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Performance of Fiber Self Compacting Concrete at High Temperatures

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Abstract

The goal of this study is to assess the fresh and hardened properties of self-compacting concrete (SCC) prepared using locally available materials. This research includes also the impact of polypropylene (PP), steel and hybrid fibers on the same properties. In addition, the mechanical properties of SCC specimens (with and without fibers) at high temperatures, including as compressive, tensile, and flexural strengths, will be determined. Four different SCC mixtures (with and without fibers) are prepared, tested, and assessed in order to attain these goals. The specimens were heated to various temperatures (200, 400, 600, and 800) at a rate of 5 degrees Celsius per minute for each test. The temperature was remained constant at the target temperature for one hour before cooling to ensure a consistent temperature throughout the specimen. According to the test results, all of the mixes have good consistency and workability in terms of filling and passing ability. In addition, the inclusion of fibers lowered the workability of SCC slightly. Also, the compressive, tensile, and flexural strengths improved with increasing temperature up to 200 °C and dropped at temperatures over 200 °C, according to these findings. Within the SCC, the PP fibers lowered and removed the risk of spalling. Concrete mixtures containing steel fibers and hybrid fibers have the finest mechanical characteristics and spalling resistance as temperature rises. Weight losses were lower in SCC mixtures with PP and steel fibers than in those without PP and steel fibers. As the temperature rose, all SCC mixes lost mass and UPV decreased until the samples spalled (as in plain SCC and SCC with steel fibers) or were questionable (as in SCC with PP and SCC with hybrid fibers).

Keywords: Self-Compacting Concrete; Fiber Reinforced Self-Compacting Concrete; High temperature; Steel Fiber; Polypropylene Fibres; Hybrid Fiber.

1. Introduction

Self-compacting concrete (SCC) was first developed in Japan in the mid-1980s with the goal of reducing durability issues in complex and substantially reinforced concrete structures caused by a shortage of skilled employees and inadequate communication between designers and construction engineers [1]. SCC is a type of concrete that can flow under its own weight and entirely fill the formwork, retaining homogeneity even when reinforcement is present, and then consolidate without the use of vibration. SCC is thought to offer a number of benefits, including reduced construction time, labor costs, and noise pollution, as well as the ability to fill crowded and thin portions with ease. Hardened concrete is dense and uniform, with the same engineering properties and durability as traditional vibrated concrete [2, 3].

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Various types of filler have been frequently employed in SCC as a partial cement substitute in recent years. SCC could become a more sustainable material as a result of this substitution [4]. SCC's high flow and resistance to segregation can be accomplished by using a considerable amount of super-plasticizer and filler materials. Though a variety of filler materials have been utilized in SCC production, the most typically used fillers include fly ash, silica fume, iron slag etc. [5]. As a partial substitute for cement, SCC produced with micro-fillers and mineral admixtures becomes cost effective [6]. Several studies have studied the influence of mineral additives on the fresh and hardening properties of SCC [7-10]. When compared to ordinary concrete created with vibrators, SCC is typically made with a lower water cement ratio, resulting in higher strength, lower permeability, and greater durability. The inclusion of fibers improves SCC's characteristics even more. The fibers act as crack arresters, bridging cracks and preventing crack growth [11]. Due to the addition of fibers, FR-SCC combines the benefits of SCC in the fresh state with increased performance in the hardened state [12-14]. With the inclusion of fibers, however, the workability of SCC decreases, and this decrease is depending on the type, shape, size, and dosage of fibers utilized [15]. Researchers [16, 17] added steel fibers to SCC and found that, although having a lower shear strength than conventional concrete, SCC with fibers achieved resistance values comparable to traditional vibrated concrete.

However, in dense concrete mixes, such as high strength concrete, or if the concrete is exposed to extremely high temperatures, the pore pressure created can be extremely damaging to the concrete matrix, resulting in material failure through spalling [18]. Adding PP and steel fibers to concrete lessens these negative impacts while also improving its mechanical properties at high temperatures [19-21].

Furthermore, because SCC has a tiny pore structure, it is susceptible to substantial degradation and violent spalling when exposed to high temperatures [22]. The influence of higher temperature has primarily been examined on vibrated and high-performance concretes to date. The limited investigations on SCC exposed to high temperatures indicate a loss in strength as well as an increased danger of spalling [23-27], or behavior identical to vibrated concrete [28].

Despite the significant uncertainties and the growing usage of SCC in a variety of applications, the temperature behavior of SCC has not been adequately researched, and the processes involved are not completely understood.

The goal of this research is to assess the fresh and hardened properties of SCC made from locally available materials. This research also considers the effects of steel, PP, and hybrid fibers on the same properties. In addition, the mechanical properties of SCC specimens (with and without fibers) at high temperatures up to 800 ° C for one hour, including compressive, tensile, and flexural strengths, are the focus of this research.

In this work, section 2 refers to the experimental program used (materials and methods and Mixing, moulding and curing) to produce SCC. Section 3 refers to the results obtained from this study for fresh concrete (slump flow and T50 slump flow time, L-box test and screen stability (GTM)) and hardened concrete (residual Compressive Strength, spalling, splitting Tensile Strength, flexural strength, ratio for mass losses and velocity of ultrasonic pulses (UPV)) under the influence of room temperature and high temperatures and discussion these results. The fourth part refers to the conclusions summarized from this study.

2. Materials and Methods

Ordinary Portland cement, silica fume (SF), aggregate (fine and coarse), water, super-plasticizer, and fibers (steel or polypropylene) are the mixture components. Table 1 describes the proportions of the SCC mix, the components of the SCC mix and their amounts. Natural sand with a maximum size of 4 mm and broken dolomite with a maximum size of 9.5 mm are used as coarse aggregates. The fine and coarse aggregate grain size distributions are depicted in Figure 1. A 25 per cent proportion of silica fume were added by cement weight. Silica fumes, specific gravity 2.1, specific area 172000 cm^2 / g (production data sheets). Figure 2 shows the particle size distribution of silica fume. In this study, a locally developed third generation super-plasticizer called Visco-Crete 3425 was used to help improve concrete workability without water added and to help fine particles occupy the pore space and minimize the amount of mixing water. This is a modified polycarboxylate aqueous solution, with a specific gravity of 1.08. It is ASTM C494 compliant type G and F [29]. Steel fibers with a hooked end, 25 mm length, 80 μm diameter, and 7.85 g/cm^3 density, and polypropylene fibers with a 12 mm length, 18 μm diameter, and 0.91 g / cm^3 density, were employed. In this case, tap water converted into used during mixing and curing phases for the concrete.

Four forms of mixture concrete have been designed: control mix (SCC) has been made without adding fibers, mixture contains 1% polypropylene fibers ($SCC\text{-}_{PPF}$), mixture contains 1% steel fibers ($SCC\text{-}_{StF}$), and mixture contains hybrid fibers 0.5% for both steel and polypropylene fibers ($SCC\text{-}_{StF\ \&\ PPF}$) by concrete volume. Figure 3 summarizes the testing program used to meet the goals of this research.

All mixtures were made with generic Portland cement weighing 420 kg/m^3 and containing 25, 1, and 45 percent silica fume, super-plasticizer, and water by weight, respectively.

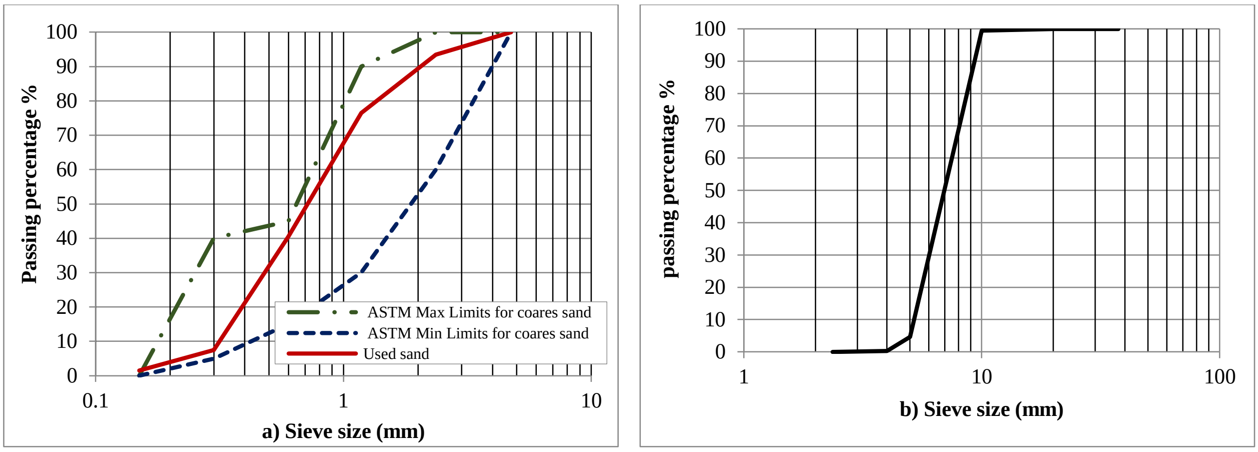


Figure 1. Grading curve of a) fine aggregate, b) coarse aggregate

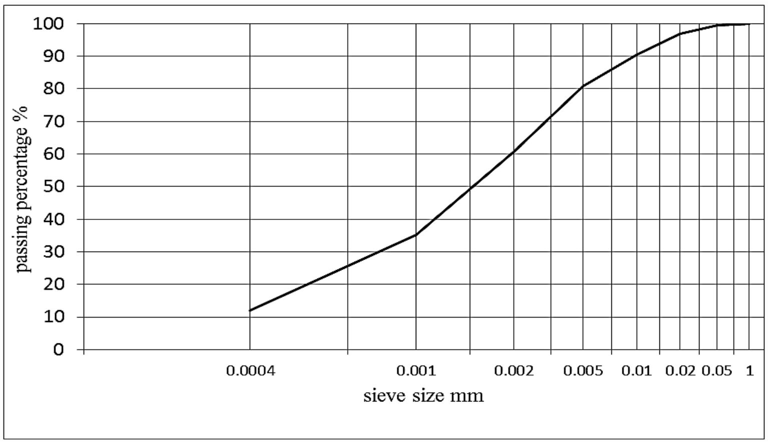


Figure 2. Particle size distribution of silica fume (source: from supplier)

Table 1. The constituents of the mixture are per kg/m^3

Mix No.	Cement	Silica fume	Aggregate		Water	Super-Plasticizer	Fibers	
			Coarse	Fine			Steel	PPF
SCC	420	105	810.58	810.58	189	4.2	0	0
SCC-$_{PPF}$	420	105	755.56	755.56	189	4.2	0	0.91
SCC-$_{SF}$	420	105	797.48	797.48	189	4.2	78.5	0
SCC-$_{SF\ \&\ PPF}$	420	105	776.7	776.7	189	4.2	40	0.45

3. Mixing, Moulding and Curing

In dry conditions, Portland cement, aggregate and silica fumes were mixed, then water and super-plasticizer were added. Fibers were introduced to dry materials before water, and additives were applied in the case of FR-SCC. For compressive testing, a (10×10×10) cm volume cube, a 10 cm diameter cylinder and a 20 cm height cylinder for tension test, as well as a (10×10×30) cm bending strength prism were applied. The slump-flow experiment, L-box, time series T_{50} and stability of the GTM screen were measured to investigate the fresh characteristics of SCC (filling strength, passing capacity and segregation resistance).

Flow-chart describing the SCC study methodology.

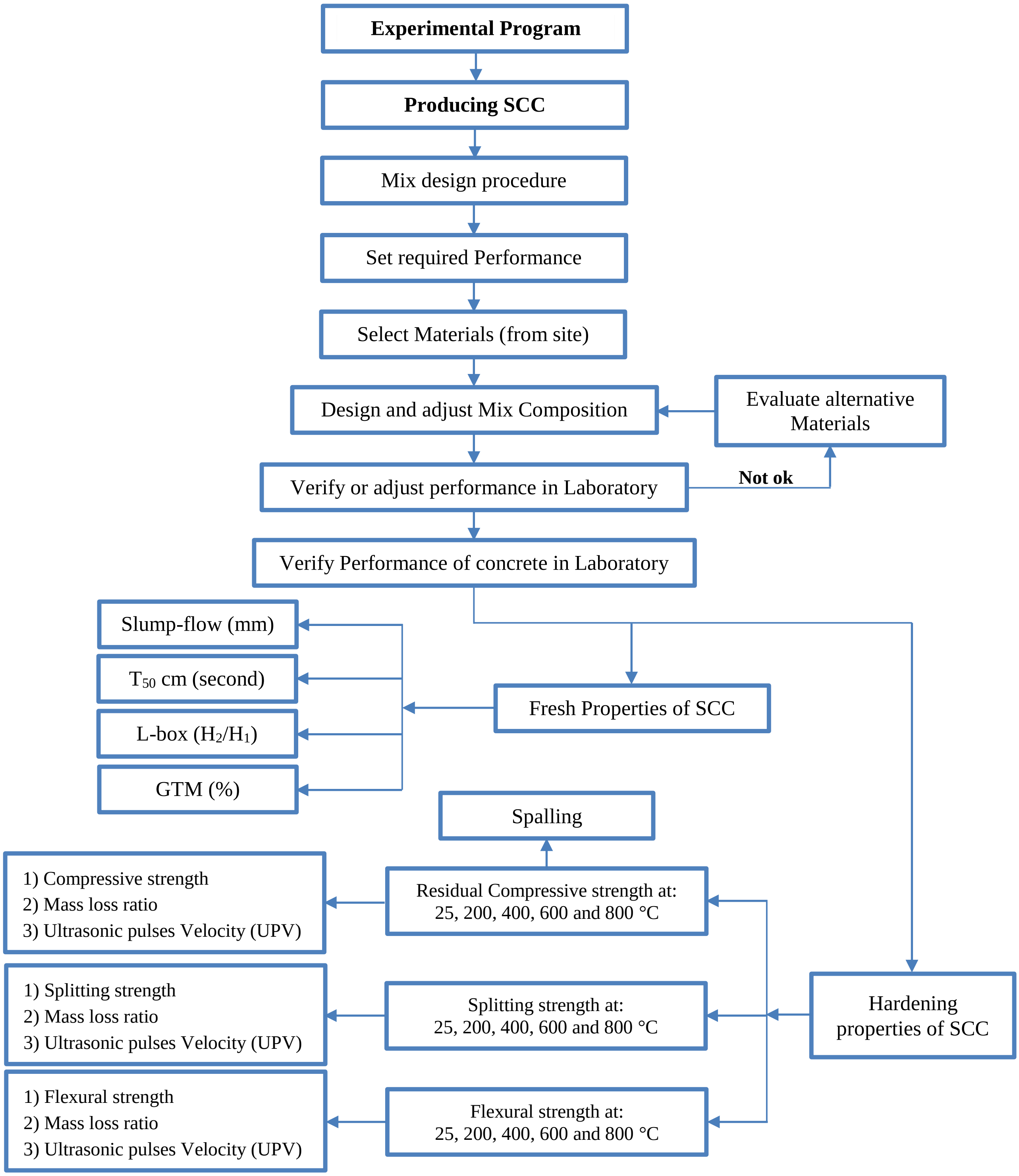


Figure 3. Overview of the Experimental Program

4. Results and Discussion

4.1. Fresh Properties of SCC

The behavior of SCC in its fresh condition is defined, categorised, and determined. The stated principles mentioned in standards such as EFNARC are one approach to identify the behavior of concrete and determine whether it fits certain specific requirements for its use or not. For all mixtures in this investigation, the slump flow, T_{50}, L-box test, and Screen stability (GTM) were utilized, as shown in Table 2, which is based on the results of the four tests and the limits of EFNARC listed [30]. The values of (D) represent the greatest spread (slump flow ultimate diameter) in Figures 4–7, whereas T50 values represent the time necessary for the concrete flow to reach a circle with a diameter of 50 cm. The blocking ratio is represented by (H_2/H_1). In Figures 1 and 3, D and (H_2/H_1) are plotted in descending order, while T_{50} is plotted in ascending order in Figure 2.

The ability of the SCC to flow unrestrictedly to fill the mold with its full volume, based solely on the influence of its weight, is referred as filling ability (unconstrained flowability). Passing ability (confined flowability) is defined as the ability of concrete to flow and pass through a narrow space, similar to the normal situation during casting, as well as the influence of reinforcing steel and its ratios through the mold and the space left behind, allowing concrete to flow uninterrupted. Segregation resistance (stability) is measured by the amount of time it takes to keep concrete uniform and homogeneous throughout transit and casting.

Table 2. Results of fresh SCC properties

Mix No.	Slump-flow (mm)	T_{50} cm second	L-box (H_2/H_1)	GTM (%)
SCC	780	2.3	0.96	11.1
$SCC\text{-}_{PPF}$	690	3.6	0.83	9.0
$SCC\text{-}_{StF}$	710	3.3	0.90	9.1
$SCC\text{-}_{StF\ \&\ PPF}$	700	4.0	0.82	8.6
Limit of EFNARC (2005) [30]	650-800	2-5	0.8-1.0	≤ 15

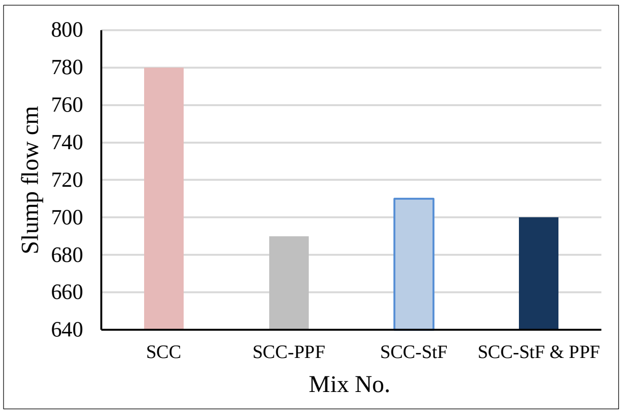


Figure 4. Slump Flow Diameter (mm)

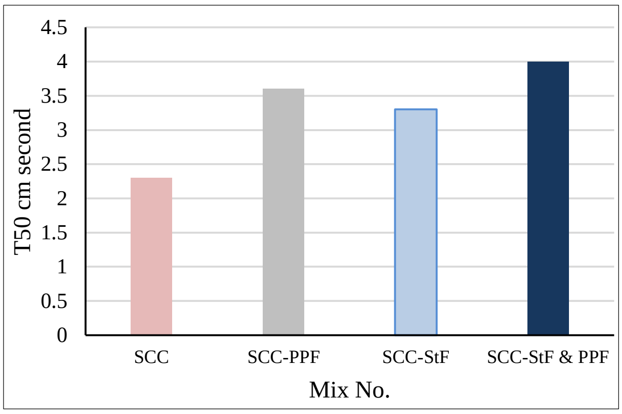


Figure 5. Time Required Passing (50 cm Dia.) Circle (T_{50})

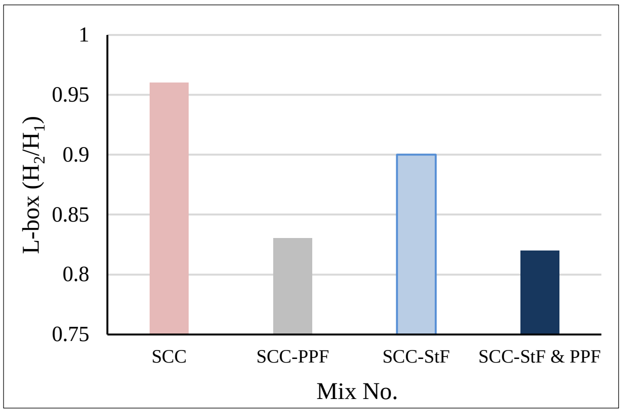


Figure 6. Fiber content impact on blocking ratio

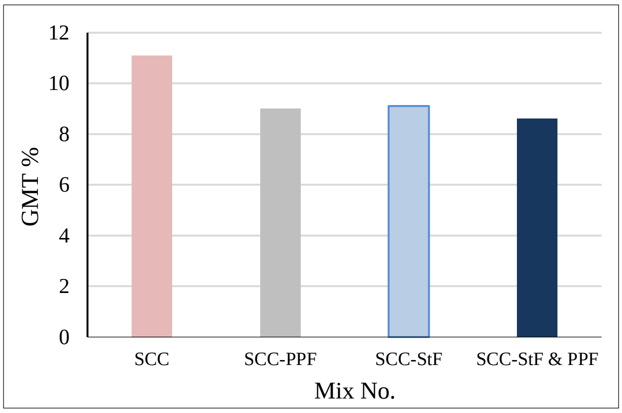


Figure 7. Fiber content impact on segregation ratio

The viscosity of SCC can be calculated using the T_{50} time or estimated using the V-funnel flow time. The time amount collected does not calculate the viscosity of SCC, but it is associated with it by defining the flow rate. Concrete with a medium viscosity should flow quickly at first and then halt. Concrete with a high viscosity may proceed to creep forward over a lengthy period of time. It is obvious from Figures 4 to 7 that:

- All of the mixtures meet the SCC standards outlined in the EFNARC specifications. As a result, all of the mixtures are deemed to have high consistency and workability in terms of filling and passing ability.
- It is obvious that the SCC mix (without fibers) is a low viscosity concrete, but the mix containing steel fibers is a high viscosity concrete. This behavior can be attributed to increased friction between fibers and aggregates particles in addition to the increased viscosity resulting from the addition of fibers [31].
- There is no segregation or bleeding when the flow is flowing or when the flow is stopped.
- It is clear from Table 2 and Figures 4 to7 that adding PP, steel, and hybrid PP and steel fibers with 1, 1 and 0.5 % decreases the slump flow by 11.5, 9 and 10%, increases T_{50} by 56.5, 43, and 74 %, reduces L-box by 13.5, 6 and

14.6 %, and reduces GTM by 19, 18 and 22.5 %. This loss of workability is caused by the presence of steel or PP fibers, which act as a barrier to the movement of mix components. The properties of the concrete are listed I Table 2, and it can only be classed and represented as an SCC if it fits all of the standards. These results are in accordance with those of other researchers [32, 33].

4.2. Test Procedure

Both mass and velocity of the ultra-sonic pulse were determined after the end of the sample processing time and before heating in the electrical furnace. Samples were heated at 5 °C per minute up to 200, 400, 600 and 800 °C using an electric oven. The temperature was then kept constant for an hour to guarantee that the specimens were all at the same temperature (Figure 8).

Figure 8. The electric oven used for heating the specimens

The final stage of the cycles involved a cooling down to room temperature. Figure 8 depicts the electric oven that was used to heat the specimens. The samples were removed from the oven and then tested for ultrasonic wave frequency, mass loss, compressive, tensile and flexural strengths.

4.3. Hardened Properties

4.3.1. Residual Compressive Strength

For all (100 mm) cubes, the compressive strength test was performed in accordance with ASTM C109-20 [34]. The compressive strength of each mix at each stage of heating was determined using three cubes. The following points can be noted from the test results shown in Table 3 and Figures 9 and 10:

- Behavior of unheated SCC: The compressive strength of SCC specimens containing PP fibers reduced at room temperature. When compared to reference mixtures without fibers, the strength loss is roughly 2.7 %. This could be attributed to the high air content and big volume of voids percentage in the mixes as a result of adding a high volume fraction of PP fibers. However, when compared to reference mixes without fibers, the compressive strength of SCC containing steel fibers and hybrid PP and steel fibers increased by about 15% and 2%, respectively, by the total volume. Steel fibers were a powerful material due to their higher stiffness, which improved compressive strength. As a result, steel fibers can withstand a higher load, have a higher carrying capacity, and provide better performance for SCC mixes. The enhanced interface between the aggregate and paste due to the absence of vibration may also account for the increased compressive strength of SCC. These results are consistent with those of other researchers [35, 36]. The failure of SCC specimens containing fibers proceeded gradually, and the fibers connected the segments together. In SCC specimens lacking fibers, however, failure occurs rapidly, and the cube splits into numerous fragments. The shape of failure is depicted in Figure 11.
- Behavior of SCC/FR-SCC specimens after heating: The compressive strength of SCC without fibers, SCC with steel fibers, and SCC with hybrid fibers improved by 1.8, 3.8, and 4.3 %, respectively, when the temperature was increased to 200 °C. As the temperature climbs to 200 °C, increasing cement hydration could be the main cause of enhanced compressive strength. However, SCC incorporating PP fibers had a 13.6 % reduction in compressive strength. Above 300 °C, the mechanical and physical characteristics of the SCC and FR-SCC specimens rapidly deteriorated. Mechanical properties were related with physical properties in specimens heated to 600 °C (appearance of cracking). The strength diminished as the temperature rose. When the furnace temperature is (400, 600, and 800) °C, the compressive strength of SCC specimens (without fibers) decreases by about (38, 73.5, 86.7) %, SCC specimens with PP fibers decrease by about (45.5, 68, 87.5) %, SCC specimens with steel fibers decrease by about (23, 54, 84.8) %, and SCC specimens with hybrid fibers decrease by about (43, 65, 85) %. The breakdown of the interfacial link caused by incompatible volume changes between cement paste and aggregate during heating and cooling is blamed for the loss in concrete's compressive strength. When the temperature rises over (400°C), the calcium hydroxide dehydrates, causing the cement paste to shrink. At around (600°C), many quartz-like aggregates undergo a crystalline transition, causing significant expansion and fracture of the concrete [12].

- The drop in compressive strength in specimens containing 1.0 % PP fibers is greater than in SCC specimens (without fibers). When the heating temperature is (200, 400, 600, and 800) °C, this reduction is roughly (21, 16.7, 9.1) % when compared to SCC specimens (without fibers). This could be due to the combined effect of the high temperature, which alters the structure of concrete as shown in point above, and the melting point of PP fibers (particularly at 400 and 600 °C), which results in a significant number of weak places between concrete materials. These findings are consistent with those of other researchers [37, 38].
- When the heating temperature is (200, 400, 600, and 800) °C, the compressive strength of specimens having 1.0 % steel fibers and specimens containing hybrid (0.5% steel + 0.5% PP) fibers is more than that of SCC specimens (without fibers). This increase is approximately (15, 42.8, 100, 33) % and (4.3, 7.6, 33.3, 16.7) %, respectively. Steel fibers improve the load-carrying capacity of the SCC matrix when exposed to tensile stresses, which explains the improvement in mechanical properties of SCC. Steel fibers play a function in preventing cracking and reducing the severe damage caused by high temperatures, which can influence all mechanical properties of concrete. The fibers perform well until the concrete reaches 700°C, after which it becomes brittle, crumbly, and loses its bonding strength with the fibers. Concrete expansion during heating, vapor pressure from water gel and holes, and the decomposition of cement-hydrating components are all elements that contribute to the formation of fractures [39].

Table 3. Compressive strength values after 28 days of cure for all SCC mixtures (MPa)

Mix No.	Compressive strength at high temperature (MPa)				
	25°C	**200°C**	**400°C**	**600°C**	**800°C**
SCC	45.2 (1)	46 (1.02)	28 (0.62)	12 (0.27)	6 (0.13)
SCC-$_{PPF}$	44 (1)	38 (0.86)	24 (0.55)	14 (0.32)	5.5 (0.13)
SCC-$_{StF}$	52 (1)	54 (1.04)	40 (0.77)	24 (0.46)	8 (0.15)
SCC-$_{StF\ \&\ PPF}$	46 (1)	48 (1.04)	26 (0.57)	16 (0.35)	7 (0.15)

Note: Bracket results for the different SCC mixes indicate the relative compressive strength

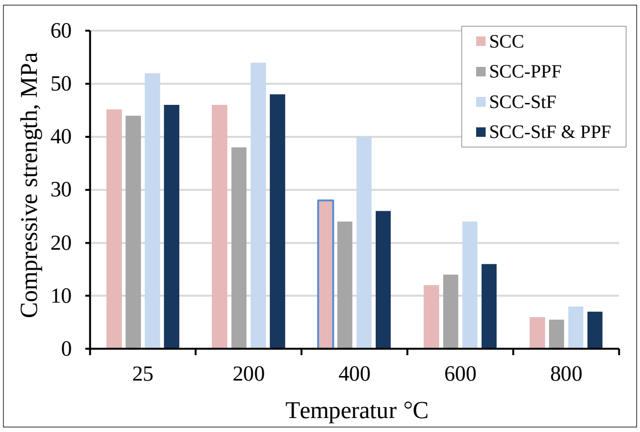


Figure 9. Results of compressive strength of different SCC mixes after high temperature exposure

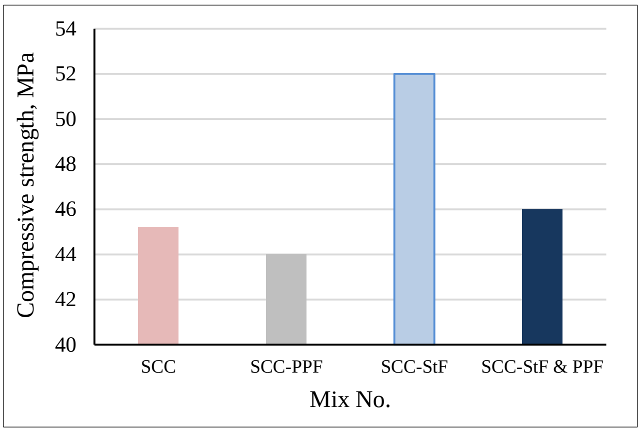
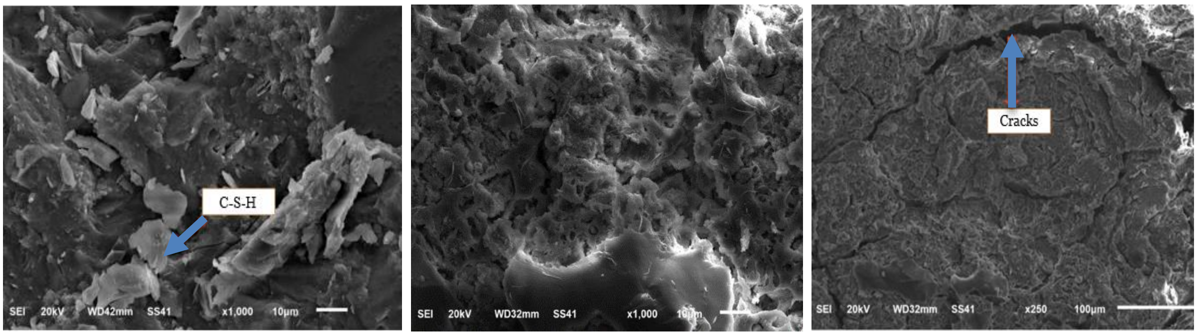


Figure 10. Effect of fiber type on the compressive strength for different types of SCC mixes

Specimens without fiber Specimens with fiber

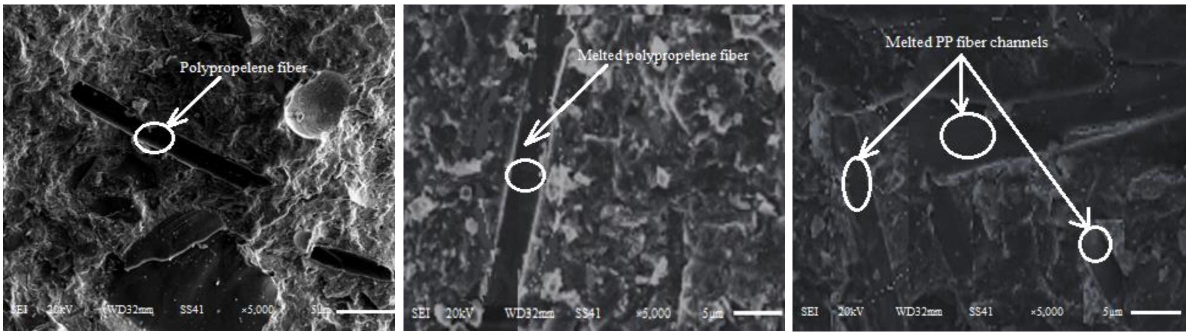
Figure 11. Modes of Failure

Figures 12 to 14 show a scanning electron microscope (SEM) micrographs of several SCC samples at high temperatures. SCC samples decomposed at temperatures beyond 800 ℃. SEM pictures of SCC (without fibers) mix at 20, 200 and 400 °C are shown in Figure 12. SEM micrographs of SCC with PP fibers samples at 200, 400 and 600 °C are shown in Figures 13a, b and c. When heated to 200°C, the rigid structure of polypropylene fibers was lost. Figure 13c shows SEM observations of samples that were subjected to 600 °C. Polypropylene fibers melt and volatilize easily at this temperature, resulting in more holes and narrow channels in the mortar. Figure 14a demonstrates SEM analysis of fracture surface for the distribution of steel and PP fibres in the SCC matrix (samples with hybrid fibers) after the test at room temperature. The failure pattern of steel fibre is mainly pulled out from the matrix (Figure 14b), PP fibres are partly pulled out and partly broken down (Figure 14c).



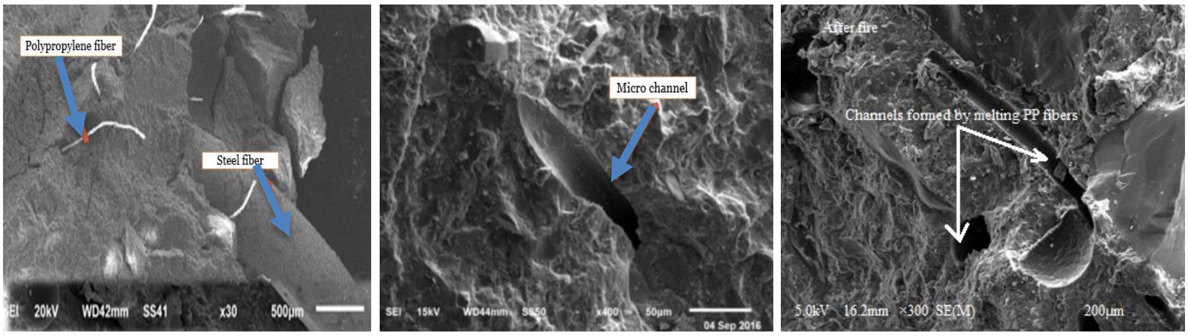
(a) (b) (c)

Figure 12. SEM pictures of SCC samples, (a) at 20 °C, (b) at 200 °C and (c) at 400 °C



(a) (b) (c)

Figure 13. SEM pictures of samples of SCC with PP fibers (a) at 200° C, (b) at 400 ° C, (c) at 600 ° C



(a) (b) (c)

Figure 14. SEM pictures of samples SCC matrix contain hybrid fibers (a) at room temp. and (b) failure pattern of steel and (c) failure pattern of PP fibers at 200°C

Spalling

After being exposed to high temperatures, the specimens were submitted to a comprehensive visual examination to assess visible symptoms of cracking and spalling on their surfaces. There was no noticeable cracking or breakage in specimens with temperatures between 200-400 °C. At high temperatures, Figure 15 depicts the surface feature of SCC specimens with and without fibres. At around 600 °C, hairline cracks started to form in large numbers. Just a little degree of spalling was apparent on the corners and edges of certain specimens at 600 °C. Whenever the furnace temperature is between 425 and 475 °C, explosive spalling occurs in SCC samples and this observation agrees with Kanema [40]. Low permeability is linked to a dense microstructure in concrete, which inhibits water vapors from dissipating due to heat, resulting in greater pore pressure.

Figure 15 shows that SCC samples with steel fibers suffers far less damage and spalling than SCC mixture. At elevated temperatures, silica fume can limit the development of cracks and bridge thermal cracks by mitigating concrete expansion owing to fast temperature changes and reducing wide temperature gradients due to the increased heat transfer coefficient [41]. In the SCC with PP fibers samples, the polypropylene fibers minimized the potential of explosive spalling. This could be because the PP fibers melt and evaporate during the rapid temperature increase procedure, causing micro channels to emerge in the concrete. As a result, capillary vapor tension can be reduced and discharged, that could explain why the SSC with PP fibers did not burst. At 800 °C, all of the samples displayed evident spalling at the corners and edges. The concretes containing steel fibers experienced no extensive cracking and spalling. Steel fiber-enhanced concrete did not crack or spall as much as other concretes.

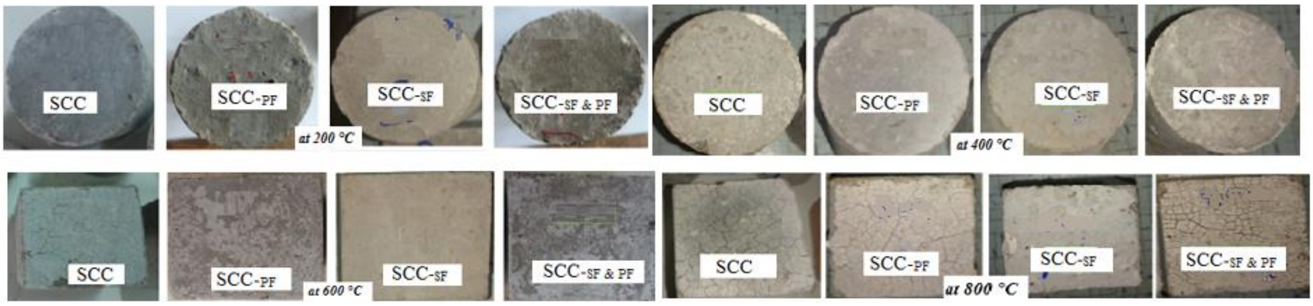


Figure 15. Surface behavior of SCC samples in 200, 400, 600 and 800 °C with and without fibres

4.3.2. Splitting Tensile Strength

The tensile strength test was carried out according to ASTM C496 [42], for all (10×20 mm) cylinders. Because concrete isn't usually built to withstand direct stress, knowing its tensile strength might help you estimate the load that will cause cracking. The absence of cracks is critical for maintaining a concrete structure's continuity and, in many situations, preventing corrosion [43]. Tensile strength is an essential factor in the creation of cracks and, as a consequence, in the prediction of concrete durability. Table 5 and Figures 16 and 17 show the test results of tensile strength of all SCC specimens. From the results, the following points are observed:

- Behavior of unheated SCC: Tensile strength increased by roughly 10, 40, 15% in SCC specimens including (PP, steel, hybrid PP and steel) fibers, while compressive strength increased by 2.7, 15, 1.8% in comparison to reference mixes without fibers. Better homogeneity from vibration-free production may also contribute to increased splitting tensile strength. These results are consistent with those of other researchers [22, 36]. Fibers help hold the cylinder parts together after they fail in specimens containing fibers, preserving the entire member and connection integrity. The failure shape is depicted in Figure 11.
- Behavior of SCC/FR-SCC specimens after heating: When the temperature was raised to 200 °C, the tensile strength of SCC without fibers, SCC with steel fibers, and SCC with hybrid fibers improved by about 5, 0.0, 7.1, and 4.3%, respectively. As the temperature climbs to 200 °C, increasing cement hydration may be the primary cause of higher tensile strength. In specimens exposed to high temperatures, there is a decrease in tensile strength. As the furnace temperature is 200, 400, and 600 °C, the tensile strength of SCC specimens (without fibers) decreases by around 5, 40, 89.5%, and SCC specimens with PP fibers decreases by about 0, 41, 91% when compared to specimens still at room temperature. In SCC specimens with steel fibers, the tensile strength decreases by around 7.1, 67.9% at 400 and 600 °C, and by about 13, 67.4% in SCC specimens with hybrid fibers, compared to specimens still at ambient temperature. The difference in thermal expansion between the cement paste and the aggregates, as well as the dryness of the cement paste and aggregate disintegration, may all play a role in the loss of strength [44].
- It is observed that the increase in tensile strength is higher in specimens containing 1.0 % PP fibers, 1.0 % steel fibers, and (0.5% steel + 0.5% PP) hybrid fibers by total volume than in SCC specimens (without fibers). As the furnace temperature is 200, 400, and 600 °C, this increase is approximately (4.8, 8.3, 4.8) %, (42.9, 117, 329) %, and (14.3, 66.7, 257) %, respectively, when compared to specimens without fibers. This could be due to the effect of the fibers, which alters the structure of concrete as shown in compressive strength [39].

Table 4. Tensile strength values after 28 days of cure for all SCC mixtures (MPa)

Mix	Tensile strength at elevated temperature (MPa)			
	25°C	200°C	400°C	600°C
SCC	4.0	4.20	2.40	0.42
SCC-$_{PPF}$	4.40	4.40	2.60	0.40
SCC-$_{StF}$	5.60	6.00	5.20	1.8
SCC-$_{StF\ \&\ PPF}$	4.60	4.80	4.0	1.5

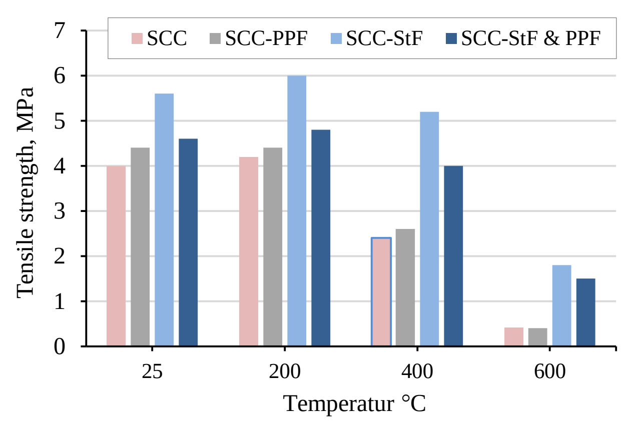


Figure 16. Values of tensile strength for all Mixes (MPa) at different temperatures

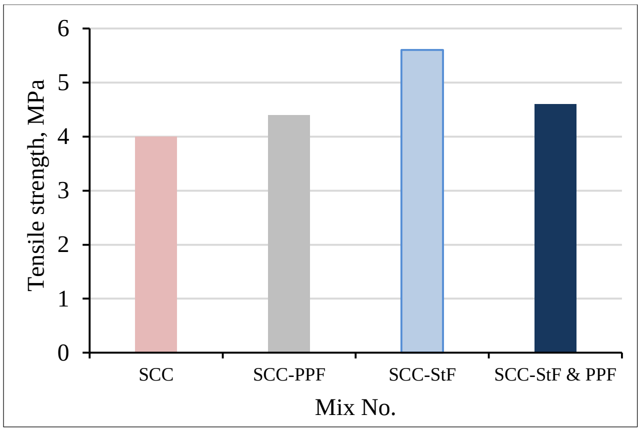


Figure 17. Values of tensile strength for all Mixes (MPa)

4.3.3. Flexural Strength

The flexural strength test was carried out according to ASTM C293 [45]. A simple concrete prisms was subjected to flexural testing in this study. Prisms measuring 10×10×30 mm were used to measure flexural strength. The cracks begins in the tension surface within the middle third of the span length in all specimens using the following relationship:

$$R=PL/bd^2 \tag{1}$$

Table 5 and Figures 18 and 19 show the test results of flexural strength of all SCC specimens. From the results, the following points are observed:

- Behavior of unheated SCC: As compressive strength increased by 2.7, 15, 1.8 % at room temperature in SCC specimens having (PP, steel, hybrid PP and steel) fibers, flexural strength increased by roughly 17.3, 42, 32.2 %, respectively, when compared to reference mixes without fibers. The restricting of cracks by fibers may account for the increase in flexural strength of SCC. These findings are consistent with those of other researchers [22, 35]. Fibers aid to hold prism elements together after they fail in specimens containing fibers, preserving the entire member and connection integrity. The failure shape is depicted in Figure 11.
- Behavior of SCC/FR-SCC specimens after heating: When the temperature was raised to 200 °C, the flexural strength of SCC with steel fibers and SCC with hybrid fibers improved by around 8.5 and 5.9%, respectively. As the temperature climbs to 200 °C, increasing cement hydration may be the primary cause of enhanced flexural strength. When specimens are exposed to high temperatures, they lose flexural strength. As the furnace temperature is (200, 400, and 600) °C, the flexural strength of SCC specimens (without fibers) decreases by about (2, 36.6, 94.4) %, and SCC specimens with PP fibers decreases by around (12, 49, 96.4) % when compared to specimens still at room temperature. In SCC specimens with steel fibers, the decrement in flexural strength is around (25.2, 81.3) %, and in SCC specimens with hybrid fibers, it is about (30.4, 88) % at (400 and 600) °C, compared to specimens still at ambient temperature. This could be due to the influence of the high temperature on the concrete construction. When the temperature rises over (400°C), the calcium hydroxide dehydrates, causing the cement paste to shrink. Because of the thermal incompatibility between cement in the past and aggregates, many micro and macro cracks appeared in the samples, reducing flexural strength. At 25 °C, steel fibers enhanced flexural strength and polypropylene fibers raised it marginally, but when the temperature rose, steel fibers also improved flexural and compressive strength, while polypropylene fibers caused some flexural strength reduction during curing before elevated temperatures exposures. A melting of PP fiber, which leads in the development of specific pores in the matrix, could explain this behavior [46].

Table 5. Flexural strength values after 28 days of cure for all SCC mixtures (MPa)

Mix	Relative flexural strength at elevated temperature			
	25°C	200°C	400°C	600°C
SCC	7.16	7.02	4.54	0.40
SCC-PPF	8.40	7.40	4.28	0.30
SCC-StF	10.16	11.02	7.60	1.90
SCC-StF & PPF	9.54	10.10	6.64	1.14

The increase in flexural strength is higher in specimens with 1.0 %t PP fibers, 1.0 % steel fibers, and (0.5 % steel + 0.5 % PP) hybrid fibers by total volume than in SCC specimens (without fibers). As the furnace temperature is (200, 400, and 600) °C, the increase is around (5.4, 6, 25) %, (57, 67.4, 375) %, and (43.8, 46, 185) %, respectively, when compared to specimens still without fibers. This could be due to the effect of the fibers, which alters the structure of concrete as shown in compressive strength [39].

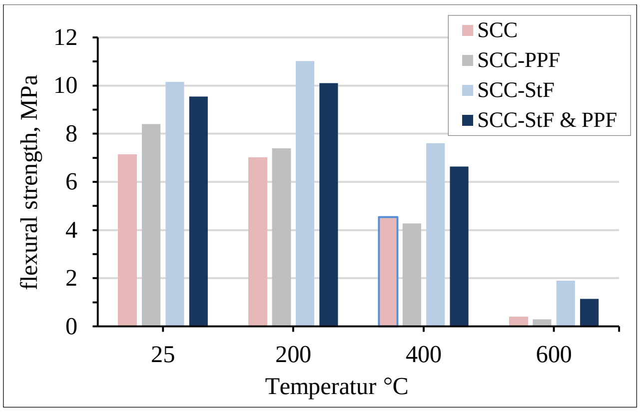


Figure 18. Values of flexural strength for all Mixes (MPa) at different temperatures

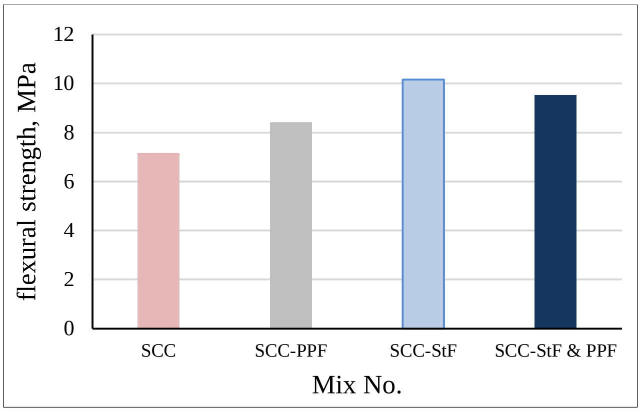


Figure 19. Values of flexural strength for all Mixes (MPa)

4.3.4. Ratio for Mass Losses

The mass loss ratio is calculated by dividing the difference between the weight at room temperature and the weight at a given temperature by the weight of various RPC specimens at room temperature. The ratio between the weight at 25°C and the weight at a particular temperature to the weight at 25°C is known as the mass loss ratio. Each specimen's mass was evaluated at 25°C and after being exposed to extreme temperatures. For the four concretes investigated, the weight loss vs. temperature was relatively similar. The mass loss ratio ranged from 2.96 to 18%, at temperature increasing from 200 to 800°C. It demonstrates that SCC had higher mass loss ratios than FR-SCC. Table 6 illustrates the mass losses of SCC mixes as a percentage of total mass as temperature rises. Figure 20 demonstrates that weight losses were smaller for SCC samples containing polypropylene and steel fibers than for those that did not. Weight loss following high-temperature concrete contact can be caused by a variety of factors. The main causes of weight loss are chunk expulsions or concrete spalling from the surface layers [46]. Small explosive spalling or chunks being ejected were seen during this test. The loss of weight at low temperatures could be owing to the escape of free water from capillary pores. The evaporation of bonded water, according to Rami et al. [47], causes weight loss among 150 – 300 °C. The fundamental explanation for this was that when the SCC samples were heated, the melted polypropylene fibers generated micro channels within the SCC samples that allowed the vapour to escape.

Table 6. Ratio of mass losses for all mixes

Mix	Mass loss ratio at elevated temperature (%)				
	25°C	**200°C**	**400°C**	**600°C**	**800°C**
SCC	0	5.16	7.58	11.24	18.00
SCC_{-PPF}	0	3.60	6.82	8.82	14.72
SCC_{-StF}	0	2.96	6.52	8.50	13.54
$SCC_{-StF\ \&\ PPF}$	0	4.64	7.16	9.06	15.44

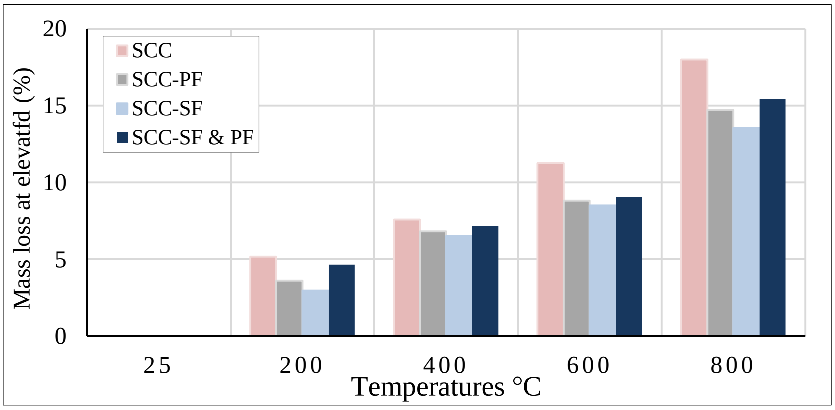


Figure 20. The relationship between the temperature and mass loss ratio

4.3.5. Velocity of Ultrasonic Pulses (UPV)

Ultrasonic pulse velocity was performed using ASTM C597 [48] Standard Method Test. A UPV test was conducted to assess the degree of damage to the SCC sample after it was exposed to high temperatures. The UPV test was carried out by sending an ultrasonic pulse through the cube samples and recording the time it took for the pulse to pass through. The greater the speeds, the better the concrete quality and consistency, as well as the lesser cracks and cavities. The UPV was computed by dividing the structure's breadth by the pulse's travel duration. The range of concrete samples' quality is shown in Table 7.

Table 7. Concrete quality assessment criterion based on speed [49]

Pulse velocity (km/s)	Concrete quality grading
Above 4.5	Excellent
3.5–4.5	Good
3.0–3.5	Medium
Below 3.0	Doubtful

The UPV findings of all of the SCC samples exposed to various elevated temperatures are shown in Table 8 and Figure 21. Each data point is the result of averaging three different SCC cubes samples tests. $SCC\text{-}_{Stf}$ had slightly higher UPV values than other SCC mixes at ambient temperature. The heated SCC specimens' UPV values declined as the temperature climbed, as seen in the figure. Plain SCC, $SCC\text{-}_{PPF}$, $SCC\text{-}_{StF}$, and $SCC\text{-}_{StF \,\&\, PPF}$ samples' UPV values have dropped by 19.3 percent, 22.2 percent, 16.6 percent, 8.1 percent, and 18.9 percent, respectively, at 200 °C. At 400 °C, all SCC specimens' UPV values indicated a continuous decrease. At this temperature, the $SCC\text{-}_{PPF}$ and plain SCC samples had the least UPV values. It's possible that the fall in UPV values for $SCC\text{-}_{PPF}$ and plain SCC samples is due to the high temperature, which causes full physical breakdown in SCC samples. In comparison to the samples at 200 and 400 °C, the frequency of micro-cracks rose and the concrete quality decreased at 600 ° C, resulting in a larger reduction in UPV values. All SCC samples kept their physical shape as the temperature was raised from 25 to 800 °C to measure UPV, which ranged from good to dubious. Due to melting polypropylene fibers, cracks and pores emerge in the $SCC\text{-}_{StF \,\&\, PPF}$ and $SCC\text{-}_{PPF}$ samples, resulting in physico-chemical variations in cement paste and thermal mismatch between aggregate and cement paste, which is assumed to be the cause of mechanical property degradation [47, 50]. Because fewer fractures form inside the SCC after evaporation, the UPV readings for $SCC\text{-}_{StF \,\&\, PPF}$ are greater at 600 and 800 °C than for $SCC\text{-}_{PPF}$, as shown in Figure 21. The amount of micro-cracks in the $SCC\text{-}_{PPF}$ samples tends to be higher, leading in a steeper decrease in UPV readings than in the $SCC\text{-}_{StF \,\&\, PPF}$ samples.

Table 8. Result of ultrasonic pulse velocity for all mixes

Mix	Ultrasonic pulse velocity at elevated temperature (km/sec)				
	25°C	200°C	400°C	600°C	800°C
SCC	4.46	3.6	2.34	1.12	0.84
$SCC\text{-}_{PPF}$	4.40	3.42	2.24	1.10	0.50
$SCC\text{-}_{StF}$	4.42	4.06	2.62	1.06	0.44
$SCC\text{-}_{StF \,\&\, PPF}$	4.34	3.52	2.42	1.56	0.84

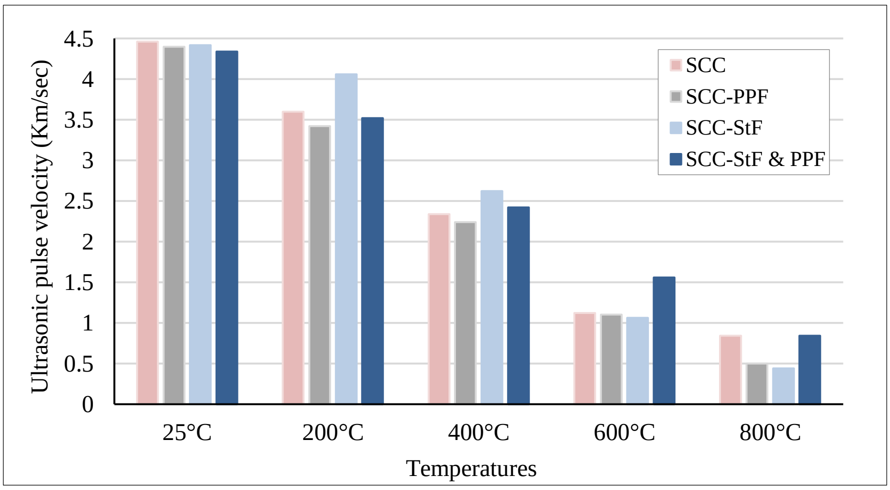


Figure 21. Relation of the ratio of mass loss to temperature

The micro-cracking of concrete has a significant impact on the transmission of pulse waves through it. As a result, decreasing pulse velocity as temperature rises is a sensitive indicator of material cracking. Fissures in the concrete can form as a result of high temperatures, thermal expansion, and dryness. The pulse velocity of the SCC samples is increased by the cracks or micro-pathways that generate rising cracks. As a result, microcracks slow down the pulse and cause low UPV levels [48].

5. Conclusions

A series of experiments were carried out throughout this study to evaluate changes in mechanical characteristics on SCC sample was subjected to considerable temperatures between 25 and 800 ° C, as well as to investigate the impact of incorporating steel fibers, polypropylene fibers, and hybrid fibers on mechanical properties. Based on the findings of this research, the following conclusions can be drawn:

- Slump flow, L-Box tests, and GMT results show that all of the mixes meet the SCC standards outlined in the EFNARC guidelines. As a result, all of the mixtures are deemed to have high consistency and workability in terms of filling and passing ability.
- Fibers can be used in SCC, and the characteristics of FR-SCC are within acceptable limits. In addition, the addition of fibers results in a more uniform and cohesive mix with just a minor reduction in workability.
- There is no segregation or bleeding when the flow is flowing or when the flow is stopped.
- When comparing reference mixes without fibers to mixes containing PP, steel, and hybrid PP and steel fibers, T50 increases by about 56.5, 43, and 74 percent, while slump flow diameter decreases by about (11.5, 9 and 10) percent, L-box decreases by 13.5, 6 and 14.6 percent, and GTM decreases by 19, 18 and 22.5 percent. As a result, substantial doses of superplasticizer are used in these mixtures to retain workability.
- The addition of steel fibers resulted in a significant increase in mechanical strength. The effect of fibers, which effectively inhibits the spread of crack due to the existence of a strong link between the matrix and steel fibers, can be attributed to this increase in mechanical characteristics. This improved the SCC mechanical strength by increasing the concrete's ability to absorb energy. Furthermore, steel fibers can bridge micro/macro cracks, limiting the growth of main cracks and changing the failure mode from brittle to ductile.
- The mechanical characteristics of SCC with steel fibers increased to 200 °C and the loses over 400 °C. Whilst the mechanical properties for SCC with PP fiber declined to 200 °C.
- In specimens exposed to high temperatures, there is a decrease in compressive, tensile, and flexural strengths.
- The better mechanical characteristics were provided by concrete mixtures which include steel fibers as well as hybrid fibres.
- The inclusion of steel fibers and polypropylene fibers minimized the possibility of explosion spilling in the self-compacting concrete.
- When the temperature is between 425 and 475 ℃, spalling happens in SCC samples.
- With the temperature rise the mass loss ratio increased.
- Using steel fibers and polyethylene fibres lowered the mass-loss ratio.
- With rising temperature, all SCC mixes showed increasing mass loss and decreasing UPV until samples spalled (as in plain SCC and SCC with steel fibers) or were suspect (as in samples of RPC with PP fibers and RPC contain hybrid fibers).

5.1. Recommendation for Future Work

On the effect of elevated temperature on FR-SCC, the following points should be researched.

- The effects of steel fibers, polypropylene fibers, and hybrid fibers on the mechanical and thermal properties of SCC exposed to varying periods of high temperatures.
- The effect of adding carbon fibers to SCC that has been exposed to high temperatures on mechanical and thermal properties.

6. Nomenclature

SCC	Self-Compacting Concrete	FR-SCC	Fiber Reinforced Self-Compacting Concrete
$SCC\text{-}_{PPF}$	Mixture contains 1% polypropylene fibres	$SCC\text{-}_{StF}$	Mixture contains 1% steel fibres
$SCC\text{-}_{StF\ \&\ PPF}$	Mixture contains hybrid fibres, 0.5% steel and polypropylene fibres	PP fibers	Polypropylene fibers

7. Declarations

7.1. Author Contributions

Conceptualization, H.H.Y.A. and H.K.S.; methodology, S.D.; software, H.H.Y.A.; validation, H.H.Y.A., S.D. and H.K.S.; formal analysis, H.H.Y.A.; investigation, H.H.Y.A.; resources, H.H.Y.A.; data curation, H.H.Y.A. and H.K.S.; writing—original draft preparation, H.H.Y.A. and H.K.S.; writing—review and editing, H.H.Y.A. and H.K.S.; visualization, H.K.S.; supervision, S.D.; project administration, S.D.; funding acquisition, H.H.Y.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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