Behaviours of sustainable self-consolidating concrete exposed to elevated temperatures

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Abstract. The collapse of the structures may be initiated by fire, which is considered one of the most severe risks. However, there are several conditions in which structures may be exposed to elevated temperatures such as nuclear applications; factory procedures; and fires in tunnels or buildings due to accidents or terrorist attacks. Recently, Self-Consolidating Concrete (SCC) has become more broadly used, and there is thus a need to recognise its behaviours when subjected to elevated temperatures, particularly in terms of sustainable SCC. Seven sustainable SCC mixes were thus investigated in this study, each incorporating certain green materials (Portland limestone cement, high volume Class F fly ash, and locally available cement kiln dust (CKD)). All mixes were subjected to temperature levels of 200 °C, 400 °C, 600 °C, and 800 °C for two hours and cooled to room temperature either slowly (air cooling) or rapidly (water cooling). The residual (compressive, splitting, and flexural) strengths and modulus of elasticity were calculated. The results indicated that SCCs with high volumes of Class F fly ash showed the best performance when subjected to elevated temperature.

Keywords: Self-Consolidating Concrete (SCC), sustainable, Portland limestone cement, Class F fly ash, cement kiln dust, elevated temperature.

1. Introduction

It is well known that fire results in a loss of life, and the destruction of homes and livelihoods; regrettably, though there have been many noteworthy developments in science and technology, the dangers to structures because of elevated temperatures during fire events are increasing instead of diminishing [1]. During their lifetimes, a large number of civil engineering constructions may face the risk of fire from a range of causes spreading from natural events to human errors, making it significant for these structures to be constructed in such manner that hazards to both persons and property are reduced as effectively as possible [2]. Due to its high specific heat and low thermal conductivity, concrete is famous for its capability to withstand high temperatures and fires. However, this does not signify that elevated temperatures do not have an impact on concrete. Properties such as compressive strength, tensile strength, and elasticity are greatly influenced by high temperatures and such permanent damage may shorten the expected service life of the structures due to loss of structural integrity [3]. As concrete is the most essential building material in many applications all over the world that required exposure to elevated temperatures, such as nuclear reactors, petrochemical industries, furnace walls, and industrial chimneys, there have already been several studies into the effects of elevated temperatures on the mechanical and physical properties of concrete, such as [4-10]. Some studies [4], [5] have concluded that in the range between 20 °C and 150 °C, there is a decrease in compressive strength for normal concrete. Other researchers [6], [7] have assessed the residual mechanical properties of high strength concretes after exposure to elevated temperatures and stated that, after heating to 200 °C, the strength of the concretes was slightly improved when compared to their strength at 100 °C. The phase distribution and microstructural changes of self-consolidating cement paste at elevated temperatures was studied by [8], who concluded that self-consolidating cement paste exhibited a higher change of total porosity compared to high performance cement paste. These studies in general reveal that, in spite of the significant work that has been done to investigate the influence of different temperature levels on different types of concrete, only a few works exist in which the impact of elevated temperatures on SCC have been investigated. SCC are used broadly all over the world where greater structural behaviours, energy saving, and eco-friendly features are required [11]. Sustainable SCCs may thus be exposed to high temperatures for considerable periods of time in a range of industries, and thus it is essential to evaluate their service performance during fire events.

2. Research significance

Due to increasing concerns about sustainable development, the construction industry is rapidly moving towards improving its sustainability; thus, the study of eco-efficient or sustainable concrete is of growing interest among the main recent publications about concrete. There are very few pieces of research available concerning the performance of sustainable concretes at elevated temperatures, however, especially those containing high volumes of fly ash and cement kiln dust. To the author's best knowledge, the impact of elevated temperatures on concrete containing high levels of Fly Ash (FA) blended with Portland Limestone Cement (rather than Ordinary Portland Cement) and Cement Kiln Dust (CKD) has not been investigated at all in the literature. The purpose of this work is thus to make experimental data are available with respect to the residual mechanical properties of sustainable SCC, as these properties are clearly very significant for understanding the behaviours of this concrete under such conditions as an aid to the safe design of structures.

3. Materials and experimental programme

3.1. Materials

3.1.1. Cement

In this study, the cement used was local Portland limestone cement (PLC), available in the markets, classified as Karasta CEM II/A-L 42.5 R, and produced by Lafarge Company in Al-Sulaymaniyah city in Iraq. It complies with European Standard EN 197-1 [12] and Iraqi industrial license No: 3868. The physical and chemical characteristics of the cement used in this study are presented in Table 1.

3.1.2. Fine and coarse aggregates

Natural sand from the Al-Najaf quarry was used in this work as fine aggregate. The grading and physical and chemical properties of the sand are shown in Table 2. It has a fineness modulus of 2.5 and lies within grading zone 3. A crushed gravel with a maximum size of 20 mm was used as a coarse aggregate. The grading and physical and chemical properties of the gravel used are shown in Table 3. Both types of aggregate satisfied Iraqi specification No. 45 / 1984[13].

3.1.3. Chemical admixture

A commercially famous high-performance superplasticizer based on modified polycarboxylic ether (GLENIUM 54) was used for the liquefaction of the concrete mixtures to achieve the desired workability throughout this study as a "high range water reducing admixture" (HRWRA). It complied with ASTM C494 [14]. Typical addition proportions were provided by the manufacturer (Basf Chemical Company) as 0.5 to 2.5 litres per 100 kg of cement (cementitious material).

Table 1. Chemical and physical characteristics of Portland limestone cement (PLC) used [a]

Oxides or Property	PLC test results	Requirement of EN 197-1 [12]	Requirement of Iraqi industrial license No: 3868 [b]
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 less than 5% ≤ 2.8% if C_3A more than 5%
Na_2O	0.2	-	-
K_2O	1.1	-	-
$(Na_2O)_{eq.}$ [c]	0.92	-	-
L.O.I	4.5	-	-
Fineness (m^2/Kg)	390	-	-
Initial setting time (min.)	128	≥ 60.0	≥ 45.0
Final setting time (hr.)	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 property tests were carried out in the laboratory of Al-Kufa cement mill.
[b] Limit by ICOSQC (Iraqi Central Organization for Standardization & Quality Control).
[c] $(Na_2O)_{eq.} = Na_2O + 0.658\ K_2O$.

Table 2. Grading and physical and chemical properties of sand used.

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No. 45/1984 [13], zone 3
4.75	97	90-100
2.36	89	85-100
1.18	75	75-100
0.60	60	60-79
0.30	22	12-40
0.15	5	0-10
Property	Test results	
Specific gravity	2.58	-
Sulphate content (SO_3) %	0.21	≤ 0.5
Absorption %	1.82	-
Materials finer than sieve No. 200	1.4	≤ 5.0
Fineness modulus	2.5	-

Table 3. Grading and physical and chemical properties of gravel used.

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No. 45/1984[13]
37.5	100	100
20	100	95-100
10	39	30-60
5	3	0-10
Property	Test results	
Specific gravity	2.62	-
Sulphate content (SO_3) %	0.03	≤ 0.1
Absorption %	0.7	-

3.1.4. Fly ash

Fly ash is generally captured from the chimneys of electric power generation facilities, and the fly ash used in present study was obtained from Turkey. The physical and chemical properties of fly ash are tabulated in Table 4. It can be seen from this table that the fly ash used is considered a class F fly ash per ASTM C618 standard [15]. A Pozzolanic Activity Index (PAI) test was conducted on the fly ash used with a result of 85%.

Table 4. Chemical analysis and physical properties of fly ash and cement kiln dust [a].

Oxides or property	Fly ash	Cement kiln dust	ASTM C618-05[15] 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	-

[a] Chemical analysis and physical properties were carried out in the laboratory of Al – Kufa cement mill.

3.1.5. Cement kiln dust

Cement kiln dust (CKD) is a by-product of cement production. CKD is a fine-grained, particulate material that is thus easily entrained in the combustion gases moving through the kiln [16]. The chemical composition of cement kiln dust differs from one cement plant to another because it depends on a wide range of factors, including the composition of the raw materials, the kiln processes incorporated in the manufacturing, and the fuel used to heat the kiln, while the particle size distribution is mainly determined by the collection method employed. Table 4 lists the chemical composition and Figure 1 shows the Scanning Electron Microscopy (SEM) of the cement kiln dust used in this research.

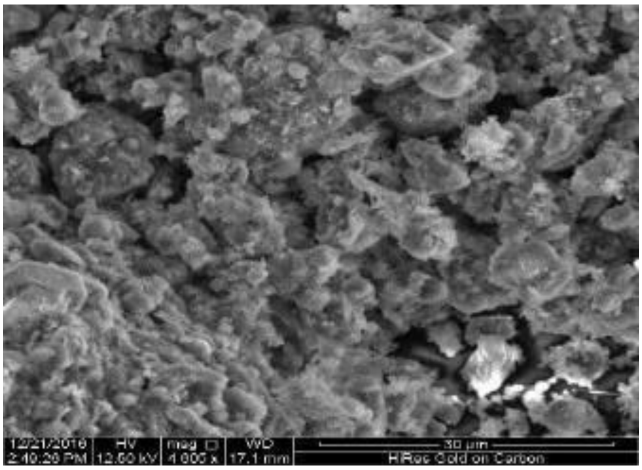

Figure 1. SEM for CKD that used in this study.

3.2. Experimental program

3.2.1. Mix proportions and mixing sequence

As SCC mixes are highly reliant on the properties and composition of their ingredients, each can be considered a delicate mix. Two contradictory properties should be found in each SCC mix; these are the high flow-ability and the high segregation resistance. In the present work, the reference SCC mix (REF) was designed according to Okamura and Ouchi [17], taking into account the recommendations of the EFNARC [18] and ACI 237 [19]. The water/powder ratio (w/p) was kept constant at 0.36, while the dose of super-plasticizer used was changed to attain the fresh properties that satisfied the limitations of EFNARC [18] and ACI 237 [19]. To achieve this, for each mix, several trial batches were produced. Seven different SCC mixes were investigated in this study. One was the reference concrete mix (REF) made with 500 kg/m3 of Portland Limestone Cement alone, while three mixes (40, 50, 60 FA) had 40%, 50%, and 60% Class F fly ash replacing some cement, and two mixes (20CKD, 30CKD) had cement replacement of 20% and 30% by cement kiln dust, respectively. In addition, one binary mixture (50B) had cement replacement of 50% of a mix of the two materials (20% CKD plus 30% FA). Table 5 shows the mixture proportions of these mixes.

A drum type mixer of 0.1 m^3 capacity was used to mix the concrete ingredients. The dry constituents of each concrete mix were placed in the mixer such that the cement or (cement plus powder materials) was placed between two layers of sand followed by two layers of gravel, to prevent the spillage of cement in air. The dry materials were well mixed for about three minutes to attain a uniform mix, then about 80% of the required quantity of tap water was added; this mix was mixed thoroughly for another three minutes. Finally, the HRWRA was diluted with the residual mixing water then presented for 30 second, and the resulting concrete was mixed for 2.5 minutes [20]. The concrete stayed at rest in the mixer for one minute to permit any major air bubbles captured throughout mixing to rise to the surface. The concrete was then remixed for one minute [21].

3.2.2. Samples preparation

After mixing, the concrete was cast in the moulds without any vibration, being immediately covered with wet burlap and plastic wrap and permitted to remained undisturbed for 24 hours in laboratory conditions. After 24 hours, the specimens were removed from the moulds and placed in a curing tank up to 28 days, before being removed from the curing tank and cured in the air in laboratory conditions until they reached 91 days.

Table 5. Mix proportions of the concrete mixes.

Mix ID	Mixture proportions (kg/m^3)							
	Cement	Fly ash	Cement kiln dust	Water	Sand	Gravel	W/P [a]	SP [b]
REF	500	-	-	180	800	800	0.36	0.8
40FA	300	200	-	180	800	800	0.36	0.7
50FA	250	250	-	180	800	800	0.36	0.6
60FA	200	300	-	180	800	800	0.36	0.55
20CKD	400	-	100	180	800	800	0.36	0.9
30CKD	350	-	150	180	800	800	0.36	1.1
50B	250	150	100	180	800	800	0.36	0.9

[a] W/P = water/powder: water/(cement + FA +CKD)
[b] Sp = superplasticizer (Lit/100 Kg cementitious material)

3.2.3. Test procedure

3.2.3.1. Tests on fresh SCC
To calculate and evaluate the fresh features of SCC, several test methods have been developed from around the world. Among these test methods, however, no single test can be used alone to assess all of the main parameters, making a combination of tests necessary to totally describe an SCC mix. In this work, the three main characteristics of SCC, filling ability, passing ability, and resistance to segregation, were examined using methods mentioned in EFNARC [18] and/or ACI 237R-07[19].

3.2.3.2. Tests on hardened SCC

3.2.3.2.1. Compressive strength test:
A concrete compressive strength test was performed according to BS EN 12390-3 [22] on 100 mm cubes using an ELE digital compression machine capable of 2,000 KN.

3.2.3.2.2. Splitting tensile strength test:
A test for the splitting tensile strength of the concrete was carried out in accordance with ASTM C496-04 [23] on cylinders of 100 mm × 200 mm using the same machine used for testing the compressive strength. The specimens were placed horizontally between the plates of the testing machine and the load was increased at a rate of 0.94 KN/s until failure by splitting along the vertical axis occurred.

3.2.3.2.3. Flexural strength test:
Concrete prisms of 100 × 100 × 400 mm were used for the flexural strength test (modulus of rupture) (MOR) as per ASTM C78-02 [24]. The flexural strength was determined using a 30,000 kg capacity testing machine, and the test was carried out using a two-point load.

3.2.3.2.4. Static modulus of elasticity test:
The static modulus of elasticity was determined according to ASTM C469-02 [25] using d=150 mm, h=300 mm cylindrical specimens and mechanical strain gauges (ELE) of effective length equal to 150 mm. The chord modulus was used in this study; in this modulus, the slope of a line drawn from a point representing 50μ€ to a point corresponding to 40% of the ultimate stress, calculated as follows:

$$Ec = S2 - S1/€2 - 0.00005 \quad (1)$$

where
Ec= chord "Young" modulus of elasticity (MPa);
S2= stress corresponding to 40% of ultimate load (MPa);

S1= stress corresponding to a longitudinal strain (0.00005 MPa); and

ε_2 = longitudinal strain produced by stress S2

3.2.4. Details of heating and cooling
At the age of 91 days, the specimens were placed in the manufactured electrical furnace; the temperature inside the furnace was room temperature at the time the specimens were placed. Then, heat was applied at a rate of 5 ˚C/min until the desired temperature was reached. After reaching the target temperature, the specimens were held at this temperature for two hours. To ensure that the specimens reached the maximum temperature, two type "K" thermocouples were placed at the surface of the specimens and the temperature was read using a digital ELE thermometer, as shown in Figure 2. To cool the specimens two techniques were adopted: slow cooling (in air) and rapid cooling (in water).

Figure 2. Measuring specimen temperature using an ELE thermometer.

4. Results and discussion

4.1. Fresh properties
According to EFNARC [18] a concrete mix can only be classified as SCC if the requirements for filling and passing and the segregation resistivity characteristics are fulfilled. Table (6) presents the fresh properties of filling ability, passing ability, and segregation resistance of the studied mixes accompanied by the acceptable criteria proposed by EFNARC [18] and ACI 234R-07 [19]. FA mixes showed the best performance because the fly ash particles have a smooth, spherical surface, reducing inter-particle friction. When fly ash is used with CKD in a binary mix, it intrinsically alleviates the higher water requirements of CKD (which also becomes a higher requirement for super-plasticizers) and improves the fresh properties. From these fresh properties, it can be seen that all SCC mixes fell within desired range of specifications.

4.2. Hardened properties at elevated temperature
At elevated temperatures, there are three ways to determine the residual strength of concrete: stressed, unstressed, and unstressed residual strength test. Xiao et al. [26] reported that the third method gives the lowest strength values, and hence it is more appropriate for finding the limiting values; based on this, the third method was chosen for this study. To normalise and analyse the experimental results the term "relative strength" was also adopted in this study, where residual strength value at a desired temperature is expressed as a percentage of the respective original strength value at room temperature. The test results given are the means of three samples in each case, leading to more trustworthy results.

Table 6. Fresh properties of SCC mixes.

Mix ID	Filling ability		Passing ability (J-ring test)			Segregation resistance %
	Slump flow (d_s) mm	Spread time (T_{50}) S.	Differences in heights (mm)	Flow (d_j)	(d_s-d_j)	
REF	695	2	3.7	676	19	7.2
40FA	727	2.3	3.1	709	18	5
50FA	740	2.7	2.8	725	15	4.8
60FA	752	3	2	738	14	4.5
20CKD	680	3.8	5	655	25	3
30CKD	668	4.5	6.3	630	38	2.5
50B	700	3	4.1	679	21	3.5
Acceptance criteria of SCC suggested by ACI [19]	450 – 760	2 – 5	-		0 – 25	0 - 10
Acceptance criteria of SCC suggested by EFNARC [18]	550 – 850	2 – 5	0 – 10		-	-

4.2.1. Residual compressive strength

The results of residual compressive strength testing after exposure to different temperature levels are shown in Table 7 and Figures 3 and 4. The global impact of exposing SCC specimens to high temperatures is a general reduction in compressive strength. This strength reduction on heating is due to a series of complex physical and chemical changes. For air cooled specimens, as shown in Figure 3, at 200 ˚C there was an improvement in residual compressive strength for all concrete mixes of 105%, 108%, 111%, 119%, 103%, 101%, and 106% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively. The increment in compressive strength at this temperature was also confirmed by [27] and [28], who supposed that the formation of siloxane elements (Si–O–Si) became shorter and stronger because of the loss of part of the binding between a silanol groups (Si–OH) and water; these alternate bonds with possibly larger surface energies could contribute to the increase in strength. At 400 ˚C, the REF mix showed a slight reduction and the relative residual compressive strength was 80%. This somewhat trivial loss (20%) in strength compared with the 40% loss reported by [29] may be due to using Portland limestone cement (PLC) in this study; in a recent study by Tayfun and Bekir [30], they studied the effect of limestone powder on the high temperature resistance of self-consolidating micro-concrete, and they reported that the addition of limestone powder to OPC improved the performance of the produced blended cement when it was exposed to elevated temperatures. After exposure to 600 ˚C, the residual compressive strengths dropped for all concretes mixes. For the REF mix, the relative residual compressive strength was 67.3%, while for 20CKD and 30CKD mixes, the relative residual compressive strengths were 66.1% and 63.6%, respectively. This reduction may be attributed to the dense microstructures of these concrete mixes, which causes a high pore vapour pressure. At 800 ˚C, the compressive strength decreased sharply except in fly ash mixes. The relative residual strength for all

FA mixes compared well to REF and CKD mixes at 61%, 65%, and 70.2% for 40FA, 50FA, and 60FA mixes, respectively. For water cooled specimens, as seen from Figure 4, lower relative residual strength was found than in air cooled concrete mixes. Similar effects have been noticed in many studies, such as [31] and [32]. Thermal shock may be one of the reasons for the drop in compressive strength when specimens are rapidly cooled from high temperatures, particularly as compared to slowly cooled specimens.

Table 7. Residual compressive strength of SCC mixes.

Mix ID	Type of cooling	Residual compressive strength (MPa) [a]				
		Max. temperature °C				
		27	200	400	600	800
REF	air	66.2 (100)	69.5 (105)	53.0 (80.0)	44.6 (67.3)	32.5 (49.1)
	water	-	57.8 (87.3)	49.0 (74.0)	37.4 (56.5)	25.1 (38.0)
40FA	air	61.1 (100)	66.0 (108)	51.3 (84.0)	44.1 (72.2)	37.3 (61.0)
	water	-	54.0 (88.4)	46.7 (76.4)	38.8 (63.5)	30.5 (50.0)
50FA	air	56.3 (100)	62.5 (111)	49.5 (88.0)	43.4 (77.1)	36.6 (65.0)
	water	-	50.6 (89.8)	44.1 (78.3)	37.2 (66.1)	29.5 (52.4)
60FA	air	50.1 (100)	59.6 (119)	45.6 (91.0)	40.0 (79.8)	35.2 (70.2)
	water	-	45.6 (91.0)	40.1 (80.0)	35.2 (70.3)	29.3 (58.5)
20CKD	air	38.1 (100)	39.3 (103)	29.3 (77.0)	25.2 (66.1)	18.3 (48.0)
	water	-	32.7 (85.8)	27.2 (71.4)	23.8 (62.5)	15.5 (40.7)
30CKD	air	34.7 (100)	35.1 (101)	25.0 (72.0)	22.1 (63.6)	16.2 (46.6)
	water	-	29.5 (85.0)	23.6 (68.0)	20.5 (59.3)	13.1 (37.8)
50B	air	64.8 (100)	69.0 (106)	53.1 (82.0)	45.5 (70.2)	36.1 (55.7)
	water	-	57.6 (88.8)	47.8 (72.6)	40.8 (63.0)	30.2 (46.6)

[a] The values in brackets indicate the relative increase or decrease in residual compressive strength as compared to room temperature (27 °C).

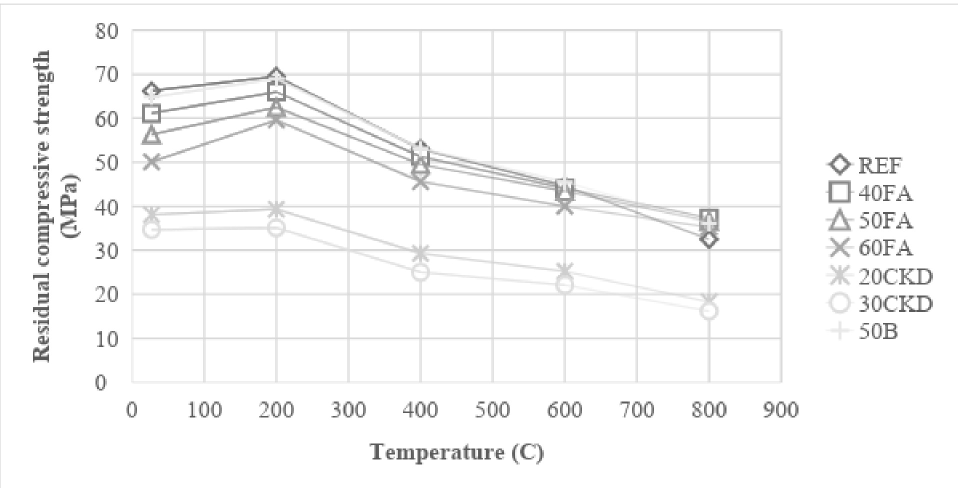

Figure 3. Residual compressive strength of air cooled SCC mixes.

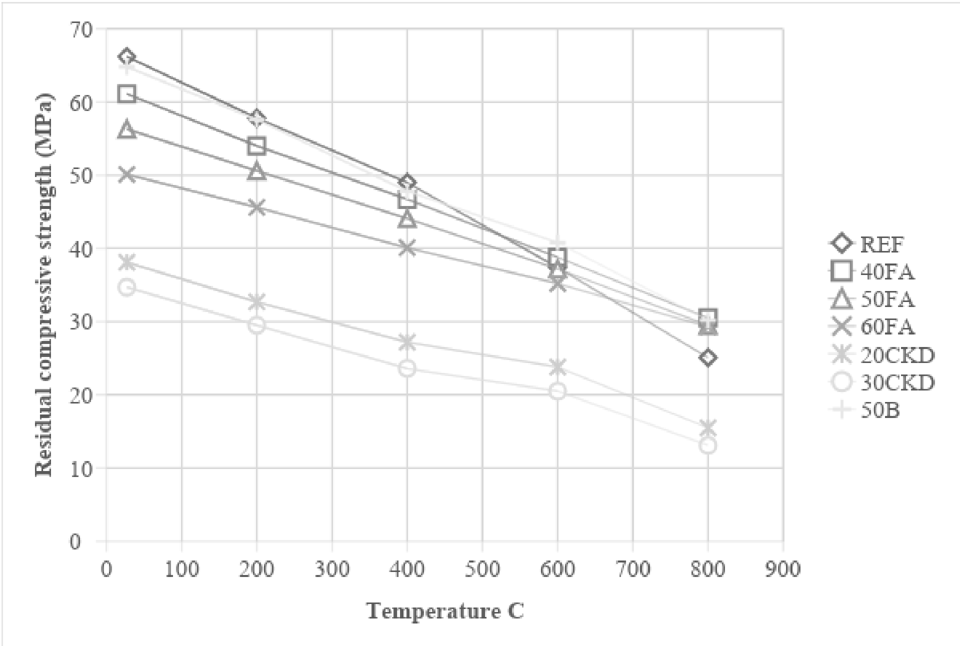

Figure 4. Residual compressive strength of water cooled SCC mixes.

4.2.2. Residual splitting tensile strength

It is significant to determine the tensile strength of concrete before and after exposure to elevated temperatures because this governs the concrete's ability to resist cracking. From the results in Table 8 and Figures 5 and 6, it is obvious that, at high temperature, the tensile strength decreases more rapidly than the compressive strength due to the features of the "Interfacial Transition Zone" (ITZ) between the cement paste and the aggregate. For air cooled specimens, at 200 °C there was a descent in the splitting tensile strength of SCC mixes, whereas, also at this temperature, an ascent was seen in compressive strength.

Table 8. Residual splitting tensile strength of SCC mixes.

Mix ID	Type of cooling	Residual splitting tensile strength (MPa) [a]				
		Max. temperature °C				
		27	200	400	600	800
REF	air	6.12 (100)	4.22 (69.0)	3.76 (61.5)	2.91 (47.5)	2.17 (35.5)
	water	-	3.85 (63.0)	3.47 (56.8)	2.57 (42.0)	2.02 (33.0)
40FA	air	5.44 (100)	3.97 (73.0)	3.45 (63.5)	2.72 (50.0)	2.10 (38.6)
	water	-	3.55 (65.3)	3.26 (60.0)	2.36 (43.4)	1.95 (35.8)
50FA	air	4.71 (100)	3.49 (74.1)	3.07 (65.2)	2.45 (52.0)	1.86 (39.5)
	water	-	3.11 (66.0)	2.89 (61.5)	2.10 (44.7)	1.74 (37.0)
60FA	air	4.42 (100)	3.38 (76.5)	2.97 (67.2)	2.37 (53.6)	1.79 (40.5)
	water	-	3.05 (69.0)	2.78 (63.0)	2.03 (46.0)	1.70 (38.5)
20CKD	air	3.45 (100)	2.38 (69.0)	2.10 (61.0)	1.58 (45.8)	1.22 (35.4)
	water	-	2.16 (62.6)	1.95 (56.5)	1.40 (40.6)	1.12 (32.5)
30CKD	air	3.22 (100)	2.18 (67.7)	1.89 (58.7)	1.42 (44.1)	1.13 (35.1)
	water	-	2.02 (62.7)	1.77 (55.0)	1.25 (38.8)	1.03 (32.0)
50B	air	5.71 (100)	4.08 (71.5)	3.58 (62.7)	2.71 (47.5)	2.13 (37.3)
	water	-	3.64 (63.7)	3.34 (58.5)	2.38 (41.7)	1.88 (33.0)

[a] The values in brackets indicate the relative decrease in residual splitting tensile strength as compared to room temperature (27 °C).

This clearly reveals that the amount of concrete cracking appears to have more effect on the tensile strength than on the compressive strength, as heating to only 200 °C created a relatively small amount of cracking, which did not cause any loss of carrying capacity in compression due to the insensitivity of compressive strength to trivial cracks. The relative residual splitting tensile strengths were 69%, 73%, 74.2%, 76.5%, 69%, 67.8%, and 71.5% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively. This reduction in splitting tensile strength at this temperature has been confirmed by many studies, such as [33] and [34]. At 400 °C, a further reduction in splitting tensile strength was noted, and the relative residual splitting tensile strengths were 61.5%, 63.5%, 65.2%, 67.2%, 61.0%, 59.0%, and 62.8% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively. It is evident from Figure 5 that FA mixes have superior relative residual splitting tensile strength compared to other mixes, however. The possible reason behind this is the inclusion of an additional hydration product, "tobermorite phase (5CaO.6SiO2 .XH2O)", which allows more efficient adhesion between the cement paste and the aggregates. This result was confirmed by the X-Ray diffraction technique used by Tanyildizi and Coskun [34]. At 600 ˚C, a significant decrease in the residual splitting tensile strength was also observed in SCC.

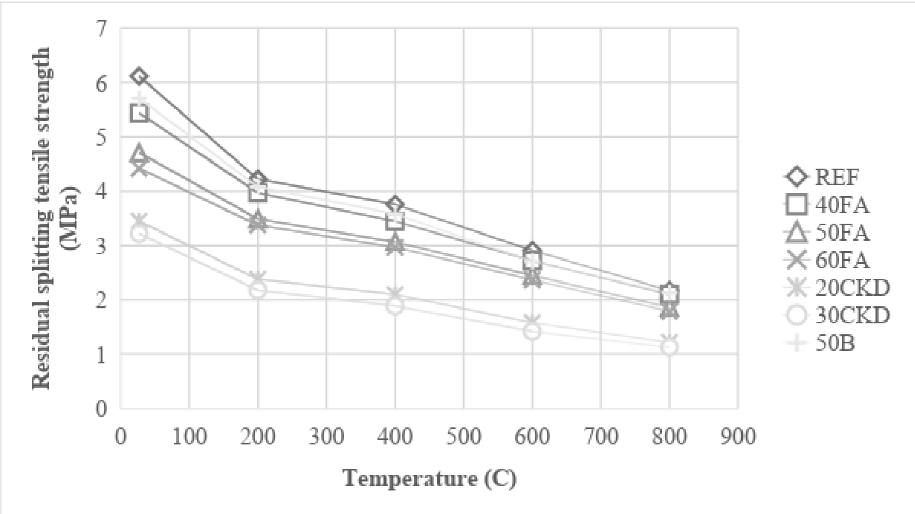

Figure 5. Residual splitting tensile strength of air cooled SCC mixes.

This may be ascribed to the weakened bond between the aggregates and the cement paste, which may be caused by the contraction of the cement paste following the loss of water and the expansion of the aggregates. Further degradation in splitting tensile strength occurred when the specimens were exposed to the highest temperature (800 °C), especially for CKD SCC mixes, where the residual splitting tensile strengths were 1.22 and 1.13 MPa for 20CKD and 30CKD mixes, respectively; this represents reductions of 43.7% and 48% compared to the REF mix. The main reason for this reduction in strength is the disappearance of the semi-crystalline CSH and tobermorite phases at this temperature level, as confirmed by XRD technique conducted by Tanyildizi and Coskun [34]. Figure 6 shows that the water cooled specimens underwent a higher reduction in splitting tensile strength compared to air cooled specimens, and that the maximum percentage reductions were at 600 °C, of 11.7%, 13.2%, 14.2%, 14.4%, 11.4%, 12.0%, and 12.2% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively.

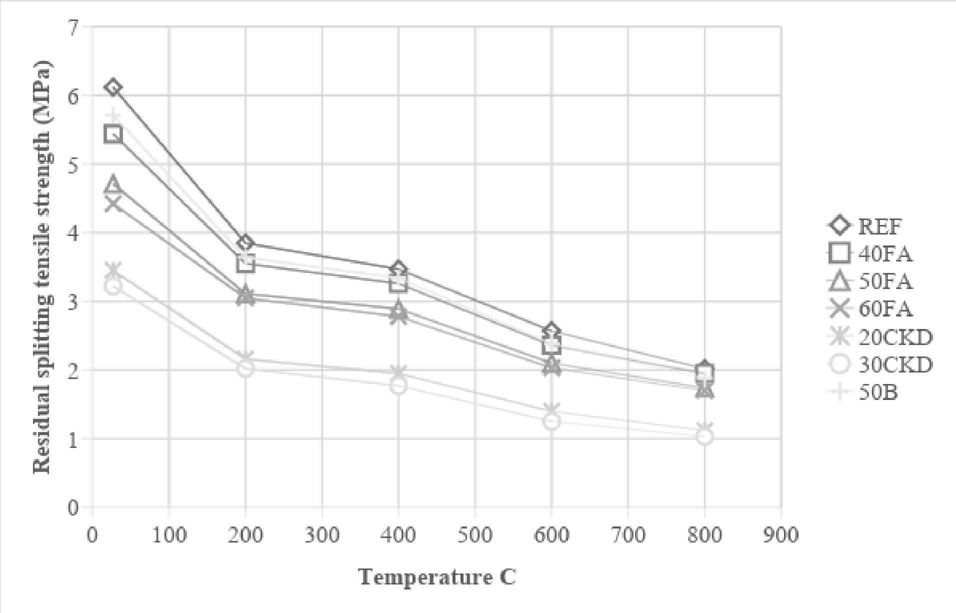

Figure 6. Residual splitting tensile strength of water cooled SCC mixes.

4.2.3. Residual flexural strength

The results of flexural strength testing after exposure to elevated temperatures are presented in Table (9) and Figures 7 and 8. The main feature of these results is the sharp drop in flexural strength when samples are exposed to elevated temperature, and this indicates that the flexural strength is more critical and vulnerable than the compressive strength when concrete is exposed to fire. For air cooled specimens (Figure 7) at 200 °C, there was a reduction in flexural strength for all mixes and the deteriorating influence of 200 °C on flexural strength was more critical than on splitting tensile strength. The relative residual flexural strengths were 60%, 62.8%, 65.2%, 66.7%, 59%, 56.4%, and 61% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively. This result was in agreement with [10] and [35], but conflicted with Wu et al. [36], who reported a slight increment in flexural strength at this temperature; this disagreement may be due to differences in the light weight aggregates and other materials used. At 400 °C, with increasing temperature, the thermal influence might cause internal stress around pores, causing micro and macro cracks to be formed due to the generation of vapour in the pores and the varied volume expansions of ingredients [28]. Therefore, further reduction in flexural strength occurred, and the relative residual flexural strengths were 49.3%, 51.2%, 53.1%, 56.2%, 47.2%, 43%, and 50% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively. At 600 °C and 800 °C, the presence of cracks decreased the effective area of cross sections, and the generation of higher tensile stress caused expansion of cracks. Due to these circumstances, in addition to the coarsening of the pore structure, micro-cracks created at these temperature levels result in more reductions in flexural strength. The relative residual flexural strengths were 37.5%, 39.8%, 41.7%, 43.2%, 34.5%, 32%, and 38.1% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes respectively. It can be seen from Table 9 and Figure 8 that water cooled specimens exhibit lower relative residual flexural strengths compared to air cooled specimens. The percentage of reduction in the flexural strength of water cooled specimens compared to air cooled specimens was between 7 to 11%, 7.5 to 12.5%, 10 to 23% and 15 to 20% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively.

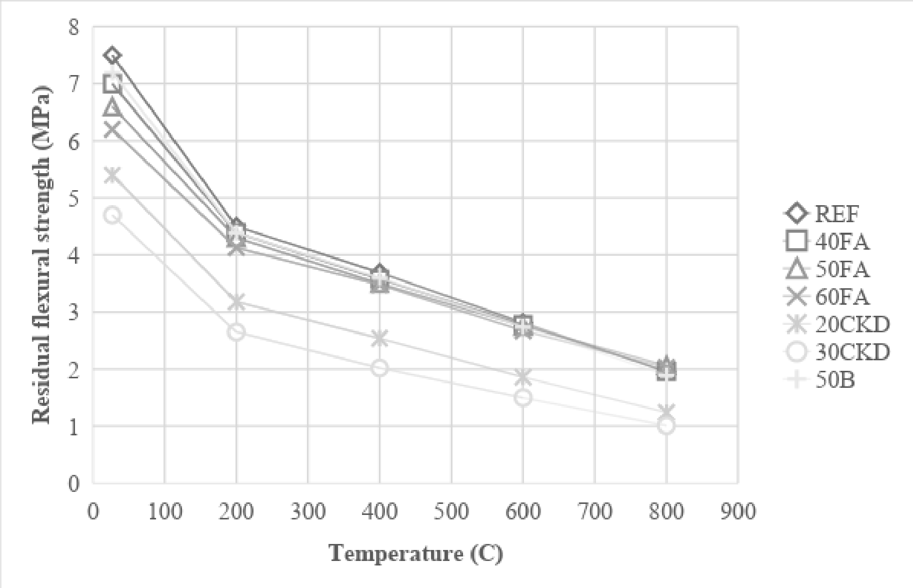

Figure 7. Residual flexural strength of air cooled SCC mixes.

Table 9. Residual flexural strength of SCC mixes.

Mix ID	Type of cooling	Residual flexural strength (MPa)*				
		Max. temperature C°				
		27	200	400	600	800
REF	air	7.5 (100)	4.5 (60.0)	3.69 (49.3)	2.81 (37.5)	1.96 (26.2)
	water	-	4.16 (55.5)	3.36 (44.8)	2.32 (31.0)	1.59 (21.3)
40FA	air	7.0 (100)	4.39 (62.8)	3.58 (51.2)	2.78 (39.8)	1.96 (28.1)
	water	-	4.0 (57.0)	3.32 (47.4)	2.20 (31.5)	1.58 (22.6)
50FA	air	6.60 (100)	4.30 (65.2)	3.50 (53.1)	2.75 (41.7)	2.06 (31.2)
	water	-	3.84 (58.2)	3.25 (49.3)	2.11 (32.0)	1.65 (25.0)
60FA	air	6.20 (100)	4.13 (66.7)	3.48 (56.2)	2.67 (43.1)	2.03 (32.8)
	water	-	3.72 (60.0)	3.22 (52.0)	2.06 (33.2)	1.67 (27.0)
20CKD	air	5.40 (100)	3.18 (59.0)	2.54 (47.1)	1.86 (34.5)	1.24 (23.0)
	water	-	2.78 (51.5)	2.34 (43.3)	1.63 (30.2)	1.03 (19.0)
30CKD	air	4.70 (100)	2.65 (56.4)	2.02 (43.0)	1.50 (32.0)	1.01 (21.5)
	water	-	2.39 (51.0)	1.88 (40.0)	1.36 (29.0)	0.86 (18.3)
50B	air	7.2 (100)	4.39 (61.0)	3.60 (50.0)	2.74 (38.1)	1.89 (26.3)
	water	-	3.98 (55.2)	3.18 (44.2)	2.23 (31.0)	1.54 (21.4)

[a] The values in brackets indicate the relative decrease in residual flexural strength as compared to room temperature (27 °C).

4.2.4 Residual modulus of elasticity

One of the most important mechanical characteristics of concrete is the elastic modulus. The knowledge of this modulus of elasticity is significant in design terms, especially for pre-stressed concrete members. Despite this, however, there are significantly fewer research studies on modulus of elasticity compared to compressive strength after exposure to elevated temperature. The residual modulus of elasticity of concrete was calculated after exposure to various temperatures and cooling by means of two techniques, and the results are presented in Table (10) and shown in Figures 9 and 10. These figures show that, regardless of the type of replacement materials, the modulus of elasticity reduces with increase in temperature.

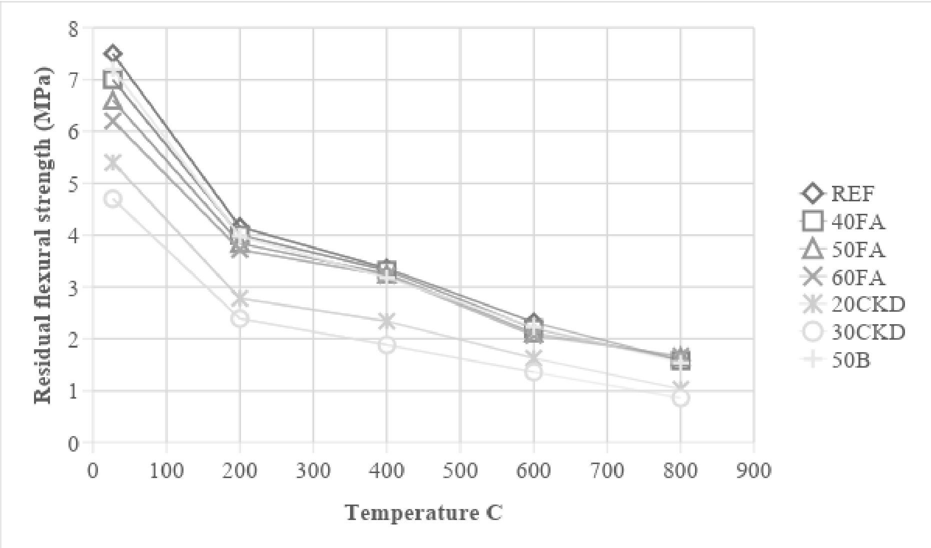

Figure 8. Residual flexural strength of water cooled SCC mixes.

Table 10. Residual modulus of elasticity of SCC mixes.

Mix ID	Type of cooling	Residual modulus of elasticity (GPa) [a]				
		Max. temperature C°				
		27	200	400	600	800
REF	air	41.15 (100)	34.36 (83.5)	21.81 (53.0)	16.46 (40.0)	11.23 (27.3)
	water	-	33.74 (82.0)	20.6 (50.1)	14.69 (35.7)	8.56 (20.8)
40FA	air	35.52 (100)	30.26 (85.2)	20.5 (57.7)	15.8 (44.5)	10.76 (30.3)
	water	-	29.65 (83.5)	19.28 (54.3)	14.28 (40.2)	7.81 (22.0)
50FA	air	35.11 (100)	30.47 (86.7)	20.85 (59.4)	16.15 (46.0)	11.12 (31.7)
	water	-	29.87 (85.1)	19.69 (56.1)	15.34 (43.7)	8.18 (23.3)
60FA	air	34.24 (100)	30.23 (88.3)	21.22 (62.0)	16.36 (47.8)	11.12 (32.5)
	water	-	29.58 (86.4)	20.10 (58.7)	15.23 (44.5)	8.45 (24.7)
20CKD	air	31.22 (100)	25.28 (81.0)	15.64 (50.1)	11.14 (35.7)	6.8 (21.8)
	water	-	24.82 (79.5)	14.83 (47.5)	9.67 (31.0)	5.33 (17.1)
30CKD	air	29.6 (100)	23.47 (79.3)	14.35 (48.5)	9.5 (32.1)	5.38 (18.2)
	water	-	23.08 (78.0)	13.32 (45.0)	8.11 (27.4)	4.56 (15.4)
50B	air	39.85 (100)	33.39 (83.8)	21.71 (54.5)	16.33 (41.0)	10.95 (27.5)
	water	-	32.71 (82.1)	20.56 (51.6)	14.34 (36.0)	8.13 (20.4)

[a] The values in brackets indicate the relative decrease in residual modulus of elasticity as compared to room temperature (27 °C).

At all temperature levels the general trend for the modulus of elasticity is approximately the same as for other mechanical properties. As shown in Figure 9, the modulus of elasticity decreased as the temperature increased, and the relative residual modulus of elasticity at 200 °C was 83.5%, 85.2%, 86.7%, 88.3%, 81.0%, 79.3%, and 83.0% for air cooled REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes respectively. A significant drop in the modulus of elasticity occurred at 400 °C owing to the relatively large decrease in compressive strength and higher deformation (higher strains); the relative residual modulus of elasticity was 53.0%, 57.7%, 59.4%, 62.0%, 50.1%, 48.5%, and 54.5% for REF, 40FA, 50FA, 60FA, 20CKD, 30CKD, and 50B mixes, respectively, and these results were in a line with Tai et al. [37]. At 600 to 800 °C, gradual decay of the modulus of elasticity occurred.

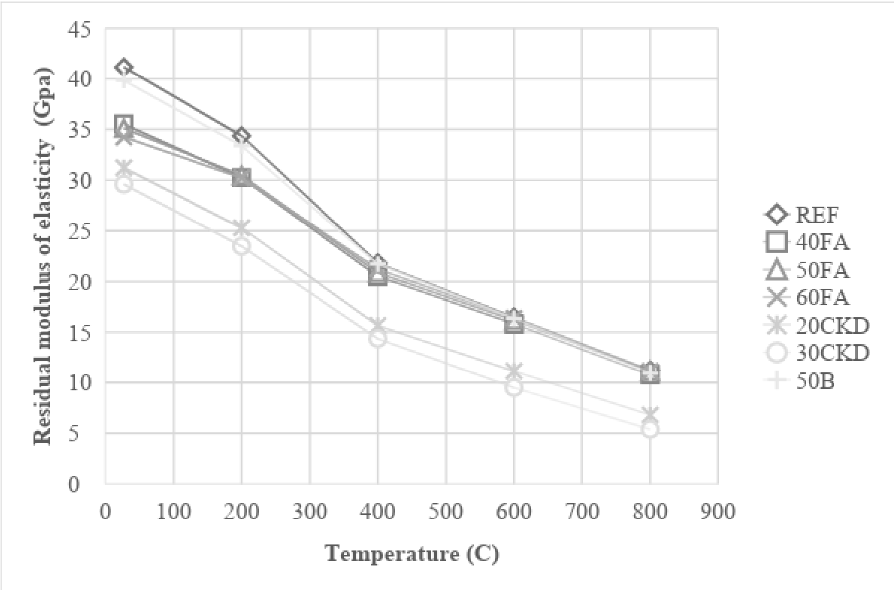

Figure 9. Residual modulus of elasticity of air cooled SCC mixes.

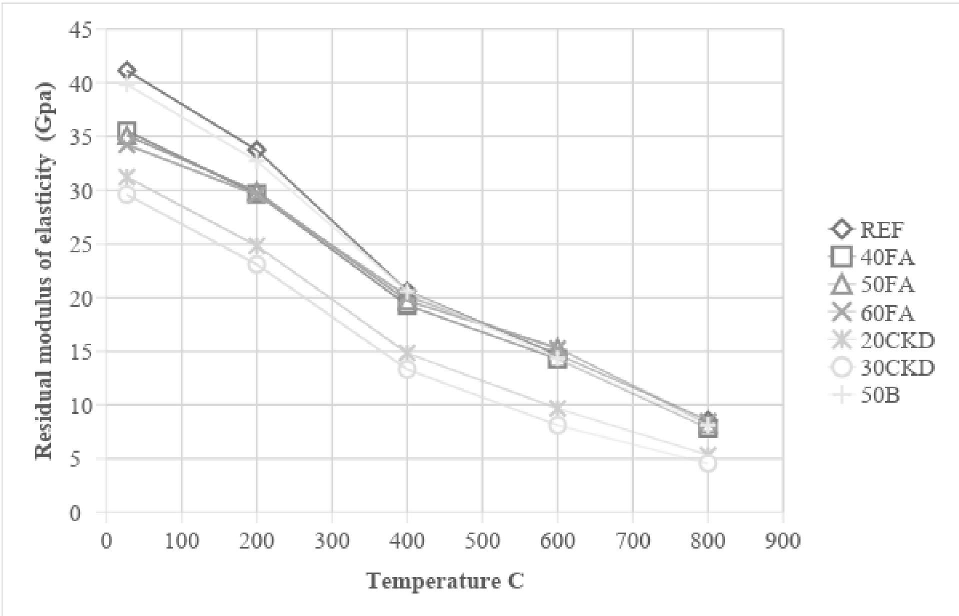

Figure 10. Residual modulus of elasticity of water cooled SCC mixes.

The relative residual modulus of elasticity at 800 °C was 27.3%, 30.3%, 31.7%, 32.5%, 21.8%, 18.2%, and 27.5% for the respective mixes. The higher amount of cement paste and lower coarse aggregate content in SCC, which have the main influence on modulus of elasticity, create a tendency in SCC for it to deteriorate rapidly with respect to modulus of elasticity at elevated temperatures. For water cooled specimens, as seen from Table (10) and Figure 10, these SCC mixes have lower elastic modulus compared to air cooled mixes; this also confirmed by Nassif [38]. This is probably due to the predominance of micro-cracks, especially in the "Interfacial Transition Zone", due to the high thermal gradients and volume changes.

5. Conclusions

- Without the use of any viscosity modifying admixtures, self-consolidating concrete mixtures were produced with sustainable materials: Portland limestone cement, high-volume class F fly ash, cement kiln dust, and low-dosage superplasticizers, with adequate fresh properties and mechanical performance suitable for structural applications.
- When fly ash was used with cement kiln dust (CKD) in a binary mix, it intrinsically alleviated the higher water requirements of CKD (including the higher requirement for super-plasticizers), and thus improved the fresh properties.
- The influence of high temperatures on compressive strength can be divided into notable ranges. At 200 °C, an increase in strength was detected in SCC mixes; at 400 °C, most mixes lost an insignificant percentage of their original strength; at 600 °C and beyond, all SCC mixes lost their strength rapidly.
- At elevated temperatures, FA concretes displayed the best performance, followed by 50B, REF, and CKD concretes. The mix containing 60% FA replacement gave the maximum relative residual strength.
- The splitting tensile strength, flexural strength, and modulus of elasticity of concrete mixes deteriorated more sharply than their compressive strength when exposed to elevated temperatures, especially after 400 °C and when water cooled.
- Water cooling methods result in higher strength losses compared with air cooling due to thermal shock; water spraying had a more remarkable influence on tensile and flexural strength than compressive strength.
- Concrete mixes that contain fly ash were found to be capable of maintaining their properties better at elevated temperatures and can thus be used in those sites where there is a high risk of fire. Concrete mixes with more than 20% CKD replacement should be avoided for such locations, because these mixes rapidly lose their strength at higher temperatures.

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