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The effect of elevated temperature on the properties of SCC's produced with different types of fibers

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ABSTRACT

Self-compacting concrete (SCC) has various advantages such as improved workability and physical properties with advanced compressive strength against traditional structural concretes. However, under high temperatures, the dense composite structure with a compact matrix can facilitate the deterioration of concrete. This study aims to determine the effect of polypropylene, steel, and glass fibers on the mechanical and physical properties of SCC at elevated temperatures. In the fibrous mixtures, polypropylene fiber was used as 0.1%, 0.3%, and 0.5%, steel fiber was used as 0.1%, 0.2%, and 0.3%, and glass fiber was used as 0.1%, 0.3%, and 0.5% by volume of concrete. In addition, a fiber-free SCC control mix was produced to determine the variation of the properties of SCC mixtures. For this purpose, ten SCC mixtures were designed to estimate the workability and hardened properties of the SCC mixtures. The effect of high temperature was investigated by performing ultrasonic pulse velocity, compressive strength, splitting tensile strength, and apparent porosity tests on hardened SCC mixtures that were exposed to 200, 400, and 600 °C. The microstructure of these specimens is observed by using Scanning Electron Microscopy (SEM) on the cross-sections obtained from the hardened SCC mixtures. As a result of the study, it was observed that the use of steel or glass fiber (up to 0.5% by volume) improved the mechanical properties of SCC up to 600 °C. However, these improvements were not seen when using polypropylene fiber in the same fiber volumes.

1. Introduction

Having a wider range of use in recent years, self-compacting concrete (SCC) is an innovative type of concrete capable of placing in the formwork uniformly without any vibration [1]. SCC, which was first developed in 1988 to produce high-strength durable concrete structures and place them perfectly under their weight inside the densely-reinforced and curvilinear formworks without applying vibration [2] has higher strength when compared to conventional concrete at the same water-cement ratios [3–5]. SCC helps to rapid concrete casting, low labor costs thanks to the advantage of placement and improved durability as it forms impermeable concrete [6]. Since its development, SCC has had many practical applications around the world. One of them is the two anchors of the Akashi-Kaikyo Bridge, which has a span of 1991 m and was opened in April 1998. In such large structures, it has been reported that the construction time is shortened, and the labor cost is reduced with the use of SCC [7].

Researchers have used different types of fibers to improve the mechanical and physical properties of SCC mixes [8–10]. Results show that each fiber improves a specific property of SCC [11]. Research has shown that the properties of fresh and hardened concrete are positively or negatively affected by the type and shape of fibers added into concrete mixtures[12]. The addition of short, dense, and uniformly distributed fibers to the SCC will significantly improve its static and dynamic properties. Fibers can be added to the mixture to widen the possible application areas of SCC and eliminate its deficiencies [13]. The addition of fibers to the high flowable SCC decreases the concrete workability while increasing the lateral strength in the hardened state [14]. Some of the most used fibers in the concrete industry are polypropylene (PF), glass (GF) and steel (SF) fibers. PF varieties are widely used in concrete roads and floor coatings, shotcrete applications, airports, fire-resistant concrete structures, concrete pipes, and military security structures [15]. PFs have several advantages over other synthetic fibers. These advantages are that they are lighter and less costly, have low thermal conductivity, and are resistant to attacks by acids and alkalis [16]. The hydrophobic surfaces of PFs are not wetted by the

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cement paste. These fibers act as bridges to keep the different phases in the composite structure close to each other, resulting in the improvement of the mechanical properties of concrete such as compressive and splitting tensile strength [17]. PFs significantly improve SCC's ductility [18,19], compressive strength, [17] splitting tensile and flexural strength [20], protect concrete from spalling at high temperatures [21,22], and evaporate at about 340 °C, resulting in increased porosity and deterioration at higher temperatures [23]. GF is a cost-effective fiber type with high tensile strength. Studies have shown that with the inclusion of this fiber, shrinkage cracks can be reduced, and the flexural and tensile strengths of structural members can be improved [24]. Among the commonly used fibers, SF is the type of fiber with the highest modulus of elasticity and stiffness. Therefore, the use of steel fibers can be very beneficial in improving the mechanical properties of concrete [25]. The studies indicate that fibers generally improve the mechanical properties of concrete by increasing tensile strength, ductility, and resistance to cracking [26]. Self-compacting concretes with an optimum steel fiber content have better ductility [27] and flexural strength [28], and less concrete bleeding. Moreover, the 28-day compressive strength of fibrous concrete is 37% higher than that of fiber-free SCC mix [29]. Khaloo et al. [30] produced SCC samples with steel fiber at 0.5%, 1.0%, 1.5%, and 2% concentrations and found that the higher the steel fiber content, the lower the workability and compressive strength and higher the splitting-tensile and flexural strength. Iqbal et al. [31] conducted a study to examine the mechanical properties of SCC with steel fiber and high strength and reported that short steel fibers significantly improved the tensile and flexural strength of the concrete. Kumar et al. [32] investigated the effect of using crimped steel fiber up to 6% by weight of cement in SCC on the workability and mechanical properties of concrete and determined that steel fiber by 3% to 4% weight of cement was appropriate for achieving a significant increase in strength properties without an important loss in flow properties. They also noted that 3% steel fiber improved compressive strength, splitting tensile strength, and flexural strength by 8.54%, 21.4%, and 25.98% respectively. Hussain et al. [33] prepared normal and high strength concrete series containing 1% by volume of steel, polypropylene, and glass fibers and compared their mechanical performances. As a result of the study, it was determined that steel fibers were more effective than glass and polypropylene fibers in increasing the compressive strength of both normal and high strength concretes by 10–12% and flexural strengths by 51–56%. Alrawashdeh and Eren [34], investigated the effect of steel fibers on the physical and mechanical properties of SCC. In their study, SCC series were produced using hooked steel fibers in three different volume ratios of 0.35%, 0.45%, and 0.55%, and in two different sizes. After physical and mechanical tests, it was determined that the addition of hooked steel fiber to SCC increased the bending and splitting tensile strengths due to crack bridging, post-crack behavior, and end shape of the fibers. Siddique et al. [35], prepared SCC series with F class fly ash and hooked steel fibers used at 0.5%, 1.0%, and 1.5% by volume. In this study, they investigated the effect of steel fibers on the rheology, strength, and permeability of SCC. As a result of the study, they reported that the workability of SCC with hooked steel fiber at 0.5% and 1.0% by volume was in EFNARC standards however, the workability was slightly reduced at 1.5% fiber volume.

High temperature causes physical and chemical reactions and results in mechanical deterioration in conventional concrete [36–38]. Elevated temperature cause moisture loss in concrete. Firstly, the free moisture, then the physically absorbed water, and finally the chemically bound water of the hydrated cement products are lost. In contrast, aggregate tends to expand as cement paste shrinks [39]. This leads to microcracks, and internal stresses caused by the thermal expansion of aggregates. In general, the decrease in concrete strength after the effect of high temperature is caused by changes in the physical and chemical composition of the concrete. Also, changes in hydrothermal conditions contribute to the initial strength loss through loss of free and adsorbed water as the temperature rises, decomposition of the mortar matrix, and deterioration of the interfacial transition zones (ITZ) at high temperatures up to 300 °C [40]. Noumowé et al. [41] compared the mechanical properties and thermal stability of conventional high-strength concrete to those of self-compacting high-strength concrete and subjected concrete cube and cylindrical specimens to a heating–cooling cycle with a heating rate of 0.5 °C per minute, rising to 400 °C and falling back to ambient temperature. They concluded that the risk of spalling for self-compacting high-strength concrete was greater than conventional high-strength concrete and that polypropylene fiber improved the thermal stability of the self-compacting high-strength concrete. Fares et al. [42] analyzed the mechanical behavior of SCC exposed to high temperatures by keeping two SCC samples and one conventional concrete sample at different temperatures (150, 300, 450, and 600 °C) for one hour and then subjecting them to four temperature cycles. They reported that the higher the temperature, the lower the mechanical properties (compressive strength, flexural strength, and modulus of elasticity) and higher the porosity and permeability. Surya et al. [43] subjected fiber-free SCC samples to high temperatures (200, 400, 600, and 800 °C) for two hours after 28 days of curing and reported a compressive strength loss of 7%, 16.09%, 50.07%, and 51.36% at 200, 400, 600, and 800 °C, respectively. They concluded that the compressive strength is reduced with the increase in temperature. Sadrmomtazi et al. [44] investigated the post-high temperature behavior of fly ash and steel fiber-reinforced SCC and detected an insignificant loss in compressive strength in concrete samples up to 200 °C and an increase in compressive strength in some samples. The compressive strength of the samples decreased by 40% and 64% at 400 °C and 600 °C, respectively. They concluded that steel fibers prevented the propagation of cracks and contributed to the resistance to the disintegration of concrete. Poon et al. [45] produced a control mix and high-performance concrete series composed of mixtures reinforced with either steel or polypropylene fibers or both to analyze the compressive behavior of fiber-reinforced high-performance concrete exposed to high temperatures. They drew three conclusions from their results. First, fibers helped reduce the compressive strength loss in concretes after exposure to high temperatures (600 and 800 °C). Second, PFs slightly increased the compressive strength in the control concrete. Third, PFs caused a severe loss in compressive strength and toughness at high temperatures. Karimipour et al. [17] investigated the mechanical properties of SCC containing 0%, 0.1% and 0.3% by volume PF after normal and high temperatures (250 °C). They found that PF helped stop crack propagation or enlargement, with the best results at both normal and high temperatures being obtained from SCCs containing 0.1% PF.

While high compressive strengths can generally be obtained from SCC, its brittle structure increases the possibility of crack development in some conditions. The brittleness of SCC, which has a dense composite structure, will increase when subjected to elevated temperatures. This may facilitate the deterioration of the SCC. In order to overcome these deteriorations, the inclusion of fibers in the SCC matrix may be a solution. For this purpose, fibers can effectively bridge cracks and stop their propagation by reducing deterioration. Recently, many studies have been carried out by researchers by adding different types of fibers to SCC. However, very few studies have investigated the physical and mechanical properties of fibrous SCCs after elevated temperatures. The use of SCCs in the concrete industry has been increasing in recent years. It is of great importance to investigate the performance of SCC after exposure to high temperatures with the effect of fire or similar environmental conditions. The novelty of this study is to investigate the behavior of the widely used types of fibers on the SCC mixtures that are subjected to elevated temperatures. As a result of the study, the effects of fiber type and volume used on the physical and mechanical properties of SCC after high temperature were evaluated comparatively.

2. Materials and method

The experimental procedure of the study is presented in the flowchart shown in Fig. 1. First, SCC mixtures with different concentrations of polypropylene, glass, and steel fibers were produced. Fresh concrete properties of these mixtures were determined by performing flow table, V-funnel, and L-box testing. For hardened concrete tests, cylindrical (ϕ100x200 mm) and cube (100 × 100 × 100 mm) specimens were prepared and exposed to standard curing for 28 days. Afterward, the specimens were subjected to high temperatures at 200 °C, 400 °C, and 600 °C. Before the experiments, the specimens were left for 24 h to cool down at room temperature. The hardened properties of the specimens were determined before ambient (20 °C) and after high temperature to analyze the effects of high temperature on concrete.

2.1. *Materials*

SCC mixtures were produced using CEM I 42.5 R Portland cement as a binder according to TS EN 197–1[46]. The Portland cement was supplied from ÇİMSA Afyon Cement Factory. Class F fly ash used in the mixtures was supplied from Kütahya Seyitömer Thermal Power Plant. Table 1 shows the properties of the Portland cement and the fly ash. Limestone-based crushed sand (50%; 0–4 mm) and crushed stone (50%; 4–11.2 mm) supplied from Afyon KOLSAN Ready-Mixed Concrete Plant were used to produce the SCC samples. The crushed sand had a specific weight and water absorption of 2.66 and 1.28%, respectively. The crushed stone had a specific weight and water absorption of 2.70 and 0.69%, respectively. Fig. 2 shows the granulometry curve of the aggregates in the mixture.

Polycarboxylic ether-based BASF ACE 450, which has a high water-reducing property, was used as a plasticizer in the SCC mixtures. Three types of fibers were used in the SCC samples. Polypropylene fiber and steel fiber were supplied from Atlas1 Construction and Engineering Inc. Co. Glass fiber was supplied from Dost Kimya Chemical Inc. Co. Table 2 shows the physical and mechanical properties of the fibers.

Table 1
Properties of Portland cement and fly ash.

Component, %	CEM I 42.5 R	Fly ash
SiO_2	18.90	58.30
Al_2O_3	4.72	19.80
Fe_2O_3	3.72	11.00
CaO	63.26	2.26
MgO	1.59	3.54
Na_2O	0.20	0.199
K_2O	0.59	1.82
SO_3	2.97	0.644
Cl^-	0.0120	0.0105
Loss on ignition	3.09	1.95
Insoluble residue	0.32	–
Physical Properties		
Specific gravity, g/cm^3	3.12	2.25
Specific surface, cm^2/g	4032	2935
Initial setting time, min	170	–
Final setting time, min	245	–
Volume expansion, mm	0.2	–
Compressive strength		
2 days, MPa	34.3	–
7 days, MPa	45.9	–
28 days, MPa	54.7	–

2.2. *Method*

2.2.1. *SCC mix design*

The abbreviations "PF," "SF," and "GF" in the names of the concrete samples stand for "polypropylene fiber," "steel fiber," and "glass fiber," respectively. Numerical values represent the percentage of fibers in the concrete volume. A fiberless SCC control mix was also produced to compare its properties to those of the fibrous SCC samples. The water/binder ratio in the mixtures was 0.39. Polypropylene fiber was used as

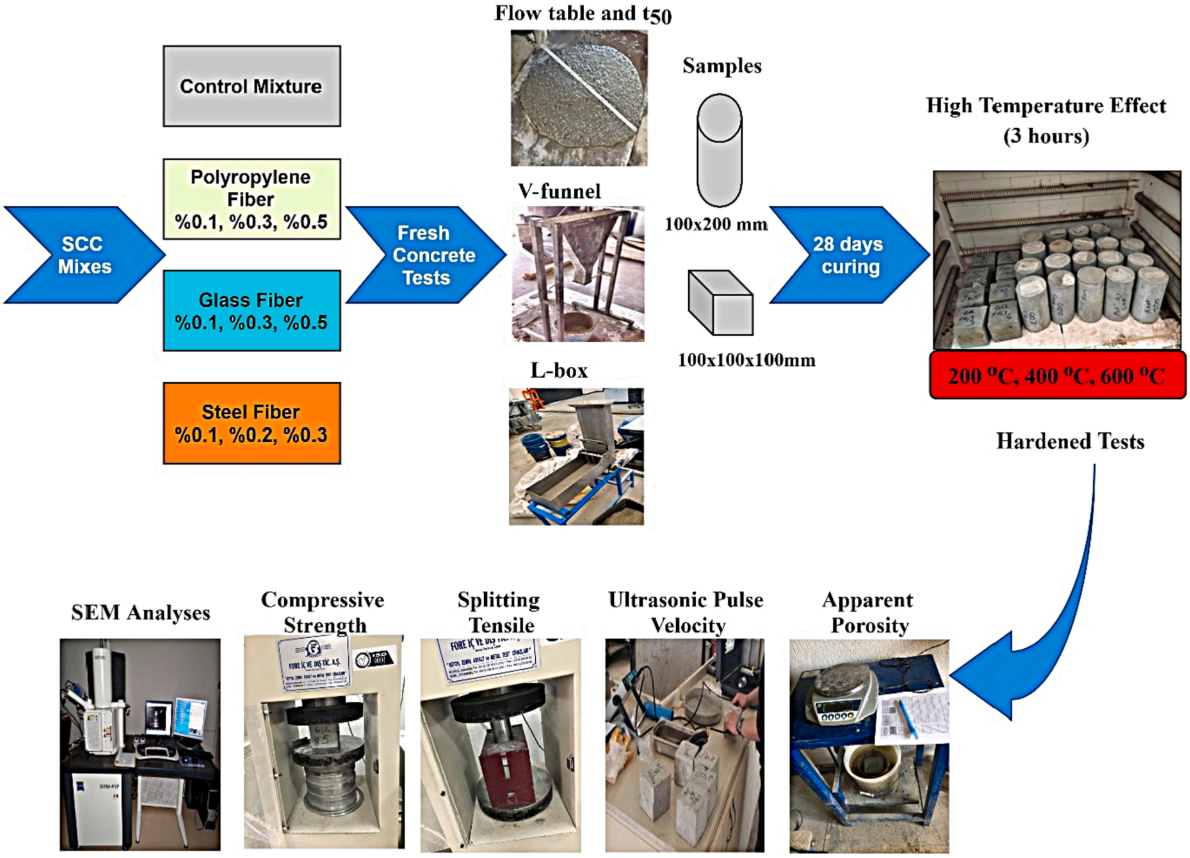

Fig. 1. Flowchart of the mixing and testing procedures.

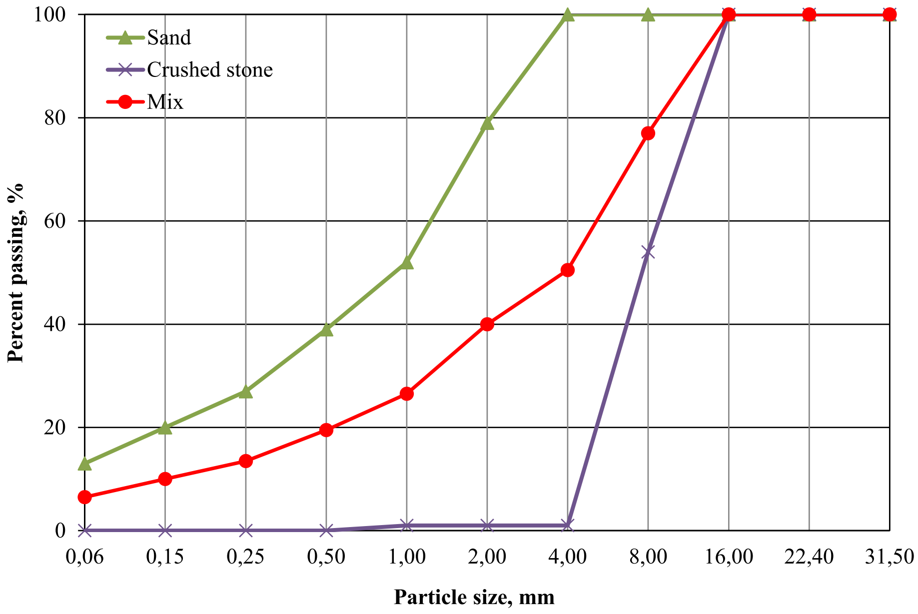

Fig. 2. The granulometry curve of the aggregates.

Table 2
The physical and mechanical properties of the fibers.

Property	Polypropylene fiber (PF)	Steel fiber (SF)	Glass fiber (GF)
Image			
Length (l) (mm)	12	60	12
Diameter (d) (mm)	0.02	0.9	0.013–0.015
Specific gravity (g/cm^3)	0.910	7.81	2.68
Tensile strength (MPa)	450–700	1100	3400
Aspect ratio (l/d)	600	67	800
Melting temperature (^{o}C)	150–170	1450–1520	1120

0.1%, 0.3%, and 0.5% of the concrete volume. Steel fiber was used as 0.1%, 0.2%, and 0.3% of the concrete volume. Glass fiber was used as 0.1%, 0.3%, and 0.5% of the concrete volume. The SCC mix design is presented in Table 3.

2.2.2. Fresh concrete tests

The consistency, flowability, and passing ability of the SCC samples were determined using the slump flow and T_{50} test [47], the V-Funnel test [48], and the L-Box Test [49].

2.2.3. Heating process

Before the hardened specimens were subjected to high temperatures, they were kept in a furnace at 105 °C until the difference between the two weight measurements was about 0.1%. The specimens were pre-

Table 3
The mixing ratios of the SCC series (kg/m^3).

Mixture	Water	Cement	Fly ash	Sand 0–4 mm	Coarse aggregate 4–11.2 mm	Fiber	Plasticizer
C	195	350	150	803	813	–	4.00
PF0.1	195	350	150	802	812	0.91	4.00
PF0.3	195	350	150	799	809	2.73	4.25
PF0.5	195	350	150	796	806	4.55	4.50
SF0.1	195	350	150	802	812	7.81	4.00
SF0.2	195	350	150	800	810	15.62	4.25
SF0.3	195	350	150	799	809	23.43	4.50
GF0.1	195	350	150	802	812	2.68	4.00
GF0.3	195	350	150	799	809	8.04	4.25
GF0.5	195	350	150	796	806	13.40	4.50

dried to minimize the possibility of explosion due to vapor pressure inside the samples during exposure to high temperatures. The furnace temperature was increased by 5 °C per minute to reach the exposure temperatures at 200 °C, 400 °C, and 600 °C. Fig. 3 shows the temperature–time curve of the furnace. SCC samples were exposed to high temperatures for 3 h to reach the thermal steady-state. Thus, the temperature in the inner core of the concrete sample to be close to the desired temperature.

Fig. 4 shows the images of the samples exposed to high temperatures. After high-temperature treatment, the small ventilation hatches of the furnace were opened to let the temperature drop gradually. The samples were left for about 24 h to cool down to ambient temperature. Then, hardened concrete tests were performed.

2.2.4. *Hardened concrete tests*

The specimens were prepared according to TS EN 12390–1 [50] and TS 12390–2 [51] standards. The specimens were subjected to standard curing in lime-saturated water at 20 ± 2 °C until day 28. Afterward, they were exposed to high temperatures and then left to cool to ambient temperature before hardened concrete tests. Ultrasonic pulse velocity tests were performed on the cube samples (100 × 100 × 100 mm) according to TS EN 12504–4 [52]. Compressive strength tests were conducted on the cube samples (100 × 100 × 100 mm) according to TS EN 12390–3 [53]. In order to indirectly determine the tensile strength of the SCC series, splitting-tensile strength tests were conducted on Φ100x200 mm cylindrical specimens according to TS EN 12390–6 [54]. Apparent porosity tests were conducted on the cube samples (100 × 100 × 100 mm). Archimedes' principle was used to measure the weight of the samples in water. Afterward, the apparent porosity of the SCC series was calculated using Equation (1) [55].

Apparent porosity (AP) (%) = $((W_d\text{-}W_0)/(W_d\text{-}W_s)) \times 100$ (1)

where W_0 is the weight of the sample after drying at 105° for 24 h (gr), W_s is the saturated weight of the sample in water (gr), W_d is the weight of the sample at the saturated condition in the air (gr), and AP is the apparent porosity (%).

The microstructure of the specimens that were exposed to high temperature was determined by performing a scanning electron microscope (SEM; Zeiss Supra 40VP) to determine the changes in the samples.

3. Evaluation of test results

3.1. *Fresh concrete test results*

Table 4 shows the results of the T_{50} test, V-Funnel test, the L-Box test, and the flow diameter of the fresh SCC mixtures. In general, SCC mixtures provided the limit values given in EFNARC [1]. The specimens had a flow diameter of 560 to 700 mm. The control specimen had the highest flow diameter. The increase in cohesion due to the increase in fiber volume in the SCC series resulted in a gradual decrease in flow diameter. The slump flow diameters in the SCC series with the PF series decreased by approximately 17% with the increase in fiber content. Similarly, Karimipour et al. [17] reported that when up to 0.3% PF was added to SCC, the workability of concrete decreased significantly. Flow diameters of the SCC series containing SF varied between 630 and 560 mm. The SF0.3 series had the highest reduction (20%) in the flow diameter. This result has indicated a significant reduction in the workability of fresh SCC mixture. In a similar study, Khaloo et al.[30] stated that when the SF volume is increased in SCC, the workability decreases and the use of high ratios of SF in the mixture leads to a decrease in other rheological properties specified by EFNARC. Flow diameters for GF used SCC mixtures were found to be in the range of 660–570 mm. Flow diameters decreased as GF increased in the mixtures. Sivakumar, et al. [13] reported in a similar study using GF that fiber increase negatively affects the workability of SCC because GF has a large surface area and friction between aggregates. The flow diameter results showed that the control, PF0.1 and GF0.1 series belonged to class SF2 and that all the other series belonged to class SF1. According to the flow diameter results, fibers had an adverse effect on workability. In addition, the flow diameters of the SCCs decreased with an increase in fiber volume. Similar results were presented in various studies that concluded that the workability of the fresh concrete is reduced with the increase in the volume of fiber usage [14,35].

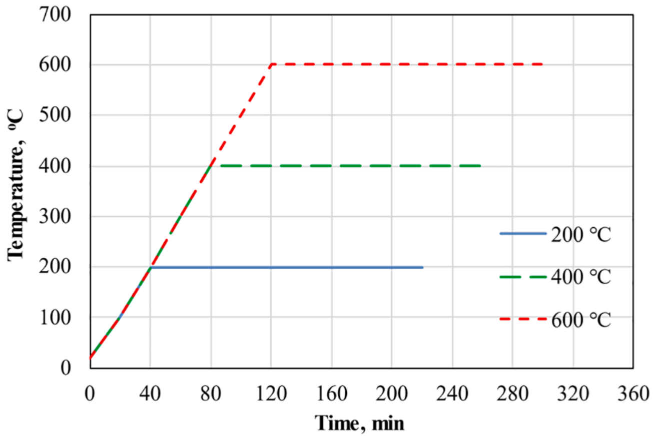

Fig. 3. The temperature–time curve of the high-temperature furnace.

The SCC samples had a T_{50} of 1.85 and 5.90 sec. Only the control series reached a flow diameter of 500 mm in less than two seconds. Therefore, the control series belonged to class VS1, while all others belonged to class VS2. The series with a lower flow diameter had higher T_{50} times. Higher T_{50} times were obtained with an increase in fiber volume in the fibrous SCC series.

The SCC series had a V-funnel flow time of 3.80 to 12.50 sec. The control, PF0.1, PF0.3, SF0.1, and GF0.1 series belonged to class VF1 because they had a flow time of fewer than 9 sec. The other series belonged to class VF2. In general, the series with higher times of flow to 500 mm diameter had higher V-funnel flow times. According to the L-box test results, all series but SF0.3 and GF0.5 had an h2/h1 ratio of greater than 0.80, indicating that they belonged to class PL2. The L-box test results ranged from 0.76 to 0.91. The L-box test results gradually decreased as the fiber volume increased. The SF0.3 and GF0.5 series had an h2/h1 ratio of smaller than 0.80, suggesting that concrete has low passing ability in narrow section molds.

3.2. *Ultrasonic pulse velocity test results*

Fig. 5 shows the temperature-dependent changes in ultrasonic pulse velocity of the SCC series. The SCC specimens kept at ambient temperature (20 °C) and those subjected to 200 °C had similar pulse velocity results. The pulse velocity results increased in some series, while they decreased in some others. This result suggests that heating SCCs to 200 °C did not significantly increase voids in the concrete structure and that the calcium silicate hydrate (C-S-H) structure did not deteriorate. High loss rates occurred in ultrasonic pulse velocity measured after the SCC series were exposed to high temperatures (400 and 600 °C). This is because the deterioration in the C-S-H structure turns into a hollow structure due to high temperature. Uysal [56], has determined a significant decrease in ultrasound pulse velocity measurements on samples exposed to high temperatures above 400 °C. When the control series were exposed to 200, 400, and 600 °C, ultrasonic pulse velocity results decreased by 5.1%, 41.2%, and 58.9%, respectively, compared to ambient temperature (20 °C). Savva et al. [57] reached similar results in their study. They stated that the ultrasonic pulse velocity obtained from concrete is greatly affected by microcracks and the reduction in ultrasonic pulse velocity after the increasing temperature is an indicator of crack propagation in concrete. In general, all fibrous SCC series and the control series had similar ultrasonic pulse velocity values.

Fig. 4. The heating process in the high-temperature furnace.

Table 4
Fresh concrete properties of SCC series.

Mixes	Slump flow (mm)	T_{50} (sec)	V-funnel (sec)	L-box (mm)
C	700	1.85	3.80	0.91
PF0.1	670	2.10	4.50	0.90
PF0.3	620	2.80	7.20	0.84
PF0.5	580	4.50	11.50	0.81
SF0.1	630	2.60	7.10	0.89
SF0.2	580	5.50	9.80	0.83
SF0.3	560	5.90	12.40	0.75
GF0.1	660	2.60	5.30	0.90
GF0.3	620	3.50	9.50	0.82
GF0.5	570	4.80	12.50	0.76

3.3. Compressive strength test results

Fig. 6 shows the temperature-dependent changes in the compressive strength of the SCC series. The compressive strength of the SCC samples decreased significantly with an increase in temperature. When the fiber-free control series were exposed to 200, 400, and 600 °C, compressive strength results decreased by 13.1%, 41.2%, and 58.7%, respectively, compared to ambient temperature (20 °C). This result indicated that the fiberless SCCs lost significant compressive strength at temperatures higher than 200 °C. As seen from test results shown in Fig. 6 each type of fiber showed different compressive strength behavior. When the series with PFs were examined, the compressive strength results of the series with PFs at 20, 200, 400, and 600 °C decreased compared to the C series at these temperatures.

When the SF series are examined, the compressive strength of the SF

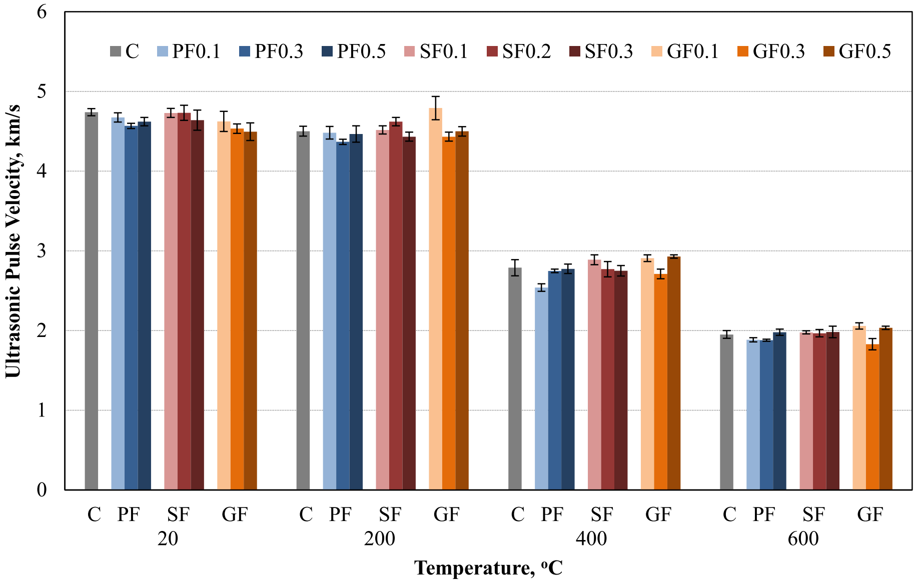

Fig. 5. Temperature-dependent changes in ultrasonic pulse velocity of the SCC series.

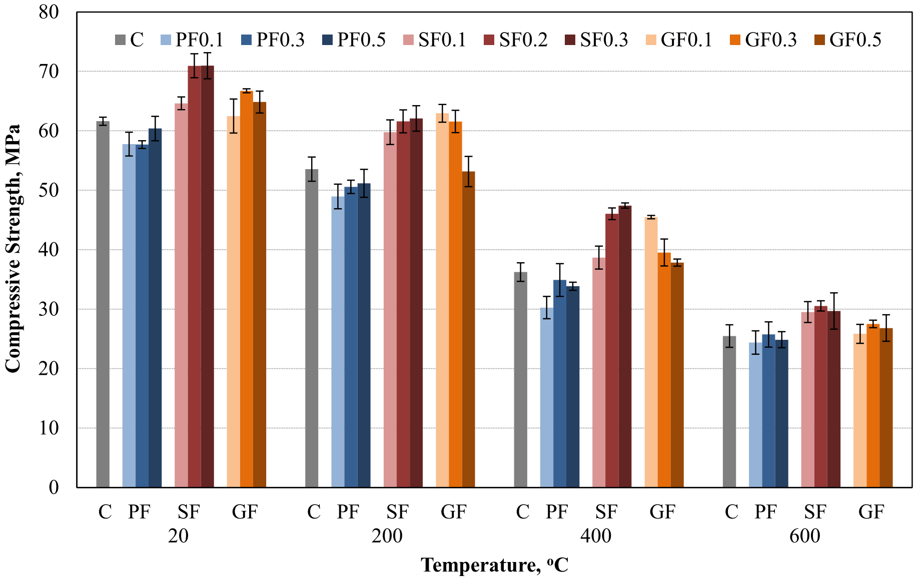

Fig. 6. Compressive strength of the SCC mixtures exposed to elevated temperatures.

SCC series increased compared to the control series at the same temperatures. In addition, the SF0.2 and SF0.3 series had higher compressive strength than the other steel-fiber SCC series as the temperature increased. For instance, it was found that the compressive strength of the SF0.3 series at 20, 200, 400, and 600 °C increased by 15.2%, 15.9%, 30.9%, and 16.5%, respectively when compared with the C series at the same temperatures. When the GF series were examined, it was observed that higher compressive strengths were obtained than the control series at every temperature, as in the SF series. With the increase in GF usage rates, the compressive strengths decreased at 200 and 400 °C temperatures, but still higher compressive strength values were obtained than the control series. In the GF series exposed to 600 °C, it was obtained that the compressive strength results are close to the C series at the same exposure temperatures.

When the results of the all-fiber series were evaluated, it was concluded that the best results were obtained from the SF series for temperatures of 20 and 600 °C. Similar results were obtained between the steel fiber series and the glass fiber (GF0.1 and GF0.3) series at 200 °C. Compared to the SCC series at ambient temperature (20 °C), SF0.3 had the highest compressive strength with an 15.2% increase compared to the control concrete, whereas PF0.3 had the lowest compressive strength with a 6.4% decrease compared to the control concrete. On the other hand, the control series at 20 °C, SF0.3, and GF0.3 series had 15.2%, and 8.3% increase in compressive strength, respectively, as the fiber volume increased.

Comparing the compressive strength of the fibrous and control SCC series at 200 °C, the GF0.1 series had a 17.5% increase in compressive strength compared to the control series, while the SF0.3 series had a 15.9% increase in compressive strength compared to the control series. The PF0.1 series also had an 8.6% decrease in compressive strength at 200 °C. Since the polypropylene fibers started to melt at around 170 °C, the fibers in the PF series exposed to 200 °C melted, and pores were formed. In the study of Noumowe [58], it was mentioned that when polypropylene fiber concretes are heated up to 170 °C, the fibers melt easily and additional porosity and small channels are formed in the concrete. Due to these pores, the compressive strength values of the PF series at 200 °C decreased.

Comparing the compressive strength of the fibrous and control SCC series at 400 °C, the SF0.3 series had a 30.9% higher compressive strength than the control series at 400 °C. On the other hand, the PF0.1 and PF0.5 series had 16.5% and 6.6% lower compressive strength than the control series at 400 °C, respectively. There was a reduction in compressive strength due to additional voids in the concrete structure with the evaporation of polypropylene fibers at about 350 °C. In addition, there were significant decreases in compressive strength because the chemical structure of concrete (C-S-H) begins deteriorating above 400 °C [59].

The SF0.2 series had the highest compressive strength at 600 °C. SF0.2 had a 19.9% higher compressive strength than the control series at 600 °C. The GF series had higher compressive strength than the control series at 600 °C. However, lower compressive strength was obtained from the PF series. These results show that we should use steel and glass fibers at high temperatures.

Fig. 7 shows the correlation between compressive strength and temperature. Since the results obtained from the series with the same fiber type are close to each other when forming the figure, the compressive strengths were calculated by taking the averages of the series with the same fiber type. The compressive strength decreased with increased temperature, and the correlation coefficient values showed a robust relationship between temperature and compressive strength. The result indicated that the SF SCC series had the best compressive strength, followed by the GF series.

3.4. Splitting tensile strength test results

Fig. 8 shows the temperature-dependent changes in splitting-tensile strength results. As the SCC series were exposed to high temperatures, their splitting-tensile strength decreased significantly. There was a 4.4%, 42%, and 68.7% loss in splitting tensile strength in the fiber-free control samples when they were subjected to 200, 400, and 600 °C, respectively. As in the control series, the fibrous SCC series generally had lower splitting-tensile strength with increased temperature.

When the PF series in Fig. 8 are examined, higher splitting-tensile strengths were obtained from the PF0.1, PF0.3 and PF0.5 series at 20 °C compared to the C series. When the PF SCCs were exposed to 200 °C, the PF0.1, PF0.3, and PF0.5 series had 4.7%, 6.8%, and 9.8% lower splitting tensile strength than the control series at 200 °C, respectively. All polypropylene-fiber SCCs had lower splitting tensile strength than the control samples at 400 and 600 °C. This is because PFs evaporate at approximately 350 °C, resulting in additional voids in the concrete structure [23]. The steel-fiber SCC series had higher splitting tensile strength than the control samples at 200, 400, and 600 °C. As can be seen in Fig. 8, higher splitting tensile strength results were obtained from the series with steel fibers compared to the series in which other

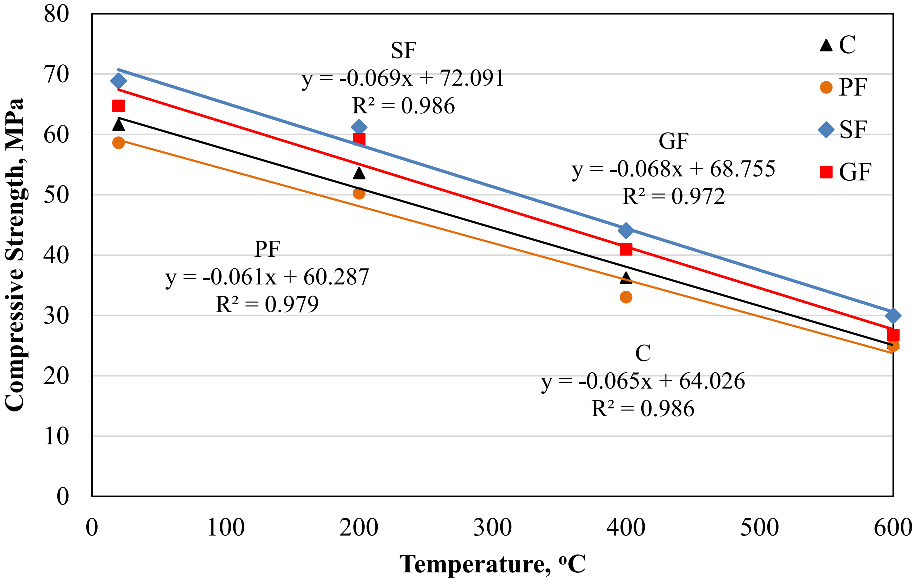

Fig. 7. Correlation between compressive strength and temperature.

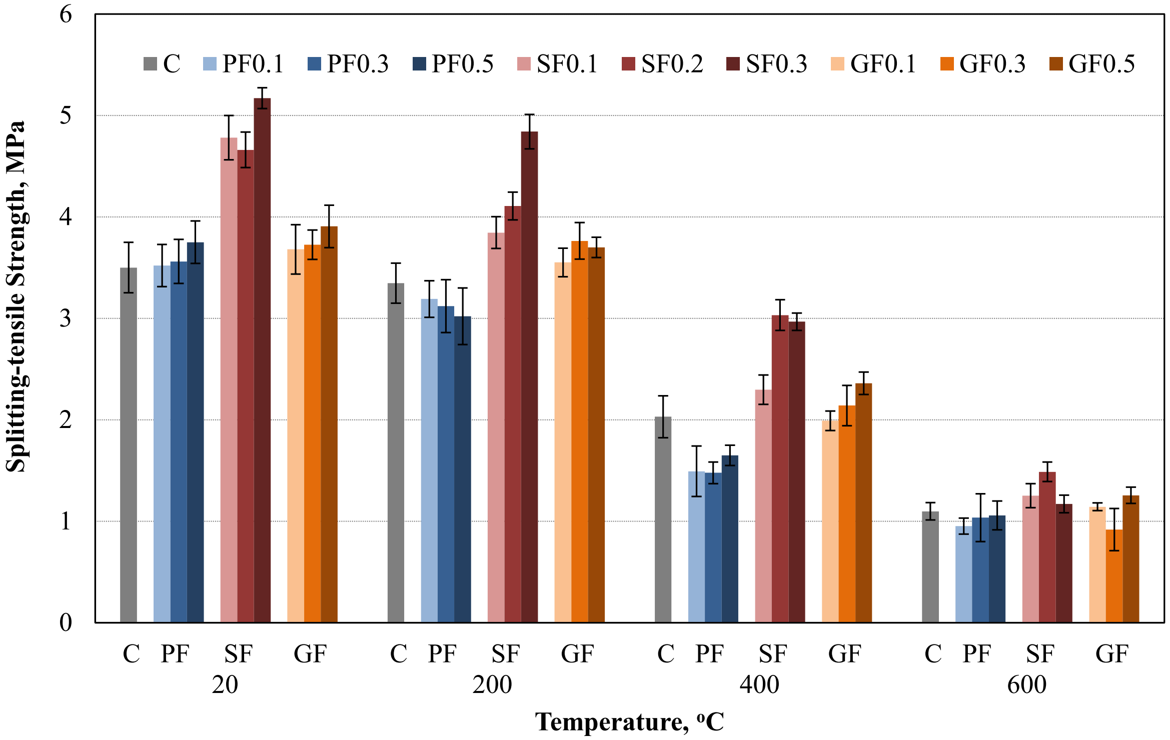

Fig. 8. Splitting tensile strength of the SCC mixtures exposed to elevated temperatures.

fiber types were used. This is because steel fibers have an excellent crack bridging activity that increases the tensile strength of concretes [60].

In general, with the increase in the GF usage volume at all temperatures, it was observed that the splitting tensile strengths increased compared to the control series at the same temperatures. For instance, it was concluded that the splitting tensile strength results of the GF0.5 series at 20, 200, 400, and 600 °C increased by 11.6%, 10.6%, 16.3%, and 14.4%, respectively, compared to the C series at the same temperatures. As can be seen from the results, it is thought that glass fibers also increase their splitting-tensile strength due to their crack bridging activity properties, although not as much as steel fibers. According to Fig. 8, the splitting tensile strength generally increased with an increase in fiber volume at all temperatures. This result suggests that the fibers contribute to tensile stresses with an increase in fiber volume in the concrete. The fibers functioned as a bridge to stop the cracks. This behavior explains the improvement in the mechanical properties of the fibrous SCC samples. Mahmod et al. [61] also found that fibers increased ductility and contributed to tensile strength.

According to Fig. 8, the control sample had the lowest splitting tensile strength, whereas the SF0.3 series had the highest splitting tensile strength with a 47.7% increase compared to the control series at 20 °C.

At 200 °C, the SF0.3 and PF0.5 series had the highest (44.6%) and lowest (9.8%) splitting tensile strength, respectively. The SF0.2 (49.3%)

and SF0.3 (46.1%) series had the highest splitting tensile strength compared to the control series at 400 °C, whereas the PF0.3 (27.3%) and PF0.1 (26.5%) series had the lowest splitting tensile strength compared to the control series at 400 °C. SF0.2 had the highest splitting tensile strength (35.5%) compared to the control series at 600 °C. On the other hand, GF0.3 (16.3%) and PF0.1 (13.3%) had the lowest splitting tensile strength compared to the control series at 600 °C.

Fig. 9 shows the correlation between splitting-tensile strength and temperature. Since the results obtained from the series with the same fiber type are close to each other when forming the figure, the splitting-tensile strengths were calculated by taking the averages of the series with the same fiber type. The steel-fiber series had the highest splitting tensile strength. The results pointed to a strong correlation between temperature and splitting tensile strength.

Fig. 10 shows the correlation between compressive strength and splitting-tensile strength at different temperatures. There was a positive correlation between compressive strength and splitting tensile strength.

3.5. Apparent porosity test results

Fig. 11 shows the temperature-dependent changes in apparent porosity. In general, the apparent porosity increased with an increase in temperature in all SCC series. At all temperatures, the highest apparent porosity values were obtained from the PF series. In addition, the apparent porosity increased with an increase in PF volume at those temperatures, and the PF0.5 series had the highest apparent porosity.

Polypropylene fibers are hydrophobic and create water pockets around them and also fiber addition lowers the workability which entraps air, both factors might increase the porosity [62]. Furthermore, polypropylene fibers could draw more air bubbles in the interfacial transition zone (ITZ) [63]. Especially at high temperatures, the melting of polypropylene fibers creates additional channels, thereby increasing the porosity compared to the control mixture.

At 400 °C, the PF0.5 series had the highest apparent porosity with a 9.1% increase compared to the control series, whereas the SF0.1 series had the lowest apparent porosity with a 6.7% decrease compared to the control series. At 600 °C, the PF0.5 series had the highest apparent porosity with a 4.4% increase compared to the control series, whereas the SF0.3 series had the lowest apparent porosity with a 9.3% decrease compared to the control series.

The steel and glass-fiber series had lower apparent porosity than the control series at all temperatures. The porosity values of steel and glass fiber concrete were obtained lower than the porosity values of polypropylene fiber concretes. Because the steel fibers have a more hydrophilic surface, the cement paste around these fibers can be properly hydrated and the space between the fiber and the matrix can be well filled [63]. For this reason, it is considered that lower porosity values are obtained from steel fiber concretes.

Fig. 12 shows the correlation between compressive strength and apparent porosity at different temperatures. There was a negative correlation between apparent porosity and compressive strength.

3.6. Internal structure analysis

The internal structure images of the PF0.3, SF0.3, GF0.3, and control series were investigated. Fig. 13 shows the internal structure images of the series exposed to 20 °C, 400 °C, and 600 °C. It has been observed that the fibers in the SCC series, which are only exposed to ambient temperature (20 °C), are dispersed in the binder matrix with proper adherence. Ettringite formations were more prominent in the control sample at 400 °C, which was similar in the PF0.3, SF0.3, and GF0.3 mixes. Polypropylene fibers, which were prominent at 20 °C in the polypropylene-fiber SCC mixture, were not observed at temperatures over 400 °C. This is because polypropylene fibers melt and evaporate around 350 °C. The water in the gel pores evaporated, and the C-S-H bonds weakened in all SCC mixtures at 600 °C, resulting in deterioration in the cement matrix. Therefore, the internal structure of the composite had a higher porosity.

The glass-fiber SCC series had fewer microcracks than the control SCC series at high temperatures. The cracks gathered around the steel, polypropylene, and glass fibers. However, the fibers functioned as a bridge to stop the cracks. This behavior explains the improvement in the mechanical properties of the fibrous SCC samples. Similarly, the fibers stopped the microcracks caused by thermal expansion and strengthened the concrete composite structure. Therefore, the SCC with fiber showed better performance than the control specimen.

4. Conclusions

This article demonstrates the effect of high temperature on the fiber used SCC mixtures. The following conclusions can be drawn from this study:

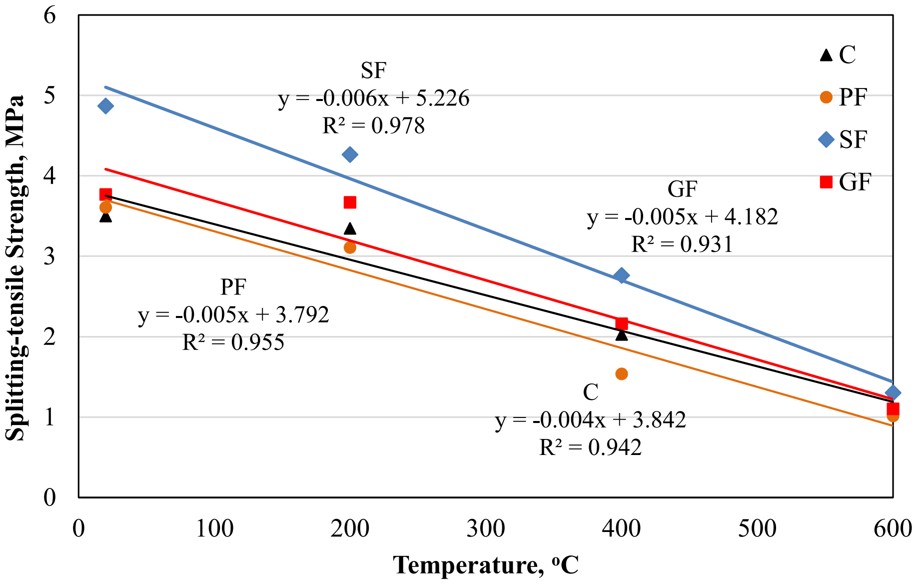

Fig. 9. Correlation between splitting-tensile strength and temperature.

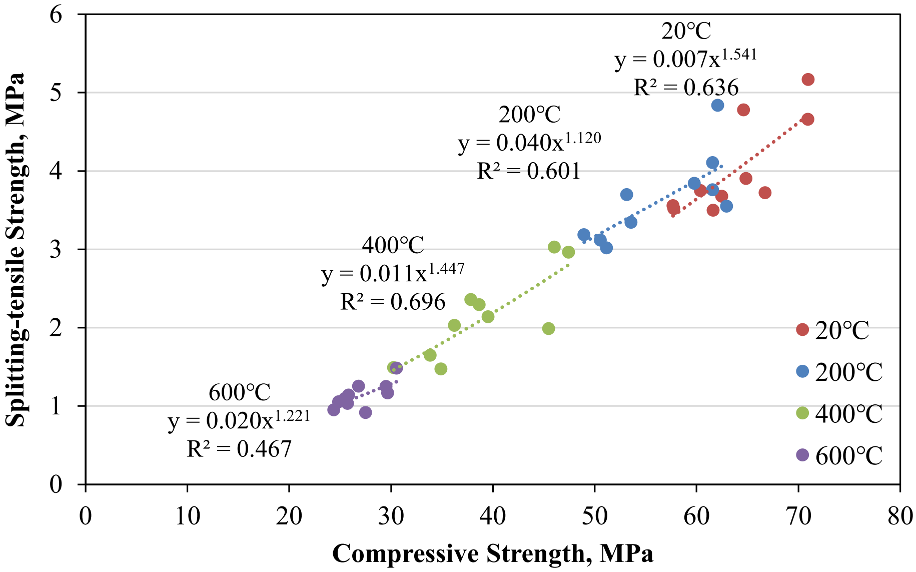

Fig. 10. Correlation between compressive strength and splitting-tensile strength.

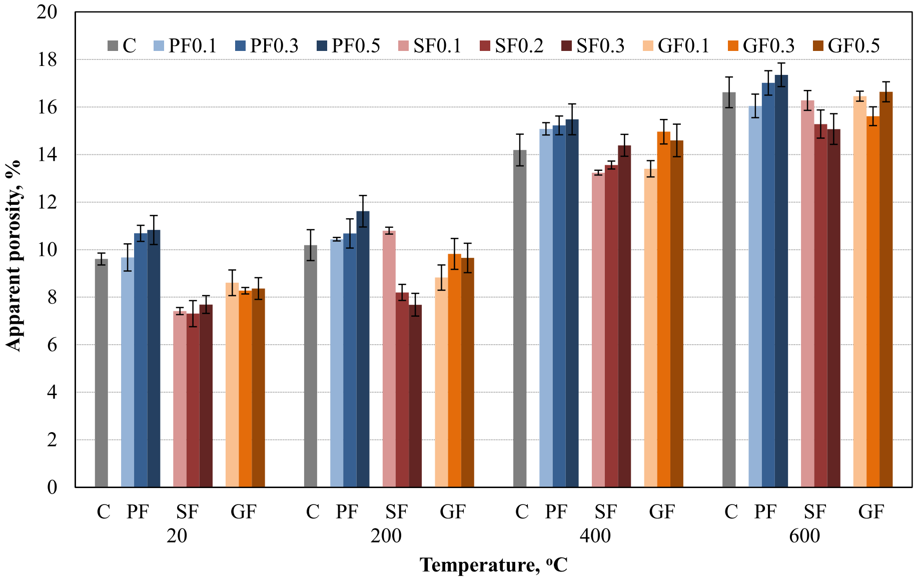

Fig. 11. Temperature-dependent changes in the apparent porosity of the SCC series.

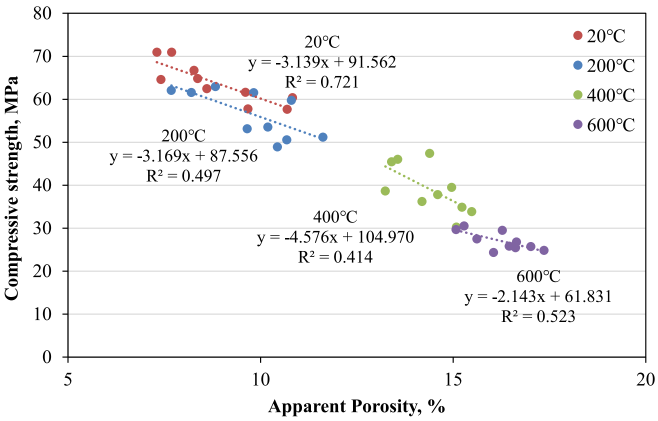

Fig. 12. Correlation between compressive strength and apparent porosity.

- Fiber volume was positively correlated with T_{50} times and negatively correlated with the flow diameter of fresh concrete (maximum reduction in SF0.3). There was a positive correlation between fiber volume and V-funnel flow times. The SF0.3 and GF0.5 series had an h2/h1 ratio of less than 0.80. There was a negative correlation between fiber volume and workability. In other words, fibers had an adverse impact on workability.
- High temperatures resulted in a significant reduction in the compressive strength of the SCC series. The steel-fiber SCC series had higher compressive strength than the control series at all temperatures. The SF0.2 series had the highest compressive strength at 600 °C. However, the polypropylene-fiber series had lower compressive strength than the control series. These results indicate that it is advantageous to use steel and glass fibers at high temperatures.
- The splitting-tensile strength decreased with an increase in temperature in the SCC series. Generally, there was an increase in the splitting tensile strength in the steel- and glass-fiber series with an

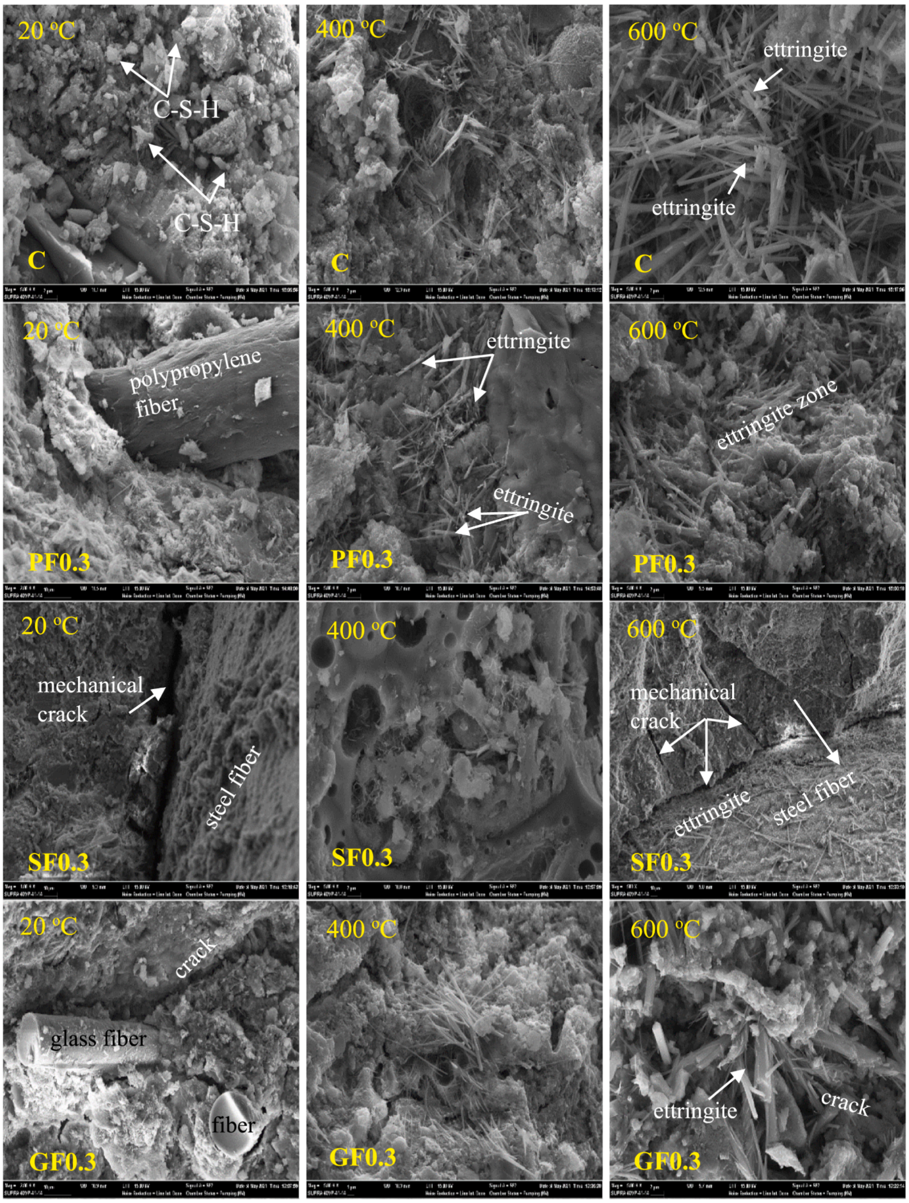

Fig. 13. The internal structure of samples exposed to high temperatures.

increase in fiber volume at all temperatures. This is because fibers have crack bridging activity that increases the tensile strength of concretes. The polypropylene-fiber series had a high splitting tensile strength at 20 °C but low splitting tensile strength at 200, 400, and 600 °C. This is because polypropylene fibers melted at temperatures above 170 °C and evaporate around 350 °C, resulting in additional pores and voids. The SEM analysis results also confirm this.

- In all SCC series, there was an increase in apparent porosity with an increase in temperature. Generally, the steel- and glass-fiber series had lower apparent porosity than the control series at all temperatures.

The results of the study showed that steel or glass fibers can be used to reduce deterioration in the dense composite structure of SCC due to the effect of high temperature.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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