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Effect of Cooling Method on Residual Properties of Sustainable Fiber Reinforced SCC Exposed to Elevated Temperature

[1]Shakir Almashhadani, [2]Faiq Al-Zwainy and [3]Mohammed Aldikheeli
[1]Department of Building and Construction Engineering, University of Technology, Baghdad, Iraq
[2]Department of Civil Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq
[3]Department of Structures and Water Resources, College of Engineering, Kufa University, Najaf, Iraq

Abstract: The current research presents an experimental investigation on the influence of cooling regime on the residual mechanical properties and cracking development of fiber reinforced eco-Friendly Self-Consolidating Concrete (FSCC). Seven Sustainable (FSCC) mixes containing high volume class F fly ash and locally available Cement Kiln Dust (CKD) were subjected to four high temperature degrees (200, 400, 600 and 800°C) for 2 h. After that, the specimens were cooled either slowly (air cooling) or quickly (water spraying cooling) and the residual compressive strength, flexural strength, modulus of elasticity, Ultrasonic Pulse Velocity (UPV), mass loss and both color change and cracks development were determined. The results indicated, for both cooling techniques, that FSCC with high volume class F fly ash showed best residual mechanical properties when exposed to elevated temperature compared to other mixes. At 800°C, the relative residual compressive strength, flexural strength and modulus of elasticity were 62, 65, 71, 51, 53, 60, 29, 32, 33, 24, 26, 28, 31, 32, 34, 23, 24, 25% for 40, 50, 60% fly ah mixes air and water cooled, respectively. Visual examination of the specimens showed that the color is gradually lightened as the temperature exposure increases and the cracks developed more severely, especially in water cooled pure and cement kiln dust FSCC mixes while in fly ash FSCC mixes smaller network minor surface cracks is observed. At 400°C air cooled fly ash FSCC mixes are classified as good quality mix while other mixes were doubtful based on (UPV). The weight loss is congruent with the residual mechanical properties and the visual inspection of the studied FSCC mixes.

Key words: Eco-friendly, fiber reinforced (FSCC), elevated temperature, UPV, class F fly ash, high volume

INTRODUCTION

The study of "green", "sustainable" or "eco-efficient" concrete has advanced rising attention among the major contemporary publications about concrete because the affairs concerning the industrial wastes recycling, durability of concrete, environment and the cost will place a pressure on the employment of waste materials (Kraus *et al*., 2009). Self-Consolidating Concrete (SCC) is a significant advance in the concrete technology and it is widely used in the world and among the most important users, the power, nuclear, gas and oil industries. Because their greater structural performance, ecological kindliness and energy-conserving effects, the uses of such concretes are increasing day by day (Sahmaran *et al*., 2011). One of the extreme circumstance that concrete may be faced during its service life is the exposure to elevated temperature such as in fire events (Ulm *et al*., 1999). This exposure may be compulsorily such as in the abovementioned industries or this exposure took place unexpectedly such as in buildings or tunnels due to human mistakes or terrorist attacks (Lau, 2003). There are several studies on the effect of elevated temperature on mechanical and different characteristics of concrete. Siddique and Kaur (2012) studied the residual mechanical characteristics and mass loss of normal strength concrete mix (35 MPa) containing 100% ordinary Portland cement and three other mixes containing (20, 40 and 60%) replacement level of Ground Granulated Blast Furnace Slag (GGBFS). These mixes were exposed to temperature level up to 350°C and air cooled. Their results indicated that the magnitudes of residual compressive strength, splitting tensile strength and modulus of elasticity for (GGBFS) were reduced 40% lower than the concrete at room temperature. The weight loss is not very important at temperature between 200 and 350°C. Morsy *et al*. (2012) investigated the impact of elevated temperature on performance of mortars containing 5% nano-metakaolin. They found that up to 250°C for air cooled specimens, there was an increment in the

Corresponding Author: Mohammed Aldikheeli, Department of Structures and Water Resources, College of Engineering, Kufa University, Najaf, Iraq

compressive and flexural strengths and then drops as the exposure temperature increases up to 800°C. They concluded that the happening of micro and macrocracks in mortars because of elevated temperatures may be the reason of this reduction. Toumi *et al*. (2012) performed a series of tests to investigate the residual compressive and flexural strengths of normal and high strength concretes subjected to elevated temperatures ranging from 300-700°C for a heating intervals between 1 and 9 h. They concluded that for 1 h exposure period and at 300°C there was an increment in residual compressive strength. Opposing the residual compressive strength, the residual flexural strength of high strength concrete declines continuously under elevated temperatures. At room temperature, the use of fibers enhances concrete possibilities, since, fibers arrest cracks and retard their propagation. At high temperature, the toughness of concrete can be improved clearly by using Steel Fiber (SF) and Polypropylene (PP) fiber can reduce the spalling (Chen and Liu, 2004).

Research significance: While several researches regarding the durability and mechanical properties of Self-Consolidating Concrete (SCC) have been studied, the fire resistance of this type of concrete have somewhat received a limited attention, especially, the sustainable SCC (as the construction industry is moving fast towards sustainability). So, there is a need to recognize its behavior when subjected to elevated temperatures particularly that self-consolidating concrete comprises different types of filler materials so different performances are expected. In actual fire events, fire is extinguished by water spraying which is clearly differ from natural cooling regime (air cooling) that is used in most researches to obtain the information about the residual strength. Therefore, studying the impact of different cooling methods on the performance of concrete is of a great importance to suitable assessment the residual strength.

MATERIALS AND METHODS

Materials and experimental program

Materials characteristics

Cement: Local Portland-Lime stone Cement (PLC) Karasta CEM II/A-L 42.5 R was used. It complies with European Standard EN 197-1 (2000) and Iraqi Industrial License No. 3868. The physical and chemical characteristics of cement used in this study are presented in Table 1 (Anonymous, 2000).

Aggregates: As fine aggregate natural sand was used in this research. It has a fineness modulus of 2.5 and within the grading zone 3. A crushed gravel with a maximum size of 20 mm was used as a coarse aggregate. Both types of aggregate were conformed to the Iraqi Specification (1984), No. 45/1984 (Anonymous, 2002a, b).

Chemical admixture: GLENIUM 54 was used in this study as a "High Range Water Reducing Admixture" (HRWRA). It complies with ASTM C494 (2005) (Anonymous, 2005a, b).

Fly ash: Fly ash used in present study was obtained from Turkey. The physical and chemical properties of fly ash are tabulated in Table 2. It can be seen from Table 2, that the fly ash used is considered as class F fly ash as per ASTM C618 (2005).

Cement kiln dust: Cement Kiln Dust (CKD) is a by-product of cement production. Table 2 indicates the

Table 1: Chemical and Physical Characteristics of (PLC) used[a]

Oxides or property	PLC test results	Requirement of EN 197-1	Requirement of Iraqi Industrial License No. 3868
SiO_2	18.8	-	-
Al_2O_3	4.8	-	-
Fe_2O_3	2.7	-	-
CaO	61.9	-	-
MgO	2.5	-	≤5.0%
SO_3	2.6	≤4.0%	≤2.5% if C_3A <5% ≤2.8% if C_3A more than 5%
Na_2O	0.2	-	-
K_2O	1.1	-	-
$(Na_2O)eq$	0.92	-	-
L.O.I	4.5	-	-
Fineness (m^2/kg)	390	-	-
Initial setting time (min)	128	≥60.0	≥45.0
Final setting time (h)	3.3	-	-
2 days compressive strength (MPa)	23	≥20.0	≥20.0
28 days compressive strength (MPa)	49	≥42.5	≥42.5

[a]Chemical analysis and physical properties were carried out in the laboratory of Al-Kufa Cement Mill

Table 2: Chemical analysis and physical properties of the fly ash and cement kiln dust

Oxides or property	Fly ash	Cement kiln dust	ASTM C618 (2005) class F requirement
SiO_2	50.5	16.7	$SiO_2+Al_2O_3+Fe_2O_3>70$
Al_2O_3	22.7	4.5	
Fe_2O_3	9.3	2.0	
CaO	10.8	44.5	
MgO	1.2	1.3	-
Na_2O	1.0	0.3	-
K_2O	0.8	3.7	-
TiO_2	0.7	-	-
SO_3	1.5	5.5	5.0 max
Loss on ignition	1.2	20.0	6.0 max
Specific gravity	2.12	-	-
Specific surface area (m^2/kg)	420	565	-

Table 3: Mix proportions of the concrete mixes

	Mixture proportions (kg/m^3)							
Mix ID	Cement	Fly ash	Cement kiln dust	Water	Sand	Gravel	W/P[a]	Sp[b]
REFF	500	-	-	180	800	800	0.36	0.80
40 FAF	300	200	-	180	800	800	0.36	0.70
50 FAF	250	250	-	180	800	800	0.36	0.60
60 FAF	200	300	-	180	800	800	0.36	0.55
20 CKDF	400	-	100	180	800	800	0.36	0.90
30 CKDF	350	-	150	180	800	800	0.36	1.10
50 BF	250	150	100	180	800	800	0.36	0.90

[a]W/P: Water/Powder: water/(cement+FA+CKD); [b]Sp: Superplasticizer: (L/100 kg cementitious material)

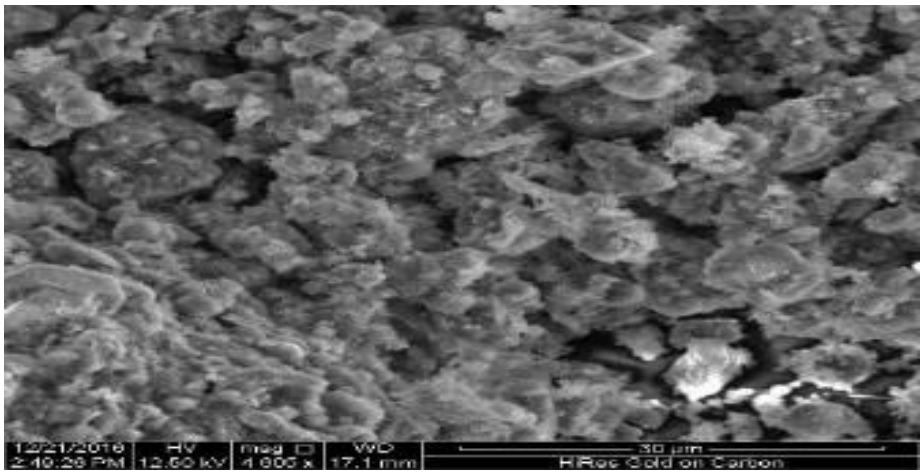

Fig. 1: SEM for CKD used

chemical composition and Fig. 1 shows the scanning Electron Microscopy (SEM) of the cement kiln dust used in this research.

Polypropylene fiber: Monofilament polypropylene fibers were used in this research. It was provided from market and it is commercially known "RHEOFIBRE".

Experimental program

Mix proportions: Because of SCC mixes highly reliant on the properties and the composition of its ingredients, it can be considered a delicate mix. Two disagreeing properties should be found in each SCC mix and these are the high flow-ability and the high segregation resistance. In the present research the reference FSCC mix (REFF) was designed according to Okamura and Ouchi (2003) taking into account the recommendations of the EFNARC (2002) and Anonymous (2007). Table 3 shows the mixture proportions of the mixes. Since, the amount of polypropylene fiber greatly affected the fresh properties of self-consolidating concrete, many trials were conducted to select the best volume fraction of fiber (V_f) and it was 0.15%. This volume fraction is within the recommended quantity by El-Dieb and Taha (2012).

Mixing sequence and samples preparation: In this study, drum type mixer of 0.1 m^3 capacity was used to mix the concrete ingredients. The dry constituents of concrete mixes were placed in the mixer such that the cement or (cement plus powder materials) is placed between two layers of sand followed by two layers of gravel, this prevents spillage of cement in air, the dry materials were well mixed for about 3 min to attain uniform mix. Then, about 80% of the required quantity of tap water was added and mixed thoroughly for another 3 min. Finally, the HRWR diluted with the residual mixing water was then presented through 30 sec and the concrete was mixed for 2.5 min (Le and Ludwig, 2016). In the end, the fibers were distributed by hand in the mixture to reach a regular scattering throughout the concrete, then mixture was mixed for 2 min. The concrete remained at rest in the mixer for one minute to enable any large air bubbles entrapped during mixing to rise to the surface, the concrete was then remixed for one minute (Long *et al*., 2014). After the end of mixing the concrete was cast in the molds without any vibration and immediately covered with wet burlap and plastic wrap and remained undisturbed for 24 h. in laboratory conditions. After 24 h, specimens were removed from the molds and placed in curing tank up to 28 days, then they removed form curing tank and cured in air in the lab conditions until 91 days.

Heating and cooling procedure: At the age of 91 days, specimens were put in the manufactured electrical furnace which has a capacity of 1200°C (the temperature inside the furnace was at the room temperature at the time of putting the specimens) then heat was applied at a rate of 5°C/min up to the chosen temperature was gotten. In addition, to room temperature four temperature degrees were investigated (200, 400, 600 and 800°C). After reaching the target temperature, the specimens were remained at this temperature for 2 h as shown in Fig. 2. To ensure that, the specimens were reached to the maximum temperature two type "K" thermocouples were placed at the surface of the specimens and the temperature was read by using a digital "ELE" thermometer as shown in Fig. 3. After that, the furnace was turned off and the specimens were slowly cooled inside the furnace for air cooling method. In case of water cooling, after two hours of reaching the peak temperature the furnace was switched off, the specimens was directly taken out and water was sprayed over the heated specimens till the specimens were cooled completely.

Test procedure

Tests on fresh FSCC: To calculate and evaluate the fresh features of SCC there are several test methods that had been developed around the world. Among these test methods there is no single test that can be used alone to assess all of the main parameters, so, a combination of tests is necessary to totally describe a SCC mix. In this work the three main characteristics of SCC which named (Filling ability, passing ability and Resistance to segregation) were performed according to the methods mentioned by EFNARC (2002) and Anonymous (2007).

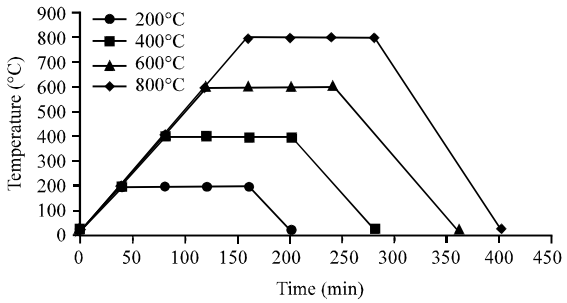

Fig. 2: Heating cycles imposed

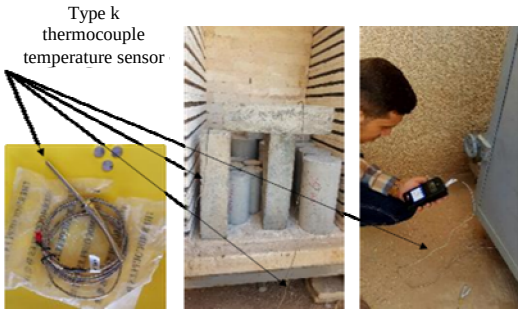

Fig. 3: Measuring the specimen temperature by using ELE thermometer

Tests on hardened FSCC

Compressive strength test: Concrete compressive strength test was performed according to the BS EN 12390-3 (2002) on 100 mm cubes by using ELE digital compression machine of 2000 kN.

Flexural strength test: The 100×100×400 mm concrete prisms were used for conducting flexural strength test (Modulus of Rupture) (MOR) according to ASTM C78 (2002). The flexural strength was determined using a (30000 kg) capacity testing machine. The test was carried out using two points load.

Ultrasonic pulse velocity test: For public security the destruction evaluation is required when a concrete structure exposed to fire. For evaluating the deterioration of concrete due to fire there are various ways available and one of them Ultrasonic Pulse Velocity (UPV). This

test was performed on 100 mm cubes that is used for compressive strength test in accordance with the standards ASTM C78 (2002) by using a PUNDIT (Portable Ultrasonic Nondestructive Digital Indicating Tester).

Weight loss: Loss of weight occurs to the concrete specimens that subjected to elevated temperatures. In the present research, the commonly approach was followed using an electronic numerical weighing scale with an accuracy of ±1 g and the following equation was used to calculate the loss of weight:

$$\text{Weight loss\%} = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where, W_1 and W_2 are the average weight of three cubes before and after heating, respectively.

Visual inspection: A close examination of the heated specimens was done for probable color changes and the propagation of surface cracks as it is the first step in evaluating the damage of concrete due to fire.

RESULTS AND DISCUSSION

Fresh properties: Table 4 presents the fresh properties namely (filling ability, passing ability and segregation resistance) of the studied mixes accompanied by the acceptable criteria proposed by EFNARC (2002) and Anonymous (2007).

The fresh properties of CKDF mixes were lower than that of FAF and REFF mixes and it reduced as CKD replacement increase. This reduction in fresh properties may be imputed to absorbing mixing water by CKD due to the free lime that found in CKD which rapidly reacts with water in addition to the higher fineness of CKD (Siddique and Rajor, 2014). The binary mix (50BF) which contain CKD together with FA showed better fresh properties than mixes with CKD alone. This may be due to spherical shape of FA particles which induces a ball bearing effect so the poor filling and passing abilities of CKD can be overcome by the incorporation of FA together with CKD to make binary system. The presence of polypropylene fiber cause a reduction in fresh properties and this may be due to the increase of friction between aggregates and the fibers throughout the matrix and due to fiber tangling that made its dispersion is difficult in addition to that fibers tend to cause fiber-aggregate interlock that resisted the aggregate movement which reduces the filling ability.

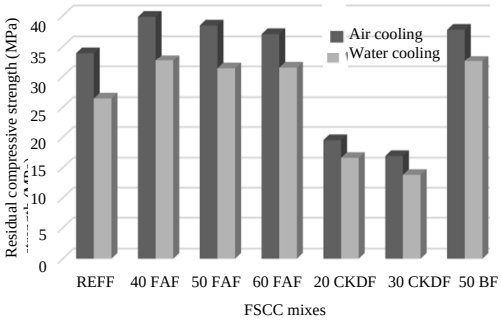

Fig. 4: Effect of cooling method on residual compressive strength for all FSCC mixes exposed to 800°C

Hardened properties at elevated temperature

Residual compressive strength: The results of remaining compressive strength after exposed to various temperature levels and for both cooling methods were shown in Fig. 4 and Table 5. At 200°C the specimens that were air cooled had been gain some strength at this temperature. This improvement in strength at 200°C is imputed to the pathways formed by the melting of the PP fibers at (165-170)°C, so, the water vapour will escape freely through the pores and getting out the surface. Another reason for this strength gain for REFF mix may be due to gradual movement of moisture from mortar at early stage of heating leads to remain some moisture in it that will permit for the hydration of the unhydrated cement particles (especially with the high amount used) to be accelerated, so, additional hydration products will be formed. The scenario is different in specimens that were water cooled. Where no such increment in remaining compressive strength is detected at 200°C. The relative residual strength for water cooled specimens were between (88-94, 71-83, 61-72 and 38-60%) for 200, 400C, 600 and 800°C, respectively. The 30 CKDF mix had the lower limit from the aforementioned percentages and it was the worst while 60 FAF mix had the superior performance and it has the higher limit. Thermal shock may be one of the reasons that justify the drop in compressive strength when the specimens rapidly cooled from high temperature compared to slowly cooled specimens. Thermal shock is happened by abrupt variation in temperature due to spraying of water on heated concrete specimens and it may encourage tensile stress in the specimens, so, the cracks may be developed which result in a considerable reduction in compressive strength. The important merit of the results at 800°C is the higher relative residual strength for all FAF mixes compared to REFF and CKDF mixes and it was (62, 65 and 71%) for 40, 50 and 60 FAF air cooled mixes, respectively. This result was in agreement with Aydin and Baradan

Table 4: Fresh properties of FSCC mixes

	Filling ability		Passing ability (J-ring test)			
Mix ID	Slump flow (d_s) mm	Spread time (T_{50}) S	Differences in heights (mm)	Flow (d_j)	(d_s-d_j)	Segregation resistance (%)
REFF	620	4.0	6.1	600	20	5.1
40 FAF	655	3.5	5.5	638	17	3.4
50 FAF	671	3.0	5.0	655	16	3.0
60 FAF	682	3.0	4.7	668	14	2.5
20 CKDF	596	4.4	7.0	572	24	2.0
30 CKDF	583	5.0	7.7	548	35	1.8
50 BF	625	4.0	6.0	603	22	2.7
Acceptance criteria of SCC suggested by ACI 237	450-760	2-5	-		0-25	0-10

Table 5: Residual compressive strength of FSCC mixes

		Residual compressive strength (MPa)*				
		Exposed temperature (°C)				
Mix ID	Types of cooling	27	200	400	600	800
REFF	Air	68.7 (100)	75.1 (109.3)	56.0 (81.5)	46.7 (68.1)	33.9 (49.4)
	Water	-	61.3 (89.2)	53.7 (78.1)	39.6 (57.7)	26.4 (38.5)
40 FAF	Air	64.2 (100)	71.6 (111.5)	54.5 (85)	46.9 (73.1)	39.8 (62)
	Water	-	58.4 (91)	50.8 (79.1)	41.6 (64.8)	32.6 (50.8)
50 FAF	Air	58.8 (100)	68.3 (116.1)	52.4 (89.2)	45.8 (78.0)	38.4 (65.3)
	Water	-	54.4 (92.5)	47.2 (80.2)	39.7 (67.6)	31.3 (53.2)
60 FAF	Air	52.3 (100)	64.8 (124)	48.5 (92.7)	42.1 (80.5)	37.0 (70.8)
	Water	-	49.3 (94.3)	43.5 (83.1)	37.5 (71.8)	31.4 (60.2)
20 CKDF	Air	39.7 (100)	43.0 (108.3)	31.3 (78.8)	26.6 (67)	19.5 (49.1)
	Water	-	35.5 (89.4)	29.1 (73.3)	25.4 (64.1)	16.6 (41.8)
30 CKDF	Air	36.0 (100)	38.5 (107.0)	26.5 (73.6)	23.3 (64.8)	16.9 (47.0)
	Water	-	31.6 (87.8)	25.4 (70.6)	21.9 (61.0)	13.8 (38.4)
50 BF	Air	67.4 (100)	75.2 (111.5)	56.4 (83.7)	48.6 (72.1)	37.7 (56.0)
	Water	-	60.8 (90.2)	51.0 (75.7)	44.1 (65.5)	32.5 (48.2)

*The magnitudes in parentheses represent the relative increase or decrease in residual compressive strength as compared to room temperature (27°C)

Table 6: Residual flexural strength of FSCC mixes

		Residual flexural strength (MPa)*				
		Exposed temperature (°C)				
Mix ID	Types of cooling	27	200	400	600	800
REFF	Air	8.74 (100)	5.85 (67.0)	4.48 (51.3)	3.36 (38.4)	2.36 (27.0)
	Water	-	5.43 (62.2)	3.97 (45.5)	2.95 (33.8)	1.90 (21.8)
40 FAF	Air	8.30 (100)	5.72 (69.0)	4.33 (52.2)	3.44 (41.4)	2.42 (29.2)
	Water	-	5.29 (63.8)	4.16 (50.2)	2.77 (33.4)	2.00 (24.0)
50 FAF	Air	7.62 (100)	5.48 (72.0)	4.26 (56.0)	3.31 (43.4)	2.40 (31.5)
	Water	-	4.96 (65.1)	3.92 (51.4)	2.72 (35.7)	1.94 (25.5)
60 FAF	Air	7.40 (100)	5.43 (73.4)	4.47 (60.4)	3.35 (45.2)	2.47 (33.4)
	Water	-	4.94 (66.8)	3.95 (53.4)	2.66 (36.0)	2.07 (28.0)
20 CKDF	Air	6.48 (100)	4.16 (64.2)	3.20 (49.4)	2.30 (35.5)	1.54 (23.8)
	Water	-	3.71 (57.3)	2.88 (44.4)	2.04 (31.5)	1.37 (21.1)
30 CKDF	Air	5.63 (100)	3.44 (61.2)	2.55 (45.3)	1.89 (33.6)	1.18 (20.9)
	Water	-	3.02 (53.6)	2.30 (41.0)	1.73 (30.8)	1.03 (18.3)
50 BF	Air	8.48 (100)	5.72 (67.5)	4.34 (51.2)	3.33 (39.3)	2.28 (26.8)
	Water	-	5.25 (62.0)	4.15 (49.0)	2.71 (32.0)	1.86 (22.0)

*The magnitudes in parentheses represent the relative decrease in residual flexural strength as compared to room temperature (27°C)

(2007) where they used X-ray analyses to examine the microstructure of cement paste incorporating fly ash, they discovered that at 800°C, gehlenite creation was detected alongside quartz, feldspar and calcite and this indicates that when the temperature has been raised up to 800°C, glassy phases that are molten appear. This molten phase fills in the pores and compressive strength of mortar increases after the mortar become cold.

Residual flexural strength: The results of flexural strength after exposure to elevated temperature were presented in Table 6 and Fig. 5. At room temperature polypropylene fibers improve the flexural strength of SCC mixes in better manner than the improvement of the compressive strength where once the concrete starts cracking, fiber starts to transmit the force. The main feature of these results was the sharp drop in flexural

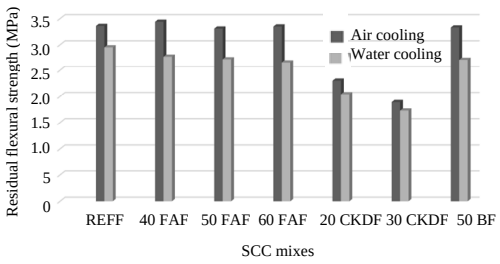

Fig. 5: Effect of cooling method on residual flexural strength for all FSCC mixes exposed to 600°C

strength when exposed to elevated temperature and this indicates that the flexural strength is more critical than compressive strength when concrete exposed to fire. At 200°C, The relative residual flexural strength was (67, 69, 72, 73, 64, 61 and 68%) for REFF, 40, 50, 60 FAF, 20, 30 CKDF and 50 BF air cooled mixes respectively. Further reduction in flexural strength occurred at 400°C and the relative residual flexural strength was (51, 52, 56, 60, 49, 45 and 51%) for abovementioned mixes, respectively.

At 800°C, the main features of this part of the results are that even though exposure to 800°C, the residual flexural strength of all fly ash FSCC mixes was still superior to other mixes. The 60 FAF SCC mix exhibited the highest relative residual flexural strength and it was (33.5%). Aydin and Baradan (2007) used X-ray analyses and detected "gehlenite" which was one of the chief ceramic mineral in cement paste incorporating fly ash. Moreover, it is recognized that at elevated temperatures (about 800°C) the collapse happened to the hydraulic binding and a ceramic binding occurred instead and this accompanied with an increment in remaining strength. So, ceramic form microstructure will be developed with greater bond between cement paste and aggregate "ITZ" at this temperature and this is the reason for the greater performance of FA mixtures at this temperature level. It could be seen from Table 6 and Fig. 5, that all specimens exposed to elevated temperature and water cooled exhibits lower relative residual flexural strength compared to air cooled specimens. The percentage of reduction in flexural strength of water cooled specimens compared to air cooled specimens was between (7-12), (4-11.5), (11-21) and (11-19.5)% at 200, 400, 600 and 800°C, respectively. The thermal shock due to rapid cooling in water is not the only reason for cracking but also the conversion of Calcium Hydroxide ($Ca(OH)_2$) to quick lime (CaO) by driven water off at temperature about 550°C as shown in Eq. 2 and 3:

$$Ca(OH)_2 \xrightarrow{\Delta \text{ about } 550^\circ C} CaO + H_2O \quad (2)$$

$$CaO + H_2O \xrightarrow{\text{Cooling after fire exposure}} Ca(OH)_2 \quad (3)$$

The fly ash FSCC mixes have the higher relative residual flexural strength compared to other mixes. The lower reduction in flexural strength for fly ash SCC mixes is due to the presence of FA and especially with high amount will reduce the tendency to cracking by its reaction with ($Ca(OH)_2$) where the main reason of cracks at 600°C is the decomposition of ($Ca(OH)_2$) into (CaO) and if this calcium oxide is become in contact with water during water cooling it will transform into ($Ca(OH)_2$) with approximately (44%) increase in volume and this volume increment will cause the cracks so the pozzolanic reaction will consume higher amount of ($Ca(OH)_2$) and thus reduce the cracking.

Residual Ultrasonic Pulse Velocity (UPV): The concrete density and elasticity considered the main factors that affect the speed of pulse propagation. Demirboga *et al.* (2004) reported that concrete quality can be categorized according to (UPV) magnitude into excellent, good, doubtful, poor and very poor when the ultrasonic pulse velocity value (m/sec)>4500, 4500-3500, 3500-300, 3000-2000 and <2000, respectively.

Table 7 and Fig. 6 present the test results of residual ultrasonic pulse velocity. For air cooled specimens at 200°C, the higher relative residual ultrasonic pulse velocity was happened in FAF SCC mixes and it was about 92% compared to (86 and 81%) for 20 and 30 CKDF, respectively and this may be due to dense microstructure of FA mixes at this temperature. All FSCC mixes showed good quality class at 200°C. At 400°C, severe drop in ultrasonic pulse velocity was occurred as shown in Fig. 6 and the relative residual ultrasonic pulse velocity was between (67-77%). At this temperature level FAF SCC mixes were classified as good quality mix while other mixes were doubtful. At 600°C as the cracks become more serious and the pores become coarser, more reduction in ultrasonic pulse velocity was expected and the relative residual ultrasonic pulse velocity was between (52-66%). At 800°C, the pore structure changed into loose structure (less densification) due to decomposition of all hydration products so the travel time of the pulse increased and subsequently the pulse velocity decreased. The relative residual ultrasonic pulse velocity was between (31-50%). Finally, the reduction in ultrasonic pulse velocity with increasing temperature is a precise measure of the cracks growth in concrete as a result of elevated temperature. For water cooled specimens (Fig. 6) the ultrasonic pulse velocity was lower than that of air cooled specimens and the drop was more sharply and this may be due to thermal shock and volume changes that will lead to more and more

Table 7: Residual ultrasonic pulse velocity of FSCC mixes

		Residual ultrasonic pulse velocity (m/sec)*				
		Exposed temperature (°C)				
Mix ID	Types of cooling	27	200	400	600	800
REFF	Air	4680 (100)	4170 (89.1)	3260 (69.6)	2800 (59.8)	1850 (39.5)
	Water	-	4010 (85.6)	3100 (66.2)	2650 (56.6)	1710 (36.5)
40 FAF	Air	4785 (100)	4420 (92.3)	3670 (76.7)	3150 (65.8)	2410 (50.3)
	Water	-	4325 (90.3)	3600 (75.2)	3000 (62.7)	2200 (45.9)
50 FAF	Air	4640 (100)	4290 (92.4)	3590 (77.3)	2980 (64.2)	2220 (47.8)
	Water	-	4215 (90.8)	3470 (74.7)	2800 (60.3)	2100 (45.2)
60 FAF	Air	4600 (100)	4200 (91.3)	3500 (76.1)	2880 (62.6)	2100 (45.6)
	Water	-	4112 (89.3)	3370 (73.2)	2750 (59.7)	2000 (43.4)
20 CKDF	Air	4520 (100)	3885 (85.9)	3140 (69.5)	2520 (55.7)	1540 (34.0)
	Water	-	3630 (80.3)	2960 (65.4)	2370 (52.4)	1310 (28.9)
30 CKDF	Air	4500 (100)	3640 (80.8)	3010 (66.8)	2330 (51.7)	1380 (30.6)
	Water	-	3570 (79.3)	2860 (63.5)	2180 (48.4)	1110 (24.6)
50 BF	Air	4618 (100)	4220 (91.3)	3280 (71.0)	2750 (59.5)	1780 (38.5)
	Water	-	4150 (89.8)	3120 (67.5)	2600 (56.3)	1660 (35.9)

•The magnitudes in parentheses represent the relative decrease in ultrasonic pulse velocity as compared to room temperature (27°C)

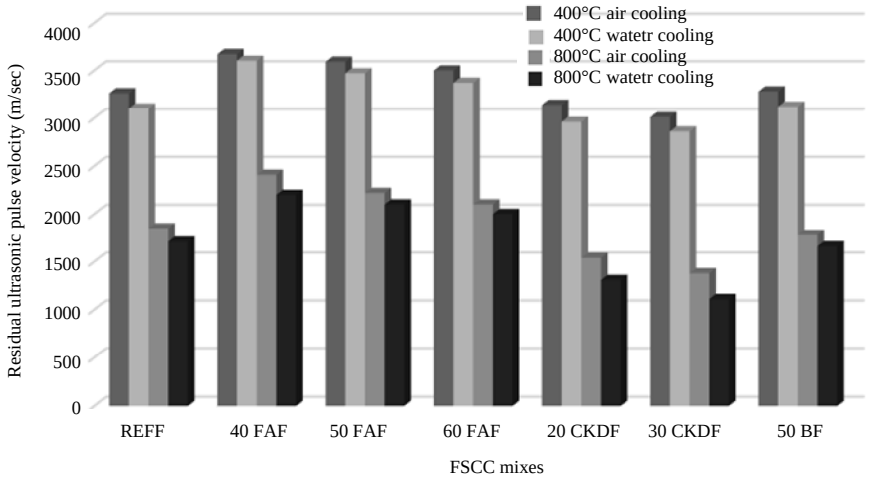

Fig. 6: Effect of cooling method on residual ultrasonic pulse velocity for all FSCC mixes exposed to 400 and 800°C

cracks, so, these cracks may delay the propagation of the pulse (increasing the travel time) resulting in a decreased ultrasonic pulse velocity value.

Weight loss due to elevated temperature: Before and after each temperature cycle, each cubic specimen was weighted and the percent of weight loss was calculated. Dehydration of cement paste is generally the main reason for weight change. Weight loss permits to quantify the dehydration of concrete after every heating. Results of weight loss are presented in Table 8 and showed in Fig. 7. It is noticed that as the temperature of exposure increased the loss of weight increased for all concrete mixes. Initially, at 200°C there was a small weight loss and it may be due to melting of PP fiber. Weight loss was (2.46, 2.55, 2.80, 2.97, 3.55, 3.90 and 2.77%) for REFF, 40FAF, 50FAF, 60 FAF, 20 CKDF, 30 CKDF and 50 BF mixes, respectively.

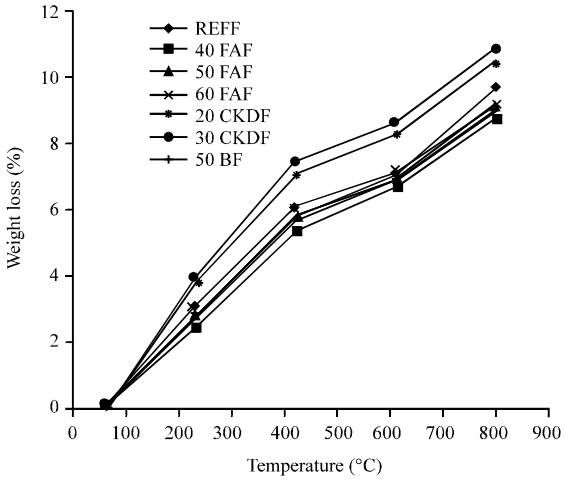

Fig. 7: Weight loss of FSCC mixes at different temperatures

Table 8: Weight loss of FSCC mixes

	Weight loss (%)				
	Max temperature (°C)				
Mix ID	27	200	400	600	800
REFF	0	2.46	5.31	6.58	9.750
40 FAF	0	2.55	5.40	6.68	8.660
50 FAF	0	2.80	5.71	6.92	8.970
60 FAF	0	2.97	6.00	7.10	9.200
20 CKDF	0	3.55	7.05	8.32	10.470
30 CKDF	0	3.90	7.48	8.67	10.910
50 BF	0	2.77	5.70	6.87	9.080

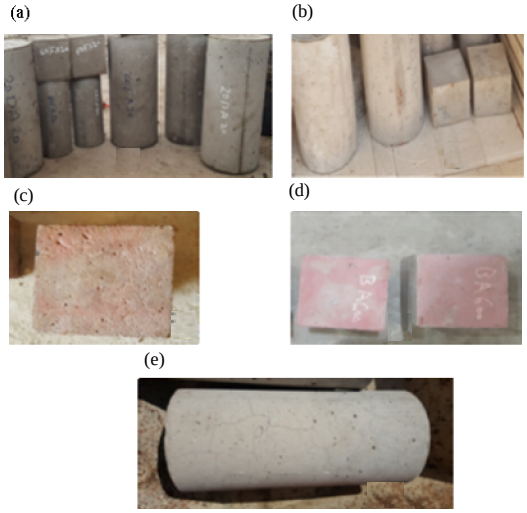

Fig. 8: Specimens color at: a) Room temperature; b) 200°C; c) 400°C; d) 600°C and e) 800°C

After that, the weight loss taken place at high rate up to a temperature of about 400°C as shown in Fig. 7 and it was (5.31, 5.40, 5.71, 6.0, 7.05, 7.48 and 5.70%) for the above mentioned mixes, respectively. The main reason of high rate weight loss up to 400°C may be because the capillary water evaporation which is followed by departure of gel water and interlayer water. Moreover, from 400-600°C, there was no momentous increase in the weight loss. The slightly less increment rate in mass loss up to 600°C because the moisture loss at this temperature is ascribed to discharge of chemically combined water which is a portion of cement hydrate products and is so hard to disappear. Thus, the descent in weight loss rate is anticipated. Later, the weight loss got more increased at a higher rate up to a temperature of 800°C and it was (9.75, 8.66, 8.97, 9.20, 10.47, 10.91 and 9.08%) for REFF, 40, 50, 60 FAF, 20, 30 CKDF and 50 BF mixes, respectively. At 800°C further mass loss was occurred due to thermal decomposition of components of hydration products.

Visual inspection: When concrete exposed to elevated temperature, the visual observations provide a first thought on concrete deterioration degree, so by checking the color change and the cracks with naked eye the concrete damage can be assessed.

Color changes: Harmonic relationship can be found between change in color and residual compressive strength when concrete exposed to elevated temperature. It may be probable to estimate how much reduction occurred to compressive strength by determining color changes and guessing heating temperature. Figure 8 shows the color change in the studied FSCC mixes. At room temperature (Fig. 8a) the greyish color was distinguished to REFF SCC mix while the specimens that contain CKD have lighter greyish color due to off-white color of cement kiln dust and the specimens that contain FA have darker greyish color due to high volume fly ash used. At 200°C (Fig. 8b) there was no noticeable change in color. However, at 400°C (Fig. 8c) the color of the specimens tends to change towards pink and at 600°C (Fig. 8d) the specimens acquired light brown color. The change in color may be related with the mineralogical history of the aggregate (Lee *et al*., 2010), the reason of approximately red color at temperature between (400-600)°C is the presence of iron in the fine or coarse aggregate and the hydrate begins to dissolve and the oxidization of iron starts around these temperature levels. At 800°C the specimens started to get pale grey color (Fig. 8e). These observations were almost similar for all the mixes in the present study.

Cracks development: Cracking is an observable kind of damage to concrete when exposed to elevated temperature and has major harmful influences on the mechanical and durability characteristics of concrete. At 200°C, there was no superficial sign of cracking in any of the studied FSCC samples that cooled in air. Where at this temperature level the cracking is typically microscopic in scale and thus is known as microcracks and concrete deterioration is controlled by only localized boundary cracking between aggregates and the cement paste "ITZ". When the exposure temperature raised to 400°C hairline cracks can be detected in RFFF SCC mix and somewhat wider cracks in CKDF SCC mixes but in FAF mixes tiny and smaller hairline cracks can be observed as shown in Fig. 9. At 600°C, the crack density increases robustly and at this temperature level the surface cracks are more noticeable as shown in Fig. 9. These cracks may be due to thermal inconsistencies between the aggregates and the hydrated cement paste. At 800°C the cracks spread severely especially in REFF and CKDF mixes where the cracks begun to connect with each other's and create one or two major cracks that totally cross around the whole

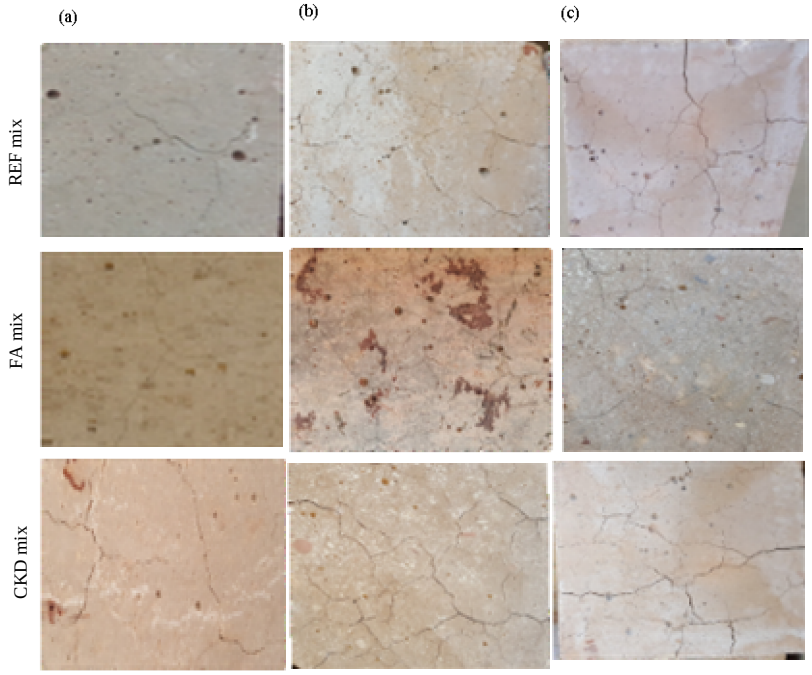

Fig. 9: Distinctive crack patterns observed in different mixes at various temperature levels: a) 400°C; b) 600°C and c) 800°C

surface area of the specimens. For FAF SCC mixes smaller network minor surface cracks was observed compared with other mixes and this may be due to the cracks started firstly around the ($Ca(OH)_2$) crystals and then grew to areas nearby to the un-hydrated cement grains, so with the high volume fly ash used, there will be a little amount of ($Ca(OH)_2$) due to pozzolanic reaction. If the specimens were taken from the furnace at elevated temperatures directly after the end of exposure duration and cooled by water spray, the number of cracks in addition to their size was larger than those generate in the specimens cooled down inside the furnace (air cooling) and this may be due to thermal shock and the rehydration of dissociated (CaO) (Eq. 2 and 3) which could result in important volume increase. For water cooled specimens also FAF mixes exhibits lower and smaller amount of cracks compared to other mixes.

CONCLUSION

More strength loss takes place when the specimens are water cooled compared with air cooled specimens due to thermal shock. Water spraying has remarkable influence on flexural strength more than compressive strength.

At ambient temperature, the presence of polypropylene fibers leads to a reduction in flow ability and passing ability of self consolidating concrete mixes but they still meet the requirements of SCC.

Two distinguished behaviors of compressive strength can be recognized. The first at 200°C where an increase in strength was detected in FSCC mixes. The second at 400°C where most mixes lost insignificant percentage of their original strength. At 600°C and beyond, FSCC mixes lost their strength rapidly.

Fly ash FSCC mixes exhibit the best performance among the mixes where the relative residual compressive at 800°C were (62, 65, 71%) and (51, 53, 60%) for air and water cooling, respectively.

A sharp drop in flexural strength when exposed to elevated temperature occurs. The 60 FAF SCC mix exhibits the highest relative residual flexural strength at 800°C and it was (33) and (28%) for air and water cooled, respectively

At 400°C, severe drop in ultrasonic pulse velocity occurs and the relative residual ultrasonic pulse velocity was between (67-77%) and (63-73%) for air and water cooling, respectively. At this temperature level FAF SCC mixes are classified as good quality mix while other mixes were doubtful.

After exposure to high temperature, the damaged that was occurred to the mechanical characteristics is validated by the increment of the weight reduction with increased temperature, where at 800°C it was (9.75, 8.66, 8.97, 9.20, 10.47, 10.91 and 9.08%) for REFF, 40, 50, 60 FAF, 20, 30 CKDF and 50 BF mixes, respectively.

Visual examination of the specimens shows that the color is gradually lightened as the temperature exposure

increases where the color starts to change towards pink at 400 at 600°C the specimens acquire light brown color and finally the color changed into pale grey. At 200°C, there is no superficial sign of cracking in any of the studied FSCC specimens and the cracks become wider as the temperature rose. At 800°C the cracks spread severely, especially in REFF and CKDF mixes while in FAF mixes smaller network minor surface cracks is observed.

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