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Experimental research for the effect of high temperature on the mechanical properties of steel fiber-reinforced concrete

Oğuz Düğenci, Tefaruk Haktanir, Fatih Altun *

Erciyes University, Engineering Faculty, Department of Civil Engineering, Kayseri, Turkey

HIGHLIGHTS

- Steel fiber addition effects positively on compressive strength until 1000 °C.
- Modulus of elasticity values was generally in parallel with compressive strength.
- Particularly 1.0% fiber rate decreased strength loss more than other fiber rates.

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ABSTRACT

It is widely known that addition of steel fibers to concrete improves properties of concrete having brittle behavior. This affects the behavior in a positive way particularly by increasing ductility of the concrete. In this study, the results of the effect of high temperature on steel–fiber concrete were investigated. RC80/60 BN type steel–fibers were added to experimental concrete as in the rates of 0%, 0.5%, 1% and 1.5% by volume and concrete cylinder samples with 7, 28 and 90-day were tested. Produced cylinder samples were exposed to 900 °C, 1000 °C, 1100 °C and 1200 °C temperatures in the furnace. The effect of temperature was applied to samples within 6 h in experiments.

In this study, compressive strength, modulus of elasticity and toughness values of fiber-concrete were given comparatively according to different fiber ratios, concrete age and varying temperature effects. Consequently, compressive strength, modulus of elasticity and toughness values of fiber-concrete substantially decreased by the effect of high temperature as it was expected. When it was examined the results with regard to percentage of steel fiber, samples of 1.0% fiber additive had specifically the lowest of compressive strength losses. Additionally in comparing results of compressive strength losses on high temperature effect were lower at 900 °C and 1000 °C than at 1100 °C and 1200 °C temperatures. Determined results of 1100 °C and 1200 °C temperatures were closed with each other. Namely compressive strength values reached the lowest value after 1100 °C.

1. Introduction

In order to improve the properties of the concrete, steel fiber additive agents can be added to the concrete [1,2]. Steel fibers are also among these substances and in recent years, they have been commonly used in concrete. The aim of producing fiber-concrete is to increase toughness of the material, its resistance against impact effects, its flexural strength and other mechanical properties. The concretes including fiber have wider range of usage areas such as field concrete, paving, industrial constructions, slope stabilization and retaining wall construction, hydraulics, construction buildings when compared to normal concretes [3–8].

Concrete may be subjected to various effects such as wearing, freezing–thawing, chemical medium, dynamic loads throughout its physical life. One of them is high temperature and fire. The effect of high temperature can be seen particularly in airport aprons, industrial ground and chimney operating under high temperature, plants producing chemical materials with high fire risk and industrial constructions.

The actual behavior of the concrete exposed to high temperatures depend on many environmental factors such as the properties of materials building up the concrete, heating rate, maximum temperature at which it was exposed to and the period of this exposure, cooling method after maximum temperature and loading level at the time of cooling [9,10].

* Corresponding author at: Erciyes University, Engineering Faculty, Department of Civil Engineering, 38039 Kayseri, Turkey. Tel.: +90 (352) 207 6666x32378; fax: +90 (352) 437 5784.

E-mail address: faltun@erciyes.edu.tr (F. Altun).

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Cement hydrated with the effect of high temperature is dehydrated by loosing water. $Ca(OH)_2$ present in the content of cement in the concrete is dehydrated at temperatures in the range of 400–600 °C and is converted to CaO. As a result of this conversion by the liberation of water, shrinkages in the current volume occur up to 30% and significant decreases are observed in compressive strength of the material. With the fire-extinguishing intervention of the fire by water, concretes loses water at high temperatures, it reacts with CaO conversely to its reaction with the effect of water and again results in $Ca(OH)_2$ [9–12]. In addition to hydration and dehydration between C–S–H at high temperatures, aggregate during heating step and thermal disconformity occur within the cement, moreover, the pore pressure of the water collected in the pores of the cement causes formation of expansions in the volume of the concrete [13,14]. As a result of these shrinkages and expansions occurred in the concrete, deep cracks occur. This also causes undesired decrease in compressive strength of the concrete.

In fired constructions, damages can be observed particularly on concrete bearings from outside to inside depending on degree of the temperature and effective time. Measurements indicated that the loss of strength in reinforced concrete bearings decreases from outside to inside and a part what we call as a shell is formed [15]. Therefore, the contribution of addition of steel–fiber to the compressive strength should not be ignored since core concrete will incur less strength losses than shell concrete. Because it is considered that it will provide very important contribution by prevention of crack development.

The aim of this study was to investigate the contribution of steel–fiber empirically to the loss of compressive strength of concrete material which was exposed to high temperature effect. Steel–fiber will come into prominence as an important auxiliary material for the prevention of shrinkages and expansions that might occur due to the effect of high temperature and formation of cracks in the cement paste.

2. Material and method

2.1. Material and concrete mixture

Three types of aggregates such as coarse graver, fine graver and crushed sand were used in the production of concrete. Specific gravity and absorption experiments were performed depending on the aggregates used [16]. In the mixture of concrete, coarse gravel with a rate of 35%, fine gravel with a rate of 25% and crushed sand with a rate of 40% were added [17]. In the production of experimental concrete, CEM I 42,5 cement was used. Cylinder concrete samples were produced without steel–fiber and with steel–fiber in the volumetric rates of 0.5%, 1.0% and 1.5%.

Steel fiber added to experimental samples was used as RC80/60 BN type. Tensile strength of steel fiber was minimum 1050 N/mm^2. The properties of this steel fiber are given in Table 1 and its schematic diagram is given in Fig. 1.

In cylinder concrete samples produced with steel fiber additive in this study [18–20], the rate of water/cement was 0.60 and its slump value was kept constant in the range of 12 cm ± 2 cm with super plasticizer for additive free concrete samples. Concrete mixture values and amounts of fiber added for 1 m^3 concrete are given in Table 2.

Experimental samples were produced without steel fiber additive in normal concrete class and with steel fiber additive in the volumetric rates of 0.5%, 1.0%, 1.5%. The samples were produced after their exposure to 900 °C, 1000 °C, 1100 °C and 1200 °C temperatures at the concrete age of 7, 28 and 90-day in 4 × 4 × 3 × 3 pieces and their experiments were carried out [18–22,24]. The appearances of the samples are given in Fig. 2.

Table 1
Properties of steel fiber.

	Steel fiber
Length *l* (mm)	60
Diameter *d* (mm)	0.75
Slenderness (l/d)	80
Density (g/cm^3)	7.48
Tensile strength (N/mm^2)	min 1050

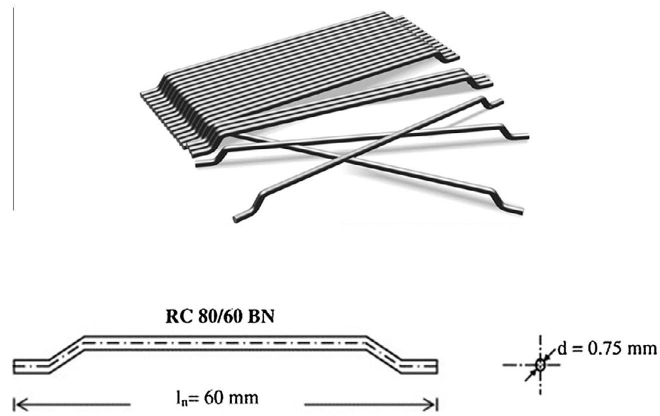

Fig. 1. The steel fiber used in the experiments.

2.2. Temperature application for experimental samples

Cylinder samples produced with and without steel fiber additive were exposed to the effect of temperatures beginning from 7th, 28th and 90th day after production. The samples were removed from curing pool the day before and put it on to dry for 24 h. In order to prevent damaging of samples because of sudden and excess expansion of the water within their structure depending on increasing temperature in high-temperature kiln, the samples were kept in a drying oven at 105 ± 5 °C for 6 h to remove *water absorbed by concrete* before kilning.

In order to supply high temperature, electrical high-temperature kiln was used with a capacity of heating up to 1200 °C. Temperatures of 900 °C, 1000 °C, 1100 °C and 1200 °C were applied respectively to the cylinder samples.

The kilning period in high-temperature kiln was taken as totally 6 h including controlled-increasing time of temperature and heating time in the case of steady-temperature (900 °C, 1000 °C, 1100 °C and 1200 °C). Applying high temperature within 6 h were including rising time until target temperature value. After 6-h heating period, the furnace door was kept closed and let it cool down by itself until its temperature reaches to room temperature to prevent exposure of experimental samples to sudden temperature variations. The samples to which different temperature were applied are given in Fig. 3.

2.3. Determination of properties of compressive strength

After exposure of cylinder samples to thermal effect for totally 6 h on the 7th, 28th and 90th day following their production and cooling them down to room temperature, they were subjected to experiments related with compressive strength [23,24]. In order to compute modulus of elasticity, a compressometer was con-

Table 2
Concrete mixture value.

Specimen	W/C	Steel fiber		W	C	C.S.	F.G	C.G.	A	Slump value
Series		%/V	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	mm
SFC 0	0.6	–	–	205	341	700	438	613	3.41	120
SFC 0.5	0.6	0.5	37.4	205	341	700	438	613	3.41	100
SFC 1.0	0.6	1	74.5	205	341	700	438	613	3.41	20
SFC 1.5	0.6	1.5	112.2	205	341	700	438	613	3.41	10

W: water, C: cement, C.S.: crushed sand, F.G.: fine gravel, C.G.: coarse gravel, A: admixture.

Fig. 2. Cylinder concrete specimens.

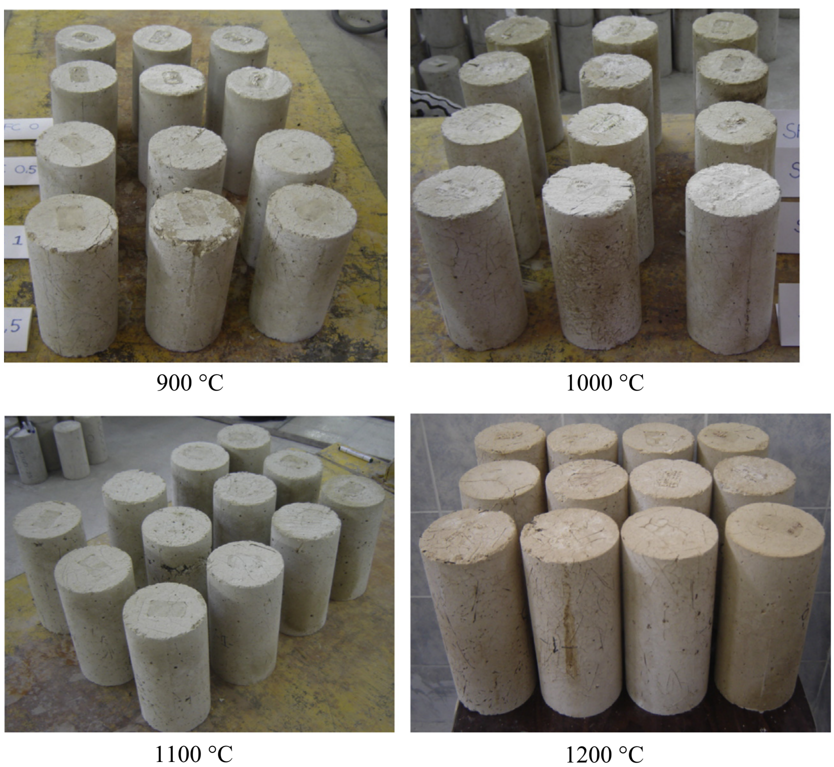

Fig. 3. Specimens subjected to temperature.

nected to the cylinder sample and deformation of the samples under load was measured [25]. Displacement measurements were recorded by measuring deformation values corresponding to each 2.5 kN-load value considering strength loss formed in samples that were subjected to temperature differently from control samples. The sensitivity of indicators present in compressometer was 1 µm. In order to compare the samples subjected to high-temperatures with control samples by using the values obtained, stress–strain curves were drawn. compressive strength, modulus of elasticity and toughness values were determined by means of these curves.

2.4. Calculation steps for modulus of elasticity

During compressive experiments, stress and strain diagrams corresponding to force–displacement values obtained by compressometer device connected to cylinder samples were drawn. By using calculated σ and ε values, σ_1, σ_2, σ_3, . . ., σ_n ve ε_1 ε_1, ε_2, ε_3, . . ., ε_n values corresponding to each measured load value were determined as points starting from $\sigma_0 = 0$ and $\varepsilon_0 = 0$ points on σ–ε axis. Second-degree regression polynomials were fitted in terms of these points by using them. A polynomial curve was obtained by these regression polynomials using the following drawn σ–ε value pairs respectively beginning first from $\sigma_0 = 0$ to σ_{maks}, then continuing from $\sigma_0 = 0$ to $\sigma_{\text{maks-1}}$ and from $\sigma_0 = 0$ to $\sigma_{\text{maks-2}}$ and finally being equal to $0.7 \times \sigma_{\text{maks}}$. Determination coefficients (R^2) of regression polynomials adapted to the axis point pairs beginning from σ_{maks} by least squares method were calculated. All polynomials pass through origin and their analytical structure is as $\sigma = b \cdot \varepsilon + c \cdot \varepsilon^2$. Tangent and secant modulus of elasticity values were calculated by taking calculated stress–strain values via a polynomial having maximum R^2 value among second-degree regression polynomials adapted to σ–ε points into consideration.

2.5. Calculation of tangent and secant modulus of elasticity

By using polynomial values with maximum determination coefficient (R^2) value, *x* coordinate of the point with y coordinate equal to $y = 0.4 \times \sigma_{\text{maks}}$ was calculated. A tangent was drawn to this previously formed from this determined point to the second-degree polynomial curve. Tangent modulus of elasticity was indicated by calculating the angle of tangent line with horizontal. Similarly, for the secant modulus of elasticity, *x* coordinate of the point with *y* coordinate equal to $y = 0.5 \times \sigma_{\text{maks}}$ was calculated by using polynomial values with maximum determination coefficient (R^2) value. A line was drawn from this point to second-degree polynomial curve formed by combining initial ($\sigma_0 = 0$, $\varepsilon_0 = 0$) point as constituting a secant. Secant modulus of elasticity was determined by calculating the angle of secant line with horizontal.

Stress–strain curve together with tangent and secant modulus of elasticity lines adapted on that curve are given in Fig. 4 for 28-day reference sample.

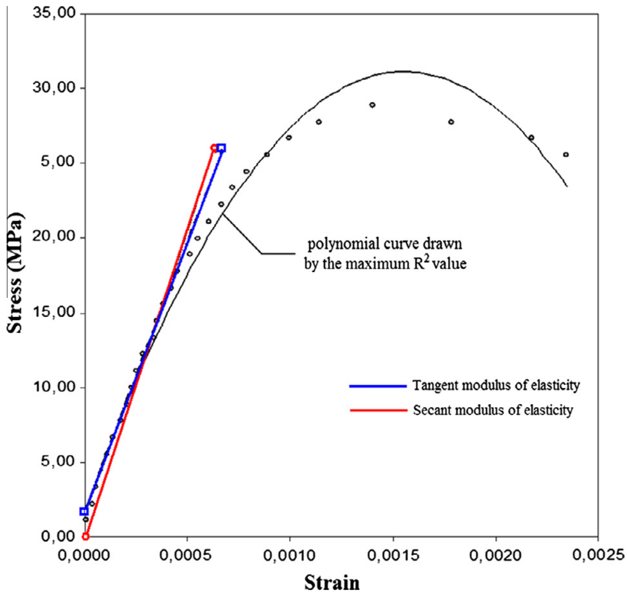

Fig. 4. Stress–strain curve (for 28-day reference specimen).

3. Results

3.1. Compressive strength findings

The compressive experiments of cylinder concrete samples with 150 × 300 mm dimensions which were produced with and without steel–fiber additive were performed on samples being 7, 28 and 90-day and subjected to the effect of 25 °C, 900 °C, 1000 °C, 1100 °C and 1200 °C temperatures. Compressive strength values of samples subjected to the effect of high-temperature were compared with either those of control samples tested at 25 °C or each other. The variation of compressive strength values with respect to sample periods for each temperature application is given graphically in Figs. 5–9.

As a result of experimental studies, when the contribution of steel fiber additive was particularly kept above 1% in volume, it was determined that the compressive strength of concrete decreased. In reference samples, maximum strength loss was observed in samples with 1.5% steel–fiber additive in each period. Difficulty in concrete layout with increasing steel–fiber dosage and coagulation in steel–fibers due to fiber density were evaluated as the reasons of compressive strength loss. This situation caused local gaps within the concrete and decreased compressive strength.

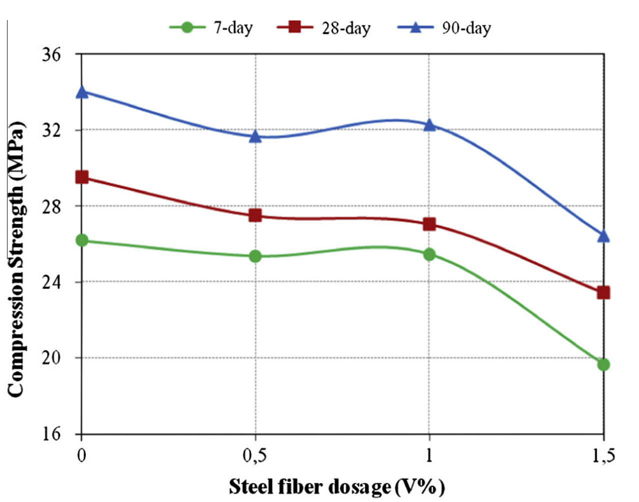

Fig. 5. Relationship between steel fiber dosage and compression strength (25 °C).

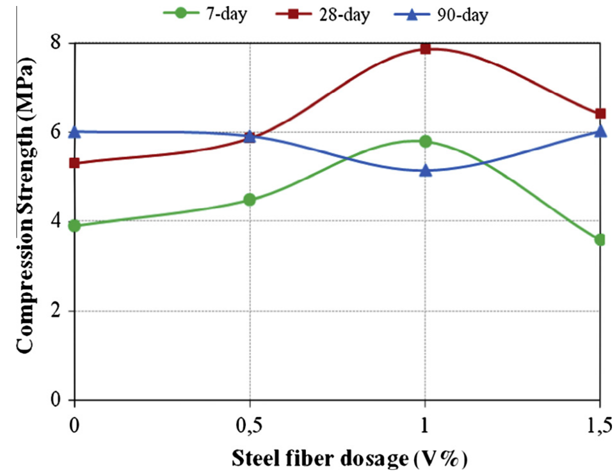

Fig. 6. Relationship between steel fiber dosage and compression strength (900 °C).

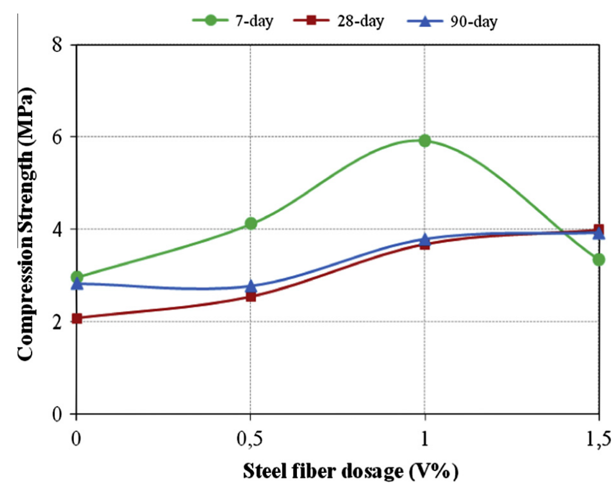

Fig. 7. Relationship between steel fiber dosage and compression strength (1000 °C).

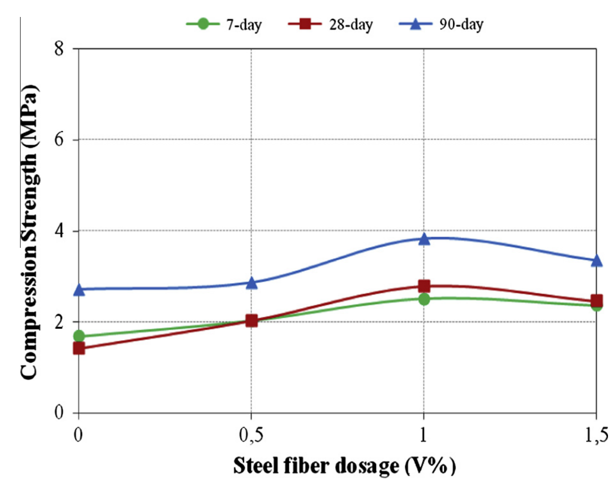

Fig. 8. Relationship between steel fiber dosage and compression strength (1100 °C).

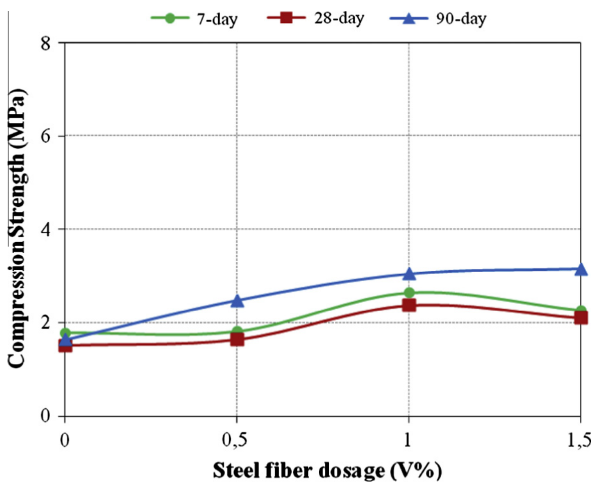

Fig. 9. Relationship between steel fiber dosage and compression strength (1200 °C).

When assessment was carried out in terms of concrete period, maximum compressive strength particularly for 7, 28 and 90-day samples was observed in 0.0% steel–fiber additives with the effect of increasing temperature. It was observed that high temperatures applied caused loss of compressive strength in samples. However, as well as causing loss of compressive strength at high temperatures, the level of decrease in compressive strength was independent of concrete age in samples with more than 1% steel–fiber rate. Especially 1% steel–fiber rate decreased the reduction of compressive strength against temperature. If steel–fiber rate is about 1.5% value, decrease in compressive strength with increasing temperature shows similarity in samples without steel–fiber additive.

At the same period for every temperature and for every steel fiber additive strength losses were calculated. The lowest strength was taken according to without steel–fiber samples at the same periods and contribution percentage was given as differences between contributing values. At 1100 °C and 1200 °C temperatures the strength values was closed to each other and for every period it was the lowest strength values.

In 7-day samples, compressive strength losses of samples of fiber additive-free were for 900 °C as 85%, for 1000 °C as 88%, for 1100 °C and 1200 °C as 93%. On account of steel–fiber additive the least strength loss was observed in samples with 1.0% steel–fiber additive for all temperatures. When compared with samples at steel–fiber additive-free, it was determined that a contribution to compressive strength was calculated for 900 °C as 32% and for 1000 °C as 49% for 1.0% steel–fiber.

In 28-day samples, compressive strength losses of samples of fiber additive-free were for 900 °C as 82%, for 1000 °C as 92%, for 1100 °C 95% and for 1200 °C as 94%. With respect to steel–fiber additive the least strength loss was observed in samples with 1.0% steel–fiber additive for 900 °C, 1100 °C and 1200 °C temperature, however, for 1000 °C the least strength loss was observed in samples with 1.5% steel–fiber temperature. While 1.0% steel–fiber additive provided 48% strength gain at 900 °C, this value was 48% at 1000 °C according to samples at steel–fiber additive-free, It was determined that a contribution to compressive strength was calculated at 1100 °C as 77% for 1.5% steel–fiber. For 1100 °C and 1200 °C, close values were also obtained as 7-day samples.

Contrary to 7-day and 28-day samples, the least strength loss in 90-day samples was observed in samples with 1.5% steel–fiber additive for 900 °C and 1000 °C. The strength values for the samples without additives were 38% for 1000 °C. At 900 °C strength value was nearly same with samples of steel–fiber additive-free. The concrete with 1.5% steel–fiber additive indicated 14% more strength value at 900 °C than the concrete with 1.0% steel–fiber additive.

Compressive strength variations of steel–fiber additives depending on high temperature values such as 900 °C, 1000 °C, 1100 °C and 1200 °C were given for 7, 28 and 90-day sample in Figs. 10–12, respectively.

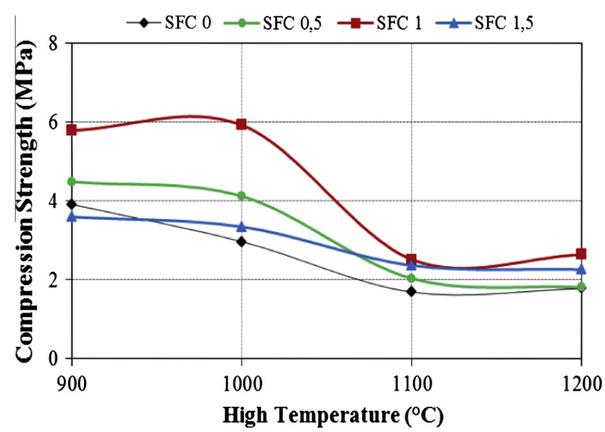

Fig. 10. Relationship between compression strength and high temperature (7-day).

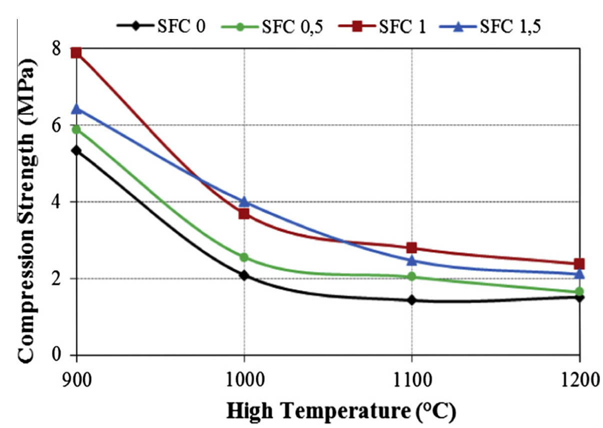

Fig. 11. Relationship between compression strength and high temperature (28-day).

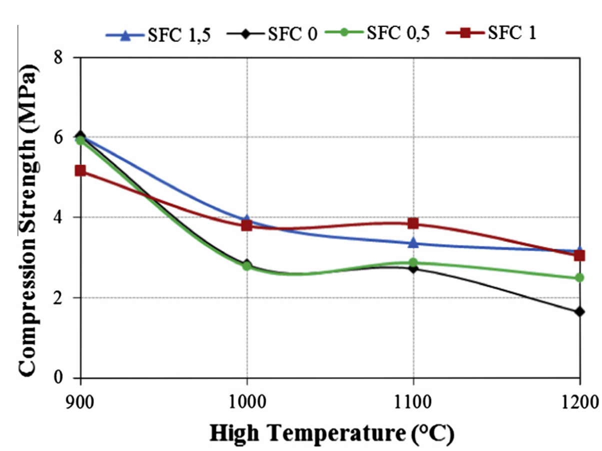

Fig. 12. Relationship between compression strength and high temperature (90-day).

Table 3
Tangent modulus of elasticity values.

Specimen	Steel fiber	Period	Tangent modulus of elasticity (MPa)				
Series	%/V	Day	25 °C	900 °C	1000 °C	1100 °C	1200 °C
SFC 0–7	0	7	17,363	659	322	197	294
SFC 0–28		28	38,352	1160	357	300	236
SFC 0–90		90	38,918	772	291	293	279
SFC 0.5–7	0.5	7	18,218	619	520	200	222
SFC 0.5–28		28	36,289	758	283	354	239
SFC 0.5–90		90	37,138	799	263	325	330
SFC 1.0–7	1.0	7	17,320	594	961	181	243
SFC 1.0–28		28	34,311	961	406	247	322
SFC 1.0–90		90	34,900	478	374	527	486
SFC 1.5–7	1.5	7	10,456	347	254	261	255
SFC 1.5–28		28	33,096	879	465	320	215
SFC 1.5–90		90	34,217	426	280	357	376

Table 4
Secant modulus of elasticity values.

Specimen	Steel fiber	Period	Secant modulus of elasticity (MPa)				
Series	%/V	Day	25 °C	900 °C	1000 °C	1100 °C	1200 °C
SFC 0–7	0	7	18,853	716	334	214	327
SFC 0–28		28	43,259	1264	395	340	259
SFC 0–90		90	42,653	728	320	332	310
SFC 0.5–7	0.5	7	20,045	667	569	211	244
SFC 0.5–28		28	40,726	837	312	387	252
SFC 0.5–90		90	40,926	614	293	355	368
SFC 1.0–7	1.0	7	18,689	638	734	189	239
SFC 1.0–28		28	39,089	986	449	269	355
SFC 1.0–90		90	38,954	536	423	609	541
SFC 1.5–7	1.5	7	12,114	381	272	291	285
SFC 1.5–28		28	37,850	967	517	322	225
SFC 1.5–90		90	38,155	473	308	394	415

Table 5
Compression toughness value according to temperatures and periods.

Specimen	S. fiber	Period	Compression toughness value (MPa)				
Series	%/V	Day	25 °C	900 °C	1000 °C	1100 °C	1200 °C
SFC 0–7	0	7	172	162	255	108	99
SFC 0–28		28	170	127	133	32	105
SFC 0–90		90	162	388	160	145	142
SFC 0.5–7	0.5	7	177	273	370	177	127
SFC 0.5–28		28	153	456	193	98	134
SFC 0.5–90		90	232	380	209	220	206
SFC 1.0–7	1.0	7	112	371	397	184	205
SFC 1.0–28		28	160	366	302	159	134
SFC 1.0–90		90	147	567	434	422	286
SFC 1.5–7	1.5	7	250	598	316	206	243
SFC 1.5–28		28	159	400	330	215	169
SFC 1.5–90		90	151	473	279	213	312

3.2. Modulus of elasticity findings

During compressive strength experiments performed on cylinder samples, vertical displacements observed on samples were recorded via compressometer experimental device installed on samples and modulus of elasticity values for samples were calculated by using these load-deformation values obtained. Calculated tangent modulus of elasticity values are given in Table 3, whereas those for secant modulus of elasticity are given in Table 4.

3.3. Toughness findings

Stress-deformation curves for cylinder samples were drawn. The areas under curves were calculated and compressive toughness values belonging to the samples were found (Table 5).

4. Conclusion

In this study, the results of the effect of high temperature on steel–fiber concrete were investigated. According to compressive strength results of produced cylinder samples, maximum compressive strength for 7-day samples was observed in 0.0% steel–fiber additives. As expected, maximum strength loss was observed in samples without additives at applied high-temperatures. For 1100 °C and 1200 °C temperatures, strength losses were found very close to each other. Therefore, the contribution of steel–fiber additive was completely terminated at temperatures above 1000 °C. At 900 °C and 1000 °C, the least strength loss was observed in samples with 1.0% steel–fiber additive. When compared with samples at steel–fiber additive-free, it was determined that a contribution to compressive strength was calculated for 900 °C as 32% and for 1000 °C as 49% for 1.0% steel–fiber.

In 28-day samples, the least strength loss was observed in samples with 1.0% steel–fiber additive for 900 °C, 1100 °C and 1200 °C temperature, however, for 1000 °C the least strength loss was observed in samples with 1.5% steel–fiber temperature. It was determined that a contribution to compressive strength was calculated at 1100 °C as 77% for 1.5% steel–fiber. For 1100 °C and 1200 °C, close values were also obtained as 7-day samples.

The least strength loss in 90-day samples was observed in samples with 1.5% steel–fiber additive for 900 °C, 1000 °C and 1200 °C. The concrete with 1.5% steel–fiber additive indicated 14% more strength value at 900 °C than the concrete with 1.0% steel–fiber additive.

The variation in tangent and secant modulus of elasticity was generally in parallel with compressive strength. However, variations can be observed with applied temperatures. The values for modulus of elasticity at 900 °C and 1000 °C were higher than those measured at 1100 °C and 1200 °C. The values at 1100 °C and 1200 °C show parallelism with each other.

According to the results of the study, difficulty in concrete layout with increasing steel–fiber dosage and coagulation in steel–fibers due to fiber density caused local gaps within the concrete and decreased compressive strength. However, when the behavior at high temperatures was evaluated, particularly 1.0% fiber rate decreased strength loss more than other fiber rates. Selection of this rate for design might be suggested according to the results of experiments. The results of study were assessed for the effect of temperature for 6 h and this fiber rate suggested for design is more important since effective period of heating in constructions will be less. With regard of effect of high temperature minor changing among the compressive strength values was observed at 1000 °C and after 1000 °C.

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