Effect of Fire Exposure on the Properties of Self-Compacting Concrete reinforced by Glass Fibers

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ABSTRACT

The optimal design of any structural elements requires examining all environmental risks, emergency accidents, and standard load cases. Exposure to fire is one of the most common safety threats. Nowadays wide developments are achieved in the field of concrete technology, therefore, experimental and theoretical investigations should be performed on the characteristics of such developed materials under different loading conditions. This study investigates the impact of fire exposure on the mechanical characteristics of self-compacting concrete, specifically compressive and tensile strength, modulus of elasticity, and stress-strain relation. The adopted fire exposure consisted of six steady-state temperatures (300, 400, 500, 600, 700, and 800°C) for one hour and a sudden cooling method. Four glass fiber volume fractions were adopted: 0, 0.5, 1, and 1.5%. The glass fiber volume fractions considered (0.5-1.5%) improved the mechanical properties investigated. Two states were detected for the effect of fire exposure. The effect of fire exposure was inversely proportional to fiber content in burning temperatures of 300-700°C, while the reduction in mechanical properties of 1.5% fiber content was greater than those of 0.5 and 1% when the temperature increased to 800°C. Furthermore, the addition of glass fiber changed the brittle mode stress-strain relation to semi-ductile for the non-burned and burned up to 600°C specimens, whereas a brittle behavior was detected when the temperature increased above 600°C. In general, a similar effect was noticed for all the glass fiber ratios considered regarding the slope of the stress-strain linear stage compared to the non-burned specimens, which was more salient when the burning temperature increased.

Keywords-self compacting concrete; glass fiber; flame; sudden cooling; modulus of elasticity; compressive strength; tensile strength

I. INTRODUCTION

Concrete is a congenital construction material. Although its tensile strength and brittleness are low [1-3], it is widely used in construction since its constitutive materials are available, workable, inexpensive, and have high strength. Currently, Self-Compacting Concrete (SCC) is classified as an advanced and widely used concrete due to its high flow ability, strength, low noise pollution, labor expense, and construction period, and it is used in important and difficult building structures [4-5]. High-rise buildings and underground structures are spreading due to continuous development in infrastructure manufacturing. These structures are more vulnerable to fire due to gas use, electrical appliances, and in some countries to terrorism. Many studies investigated the impact of fire and high-temperature exposure on the ultimate strength and durability of concrete. Fire flames and high temperatures also significantly affect spalling, stiffness, and strength properties [6]. Some studies observed that the residual compressive strength of SCC decreased when heated to an elevated temperature of up to 650°C [7-8]. Several studies showed that strength reduction is lower at burning temperatures up to 400°C [9-10].

In [11], SCC in reinforced concrete beams influenced by repeated loads and exposed to different fire-flame burning temperatures (200, 300, 400, and 500°C) for 30 minutes had a decrease in maximum ultimate load capacity (16, 23, 54, and 71%) in the case of sudden cooling conditions and a lower reduction in gradual cooling (8, 14, 36, and 64%). This variation between the two cooling methods was reduced with an augmentation in the burning temperature. In [7], the unconsumed compressive strength, tensile strength, and modulus of elasticity of SCC under the impact of different high temperatures and cooling methods were evaluated. A non-significant increase in compressive strength was observed at 150°C for both cooling cases, sudden and gradual. As the temperature rose to 300°C, the mechanical properties were being continuously decreased, and the residual compressive strength dropped by 22.26%. Regarding the tensile strength and modulus of elasticity, the reductions were approximately 50% at temperatures of 450-600°C.

Several types of fiber were considered in [12-14] to improve the mechanical properties of fire-exposed concrete. In [13], burning Reactive Powder Concrete (RPC) samples at temperatures of 300, 400, and 500°C were gradually and suddenly cooled. Three volume fraction percentages of hooked steel fiber (0, 1, and 1.5%) were considered. Increasing the burning temperature reduced the compressive strength of the concrete without fiber. In the case of 1% fiber content, there was a smaller reduction at 400°C burning temperature, especially for gradual cooling. Sudden cooling was more effective than gradual in the decrease in compressive strength. In [14], three cooling methods (sudden, gradual, and foam) were examined to investigate the influence of burning temperatures (300, 400, and 500°C) on RPC reinforced with micro steel fiber (0, 1.0, and 1.5%). The results showed that the addition of 1.5% fiber at 400°C with gradual cooling improved the concrete properties by 1.6%. Sudden cooling had a negative effect at different temperatures, especially when the burning temperature exceeded 400°C. The results also demonstrated that the worst behavior of concrete properties was observed for samples without fiber content at 500°C, reaching 42.65 and 33.5% decrease in gradual and sudden cooling, respectively, whereas there was an improvement in concrete properties with fiber content of 1.0 and 1.5% to 6.67, 3.13%, 3.14 and 0.57% for gradual and foam cooling, respectively.

This study aimed to investigate the effect of E-Glass fiber volume fraction on some fresh and hard properties of SCC and examine the influence of glass fiber reinforced SCC exposed to different burning temperatures (300, 400, 500, 600, 700, and 800°C) for one hour on different mechanical properties, such as compressive strength, splitting tensile strength, modulus of elasticity, and stress-strain diagram.

II. THE EXPERIMENTAL PROGRAM

A. Materials

This study used Tasloga Ordinary Portland cement (CEM I 42.5 N) in all SCC mixes, which follows [15] and [16]. Table I shows its physical and chemical characteristics. Crushed coarse aggregate of grade 5-20 mm and natural fine aggregate classified as zone 2, according to the requirements of the modified Iraqi specification No. 45/1984 and ASTM C33/C33M [17-18], were used, as illustrated in Tables II and III. This study also used 2% silica fume as a partial replacement for cement, which conforms to [19]. Densified silica fume of Chinese origin was supplied from "Sika Fume - HR, Concrete Additive", as displayed in Figure 1, and Table IV presents its chemical analysis and physical properties. To control the internal cracks that may occur when concrete is exposed to fire flame, different volume fraction (vf) percentages of E-Glass chopped fiber (GF) were adopted, 0.5, 1, and 1.5%, as exhibited in Figure 2. Table VI depicts the properties of the E-Glass fiber.

TABLE I. CEMENT CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES

Physical properties			
Test	**Test results**	**Limit of [15] type CEM I 42.5N**	**Limit of [16] Type I**
Specific surface area (Blaine method), (m^2/kg)	320	≥ 250	Air permeability test ≥260 [20]
Setting time (Vicat's method) Initial setting time: (hrs:min) Final setting time: (hrs:min)	 0:57 4:40	 ≥ 45 min ≤ 10 hrs.	 ≥ 45 min ≤ 6 hrs 15 min
Compressive strength (MPa) 2-day 3-day 7-day 28-day	 17.6 22.8 31.6 43.2	 ≥ 10 MPa ---- ---- ≥ 42.5 MPa	 ---- ≥ 12 MPa ≥ 19.0 MPa ---
Soundness (Autoclave method)	0.14 %	≤ 0.8 %	≤ 0.8 %
Chemical composition			
Compound	**Content %**	**Limit of [15]**	**[16] Type I**
Lime (CaO)	62.8	----	----
Silica (SiO_2)	20.57	----	----
Alumina (Al_2O_3)	5.56	----	----
Iron Oxide (Fe_2O_3)	3.32	----	----
Magnesia (MgO)	2.91	Max. 5.0	Max. 6.0
Sulfate (SO_3)	2.21	2.8 if C_3A > 3.5 ≤ ≤ 2.5 if C_3A ≤ 3.5	if C_3A > 8.0 Max. 3.5
Insoluble residue (I.R)	0.77	Max 1.5	Max 1.5
Loss of ignition (L.O.I)	1.94	Max 4.0	Max 3.0
Main compounds of OPC			
Tri calcium silicate (C_3S)	50.79		
Di calcium silicate (C_2S)	20.74		
Tri calcium aluminate (C_3A)	9.12		
Tetra calcium aluminate ferrite (C_4AF)	10.10		

TABLE II. PHYSICAL AND CHEMICAL PROPERTIES OF COARSE AGGREGATE

Sieve Size (mm)	**% Passing by weight**	**Percentage of materials by mass passing sieves**	
		[17]	**[18]**
Sieve Size (mm)		(5-20) mm	4.75-19.0 mm
37.5	100.0	100	---
25	---	---	100
20 or 19	97.9	95-100	90-100
14	100.0	Not limited	---
10 or 9.5	---	30-60	20-55
5 or 4.75	---	0-10	0-10
2.36	38.1	Not limited	0-5
SO_3 content %	0.075	Max. 0.1	---

TABLE III. PHYSICAL AND CHEMICAL PROPERTIES OF FINE AGGREGATE

Sieve size (mm)	% passing by weight	Percentage of materials by mass passing sieves	
		[17]	[18]
	Results	Zone 2	
10 or 9.5	100.0	100	100
4.75	97.6	90 –100	95-100
2.36	87.5	75 – 100	80-100
1.18	76.7	55 – 90	50-85
0.60	57.1	35 – 59	25-60
0.30	23.9	8 – 30	5-30
0.15	5.0	0 – 10	0-10
Finer than 0.075 mm	3.8	Max. 5	Max. 5
Clay lumps and friable particles	0.37	Max. 1	2-10
SO_3 content (%)	0.43	Max. 0.5	---

TABLE IV. CHEMICAL AND PHYSICAL PROPERTIES OF SILICA FUME

Chemical composition		
Oxides	**Content %**	**[19]**
SiO_2	92.95	Min. 85%
Fe_2O_3	1.22	----
Al_2O_3	0.34	----
CaO	0.54	----
MgO	0.90	----
SO_3	0.4	----
L.O.I	3.4	Max. 6%
Moisture content	1.1	Max. 3%
Physical properties		
Property	**Test result**	**[19]**
Color	Dark grey	----
Specific surface area (m^2/kg)	20000	Min. 15000
Retaining on sieve 45µ (%)	3.7%	Max. 10
Strength activity index (%)	113	Min. 105

TABLE V. PROPERTIES OF SUPER-PLASTICIZER (GLINEUM 51)*

Property	Details
Form	Viscous liquid
Color	Light brown
Relative density	1.1 @ 20 ºC
PH	6.6
Viscosity	128 ±30 cps @ 20ºC
Transport	Not classified as dangerous

*Properties of super-plasticizers according to the manufacture datasheet

TABLE VI. GLASS FIBER PROPERTIES*

Property	Details
Relative Density	2540 kg/m^3
Average Length	30 mm
Diameter	0.6 mm
Modulus of Elasticity	$80x10^3$ MPa
Tensile Strength	1200 MPa
Aspect Ratio (l/d)	50
Softining point	840 ºC
Strength degradation point	350 ºC

*According to the conformity certificate

Fig. 1. E-Glass chopped fiber.

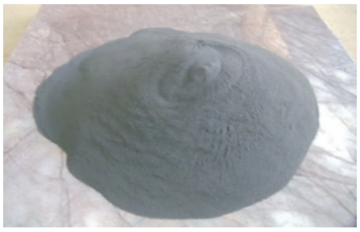


Fig. 2. Silica fume.

B. Tested Specimens

1) Self-Compacting Concrete (SCC) Mix Design

The SSC mix was designed according to [21]. Several trial mixes were created to reach a compressive strength of 45 MPa with 0.34 w/b ratio. E-Glass chopped strand glass fiber was used throughout the experimental process with an aspect ratio of 50 and volume fraction (0.5, 1.0, and 1.5%), as shown in Table VII. The fresh tests for SCC mixes were based on [21] and test methods, as portrayed in Figure 3, and were all within its standards, as illustrated in Table VIII.

TABLE VII. DETAILS OF SCC MIXTURES

Mix Type	Mix Proportion (kg/m3)					SP (% by cement weight)	Silica fume (kg/m^3)
	Water	Cement	Sand	Gravel	GF		
SR	154	445	886	942	0	1.3	9
SG0.5	154	445	886	942	12.7	1.3	9
SG1	154	445	886	942	25.4	1.3	9
SG1.5	154	445	886	942	38.1	1.3	9

TABLE VIII. SCC FRESH TEST RESULTS ACCORDING [21]

Characteristic	Tests method	Test result	[21]	
			Class	Limits
Flow/filling ability	Slump flow	735 mm	SF2	660-750
Viscosity/flow ability	T_{500}	2.5 sec	VS2/VF2	> 2
Passing ability	L-box	0.94	PA2	≥ 0.8 with three bars
Segregation resistance	Sieve segregation	19.6 %	SR1	≤ 20

Fig. 3. Slump flow test.

C. Experimental Program

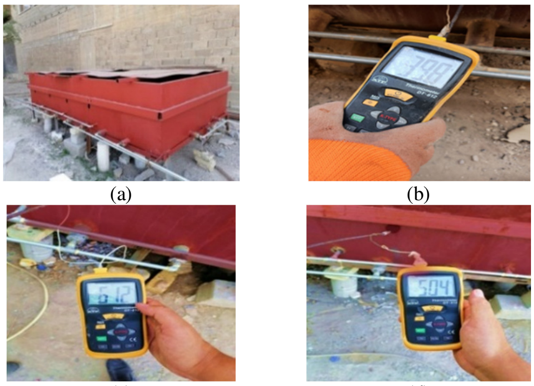
The SCC mixes were cast into molds of 150×150×150 mm to test compressive strength according to [22]. A splitting tensile strength test 150×300 mm cylinder mold was cast according to [23]. The static modulus of elasticity test for all mixes was carried out following [24]. This test was performed on a cylindrical specimen with dimensions 150×300 mm. A dial gauge with an accuracy of 0.001 was used to measure the vertical displacement, as displayed in Figure 4. The stress-strain curve was used to determine the modulus of elasticity, according to:

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

The fire exposure test procedure was performed in a U-shaped steel furnace of dimensions 3000×1350×500 mm. The considered steady-state temperatures were 300, 400, 500, 600, 700, and 800°C for one hour, which was measured after the target temperature was reached. An ATP DT-612 thermocouple device and a wire sensor type K were used to monitor the temperature, as depicted in Figure 5. The temperature rise inside the furnace was according to [25]. Sudden cooling was performed for all the specimens immediately after the burning test was completed, and then they were tested.

(a) (b) (c)

Fig. 4. Tests of SCC specimens: (a) splitting tensile strength test, (b) compressive strength test, and (c) static modulus of elasticity test.



(a) (b)

(c) (d)

Fig. 5. (a) Burning furnace, (b) digital thermometer at 400°C, (c) digital thermometer at 500°C, (d) digital thermometer at 600°C.

III. TEST RESULTS AND DISCUSSION

A. Fresh Properties of SCC

Table IX demonstrates the results of fresh properties. Slump flow diameter, L-Box test, and Segregation Index (SI) percentage ranged between 652-733 mm, 0.96-0.82, and 18.4-13.1%, respectively. The highest slump flow diameter, L-Box, and SI were achieved for the mixture without fiber (SR). The addition of fiber decreased the fresh test results compared to SR. The reduction was directly proportional to the fiber content, as for the SG1.5 mix it reached 11.05, 14.58, and 28.8% slump flow diameter, L-Box, and SI, respectively. The addition of fiber increases flow resistance and decreases flow ability as an outcome of increased interlocking and friction between fiber and aggregate, as presented in [26]. The T500 test was performed to evaluate the viscosity of the SCC mixes. The T500 test results ranged from 2.4 to 4.5 s. The findings indicate that the T500 test results for the mixtures containing fiber were longer than the mixes without. In general, adding fiber produces concrete with more cohesion and interlocking, leading to a slow flow of the SCC mixture, as it obstructs the flow within the constrained region, as shown in [27].

TABLE IX. FRESH PROPERTIES OF SCC MIXES

Mixes	Slump flow (mm)	T500 (s)	L-box	Segregation Index % (SI)
SR	735	2.5	0.94	19.6
SG0.5	692	3.3	0.89	18.7
SG1	675	3.9	0.85	17.6
SG1.5	662	4.6	0.81	15.5

B. Mechanical Properties of SCC

1) Compressive Strength

Compressive strength is one of the most essential concrete characteristics. Figure 6 and Table X illustrate the compressive strength results at 56 days, including 28 days of water curing and 28 days under laboratory conditions, after exposure to fire flame at 300, 400, 500, 600, 700, and 800˚C. The results reveal that compressive strength was directly proportional to the glass fiber content and inversely proportional to the burning temperatures for all fiber volume fractions. In the case of the SR mix, the reduction in compressive strength reached 30.3, 37.9, and 53.4% at 500, 600, and 700°C, respectively, whereas there was a difference in decrease values as the fiber content increased, being 29.5, 27.2, and 23.1% at 500℃, 36.9, 33.4, and 28.9% at 600°C, and 50.2, 47.4 and 44.6% at 700°C for 0.5. 1.0, and 1.5%, accordingly. When the specimens were burned, many changes occurred in the properties of the concrete, resulting in a considerable reduction in compressive strength. When the temperature increases above 300°C, calcium hydroxide in cement begins to dehydrate, releasing more water vapor and significantly lowering the compressive strength of concrete. The deterioration of the interfacial bond between the aggregate and the cement paste at high temperatures is responsible for the reduction in the compressive strength of the concrete [28]. This can be related to the improvement in the mechanical bond of concrete, where the fiber can delay the creation of microcracks and stop their spread to some extent [29]. This behavior changed at 800°C, causing a slight modification with 1 and 1.5% fiber content, reaching a reduction of 63.3 and 65.2%, respectively. The specific drop is attributed to the softening of the glass fiber at this temperature, i.e., a reduction in the glass fiber characteristics. Therefore, the tensile and compressive strength properties were attenuated since porosity and microcracks increased.

TABLE X. COMPRESSIVE STRENGTH TEST RESULTS

Burning temperature (°C)	Compressive strength (MPa)			
	SR	SG0.5	SG1.0	SG1.5
Normal temp.	45.23	45.78	46.89	48.4
300	38.89	40.08	41.13	43.16
400	35.39	36.55	38.42	40.29
500	31.52	32.28	34.15	37.23
600	28.07	28.9	31.23	34.41
700	21.09	22.78	24.65	26.84
800	14.12	17.78	17.23	16.84

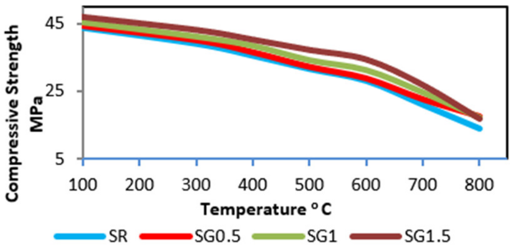


Fig. 6. Effect of burning temperature on the compressive strength of SCC.

2) *Modulus of Elasticity*

Table XI and Figure 7 exhibit the results of the elasticity modulus, indicating a behavior similar to the compressive strength test results. Glass fiber improved the static modulus of elasticity, as the optimum modification was found in the samples with 1.5% fiber content, reaching an 11.8% increase at ambient temperature. The glass fiber modulus (80×103 MPa) enhanced the modulus of elasticity of SCC. As the burning temperature increased, the deterioration of the elastic modulus for the same fiber content increased. Figure 8 demonstrates that the reduction reached 17.2, 25.7, and 36.8% at 600, 700, and 800°°C, respectively. In addition, this deterioration increased proportionally as the burning temperature rose for all fiber volume fractions. At a burning temperature of 800°C, these trends changed since the glass fiber softening point was achieved, so samples with 1.5% fiber by volume had the maximum reduction of 42.4%.

TABLE XI. MODULUS OF ELASTICITY TEST RESULTS

Burning temperature (°C)	Modulus of elasticity (MPa)			
	SR	SG0.5	SG1.0	SG1.5
Normal temp.	28219	29390.5	30732.6	31566.2
300	26167	27564.5	28910.1	29833.9
400	24961.7	26368.3	28108.4	29102.3
500	23557.5	24839.7	26520.6	27602.3
600	22230.8	23557.2	25448.9	26613.9
700	19269.8	21026.9	22832.7	23738.4
800	16847.3	18693.2	18417.2	18164.1

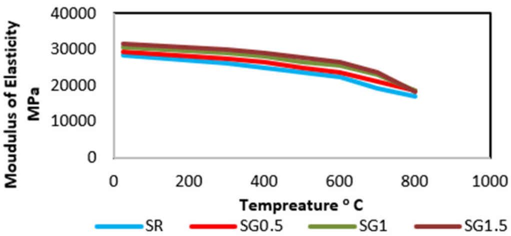


Fig. 7. Effect of burning temperature on the modulus of elasticity of SCC.

3) *Splitting Tensile Strength*

Table XII and Figure 8 present splitting tensile strength results. Glass fiber had a direct effect on splitting tensile strength, as the maximum reduction was 21.6 % for the samples with 1.5% content. This may be attributed to the fiber mechanism in preventing crack propagation and improving matrix bonding. The splitting tensile strength was inversely proportional to the burning temperature. After exposure to fire flame, it was observed that glass fiber limited splitting tensile strength reduction since it eliminates the damage, spalling, and cracking of SCC specimens. These reductions were 23.6, 21.4, and 22.7% at 500°C, 34.7, 27.6, and 25.6% at 600°C, and 39, 38.3, and 35.2% at 700°C for 0.5. 1, and 1.5% volume fractions of glass fiber, respectively. At higher temperatures the evaporation of water from concrete pores increases, resulting in an increase in shrinkage, which leads to a decrease in splitting tensile strength. Also, the worst case of splitting tensile strength reduction was achieved at 800°C with a fiber content of 1.5%, reaching 78.6%.

TABLE XII. SPLITTING TENSILE STRENGTH TEST RESULTS

Burning Temperature (°C)	Splitting Tensile Strength MPa			
	SR	SG0.5	SG1.0	SG1.5
Normal temp.	4.8	5.12	5.6	5.84
300	4.12	4.70	4.9	5.43
400	3.82	4.26	4.6	4.82
500	3.36	3.91	4.4	4.51
600	3.08	3.34	4.05	4.34
700	2.78	3.12	3.45	3.78
800	1.03	1.65	1. 54	1.25

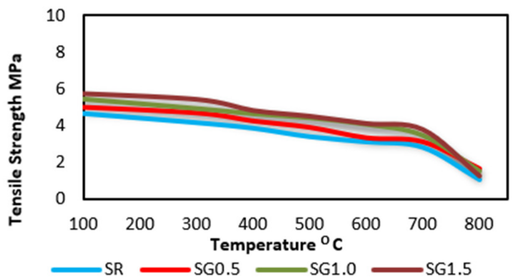


Fig. 8. Effect of burning temperature on the splitting tensile strength of SCC mixes.

4) *Stress-Strain Relation*

The specific action of stress-strain with the presence of glass fiber changed from brittle to semi-ductile behavior, as fiber contributes to concrete cracks bridging and preventing sudden failure. This behavior was present and clear at a temperature of 25°C for all samples containing glass fiber, as displayed in Figure 9. The particular behavior was lost when the burning temperatures increased and the glass fiber content changed. When the burning temperature reached 600°C, this behavior began to return to a brittle stage. The stress-strain stress relation at 25°C showed that fiber enhanced specimen rigidity, even with 0.5% fiber content. As the fiber content increased, the improvement percentages converged, i.e., there was no significant difference between the fiber volume fractions considered. The glass fiber effect was more pronounced as the burning temperature increased, since for the samples containing 1.5% glass fiber content, the decrease in the E was less than that of samples containing 0.5 or 1%. As exhibited in Figures 10-15, the curves began to diverge from each other.

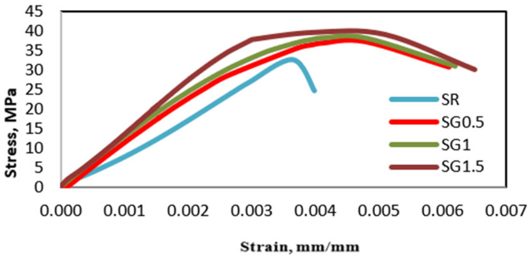


Fig. 9. Stress-strain at ambient temperature.

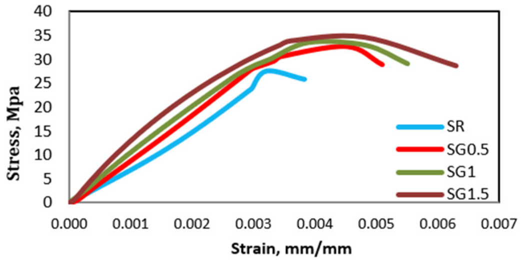


Fig. 10. Stress-strain at 300°C.

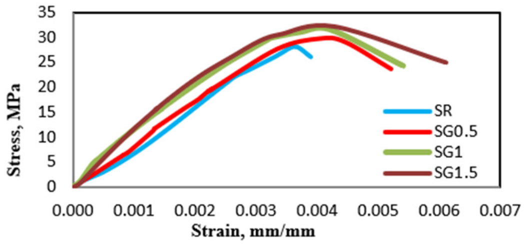


Fig. 11. Stress-strain at 400°C.

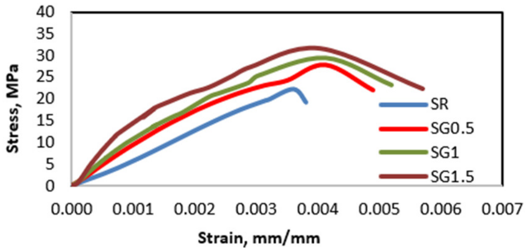


Fig. 12. Stress-strain at 500°C.

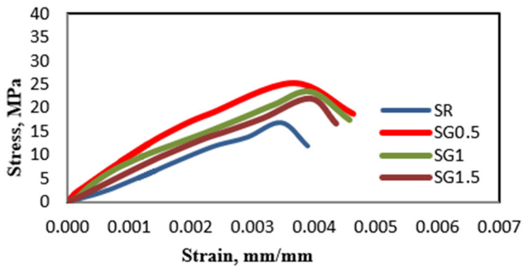


Fig. 13. Stress-strain at 600°C.

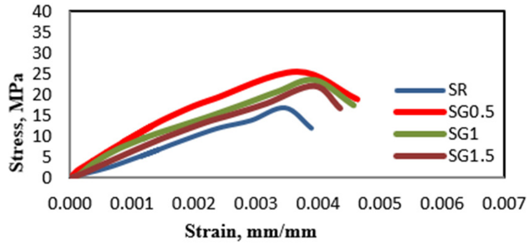


Fig. 14. Stress-strain at 700°C.

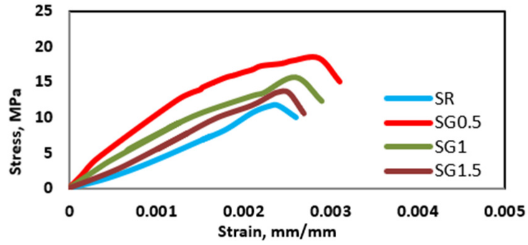


Fig. 15. Stress-strain at 800°C.

IV. CONCLUSIONS

This study investigated the effect of glass fiber content on the mechanical properties of SCC exposed to fire, concluding the following:

- Adding glass fiber deteriorated the fresh properties of SCC, i.e. slump, L-Box, and segregation. Furthermore, there was an increase in T500 compared to the reference mix. However, they were still within the EFNARC standard requirements.
- The glass fiber volume fractions considered (0.5-1.5%) improved compressive strength, tensile strength, and modulus of elasticity for the non-fire-exposed specimens.
- The reduction in mechanical properties due to fire exposure was inversely proportional to the fiber volume fraction for burning temperatures of 300-700°C.
- Increasing the burning temperature to 800°C changed the context of the glass fiber effect. The percentage of decrease in mechanical properties of samples with 1.5% fiber content was greater than those of 0.5, and 1%.
- Adding glass fiber changed the brittle trend of concrete stress-strain relation to semi-ductile for the non-burned and burned up to 600°C specimens, while the behavior was more brittle as the temperature increased more than 600°C.
- A similar effect was noticed for the considered glass fiber ratios regarding the slope of the stress-strain linear stage concerning the non-burned specimens.
- Increasing the glass fiber volume fraction was more significant in terms of linear stage behavior as the burning temperature increased, i.e., the stress-strain curves diverged more as the burning temperature rose.
- For the fire exposure of structural elements, it is recommended to limit the glass fiber volume fraction to

avoid reducing strength as the burning temperature approaches the glass fiber softening point.

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