were performed using the universal testing machine with 300 KN total capacity. The flexural strength (f_r) was calculated the average of three specimens.

Fire test Setup

The concrete specimens were placed in the furnace. The furnace was put on and when the temperature reached 400,600,800°C, it was maintained at same temperatures for a period of 120 minutes. To achieve these settings, the furnace used in this research work was a natural gas oven as shown in **Fig. 1.** Equipped with two net of gas burners, each network contains twenty one of the gas burners with dimensions of (400×1300 mm) as shown in **Fig. 2.** The outer dimensions of the furnace are 150×120×80 cm while, the inner dimensions are 140×110×70 cm. The flame was intended to simulate the heating conditions in an actual fire. The concrete specimens were burnt by direct fire flame as shown in **Fig. 3.** When the target temperature was reached, control valves and thermocouples to control and measure the inside temperature during the firing process. The digital thermometer continuously recorded the temperature as shown in **Fig. 4**.

After elapsing the curing period, concrete specimens were removed from their curing tank and were then put in the furnace at a temperatures of 400,600,800ºC for a period of 120 min after reaching the target temperature . After that, specimens were removed from the furnace and were left to cool to room temperature using one of the used cooling regimes namely, air cooling, water cooling, 15min spraying water and CO_2 cooling.

The surface temperature of specimens was monitored by attaching further thermocouples on the surfaces, the temperature data was stored until to down loading computer. The time-temperature schedule used in heating was plotted. A comparison was made between the actual temperature and the standard fire-time according to ISO384 as shown in **Fig. 5.**

Fig. 1: the furnace used in this research work

Fig. 2: The Network of Burners

Fig. 3: Burning of Concrete specimens

Fig. 4: Digital Thermometer

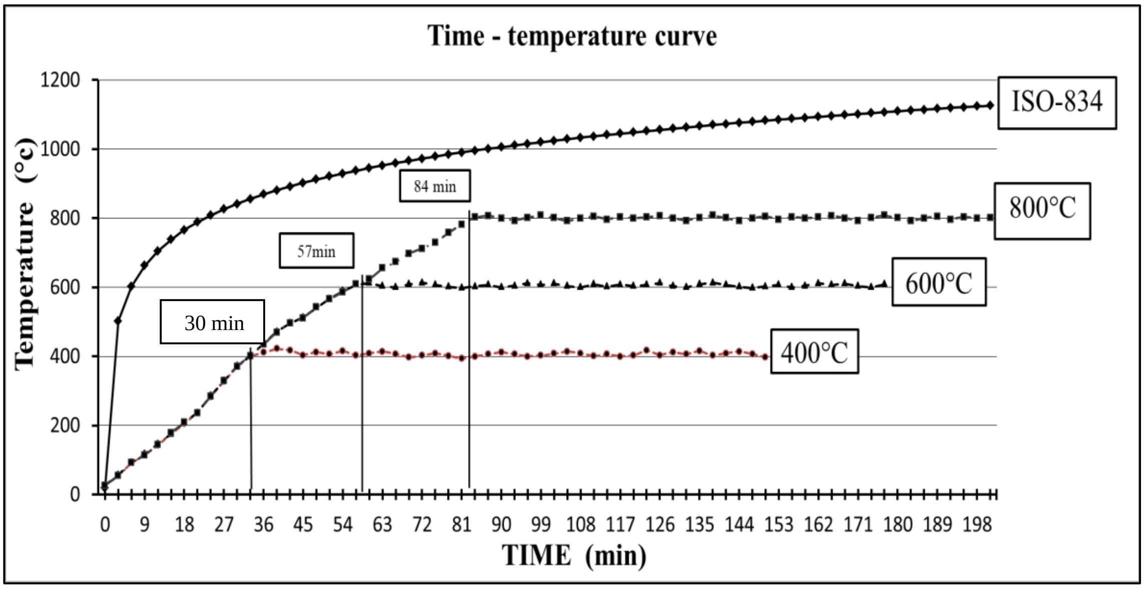


Fig. 5: Time-temperature schedule used in heating compared with the standard fire-time temperature (ISO384)

Temperature Determination Specimens Subjected to Heating and Cooling

Temperature was determined on two types of 100 mm concrete cubes designated by G-0, and D-0, which were heated in a natural gas furnace. The target temperature was maintained at 800°C for 2 hr after reaching the target temperature. After heating, from four cubes a batch, one was subjected to quenching by immersion in water, another was subjected to water spraying water for 15 min, another was subjected to CO_2 cooling and the other was cooled naturally in the furnace. The furnace and a typical cube specimen with two thermocouples. Thermocouples were fixed at two locations inside the cubes, and on the lower surface of the cubes as shown in **Fig.6**. Temperatures at the various locations were determined continuously throughout heating and cooling.

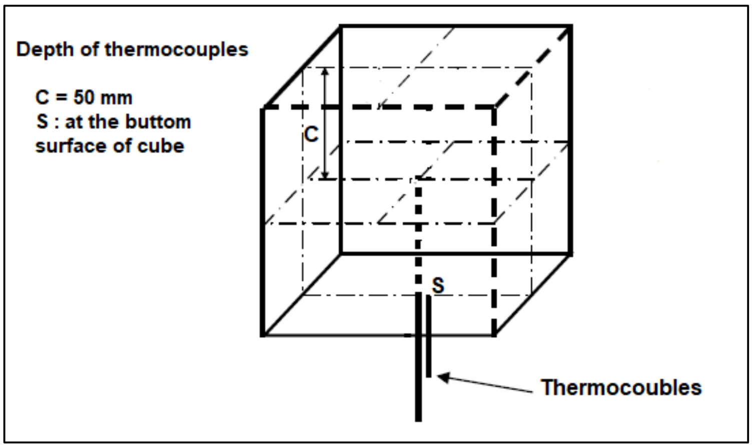
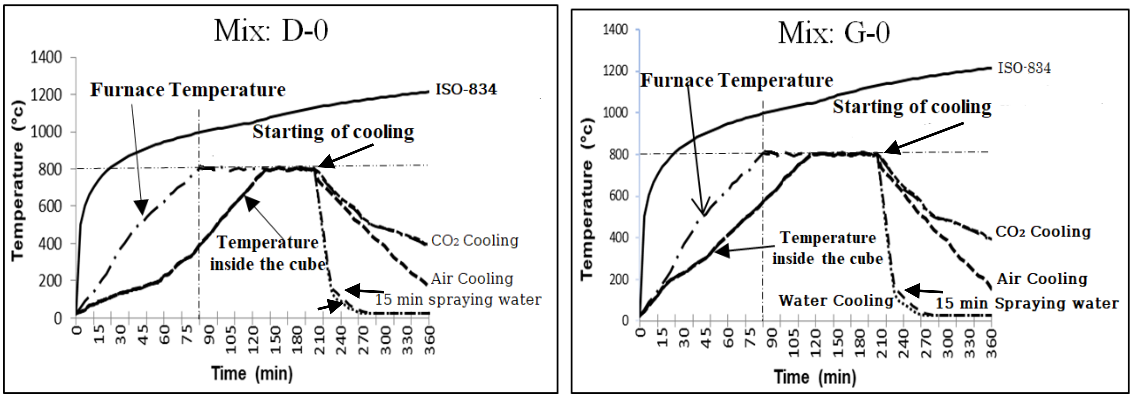


Fig. 6: Thermocouple locations at various depths in a cube of 100 mm size

TEST RESULTS AND DISCUSSIONS

Temperature in specimens during heating and cooling

The temperature determination results are shown in **Fig. 7a** and **Fig. 7b** for concrete mixes D-0 and G-0 respectively. These results indicate that the inner temperature decreasing rate of a specimen during cooling, either under quenching or under water spraying for 15 min, was significantly higher than that of the specimen subjected to natural cooling and chemical cooling with CO_2 cooling. In general, the specimens subjected to quenching, or water spraying for 15 min, could cool to 100°C within 25 min. For mix D-0 subjected to quenching, temperature at 50 mm depth dropped from 793 to 102°C within 24 min while the temperature of the concrete exposed to both natural cooling and Chemical cooling at CO_2 is at the same depth dropped from 800°C to 640°C during 24 minutes in CO_2 cooling while the temperature dropped from 800°C to 668°C during 24 minutes in natural cooling as shown in **Fig. 7a**. The results indicate that, the cooling regimes such as quenching in water, or water spraying for 30 min or more, caused an action of “thermal shock” to concrete under elevated temperature, characterized by a high rate of temperature decreasing ranged from 30 to 48 min/°C, which was calculated from **Fig. 7(a,b).** It can be concluded that, in terms of thermal shock, water spraying for duration of 15 min or more is in consistency with quenching in water with a slight difference between them.



(a) Crushed Limestone **(b) Gravel**

Fig. 7. Temperature of concrete subjected to different cooling regimes

Effect of type aggregates and type of fibers on compressive, splitting tensile and flexural strengths

The compressive, splitting tensile and flexural strengths test results of the investigated mixes that made with various aggregate types and fiber types (Polypropylene fibers and steel fibers) were assessed at age of 28 days as shown in **Figs.8, 9** and **Tables 4-6**. As seen from the results plotted in **Figs.8, 9,** crushed limestone aggregates provided the highest compressive strength results compared with that of gravel aggregates for all mixes. On the contrary, gravel aggregate provided the least values. The results recorded decreases about 6.75%, 5.08%and 5.27% for mixes G-0, G-P0.5, G-S0.5, respectively in compared with mixes D-0, D-P0.5, D-S0.5 respectively for compressive strength as shown in **Fig. 8**. The results also recorded decreases about 4.55%, 4.06% and 5.04% for mixes G-0, G-P0.5, G-S0.5 respectively in compared with mixes D-0, D-P0.5, D-S0.5 respectively for splitting tensile strength as shown in **Fig. 9**. The results also recorded a decrease about 1.35%, 1.26% and 1.07% for mixes G-0, G-P0.5, G-S0.5 respectively in compared with mixes D-0, D-P0.5, D-S0.5, respectively for flexural strength as shown in **Fig. 9**. Polypropylene fibers and steel fibers achieved a slight decrease on the obtained results of compressive strength compared with the control mix. This may be due to the excess of water to powder ratios. However, it greatly improved the splitting tensile and flexure strength results of all investigated mixes as shown in **Fig. 9**. The effect of adding steel fibers was founded to be higher than that of PP fibers. **Figure 8** showed that, a decrease of 2% for mix D-P0.5 in compared with mix D-S0.5 for compressive strength. **Figure 9** showed that, increases of 27.4% and 11.53 for mix D-S0.5 and D-P0.5 in compared with mix G-S0.5 and G-P0.5 for splitting tensile and flexural strengths, respectively. This could be attributed to the bridging effect of the Polypropylene fibers and steel fibers which postpones the initiation of cracks. Hybrid fibers achieved a slight decrease on the obtained results of compressive strength compared with the control mix as shown in **Fig.8**. The results recorded a decrease about 9.17% for mix D-PS1 in compared with mix D-0. The results also recorded increases of 79.9% and 28.43% for mix D-PS1in compared with mix D-0 for splitting tensile and flexural strengths, respectively as shown in **Fig. 9**.

Table 5: Test values of compressive strength of concrete specimens before and after exposure to fire flame at 28 days age

Mix ID	Compressive Strength MPa												
	25°C	400°C				600°C				800°C			
	Ref	Cooling regimes				Cooling regimes				Cooling regimes			
		CO2	Air	15min sp	Water	CO2	Air	15min sp	Water	CO2	Air	15min sp	Water
D-0	66.35	52.64	50.76	41.68	40.17	34.66	33	27.5	27.35	19.54	18.37	13.23	12.98
G-0	65.87	45.74	44.53	38.59	37.32	28.59	27.65	21.54	20.45	14.43	13.64	10.45	9.33
D-S0.5	63.13	56.23	54.1	49.15	47.13	39.16	36.65	31.73	31.64	26.37	25.11	22.26	21.76
G-S0.5	62.92	51.27	50.56	43.85	42.25	30.43	29.96	22.56	21.63	18.69	18.25	13.56	13.12
D-P0.5	61.84	54.51	53.05	45.47	44.83	37.66	34.16	30.33	29.96	24.73	24.17	20.08	19.87
G-P0.5	60.58	46.1	45.5	39.51	38.38	29.67	28.54	21.95	21.37	15.783	14.97	10.97	10.04
D-PS1	60.26	53.72	52.8	44.46	43.49	36.5	35.33	30.83	29.67	25.34	24.23	19.14	18.67

Table 6: Test values of splitting tensile strength of concrete specimens before and after exposure to fire flame at 28 days age

Mix ID	Splitting tensile Strength MPa												
	25°C	400°C				600°C				800°C			
	Ref	Cooling regimes				Cooling regimes				Cooling regimes			
		CO2	Air	15min sp	Water	CO2	Air	15min sp	Water	CO2	Air	15min sp	Water
D-0	3.82	3.1	2.89	2.73	2.7	2.17	2.02	1.89	1.77	1.59	1.46	1.02	0.93
G-0	3.64	2.87	2.46	2.1	1.93	1.87	1.77	1.54	1.44	1.23	1.16	0.87	0.76
D-S0.5	6.29	5.74	5.57	5.11	5.05	4.44	4.19	3.81	3.34	2.94	2.78	2.26	2.16
G-S0.5	6.03	5.34	5.16	4.91	4.41	4.15	4.03	3.48	3.21	2.78	2.64	2.08	1.89
D-P0.5	4.56	4.1	3.92	3.53	3.47	2.93	2.76	2.46	2.28	2.07	1.9	1.54	1.38
G-P0.5	4.33	3.82	3.54	3.01	2.91	2.67	2.42	2.16	2.01	1.74	1.56	1.04	0.94
D-PS1	6.87	6.26	6.12	5.66	5.54	4.91	4.53	4.18	4.16	2.97	2.89	2.18	2.11

Table 7: Test values of flexural strength of concrete specimens before and after exposure to fire flame at 28 days age

Mix ID	Flexural Strength MPa												
	25°C	400°C				600°C				800°C			
	Ref	Cooling regimes				Cooling regimes				Cooling regimes			
		CO2	Air	15min sp	Water	CO2	Air	15min sp	Water	CO2	Air	15min sp	Water
D-0	7.68	6.25	6.02	5.67	5.44	4.52	4.19	3.41	3.12	3.01	2.89	2.31	2.17
G-0	7.58	5.83	5.54	5.21	5.12	4.13	4.02	3.11	2.83	2.18	1.73	1.28	1.16
D-S0.5	9.45	8.06	7.89	7.12	7.02	5.5	4.88	4.97	3.82	3.96	3.82	3.25	3.08
G-S0.5	9.33	7.73	7.4	6.83	6.43	5.36	4.33	4.47	3.46	3.23	3.14	2.71	2.59
D-P0.5	8.36	6.87	6.67	6.27	5.98	4.93	4.37	3.6	3.47	3.43	3.24	2.86	2.67
G-P0.5	8.45	6.62	6.35	5.93	5.73	4.42	4.13	3.33	3.16	3.23	3.11	2.67	2.44
D-PS1	9.87	7.81	7.65	7.1	6.93	5.68	4.93	3.89	2.61	3.92	3.87	3.24	3.17

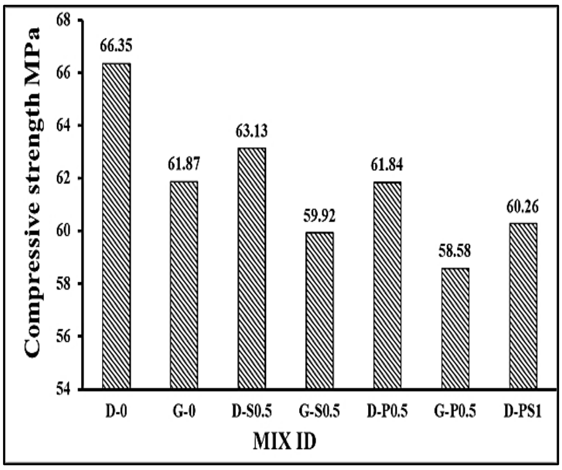


Fig. 8: Compressive strength of Mixes at 25°c

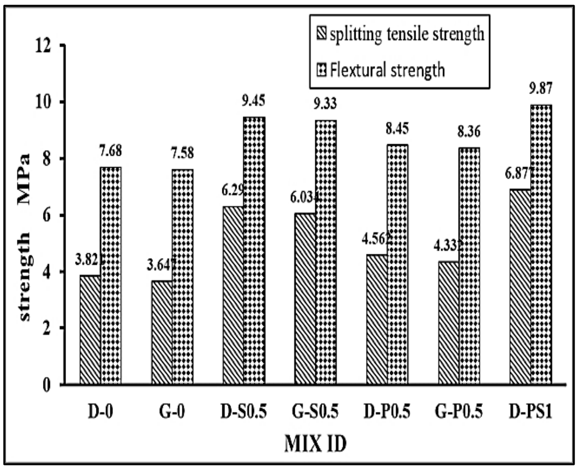


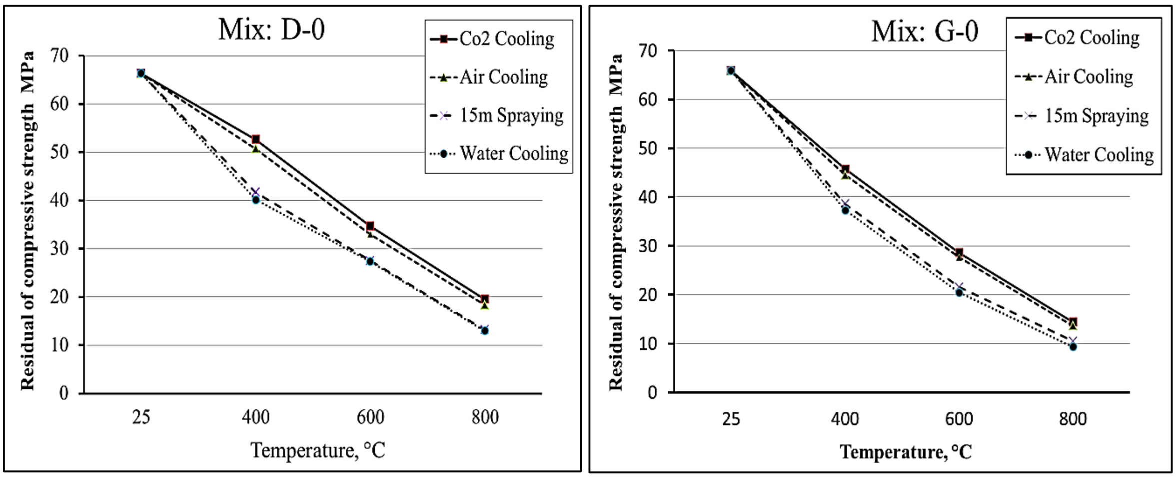
Fig. 9: splitting tensile and Flexural strengths of Mixes at 25°c

Effect of cooling regimes on compressive strength after exposure to fire flame

The results of residual compressive strength of the seven mixes of concrete subjected to various cooling regimes are given from **Figs. 10–13**, respectively. It is obvious in these figures that residual compressive strength of concrete was significantly influenced by the cooling regimes. For each type of concrete under an identical target temperature, among the four cooling regimes, CO_2 cooling regime (chemical) maintained a relatively higher value of residual compressive strength, while both quenching in water or spraying over 15 min caused a low and almost equal compressive strength. The results showed that the residual compressive strength of the mix D-0 for example was 79.33%, 52.23% and 29.44% for CO_2 cooling at 400,600 and 800°C, respectively. While the residual compressive strengths of the mix D-0 for example were 62.81%, 41.44% and 19.93% for 15 min spraying cooling at 400,600 and 800°C, respectively this is clear in all mixes. Also, the residual compressive strengths of the mix D-0 for example were 60.54%, 41.22% and 19.56% for water cooling at 400,600 and 800°C, respectively as shown in **Fig.10(a, b)**. 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. Solid-state CO_2 is also known as dry ice, which turns directly from solid to gaseous at normal atmospheric pressure. This direct transition from solid to gas makes dry ice an effective cooling device, especially since it is colder than ice and never leaves traces of moisture. While, sudden water cooling regime caused a negative thermal shock for the concrete specimens and thereby increased the near-surface cracks. As a result, the compressive strength decreases. This agrees with the results of previous findings by Xin et al [20].

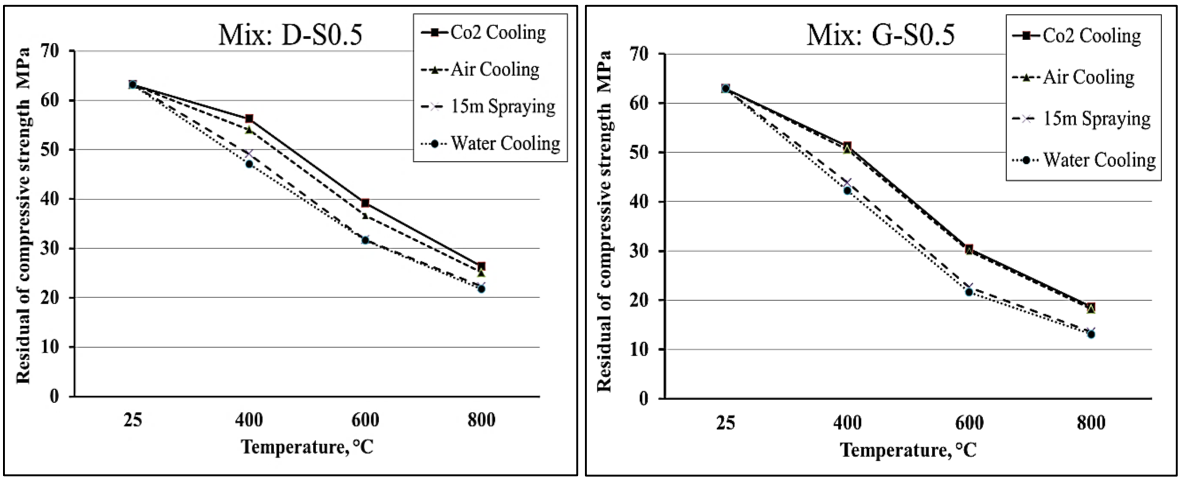
On the other hand, Steel fiber could reduce the deterioration of concrete when subjected to high temperatures. Besides, the addition of polypropylene fiber did not cause a significant decrease in residual strength compared to the case when they are not added as shown in **Figs. 11, 12**.

On the other hand, the effects of aggregate type on the compressive strength and residual compressive strength of FRC after exposure to elevated degrees of temperature of 400, 600 and 800°C are demonstrated in **Figs.10 to13**. As shown, increasing the exposure temperature caused a major reduction in the concrete compressive strength. However, crushed limestone aggregates concrete provided higher values of compressive strength in the range of 7 to 12% compared with that of gravel for mix D-0 and G-0 at 400,600 and 800°C as shown in **Fig.10a, Fig.10b** respectively. This is because the mineral components - calcite ($CaSO_3$) and dolomite ($CaSO_3 \cdot MgCO_3$), at temperatures around 870°C (for calcite) and 800°C (for dolomite), turn into CaO and MgO oxides. However, for the complete decomposition of one carbonate rock, a long-term effect of high temperatures is required, so possible chemical changes in short-term fire exposure do not affect the physical state of the material, while in the case of intense fire exposure; they are mainly reflected only in surface degradation [2-3].



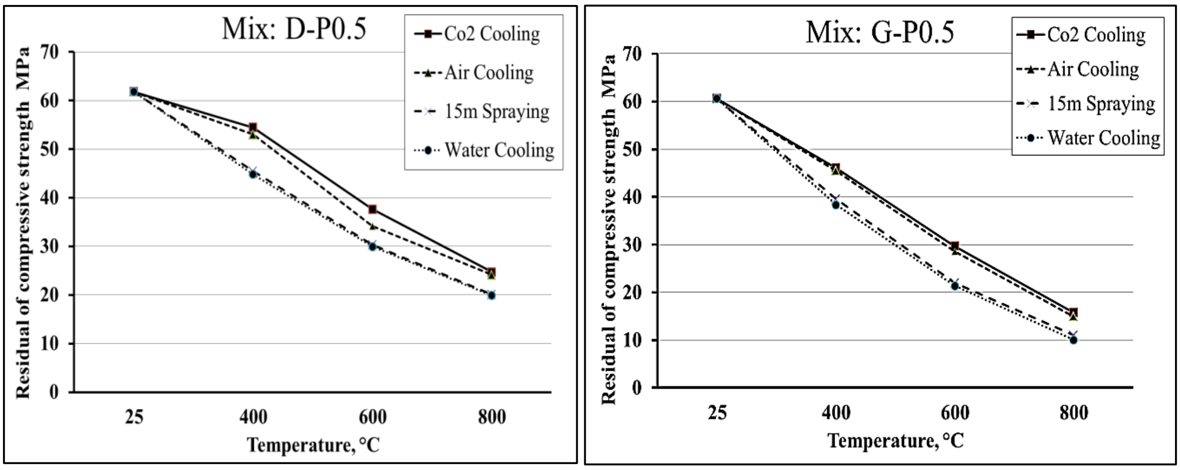
(a) Crushed Limestone **(b) Gravel**

Fig.10: Residual compressive strength of mixes without fibers



(a) Crushed Limestone (b) Gravel

Fig. 11: Residual compressive strength of steel fiber mixes



(a) Crushed Limestone (b) Gravel

Fig. 12: Residual compressive strength of polypropylene fiber mixes

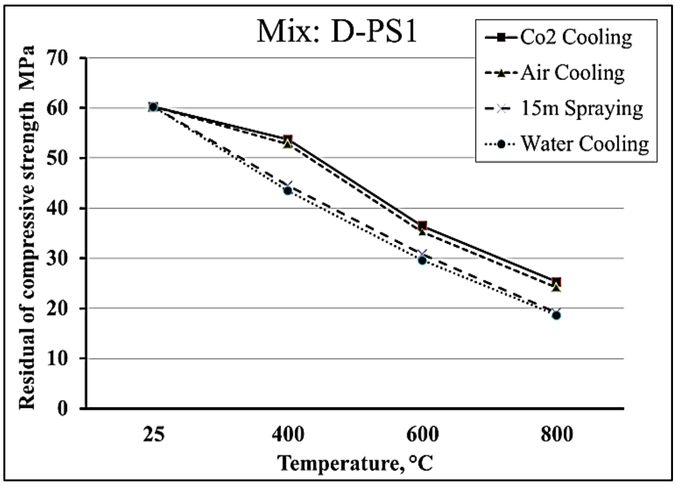
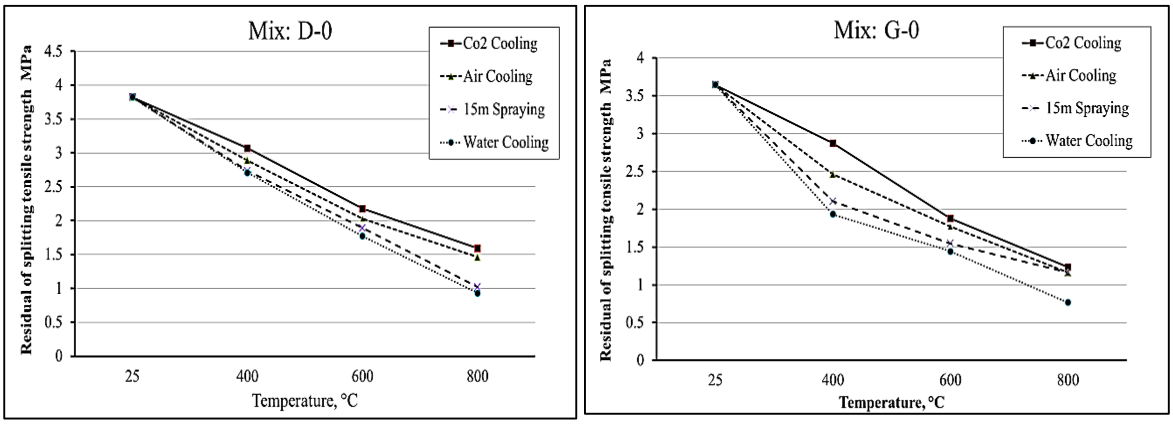


Fig. 13: Residual compressive strength of hybrid fiber mix

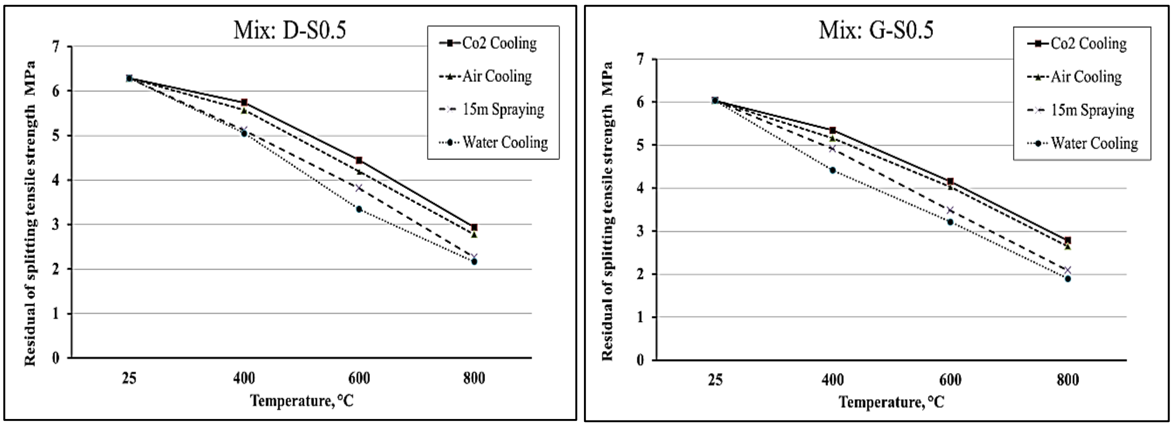
Effect of cooling regimes on residual splitting tensile strength

The results of residual tensile splitting strength of the seven mixes of concrete subjected to various cooling regimes are given from **Figs. 14–17**, respectively. Similar to the results of residual compressive strength, residual tensile strength under CO_2 cooling regime (chemical) was still relatively higher than that under the other cooling regimes at each target temperature. It can be seen that, the residual tensile strength decreases with increasing the degree of temperature for the investigated mixes regardless of the used aggregate type. The percentage of the residual splitting tensile strength of crushed limestone aggregate concrete at different temperatures 400,600,800°C are 6.35% , 13% and 22% for D-0, respectively, which is higher than that of gravel aggregate concrete as shown in **Figs 14 to 17**. Concrete incorporating PP fiber lonely, identified by (D-P0.5), (G-P0.5), suffered a loss in tensile strength more considerably than concrete incorporating steel fiber and hybrid fiber (steel fiber and PP fiber), identified by (D-S0.5), (G-S0.5) and (D-PS1) respectively. It is shown in **Fig.16 (a, b)** that (D-P0.5), (G-P0.5) respectively concrete incorporating PP fiber lonely had a low value of residual tensile strength under 400°C, 600°C and 800°C compared with the results in **Figs.15 and 17** steel fiber and hybrid fiber concrete performed significantly better, characterized by a much slower decrease in tensile strength for temperature increasing from 400 to 800°C, as shown in **Figs. 15(a, b) and 17** respectively. The results in that investigation indicate that steel fiber and hybrid fiber (steel fiber and PP fiber) can enhance fire resistance of FRC in the form of relatively high residual strength, at the mean-time hybrid fiber FRC is still resistant to explosive spalling due to the incorporation of PP fiber, which has been proved in a preceding experimental investigation [22].



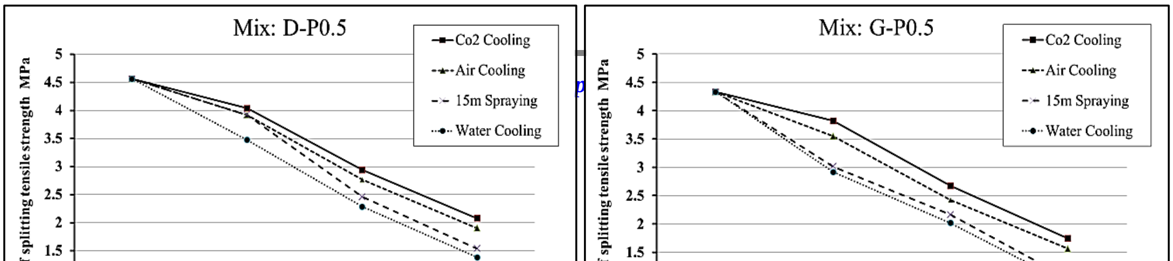
(a) Crushed Limestone **(b) Gravel**

Fig. 14: Residual splitting tensile strength of mixes without fiber



(a) Crushed Limestone **(b) Gravel**

Fig. 15: Residual splitting tensile strength of steel fiber mixes



(a) Crushed Limestone **(b) Gravel**

Fig. 16: Residual splitting tensile strength of polypropylene fiber mixes

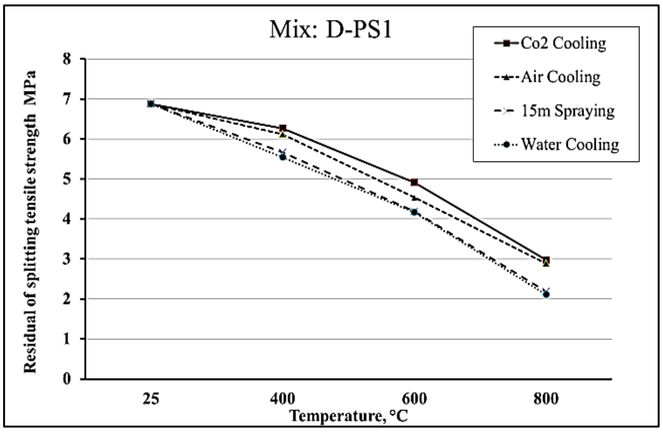
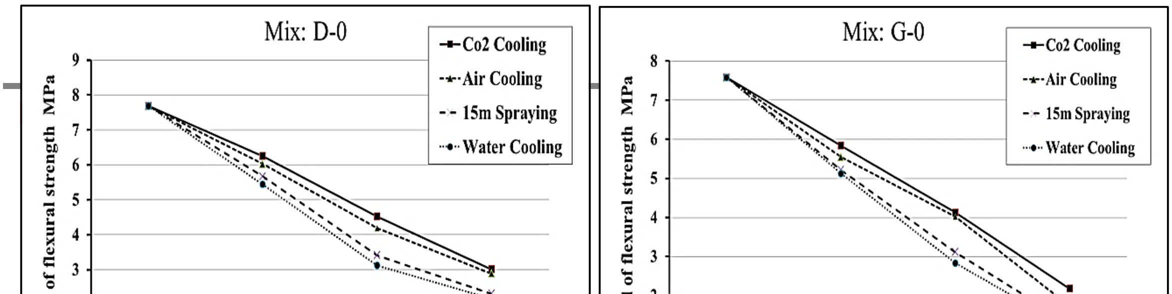


Fig. 17: Residual splitting tensile strength of hybrid fiber mix

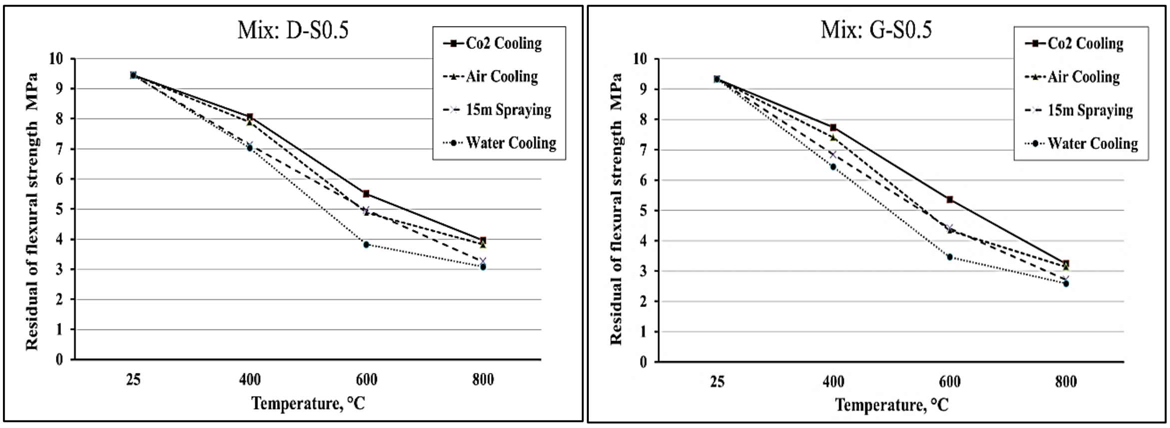
Effect of cooling regimes on residual flexural strength

The results of residual flexural strength of the seven types of concrete subjected to various cooling regimes are given from **Figs.18–21,** respectively. Similar to the results of residual compressive strength, residual flexural strength under CO_2 cooling regime (chemical) was still relatively higher than that under the other cooling regimes at each target temperature. It can be seen that, the residual flexural strength decreases with increasing the degree of temperature for the investigated mixes regardless of the used aggregate type. The percentage of the residual flexural strength of crushed limestone aggregate concrete at different temperatures 400,600,800°C are 6.59%, 8.62% and 27.5% for D-0, respectively, which are higher than that of gravel aggregate concrete as shown in **Figs.18 to 21**. Concrete incorporating PP fiber lonely, identified by (D-P0.5), (G-P0.5), suffered a loss in flexural strength more considerably than concrete incorporating steel fiber and hybrid fiber (steel fiber and PP fiber), identified by (D-S0.5), (G-S0.5) and (D-PS1) respectively. It is shown in **Fig.20(a, b)** that (D-P0.5), (G-P0.5) concrete incorporating PP fiber lonely had a low value of residual flexural strength under 400°C, 600°C and 800°C. Compared with the results in **Fig.19(a, b)**, steel fiber and hybrid fiber concrete performed significantly better, characterized by a much slower decrease in flexural strength for temperature increasing from 400 to 800°C, as shown in **Figs.19(a, b) and 21** respectively .



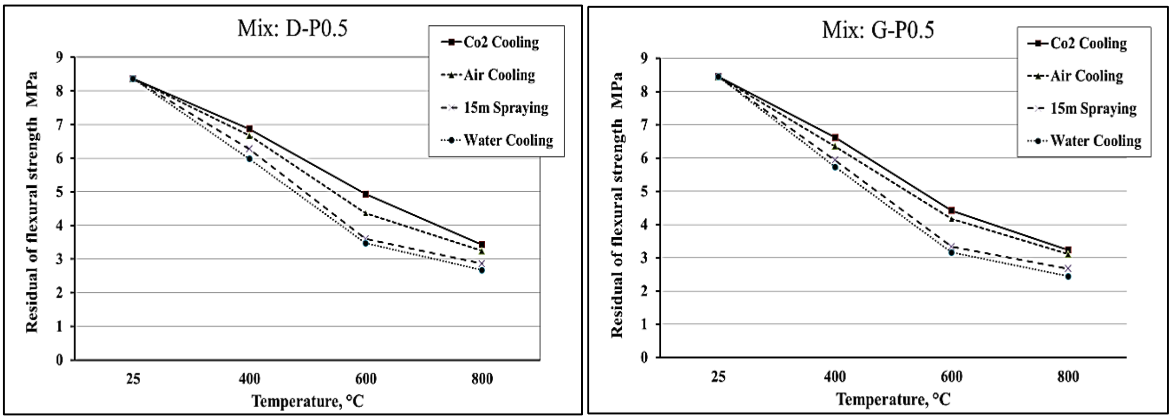
(a) Crushed Limestone **(b) Gravel**

Fig.18: Residual flexural strength mixes without fiber



(a) Crushed Limestone **(b) Gravel**

Fig.19: Residual flexural strength of steel fiber mixes



(a) Crushed Limestone **(b) Gravel**

Fig.20: Residual flexural strength of polypropylene fiber mixes

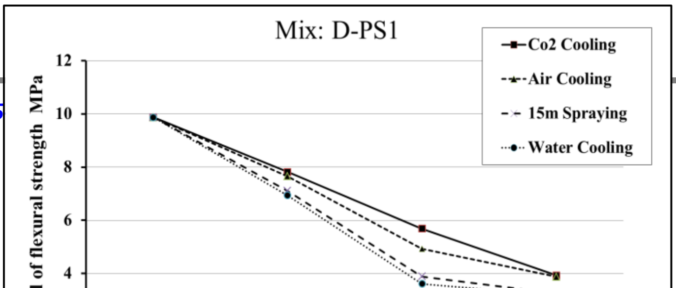


Fig. 21: Residual flexural strength of hybrid fiber mix

CONCLUSIONS

The following conclusions can be drawn from this research program:

1. The experimental results indicate that, cooling regimes significantly influences residual properties of concrete, such as compressive strength, tensile splitting strength, and flexural strength. The impact of spraying water for 15 min or more on mechanical properties was almost the same as that of water quenching, indicates that spraying water for 15 min or more could cause thermal shock to a similar degree to water quenching.
2. For each type of concrete under identical target temperature, among the four cooling regimes, CO_2 powder cooling maintained a relatively higher value of residual compressive strength. The similar results were also obtained on tensile splitting strength and flexural strength.
3. Crushed limestone aggregates provided the highest resistance to fire while gravel aggregate gave the least resistance.
4. The mixtures containing the polypropylene fibers achieved a slight decrease compared to the control mixes.
5. Steel fiber could reduce the deterioration of concrete to an extent. Polypropylene fiber used to prevent spalling of FRC did not lead to a marked degradation in residual strength even if it evaporated at high temperatures. Thermal shock due to rapid cooling caused slightly more of deterioration in strength than in the case of gradual cooling without thermal shock. However, thermal shock did not increase the spalling of FRC.
6. Hybrid fiber (steel fiber and PP fiber) and steel fiber can enhance both residual strength of concrete subjected to thermal shock induced by rapid cooling from elevated temperature up to 800°C.

REFERENCES

1. Swamy R.N., Mangat P.S., and Rao C.V.S.K. (1974), “The Mechanics of Fiber Reinforcement of Cement Matrices “Vol 44, pp. 1-28.
2. Kalifa P., Che´ne G., Galle C. (2001), “High-temperature behaviour of HPC with polypropylene fibers from spalling to microstructure “, Cement and Concrete Research, Vol 31, pp. 1487–1499.
3. Colombo M., Fatemeh. (2016),” Behavior of high performance fiber reinforced concrete beam exposed to fire” M.Sc. Thesis, Master of science in civil engineering for risk mitigation.
4. Luo X., Sun W., Chan S.Y. (2000), “Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high-performance concrete “, Cement and Concrete Research, Vol 30, pp. 379–383.

5. Abdelalim A.M.K., Abdel-Aziz G.A., El-Mohr M.A.K., Salama G.A. (2009). “ Effect of Aggregate Type on The Fire Resistance of Normal and Self-Compacting Concretes”, Engineering Research Journal, Vol 122, pp. 47–62.
6. Yan X., Li H., Wong Y.L. (2007), “Effect of aggregate on high-strength concrete in Fire”, Magazine of Concrete Research, Vol 59, pp. 323–328.
7. Nassif A.Y., Burley E., Rigden S. (1995) “A new quantitative damage to concrete method of assessing fire structures” Magazine of Concrete Research, Vol 47, pp. 271–278.
8. Hager I., Tracz T., Śliwiński J., Krzemień K. (2015), “The influence of aggregate type on the physical and mechanical properties of high-performance concrete subjected to high temperature”, Fire and Materials.
9. Savva A., Manita P., Sideris K.K. (2005), “Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates” Cement & Concrete Composites, Vol 27, pp. 239-248.
10. Xing Z., Beaucour A.L., Hebert R., Noumowe A., Ledesert B. “Influence of the nature of aggregates on the behaviour of concrete subjected to elevated temperature” Cement and Concrete Research, Vol 41, pp. 392-402.
11. Afroughsabet V., Biolzi L., and Ozbakkaloglu T. (2016) “High-performance fiber-reinforced concrete: a review” J Mater Sci.
12. Varona F.B., Baeza F.G., Bru D., Ivorra S. (2018), " Evolution of the bond strength between reinforcing steel and fiber reinforced concrete after high temperature exposure”, Construction and Building Materials, Vol 176, pp. 359–370.
13. Gyorgy L., Bala z.s., Lublo y. (2012), “Post-heating strength of fiber-reinforced concretes”, Fire Safety Journal, Vol 49, pp. 100–106.
14. Poon C.S., Shui Z.H., Lam L., Morillas L. (2004), “Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures”, Cement and Concrete Research, Vol 34, pp. 2215–2222.
15. Sideris K.K., Manita P., Chaniotakis E. (2009), “Performance of thermally damaged fiber reinforced concretes”, Construction and Building Materials, Vol 23, pp. 1232–1239.
16. Varghese A., Anand.N. (2016) “Role of fiber on fire endurance of concrete – A literature review”, international journal of innovative research in science and engineering, Vol 2.
17. Kalifa P., Che´ne G., Galle C. (2001), “High-temperature behaviour of HPC with polypropylene fibers from spalling to microstructure”, Cement and Concrete Research, Vol 31, pp. 1487–1499.
18. Phan L.T., Lawson J.R., Davis F.L. (2001), “Effects of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete”, Materials and Structures, Vol. 34, pp. 83–91.
19. Xiangjun D., Yining D., Tianfeng W. (2008), “Spalling and Mechanical Properties of Fiber Reinforced High-performance Concrete Subjected to Fire”, Journal of Wuhan University of Technology-Mater.
20. Haddad R.H., Al-Saleh R.G., Al-Akhras N.M. (2008), “Effect of elevated temperature on bond between steel reinforcement and fiber reinforced concrete”, Fire Safety Journal, Vol. 43, pp. 334–343.
21. Govindarajan S., Muthuramu K.L., (2015) “Improving properties of concrete by fiber reinforced polymers”, Journal of Structural Engineering, Vol. 41, No. 6, pp. 570-574.
22. Bangi M.R., and Takashi, (2011) “Pore pressure development in hybrid fiber-reinforced high strength concrete at elevated temperatures”, Cement and Concrete research , Vol.41, pp. 1150-1156.
23. Al Quadi N.S., Arabi and Al-Zaidyeen M., Sleiman. (2014) “Effect of fiber content and specimen shape on residual strength of polypropylene fiber self – compacting concrete exposed to elevated temperatures”, Journal of King Saud University – Engineering Sciences, Vol.26, pp. 33-39.
24. Benhood A., and Ghandehari M. (2009) “Comparison of compressive and splitting tensile strength of high strength concrete with and without polypropylene fibers heated to high temperatures”, Fire Safety Journal Vol.44, pp. 1015-1022.
25. Husem M. (2006), “The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete”, Fire Safety Journal, Vol 41, pp. 155

26. Chan S.Y.N., Luo X., Sun W. (2000), “Effect of high temperature and cooling regimes on the compressive strength and pore properties of high performance concrete”, Construction and Building Materials, Vol.14, pp. 261–266.
27. Lau A., Anson M. (2006), “Effect of high temperatures on high performance steel fiber reinforced concrete”, Cement and Concrete Research, Vol. 36, pp. 1698–1707.
28. Peng G.F., Bian S.H., Qi Guo Z., Zhao J. (2008), “Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures”, Construction and Building Materials, Vol. 22, pp. 948–955.
29. Abdelalim A.M.K., Abdel-Aziz G.E., El-Mohr M.A.K., Salama G.A. (2012), “Effect of Elevated Fire Temperature and Cooling Regime on The Fire Resistance of Normal and Self-Compacting Concretes", Engineering Research Journal, Vol.122, pp. 63–81.