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Effect of Fiber on Mechanical Properties and Toughness of Self-Compacting Concrete Exposed to High Temperatures

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ABSTRACT: The weakness of concrete in tension and its brittleness under various types of loadings has resulted in using different and convenient fibers, including steel and poly propylene, which in addition increasing of ductility and improvement in post-cracking behavior of concrete, have a major role in minimizing shrinkage and thermal cracks. In this study, the effects of high temperatures (200, 300, 400 and 600 °C) on compressive strength, splitting strength, flexural strength and energy absorption capacity or toughness of self-compacting concretes containing steel, polypropylene and polyethylene terephthalate (PET) fibers were evaluated. The test results on fresh concrete imply that the increase in fibers make some criteria of self-compacting concrete unachievable. Compared to the unheated non-fiber specimens (SCC2), increasing temperature up to 600oC decreased compressive strength at steel, polypropylene and PET fiber containing specimens 30, 37.5 and 34.5%, respectively. However, residual strengths were 22, 8 and 13% higher than the heated non-fiber specimens. At 600 oC, flexural toughness and maximum flexural load were 5 and 1.8 times higher than control specimens. Adding fibers had a positive effect on specimens' explosive spalling so that spalling threshold was shifted to higher temperature levels. The proposed relationships and models at the elevated temperature are compared with experimental results. These results are used to predict more accurate and general compressive and splitting strengths, flexural strength, elasticity modulus, flexural load peak-point and flexural deflection relationships.

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1- Introduction

The concrete industry has experienced impressive development and improvement in recent years and this has led to the production and development of concretes with high qualities and performance in cases such as durability and strength, including high performance concretes (HPC) and self-compacting concretes (SCC). Self-compacting concrete was presented in 1988 for the first time and the studies on its workability were implemented between the years 1989 and 1993 at Tokyo University [1-3]. Self-compacting concrete is a concrete with a high workability and no segregation which could fill the space provided by frameworks and between reinforcing bars without mechanical compaction [4]. Due to the three significant characteristics called "filling ability", "pass ability" and "resistance against segregation", self-compacting concretes raise economic efficiency. Considering the increasing use of self-compacting concretes, the need for knowledge about the effective parameters in lowering the quality and service time; including experiments on concrete elements in different environmental and temperature conditions has been a case of inevitability. Due to the non-flammable nature of concrete structures in high temperatures, they have considerable advantages. But among various types of concretes, concrete mixtures with a high compaction such as self-compacting concretes and high strength concretes are more vulnerable to temperature rise effects. Due to less porosity and decreased void connections in self-compacting concretes and high strength concretes, humidity and water vapor hardly could escape from their structure that leads to internal pressure rise and may cause vulnerability of the structure. The evaluation of concrete structures' resistance to fire requires enough knowledge about behavioral properties of their constituent materials in high temperatures [5]. Among the first studies conducted on concrete under higher heat rates, the studies by Malhotra [6] in 1956 can be mentioned. In line with this, more studies are performed in order to analyze some properties of self-compacting concretes under fire, including thermal and mechanical properties, deformations and the consequent phenomena such as explosive spalling. If severe, spalling can have a deleterious effect on the strength of reinforced concrete structures. Spalling may significantly reduce or even eliminate the layers of concrete cover. This exposes the reinforcement to high temperatures, leading to a reduced strength and, hence a deterioration of the mechanical properties of the structure as a whole [7, 8].

Considering the low tensile strength of concrete and consequently, the brittleness of this material, the fibers with different length and- thickness ratios have been used in the recent decades. Using fibers in concrete and cement-based composites has been increased considerably in order to increase the toughness and ductility in the post-crack region. Collapse and failure of the concrete are strongly dependent on the formation of micro and macro cracks under loading or environmental effects [9]. Heat and humidity changes in cement paste create micro-cracks which concentrate on coarse aggregate surfaces. By increasing the loading and other environmental factors, micro-cracks spread into the concrete matrix. Using various fibers is an effective

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Corresponding author, E-mail: behzad.tahmouresi@gmail.com factor to prevent developing cracks. It also leads to the improvement of energy absorption property and toughness. As a replacement for thermal reinforcement, they can play a major role in preventing explosive spalling, shrinkage and thermal cracking. The Most common fibers which could be mentioned are steel and polypropylene (PP) fibers [10-12].

Furthermore, considering the population rise and the consequent increase of oil and polymeric-based waste materials, some concerns have raised about their destructive effects on eco-systems. Due to this fact, using new recycled materials such as polyethylene terephthalate (PET) as fibers or fine aggregates in concrete and cementitious products is inevitable [13-15]. Impact resistance and energy absorption of recycled plastic fiber containing concrete and PET were studied by Soroushian et al. The obtained results implied an improvement in strength [16].

The research of Khaliq and Kodur [3] on self-compacting concrete under high amounts of heat showed the presence of fibers has noticeably improved the flexural strength and helped the integrity and stability of the concrete structure. It also had a positive effect on the spalling phenomenon. The research performed by Bolt et al. [14] about the effect of recycled PET materials on thermal properties of concrete implied that the presence of recycled materials has prevented the heat loss considerably and led to the performance improvement in heat conduction. In another study [15] performed on mechanical-thermal properties of PET containing concretes, it was found that PET led to 18% decrease in thermal conduction coefficient, 35% increase in compressive strength, increase of at least 2% and at most 41% of the first crack point and increasing at least 8% and at most 656% increase in toughness. Also, they implied that using PET fibers may be a suitable reinforcing technique for concrete and a good nominee with a high potential for analytical and experimental research in real scale. Another research [17] named polypropylene effect on self-compacting concrete with a high strength subjected to fire showed that using polypropylene fiber together with increasing the thermal resistance of concrete, leads to thermal gradient improvement (due to thermal stresses) in concrete specimens under heating-cooling cycles. In evaluations performed by Pol et al. [18] on steel and polypropylene fiber effects on thermal and mechanical properties of concrete, the rise of 2.63 to 3.49 times of peak point strain and also keeping 26% of toughness of post-peak point were observed.

In this study, the effect of steel, polypropylene and PET fibers on fresh (rheological) and hardened properties (compressive, indirect tensile and flexural strength and toughness) of self-compacting concrete under heat regimes of room temperature (20), 200, 300, 400 and 600 °C was evaluated.

2- Experimental program

2- 1- Materials

Cement used in this research was type 1:42.5 according to ASTM C150. Consumed silica fume (SF) in accordance with ASTM C1240 standard was also prepared as a mineral pozzolan from Ferroalloys Co. Physical properties and chemical composition of cement and silica fume are presented in Table 1. Coarse aggregate used in this research was river-based and the maximum aggregate size of 12.5 mm was chosen. Fine aggregate also had a natural source in which 80% of the mass was 0 to 3 mm and the remaining 20% was 3 to 6 mm. Coarse and fine aggregates had densities of 2.67 and 2.61 (g/cm^3) and their water absorptions were, 0.76% and 2.1% of mass, respectively. Limestone powder (LSP) was used as a filler in concrete mixture due to its positive effect on increased flowability and viscosity and also decreased segregation. The particle size distributions of aggregates are plotted in Figure 1.

Table 1. Characteristics of cement and silica fume

Physical Properties			Chemical Composition (% Mass)		
Initial set time (min)	Cement	110		Cement	SF
Final set time (min)	Cement	170	CaO	64.38	1.5
density (gr/cm^3)	Cement	3.15	SiO2	21.08	92
	SF	2.2	Al_2O_3	5.36	1.5
			Fe_2O_3	3.64	2.5
Specific area (cm^2/gr)	Cement	3150	MgO	2	2
	SF	19000	K_2O	0.82	-
			Na_2O	0.5	-

In this research, three different types of fibers, including steel, polypropylene (PP) and PET were used. Considering limitations advised by European Federation of National Associations Representing for Concrete (EFNARC) instruction [19] and also in order to reach self-consolidation conditions of concrete, different amounts of fibers were chosen. Consuming percentage of steel fibers were 0.4, 0.5 and 0.6%, for polypropylene fibers 0.03, 0.05, 0.1% and PET fibers 0.2, 0.3, 0.4% of concrete volume was used (Figure 2). Characteristics of fibers are addressed in Table 2.

Table 2. Characteristics of fibers

Fiber Type	Length (mm)	Diameter (mm)	Tensile Strength (MPa)	Density (gr/cm^3)	Melting point (°C)
Steel	52	1	1000	7.85	1500
PP	12	0.1	450-550	0.91	165
PET	40	3×0.2	420-490	1.33	160

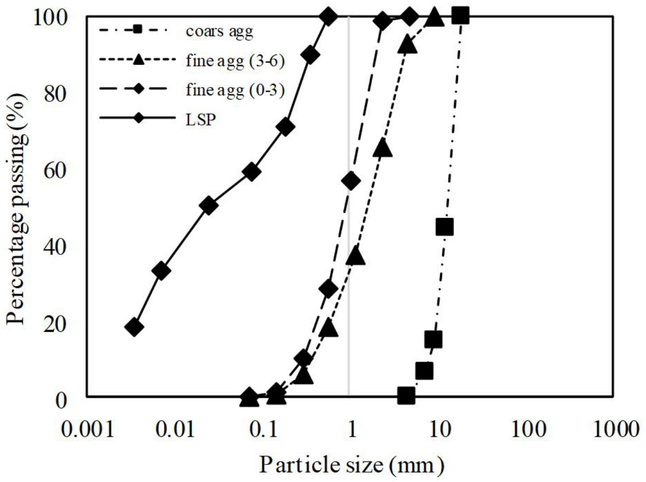

Fig. 1. Particle size distributions of aggregate and LSP.

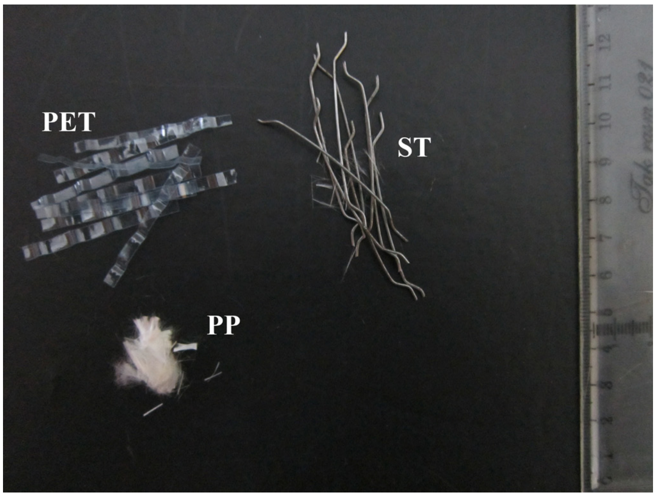

Fig. 2. The type of fiber used

2- 2- Mix designs

Considering the main factor of self-compacting concrete from the perspective of workability, fill ability, and segregation resistance, the mix designs were evaluated in two phases. The first phase is rheological properties (fresh concrete) and the second phase is hardened concrete. In the first phase, three different volume percentages of every type of fibers were used in mix designs and after mixing, the rheological experiments were performed on fresh concrete. In the second phase, one of the best-made mix designs, in terms of meeting the rheological properties in the first phase, compatible to EFNARC instruction [19] was chosen as the main mix design. In the first phase, the slump test was performed on all of the mix designs. V funnel and L box tests were performed on mixtures which had slumps in desirable range and no signs of segregation and bleeding was observed. At the second phase, the concrete mixture was poured into molds in order to evaluate the mechanical properties. Molds were covered by plastic sheets in order to prevent the loss of humidity in fresh concrete. According to ASTM C192, after 24 hours, specimens were demolded and placed in a saturated lime water tank at the controlled temperature of 20 °C till the testing day. Figure 3 shows concrete specimens under curing. Mix designs are mentioned in Table 3.

2- 3- Test Procedures

2- 3- 1- Rheological properties

Experiments related to fresh concrete were included (slump flow, T50, V funnel, and L-Box). In slump flow test, the diameter of the overspread circle and the time to reach the circular diameter of 500 mm were measured as an index for plastic viscosity. In V funnel experiment, time and quality of concrete extraction from funnel are important. This test also can be a good index for concrete uniformity in a visual evaluation. The L-Box experiment can be an index for filling ability and evaluation of the passing ability of concrete through reinforcements.

2- 3- 2- Mechanical Properties

The compressive strength of self-compacting concrete was evaluated using cubic specimens with dimensions of 150 mm according to BS EN 12390-3. The test speed was 0.3 MPa/s. the splitting tensile strength test was performed according to ASTM C496 on cylindrical specimens with a diameter of 150 mm and height of 300 mm.

The flexural three-point strength test was performed by universal testing machine with a loading rate of 0.5 mm/s according to ASTM C1609 on prismatic specimens with dimensions of 100×100×500 mm. The distance between two supports as shown in Figure 4, was 400 mm. Toughness is a characteristic of the material which shows its resistance to failure under applied stresses. According to its definition, toughness is the ratio of absorbed energy (area under the load-deflection curve) to the section area in flexural test procedure which can be calculated by Equation 1:

$$\text{Toughness=absorbed energy}/\left(b\times h\right)\ \left(J/m^2\right) \qquad (1)$$

Where b is the width of the prismatic specimen (mm) and h is the depth of prismatic specimen (mm).

For the evaluation of heat effect on mechanical strength behavior, fiber reinforced self-compacting concrete specimens were experimented at four thermal regimes of 200, 300, 400

Table 3. Mix designs (kg/m^3)

MIX ID	Water	Cement	Silica Fume	LSP[a]	aggregate		Fiber		
					Coarse	Fine	ST	PP	PET
SCC0	171	450	0	0	655	1150	0	0	0
SCC1	171	405	45	0	650	1140	0	0	0
SCC2	171	405	45	250	651	984	0	0	0
SCC2-ST6	171	405	45	250	651	984	47.1	0	0
SCC2-ST5	171	405	45	250	651	984	39.51	0	0
SCC2-ST4	171	405	45	250	651	984	31.4	0	0
SCC-PP1	171	405	45	250	651	984	0	0.91	0
SCC2-PP05	171	405	45	250	651	984	0	0.454	0
SCC2-PP03	171	405	45	250	651	984	0	0.273	0
SCC2-PET4	171	405	45	250	651	984	0	0	5.36
SCC2-PET3	171	405	45	250	651	984	0	0	4.02
SCC2-PET2	171	405	45	250	651	984	0	0	2.68

[a]: Limestone powder

and 600 °C inside the electrical furnace. In the furnace, the specimens were heated at a constant rate of 6℃/min, from the room temperature to the prescribed temperatures. The theoretical heating procedure described by the temperature time curves shown in Figure 5 was used in heating the test specimens in the present study [20-22]. The target temperature was maintained for 2 hours before electric heating was turned off and then the specimens were naturally cooled down to the room temperature. An air mixing device helped to ensure that all specimens experienced the same temperature exposure. During the heating period, water vapor was allowed to escape freely. Mechanical testing was performed (after 24 hours cooling period) on three specimens (for each mix), that the average value was reported as the final result.

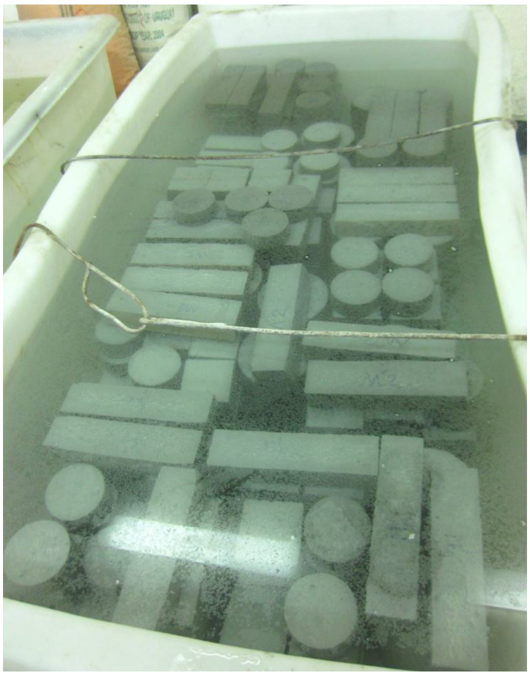

Fig. 3. Concrete specimens under curing

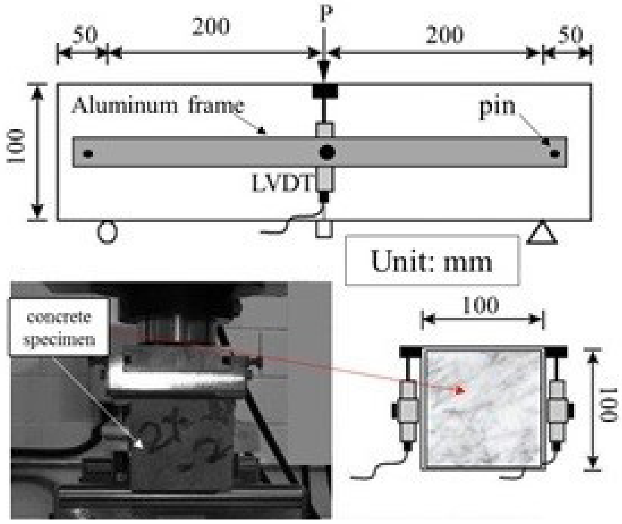

Fig. 4. Test setup for the three-point flexural test.

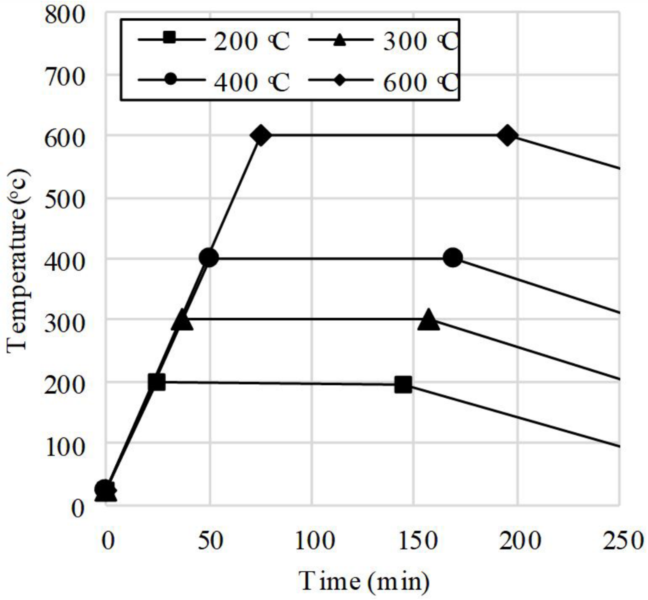

Fig. 5. Schematic of temperature-time curve

3- Results and discussion

3- 1- Rheological Properties

For all of the mixes related to phase 1, slump flow experiment and T50 were performed (Figure 6). V funnel and L-Box experiments were implemented on the mixes which did not show any bleeding and segregation. Test results for mixes in the first phase is presented in Table 4. It is observed that SCC0 and SCC1 mixes are not classified in the range of self-compacting concrete because of water separation and segregation. In the mix of SCC2 with an increase in fine aggregate amount, the conditions of self-compaction would be satisfied. Among these three mixes, SCC2 is selected as the control mix. It is obvious that slump flow index will decrease with the increase in fiber amount which could be seen in Table 4. During the slump test procedure, aggregation of the mixture in the central area is obvious that, with a decrease in fiber percentage, this phenomenon tends to disappear. Considering this fact, mixes named SCC2-ST4, SCC2-PP03, and SCC2-PET2 were chosen for the second phase.

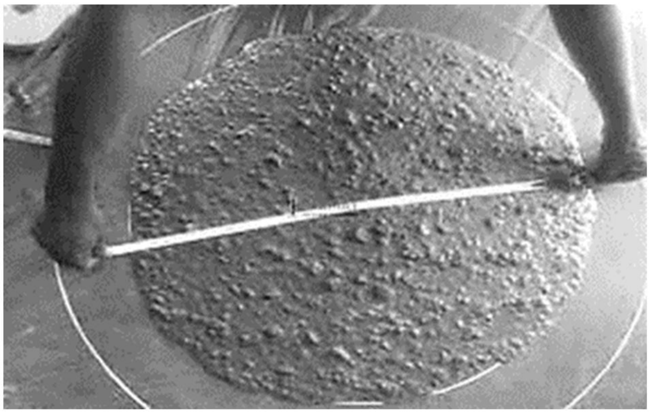

Fig. 6. Slump flow and T_{50} test

Table 4. Summary of rheological tests results

MIX ID	Slump (mm)	T_{50} (s)	L- Box (H2/H1)	V- Funnel (s)
SCC0	670	-	-	-
SCC1	650	-	-	-
SCC2	670	1.8	3	0.92
SCC2-ST6	610	-	-	-
SCC2-ST5	630	7	19	0.71
SCC2-ST4	530	4	10	0.82
SCC-PP1	600	7	-	-
SCC2-PP05	680	5	-	0.85
SCC2-PP03	610	3.5	5	0.94
SCC2-PET4	610	-	-	-
SCC2-PET3	650	5.5	18	0.78
SCC2-PET2	680	3	6	0.9
EFNARC*	650-680	2-5	6-12	0.8-1

3- 2- Mechanical Properties

The results of compressive strength test under room temperature conditions (20 ℃) in different ages are presented in Figure 7. With an increase in age, the compressive strength of specimens also increased. The presence of steel fibers led to compressive strength increase up to 10%. Adding polypropylene and PET fibers to the mixtures caused a decrease of minimum 9% and 7% percent and maximum 15.1% and 15.5% in compressive strength, respectively. Specimens, including steel fibers had strength increase up to 30% compared to polypropylene and PET fibers containing specimens.

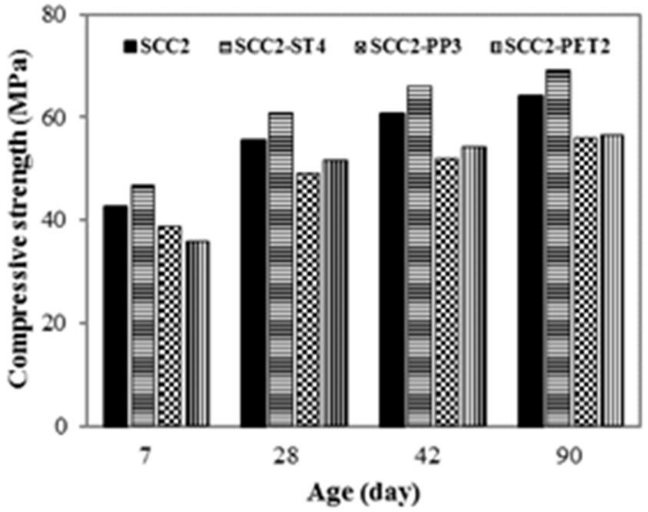

Fig. 7. Compressive strength of unheated specimens in different ages

Figures 8 and 9 show the compressive strength and splitting strength results under different thermal conditions. The steel fibers containing specimens showed more strength under various thermal regimes compared to the others, respectively. Increasing the temperature to 600°C, the compressive strength of steel fiber reinforced specimens, compared to SCC2 and SCC2-ST4 unheated specimens, had 29% and 35% decrease, respectively. Compressive strength of polypropylene and PET fibers containing specimens at 600 ° C, compared to SCC2 unheated specimen, had 37.5% and 34.6% decrease, respectively. According to Figure 8, it is observed that compressive strength of polypropylene and PET fibers containing samples up to 300 ° C is less than the strength of SCC2 specimens' strength; but by increasing temperature, the decrease rate of strength for SCC2 specimen rises which shows the positive effect of fibers in high temperatures [18, 22]. The amount of strength maintenance in fiber reinforced specimens in temperatures of 600 ℃ compared to SCC2 specimens that was 8% to 21%. Figure 8 shows the tangible reduction in compressive strength at temperatures above 400 ℃ which could be a reason for the emerged physical and chemical changes [3]. Based on the report by Liu et al. [22] the increase in porosity for polypropylene fibers containing specimens, despite the tendency of fibers to melt down, is not considerable. It appears to be a shortcut for bridging between pores and the consequent increase in gas permeability. The presence of fibers during the increase of heat regime has caused vulnerability reduction in cementitious matrix. With an increase of heat, vaporization of internal cementitious matrix water induced pore pressure of concrete which eventually causes explosive spalling phenomenon. For non-fiber specimens no spalling occurred at any temperature and concrete was not seriously damaged when heated at temperatures up to 300 °C. Explosive spalling occurred above 400 °C and destroyed most of non- fiber specimens (Fig. 10). Using fibers had a positive effect on the reduction of this kind of damage. The addition of steel fiber improved the behavior of SCC-ST4 at the low temperature range and reduced the spalling tendency at the higher one. Steel fibre bridges the cracks caused by the increased vapor pressure and leads to the more gradual degradation. The threshold temperature for spalling was therefore shifted to higher levels. However, when spalling took place, this was more violent and resulted in increasing alterations in concrete's microstructure. As mentioned above, the polypropylene or PET fibers melt at 160–168 °C, and in this manner an additional pathway is created aiding the internal vapor pressure to expand. It therefore seems that addition of polypropylene or PET fibre did not influence the behavior of SCC-PP3 or SCC-PET2 at higher temperatures. The formation of additional pores led to rapid reduction of residual strength at the temperature range of 100–300 °C for PP or PET containing mixtures. This is the temperature range in which fibers melt. Residual strength is further reduced in higher temperatures and this was observed more intensely for SCC-PP3, since additional cracks were formed in the denser microstructure of those mixtures after heating at elevated temperatures.

Figure 11 represents the flexural strength of 28 and 90 days' age unheated specimens. In the presence of steel fibers, the flexural strength has raised to at least 30% and also for polypropylene and PET containing specimens, the increase of 9% to 20% is observed. The recycled PET fibers had a rather desirable performance compared to polypropylene fibers.

Figure 12 implies the positive effect of fibers on flexural strength of 28 days' specimens under various heating regimes. Steel fibers containing specimens under various heating regimes have more strength compared to others. By increasing the temperature, the flexural strength of the specimens decreases which gets more tangible at temperatures over 400 ℃. Steel fiber containing specimens compared to

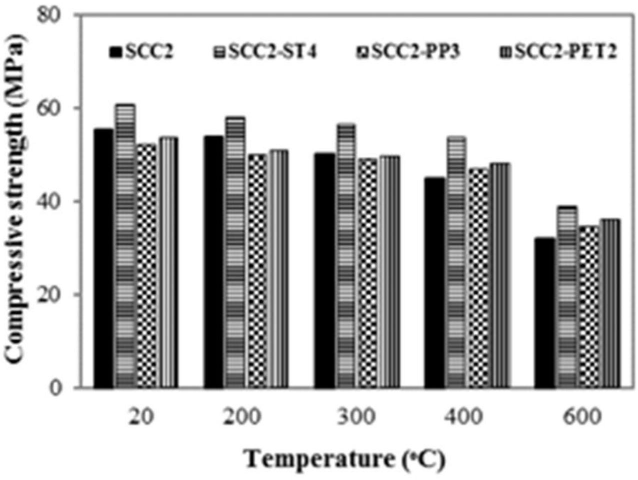

Fig. 8. Compressive strength of 28 days' specimens under various heat regimes

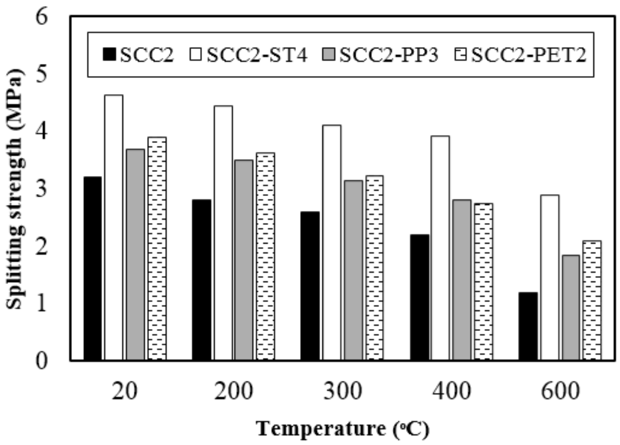

Fig. 9. Splitting strength of 28 days' specimens under various heat regimes

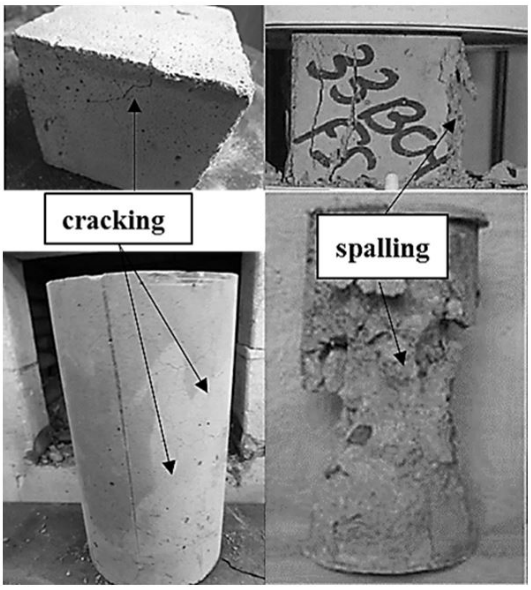

Fig. 10. Explosive spalling and cracking of concrete specimens after heating.

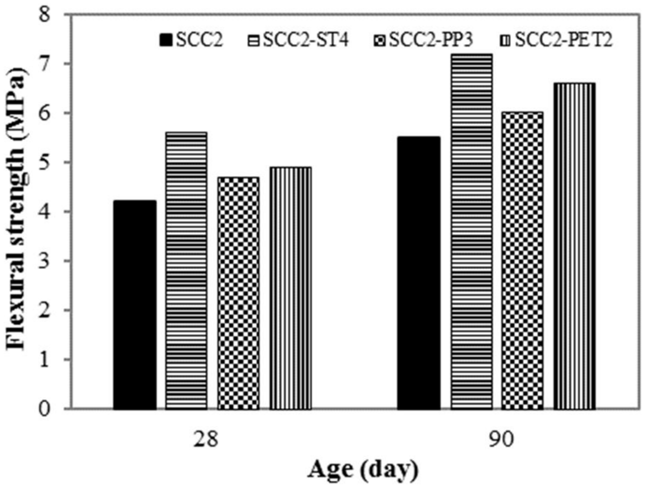

Fig. 11. Flexural strength of unheated specimens at the ages of 28 and 90 days.

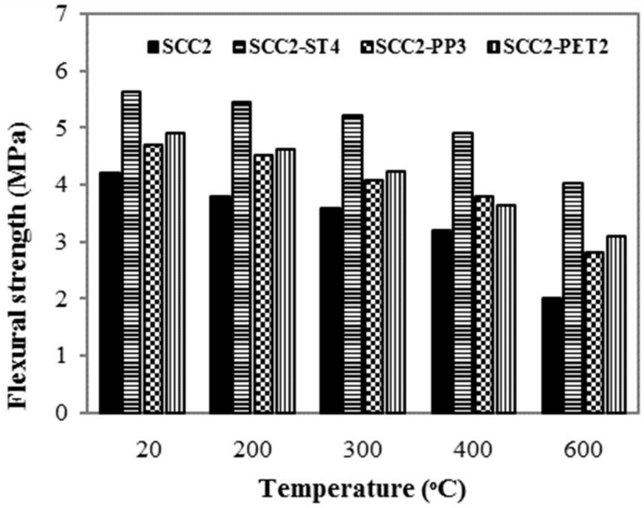

Fig. 12. Flexural strength of 28 days' specimens under different heating regimes

unheated SCC2 specimens have a 4% strength decrease and compared to unheated SCC2-SF4 specimens, they show the 28% decrease. Polypropylene and PET fiber containing specimens have more strength maintenance compared to SCC2 specimens in various heating regimes. Polypropylene and PET fiber containing specimens had flexural strength decrease of 33% and 26% compared to unheated SCC2 specimens. Also, the amount of strength maintenance for specimens containing polypropylene fibers was between 13.5% and 40% and for PET it was 14% to 55%. Flexural strength of specimens containing steel fibers in different temperatures, in comparison with polypropylene and PET fibers was at least 20.5% and 23.5% and at most 43% and 34.5%, respectively.

Figures 13 to 17 show the load-displacement curves and Table 5 represents the amount of toughness for flexural specimens under various heating regimes. In Figure 12, it could be seen that, having reached the peak-point of flexural loading, all specimens experienced a sudden drop of curves, but in fiber reinforced specimens, after the first crack, the fibers entered the load-bearing capacity of specimen which caused ductility and rather a soft fracture which is more sensible in steel fiber reinforced specimens. The behavior of strain-hardening and after that, strain-softening could be seen in specimens containing steel fibers which may imply the bridging phenomenon. Also, this behavior is observed in specimens containing PET fibers. In return, specimens containing fibers represented more ductile behavior. Also, it could be observed that by adding fibers, the area under load-displacement curve has been increased which states the improvement of flexural toughness. The amount of increase for specimens containing steel, polypropylene and PET fibers in comparison with SCC2 are 6, 1.5 and 2 times, respectively. The main reason is the rather desirable distribution of fibers in a cementitious matrix which keeps the micro cracks together and prevents their growth.

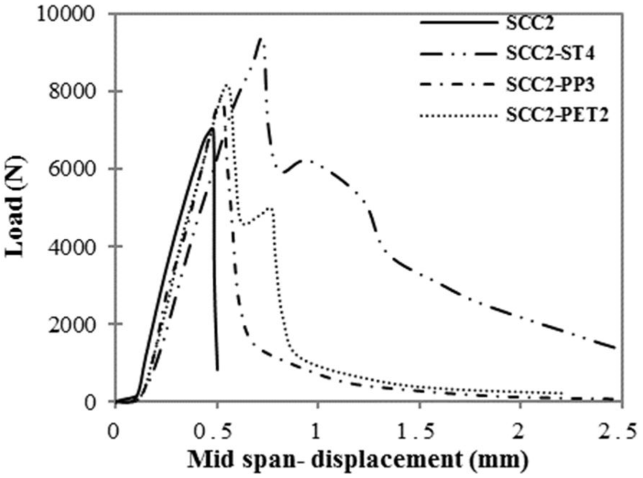

Fig. 13. Load-displacement curve of unheated specimens (20 °C)

The behavior of post-peak area of specimens containing steel fibers compared to polypropylene and PET fibers had more ductility. In Figure 14 and also partially in Figure 17 specimens containing steel fibers showed the strain hardening behavior. By increasing temperature, the amount of toughness in specimens without fibers had a reduction of about 42.6%, but fiber reinforced specimens had more toughness than the unheated SCC2 specimens up to 600 °C (except 3% decrease in SCC2-PP3 specimens in 600 °C).

It could be seen that Load-displacement diagrams in most

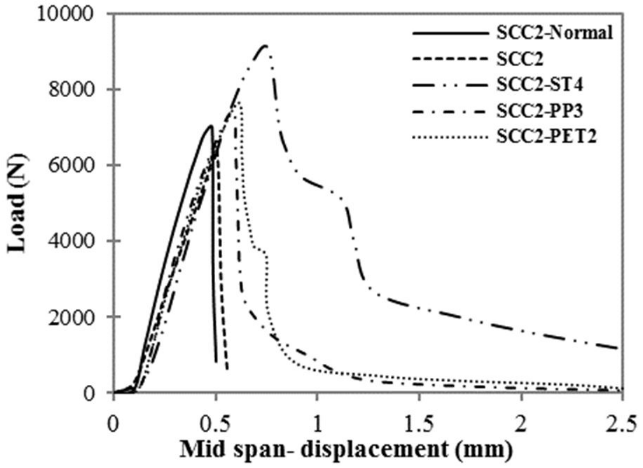

Fig. 14. Load-displacement curve of specimens under heat regime (200 °C)

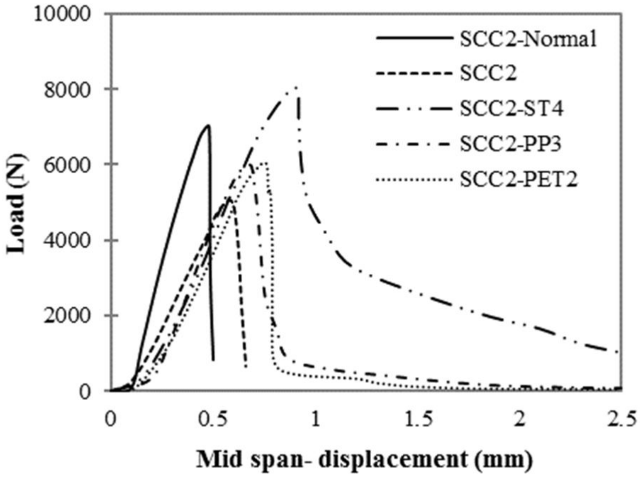

Fig. 16. Load -displacement curve of specimens under heat regime (400 °C)

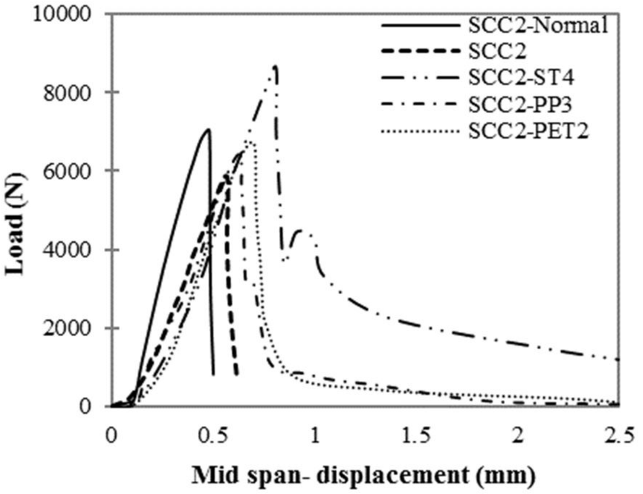

Fig. 15. Load -displacement curve of specimens under heat regime (300 °C)

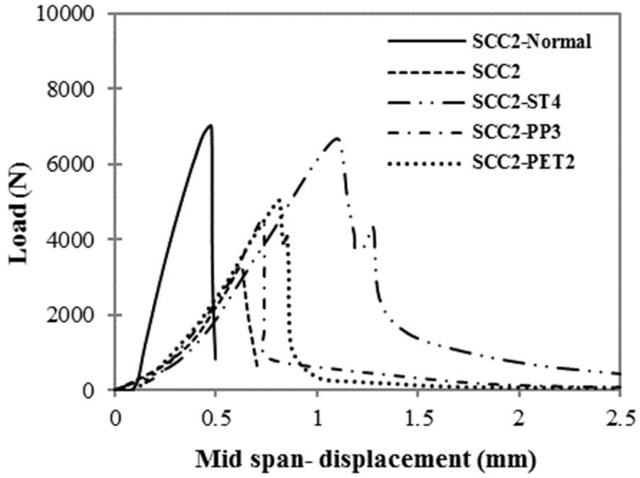

Fig. 17. Load -displacement curve of specimens under heat regime (600 °C)

cases are linear in the area before the peak-point. The slope of this line could be proportional to fracture modulus or static elasticity modulus [24]. By the increase in heat regime, the slope of line decreases which implies the drop in flexural toughness. The drop amount of this line for specimens without fibers compared to unheated SCC2 specimens is 55% and for specimens containing steel, polypropylene, and PET fibers are 52, 53 and 52.5%, respectively. It seems that temperature affects the behavior of deflection of corresponding flexural peak-point. Temperature rise has shifted the peak point to the right hand of Load-displacement diagram. The change amounts of peak-deflection point are presented in Table 6.

4- Analysis and prediction of (numeral) results

In recent years, computational methods and techniques have been developed for the evaluation of structural elements' performance under elevated temperatures, but related articles on this subject have been poorly developed in the literature. However, the modeling can be a suitable solution for prediction of concrete structures behavior or performance in the elevated temperatures conditions. In this study, in addition to the comparison of experimental results with the proposed models by other researchers, a regression analysis performed on experimental results and formulations for compressive strength, modulus of elasticity, flexural strength, modulus of rupture, maximum flexural load and corresponding strain were presented.

4- 1- Compressive strength of FRSCC

In this section, the main focus is on making a logical relevance for compressive strength of fiber reinforced self-compacting concrete specimens under various heating regimes. Therefore, prediction relations and models of compressive strength for concrete mixtures containing steel and polypropylene fibers under various heat regimes studied by other researchers, are presented in Table 7. Comparing experimental results of Self-compacting concrete compressive strength containing 0.4% steel fibers and 0.02% polypropylene fibers in room temperature (20 ºC) with the proposed model presented in references [25, 26] has less than 18% and 5% difference, respectively.

In this section, the proposed relations for the compressive strength of simple self-compacting concrete and the concretes containing steel, polypropylene and PET fibers under various heating regimes based on regression analysis with second-degree equation (parabolic) presented in Equations 2 to 5. Figure 18 indicates the comparison between the compressive strength of fiber reinforced self-compacting concretes under various heating regimes performed in this experiments with the results of other studies.

$$f'_{cT} = f'_{c}\left[-1\times10^{-6}T^{2} + 0.0002T + 1.0473\right] \rightarrow 200℃ \le T \le 600℃ \quad (2)$$

$$f'_{cT-st} = f'_{c}\left[-2\times10^{-6}T^{2} + 0.0009T + 0.9542\right] \rightarrow 200℃ \le T \le 600℃ \quad (3)$$

$$f'_{cT-pp} = f'_{c}\left[-2\times10^{-6}T^{2} + 0.0009T + 0.7959\right] \rightarrow 200℃ \le T \le 600℃ \quad (4)$$

$$f'_{cT-pet} = f'_{c}\left[-2\times10^{-6}T^{2} + 0.0009T + 0.8159\right] \rightarrow 200℃ \le T \le 600℃ \quad (5)$$

4- 2- Elasticity Modulus of FRSCC

Affecting factors on compressive strength have a direct influence on the modulus of elasticity. Proposed models of researchers for concrete's modulus of elasticity under various heating regimes are displayed in Table 8. The difference between experimental results for modulus of elasticity in this research with the results of modeling performed by other researchers for steel and polypropylene fibers is less than 11.2% and 7.7%, respectively.

Proposed relations for the modulus of elasticity of fiber reinforced self-compacting concretes in Equations 6 to 9 are presented for specimens without fibers and with steel, polypropylene and PET fibers. In Figure 19 also a

Table 5. The toughness results of prismatic samples under flexural test

MIX ID	T20	T/T20 (%)	T200	T/T20 (%)	T300	T/T20 (%)	T400	T/T20 (%)	T600	T/T20 (%)
SCC	190.15	-	174.6	-8.4	173.3	- 8.9	140.6	-26	109.7	- 42.6
SCC2-ST4	1148.7	504	918.9	383	763.5	301	788.7	314.7	539.1	183.6
SCC2-PP3	290.8	52	307.6	61	279.6	46.8	269.2	41.5	184.4	- 3
SCC-PET2	394.1	107	352.4	85.2	290.8	52.6	243	27.6	212.5	11.6

Table 6. Corresponding deflection of peak flexural load

	Δ_1 (mm)					Δ_1/Δ_0^*				
MIX ID	**20 °**	**200 °**	**300 °**	**400 °**	**600 °**	**20 °**	**200 °**	**300 °**	**400 °**	**600 °**
SCC2	0.55	0.51	0.57	0.59	0.62	1	0.91	1.01	1.02	1.127
SCC2-ST4	0.73	0.76	0.78	0.91	1.1	1.32	1.38	1.41	1.65	2
SCC-PP3	0.52	0.58	0.63	0.68	0.73	0.94	1.03	1.14	1.23	1.32
SCC-PET2	0.56	0.61	0.7	0.76	0.81	1.01	1.1	1.27	1.38	1.47
			Δ_f^{**}/Δ_1					$\Delta_{uf}^{***}/\Delta_f$		
SCC2-ST4	1	1.04	1.068	1.24	1.5	4.8	5.2	4.48	3.5	3.18
SCC-PP3	1	1.11	1.21	1.3	1.4	4.8	4.3	4.76	2.82	2.32
SCC-PET2	1	1.089	1.25	1.35	1.44	3.98	4.09	4.28	3.28	2.45

*: Δ_0 is 0.55 mm, **: Δ_f is fibrous specimens deflection, ***: Δ_{uf} is fibrous specimens ultimate deflection

Table 7. Proposed model by researchers for concrete compressive strength under various heating regimes

Ref	f'_{cf} (MPa)	Pred	Exp
[25]	$f_c' + 40.14V_{f-st} + 1.02V^2_{f-st}$	71.21	60.7
[26]	$f_c' - 46.36V_{f-pp}$	54	53.7
	f'_{cT}		
[25]	$f'_{cT-st}\begin{cases}1.0 \rightarrow 20°c \\ I):0.93+0.0025T-7\times10^{-6}T^2 \rightarrow 100°C \le T \le 400°C \\ II):1.0452-0.00092T+2\times10^{-7}T^2 \rightarrow 100°C \le T \le 600°C \\ III):1.0242+0.0006T-2\times10^{-6}T^2 \rightarrow 400°C \le T \le 800°C\end{cases}$		
[26]	$f'_{cT-pp}\begin{cases}1.0 \rightarrow 20°c \\ 1.0237-0.00105T+1\times10^{-7}T^2 \rightarrow 100°CT \le 800°C\end{cases}$		

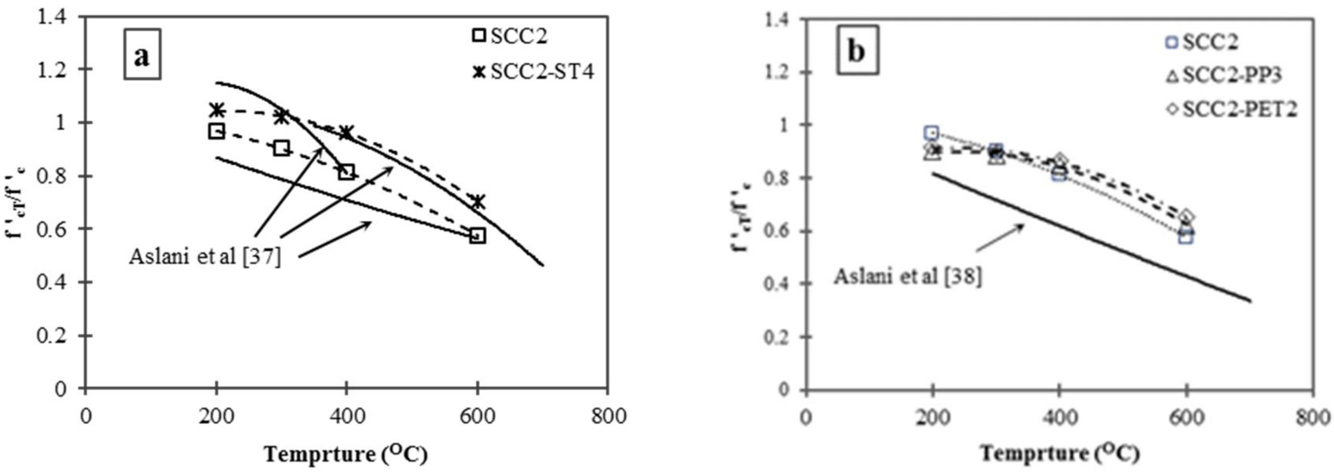

Fig. 18. Comparison between compressive strength of fiber reinforced self-compacting concretes under various heating regimes: a) steel fibers, b) polypropylene and PET fibers

comparison is made on the modulus of elasticity for plain and fiber reinforced self-compacting concretes under various heating regimes. It could be observed that the obtained results have rather desirable consistency with the results of other researchers.

$$E'_{cT} = E'_c\left[-1\times10^{-8}T^2 + 0.0011T + 1.0136\right] \rightarrow 20°C \le T \le 600°C \quad (6)$$

$$E'_{cT-st} = E'_c\left[-2\times10^{-7}T^2 + 0.0009T + 1.0602\right] \rightarrow 20°C \le T \le 600°C \quad (7)$$

$$E'_{cT-pp} = E'_c\left[6\times10^{-8}T^2 - 0.0011T + 1.0543\right] \rightarrow 20°C \le T \le 600°C \quad (8)$$

$$E'_{cT-pet} = E'_c\left[3\times10^{-7}T^2 - 0.0013T + 1.0503\right] \rightarrow 20°C \le T \le 600°C \quad (9)$$

4- 3- Flexural Strength FRSCC

Considering this fact that the majority of fiber effects in sections and flexural concrete elements such as beam and slab is more sensible, various studies in the field of heat effects on flexural strength (modulus of rupture) are performed. For example, of these kinds of experiments, the work of Anson and Lau [36] is mentionable. They measured the compressive and flexural strength of concrete containing steel fibers in temperatures between 105 °C to 1200 °C. They stated that in high temperatures fibers will play an effective role in keeping the flexural toughness of concrete.

In Table 8, the proposed model by researchers is presented for the evaluation of fiber reinforced concrete under various heating regimes. The results of flexural strength in this research for prismatic specimens containing steel and polypropylene fibers under room temperature (20 °C) with predicted results by other researchers have the difference less

Table 8. Proposed model by researchers for modulus of elasticity under various heating regimes

Ref	E_{cf} (GPa)	Pred	Exp
[25]	$E_c + 1.9V_{f-st}$	24.09	26.8
[26]	$E_c - 31.77V_{f-pp}$	22.37	24.1
	E_{cT}		
[25]	$E_{cf-st}\begin{cases}1.0 \rightarrow 20^\circ C \\ 1.1344 - 0.0017T + 5\times10^{-7}T^2 \rightarrow 100^\circ C T \le 800^\circ C\end{cases}$		
[26]	$E_{cf-pp}\begin{cases}1.0 \rightarrow 20^\circ C \\ 1.01 - 0.0013T + 10^{-7}T^2 \rightarrow 100^\circ C T \le 800^\circ C\end{cases}$		

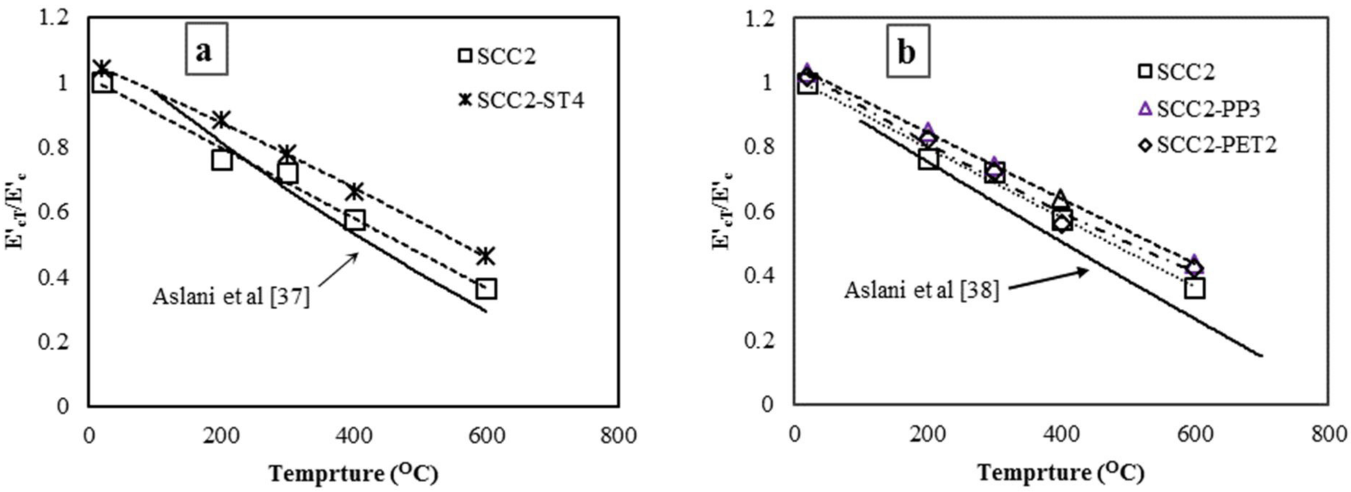

Fig. 19. Comparison of modulus of elasticity for self-compacting concretes under various heating regimes: a) steel fibers b) polypropylene and PET fibers

Table 9. Researchers' proposed model for flexural strength (modulus of rupture) of concrete under various heating regimes

Ref	f_{crf} (MPa)	Pred	Exp
[25]	$f_{cr} + 2.71V_{f-st} + 0.6V^2_{f-st}$	5.38	5.63
[26]	$f_{cr} - 1.7261V_{f-pp}$	4.16	4.7
	f_{crT}		
[25]	$f'_{crf-st}\begin{cases}1.0 \rightarrow 20^\circ C \\ 1.095 - 0.0012T + 2\times10^{-7}T^2 \rightarrow 100^\circ C T \le 1100^\circ C\end{cases}$		
[26]	$f'_{crf-st}\begin{cases}1.0 \rightarrow 20^\circ C \\ 1.1 - 0.0019T + 8\times10^{-7}T^2 \rightarrow 100^\circ C T \le 900^\circ C\end{cases}$		

than 4.6% and 13%, respectively. The proposed relations for flexural strength of self-compacting concrete in Equations 10 to 13 are presented for specimens without fibers and with steel, polypropylene and PET fibers, respectively. In Figure 20, also the comparison of flexural strength for self-compacting concrete with and without fibers under various heating regimes.

$$f'_{crT} = f'_{cr}\left[-1\times10^{-6}T^2 - 0.0001T + 0.9969\right] \rightarrow 20°C \leq T \leq 600°C \quad (10)$$

$$f'_{crT-st} = f'_{cr}\left[-1\times10^{-6}T^2 - 2\times10^{-5}T + 1.3411\right] \rightarrow 20°C \leq T \leq 600°C \quad (11)$$

$$f'_{crT-pp} = f'_{cr}\left[-1\times10^{-6}T^2 - 1\times10^{-4}T + 1.1265\right] \rightarrow 20°C \leq T \leq 600°C \quad (12)$$

$$f'_{crT} = f'_{cr}\left[-4\times10^{-7}T^2 - 5\times10^{-4}T + 1.191\right] \rightarrow 20°C \leq T \leq 600°C \quad (13)$$

4- 4- Flexural Load Peak-Point and the Corresponding Deflection

In flexural load peak-point, produced micro cracks in prismatic specimens will develop and turn to macro cracks. Considering the relevance of flexural load peak-point with flexural strength (modulus of rupture), the proposed Equations 10 to 13 can make a good estimation of flexural load peak-point. Equations 14 to 17 for the corresponding deflection of flexural load peak-point is presented for prismatic samples without fibers and with steel, polypropylene and PET fibers, respectively. In Figure 21 also the regression model for flexural load peak-point and corresponding deflection has been presented for various heating regimes.

$$\Delta_{cT} = \Delta_c[0.9701e^{0.0006T}] \rightarrow 20°C \leq T \leq 600°C \quad (14)$$

$$\Delta_{cT-st} = \Delta_c[1.3955e^{0.0008T}] \rightarrow 20°C \leq T \leq 600°C \quad (15)$$

$$\Delta_{cT} = \Delta_c[1.0665e^{0.0007T}] \rightarrow 20°C \leq T \leq 600°C \quad (16)$$

$$\Delta_{cT-pet} = \Delta_c[1.1214e^{0.0007T}] \rightarrow 20°C \leq T \leq 600°C \quad (17)$$

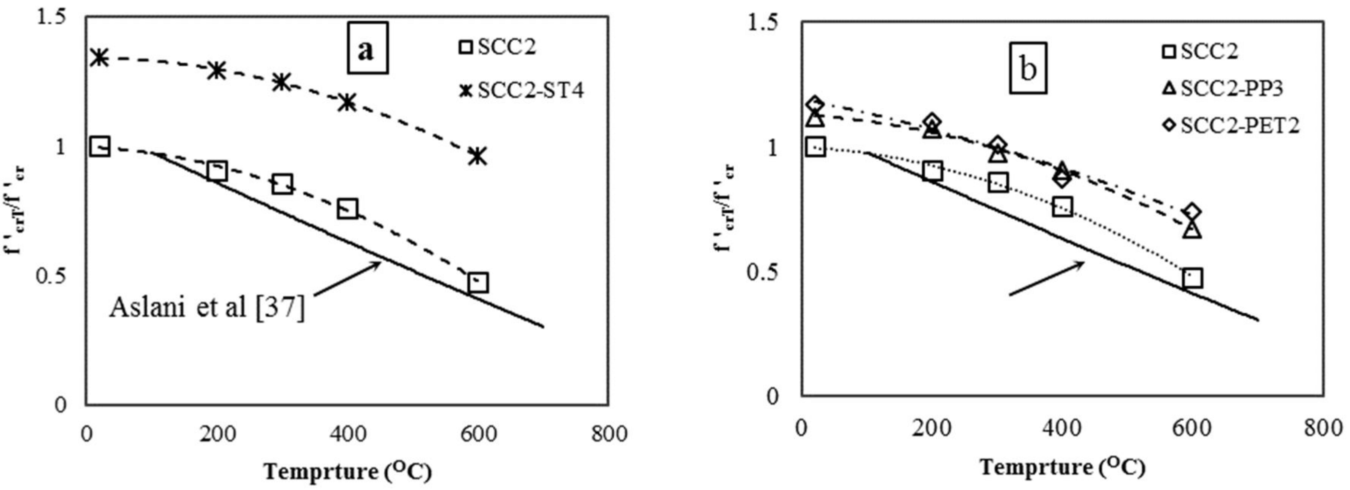

Fig. 20. Comparison of flexural strength of fiber reinforced self-compacting concrete under various heating regimes a) steel fibers b) polypropylene and PET fibers

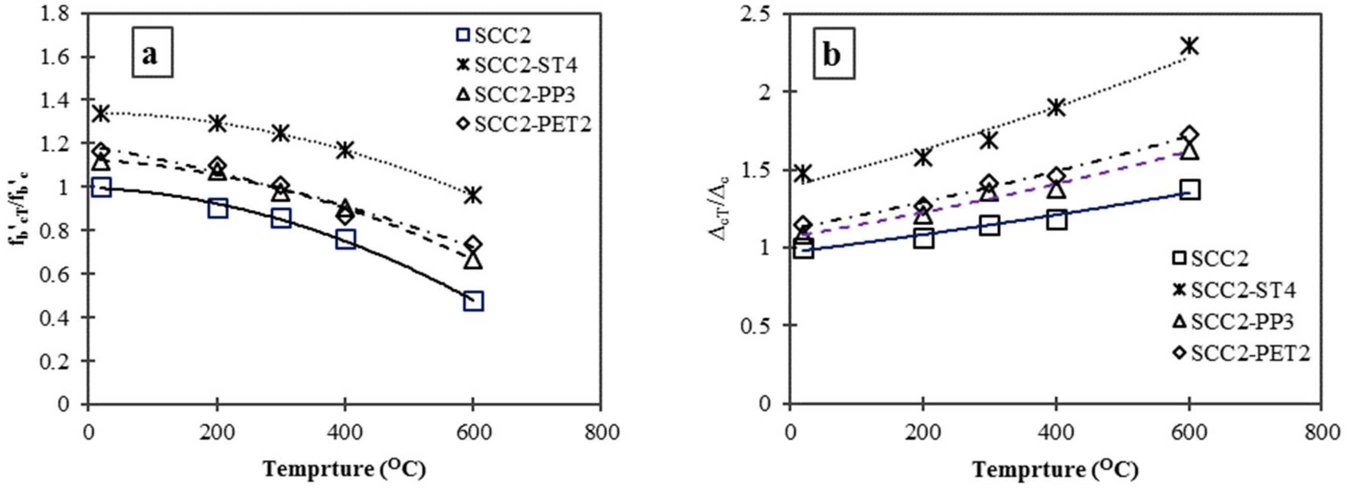

Fig. 21. Regression equation a) flexural load peak-point b) corresponding deflection with flexural load peak-point under various heating regimes

5- Conclusion

In this research, the effect of high temperatures on mechanical properties of FRSCC was evaluated. The following conclusions can be drawn from this study:

- Using various types of fibers had negative effects on fresh self-compacting concrete and by increasing the fiber content, its effect gets more tangible.
- The presence of steel fibers causes the increase of compressive strength at the maximum amount of 10% and adding polypropylene and PET fibers caused a drop in strength about 15% and 15.5% in unheated specimens, respectively. By increasing temperature up to 600 °C, the compressive strength of steel, polypropylene and PET fiber reinforced specimens in comparison to SCC2 specimens had 30, 37.5 and 34.5% decrease, respectively. Also, the amount of maintaining compressive strength (stability against heat) of fiber reinforced samples in 600 ˚C was 8% to 21%.
- Steel fibers containing specimens in comparison to unheated SCC2 specimens had 3.8% drop and compared to SCC2-ST4 had 28.2% drop. The specimens containing polypropylene and PET fibers had 33% and 26.1% decrease compared to SCC2 unheated specimens. Also, the amount of keeping strength in elevated temperatures for specimens containing polypropylene fibers was 13.5% to 40% and for PET was 14% and 17%.
- The amount of flexural toughness by increasing heat for specimens without fibers had a decrease up to 42.5%; however, fiber reinforced specimens heated up to 600 ℃ showed more toughness in comparison to unheated SCC2 specimen (except 3 percent decrease in SCC2-PP3 in 600 ℃).
- The influence of adding fiber reinforcement on the fire performance of concrete was twofold. On the one hand, the material compaction got more difficult. The total porosity was slightly increased and this led to the increased permeability, which reduced the risk for explosive spalling. On the other hand, there was the mechanical benefit which ensues from the ability of the fiber to bridge the cracks.
- Addition of steel fiber eliminated the spalling tendency of FRSCC mixtures and it shifted threshold temperatures to higher levels. Polypropylene or PET fiber reinforced mixtures were not destroyed at any temperature achieved in this research. Additions of these types of fibers increased the spalling resistance of FRSCC mixtures. However, they had a negative effect on concrete's residual mechanical properties. It is therefore recommended to use polypropylene or PET fires as part of a total spalling protection design method in combination with other materials such as external thermal barriers. Otherwise, the overall thickness of the concrete members should be increased to provide a sacrificial layer who will be removed after a fire in order to efficiently repair the structure.
- Comparison of experimental results in this research such as compressive strength, flexural strength, modulus of elasticity with the proposed model of other researchers had rather desirable consistency. The proposed compressive strength relationship is simple and reliable for modeling the compressive behavior of FRSCC at elevated temperatures. Also, using these relationships in the finite element method is more simple and suitable. The difference between results was due to the difference in concrete type, water-cement ratio, heating rate, heat amount.
- The proposed relationships for the compressive strength, flexural strength, elasticity modulus, flexural load peak-point and flexural load- deflection of FRSCC with different types of fibers at elevated temperatures are in a good reasonable agreement with the experimental results. Also, the relationships are proposed for the above-mentioned mechanical properties that can calculate these properties related to the fiber type and different temperatures. The paper emphasized the fact that additional tests at different temperatures are needed to investigate the role of initial compressive and tensile stresses on the FRSCC compressive strength, strain at peak stress, modulus of elasticity, free thermal strain, load-induced thermal strain, creep strain and transient strain.

Nomenclature

f_c'	compressive strength without fiber
f_{cf}'	compressive strength with fiber
f_{cT}'	compressive strength at elevated temperatures
V_f	Fiber content
E_c	modulus of elasticity without fiber
E_{cf}	modulus of elasticity with fiber
E_{cT}	modulus of elasticity at elevated temperatures
f_{cr}	Flexural strength without fiber
f_{crf}	Flexural strength with fiber
f_{crT}	Flexural strength at elevated temperatures
Δ_c	Corresponding deflection to flexural load peak-point without fibers
Δ_{cf}	Corresponding deflection to flexural load peak-point with fibers
Δ_{cT}	Corresponding deflection to flexural load peak-point in elevated temperatures

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