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The Rheological, Mechanical, and Durability Behavior of Self-Compacted Concrete (SCC) Mixed with Hybrid Fibers after Exposure to High Temperatures and Cycles of Freezing and Thawing

Ahmed Ashteyat,[1,*] Ala' Taleb Obaidat[2] and Rahaf Qerba'a[1]

Abstract

This study presents the influence of hybrid fibers basalt (BF), steel (SF), and polypropylene (PP) on the rheological, mechanical properties, and durability behavior of self-compacted concrete (SCC). Seven SCC mixes with varying fiber levels (0%, 0.05%, 0.1%, and 0.15%) and combination were cast. Mechanical properties such as compressive strength, splitting tensile strength, and flexural strength were investigated after exposure to high temperatures (400 °C, and 600 °C) and 200 freeze-thaw (F/T) cycles. The rheological properties of fresh self-compacting concrete (SCC) were investigated using slump flow and V-funnel flow. Results showed a significant decrease in rheological properties of SCC with increase in fibers volume. The specimens' compressive strength was shown to increase as the volume ratio of the fibers increased to 0.15%. The optimal fiber mixture for SCC compressive strength was (BF-SF-PPF), which is approximately 18.5% more than the control specimen. The SCC groups, which included fibers exposed to high temperatures and 200 freeze-thaw cycles, had mechanical properties that were higher to those of the control group. The ability of concrete to absorb water was improved by the addition of fibers to SCC. The ultrasonic pulse velocity UPV is improved more when specimens reinforced with double hybrid fibers (basalt and steel) are used than when specimens reinforced with triple hybrid fibers.

Keywords: Basalt; Polypropylene; Fibers; High temperature; Freeze and thaw; Self-compacted concrete (SCC); Ultrasonic pulse velocity.
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1. Introduction

Concrete is generally used extensively in reinforced structural applications and consumption has been increasing due to the population's rapid growth as well as its benefits, including component prices, availability, durability, and high compressive strength, but the material's tensile strength, crack resistance, and ductility are low, as they are for any brittle material.[1,2] In concrete structure, the steel reinforcement has increased in complexity and weight, which causes challenges with concrete pouring, compacting, loss of workability, and a lack of long-term durability of concrete buildings.[3,4] Therefore, Self-compacting concrete (SCC) may be used inreinforced concrete constructions because of its workability, passing and filling capabilities, and resistance to segregation and bleeding, without experiencing many of the problems that come with utilizing conventional concrete. Japanese scientists developed SCC to address issues with vibrated concrete (VC) and to allow form filling through in the presence of crowded steel reinforcement and complex formworks.[5-7] By increasing productivity and offering higher quality and durability of structural buildings, particularly in reinforced concrete structures, SCC has revolutionized the field of concrete technology. SCC enables for creative architectural ideas and provides the structure with an excellent level of finish, performance, and durability. Additionally, the efficacy on-site may be improved by cutting down on labor expenses and

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[1] *Civil Engineering Department, University of Jordan, Amman 11942, Jordan.*
[2] *Civil Engineering Department, Philadelphia University, Amman 19392, Jordan.*
**Email:* a.ashteyat@ju.edu.jo (A. Ashteyat)

construction time, reducing the use of compaction equipment, and creating a secure environment for formwork.[8,9] The fundamental components of self-compacted concrete are the same as those of vibrated concrete (VC): coarse aggregate, fine aggregate, cement, water, additives made of chemicals and minerals, and fines.[4,10-13] The rheological features of self-compacting concrete, which include resistance to segregation, passing ability, and filling ability, are an obvious distinction between it and conventional concrete. All of these characteristics in their unhardened condition led to concrete that is stronger and more durable. Therefore, these qualities are obtained by utilizing high range water reduction agents (HRWR), viscosity-modifying agents (VMA), and air entraining admixtures (AEA), as well as increasing the fine particles content.[14,15]

In order to address common concrete issues including poor tensile strength and ductility, the construction industry's fast global expansion has created a demand for new forms of enhanced quality concrete. Self-compacting concrete may be made more effective and efficient by adding various types and shapes of fibers. Fiber-reinforced self-compacting concrete (FRSCC) is a novel building material that, in general, combines the advantages of SCC with the advantages of fibers.[16-18] As stated by,[9,19-21] the addition of fibers to concrete is a key factor in improving the engineering properties of hardened concrete, including reducing crack width and delaying its spread, preventing sudden failure, frost and fire resistance, reducing shrinkage, increasing tensile and flexural strength, improving ductility and stiffness, and improving the bearing capacity for concrete structures. The size, type, length, and orientation of the fibers, as well as the aspect ratio and shape of the fiber ends and the surface roughness[9,22] all play a role in how the fibers affect the fresh and hardened properties of concrete. The characteristics of concrete with the addition of various fiber types, including polypropylene fibers, carbon fibers, glass fibers, basalt fibers, steel fibers, natural organic fibers, and polyester fibers, have been the subject of several research investigations.[1,2,8,9,18,21,22] Hybrid fibers are created by combining two or more different fiber types to create a substance that combines the advantages of each fiber type utilized separately. The performance of concrete is efficiently and more beautifully improved by the hybridization of fibers with various kinds, forms, and sizes. On the other hand, using a certain type of fiber enhances concrete's characteristics on a particular level. The management of cracks of various sizes may be accomplished by hybrid fiber reinforced concrete (HFRC).[9,19,23,24] In order to create a composite with superior and more attractive qualities in both the fresh and hardened stage, hybrid fiber reinforced self-compacting concrete (HFRSCC) combines the advantages of SCC with the beneficial characteristics of fibers.[6,25] investigated how basalt and polypropylene fibers affected the mechanical characteristics of high-performance concrete (HPC). 16 mixes of single polypropylene fibers (0.0, 0.025, 0.033, and 0.042%), single basalt fibers (0.0, 0.1, 0.15, and 0.2%), and hybrid fibers in various ratios were utilized. Depending on the findings of the tests, HPC mixes including polypropylene or basalt fibers increase stronger as the fiber ratio increases. As a result, as compared to HPC mixes without fibers, the splitting tensile and flexural strengths were dramatically increased by 48.6% and 22.8%, respectively, while the compressive strength increased by 14.1%. When 0.033% of the polypropylene fiber and 0.15% of the basalt fiber combined, the synergy effect of hybrid fibers was optimum.

Aslani and Nejadi[26] investigated how well steel and polypropylene fiber additions affected the characteristics of self-compacting concrete (SCC). In this investigation, four SCC mixes were used, including one as a control and three containing steel, polypropylene, and hybrid fibers. According to the findings, the combinations displayed high homogeneity and cohesion, and there were no signs of segregation or considerable bleeding. The SCC mix containing hybrid fibers exceeded the control, steel, and polypropylene SCC mixes in terms of compressive strength and elasticity modulus, respectively. On the other hand, steel fiber reinforced self-compacting concrete had the maximum tensile strength. In comparison to mixes without fibers, the addition of fibers in SCC mixtures improved the rupture coefficient.

Afroughsabet and Ozbakkaloglu[23] examined experimentally the mechanical and durability properties of steel and polypropylene fiber-infused high-strength concrete. Twelve different mixtures were used, including one that was plain, one with 10% silica fume, four with different amounts of hooked-end steel fibers (1.0, 0.75, 0.5%, and 0.25%), three with different amounts of polypropylene fiber (0.45%, 0.3%, and 0.15%), and three with hybrid fibers (steel and polypropylene) at a total ratio of 1%. The results revealed that adding steel fibers and polypropylene at different ratios improved the mechanical characteristics of high-strength concrete. Additionally, concrete's splitting tensile strength and flexural strength both increased by 55% and 61%, respectively, with the addition of 1% steel fiber. Additionally, a combination of 0.15% polypropylene and 0.85% steel had the maximum compressive strength of 97.5 MPa.

Akcay and Tasdemir[27] investigated different ratios of the three types of steel fibers (1.5 and 0.75% of the total volume of concrete). Test findings revealed that the insertion of steel fibers had reduced SCC's workability, with the shape of the fibers serving as the major determining factor. Additionally, concrete's flexural strengths increased when high strength steel fibers were utilized, but the material's splitting tensile strength remained unaffected.

Tabatabaeian *et al*.[28] investigated how hybrid fibers affected the rheological, mechanical, and durability characteristics of high-strength self-compacted concrete. Eleven specimens of self-consolidating concrete (SCC) were constructed using two distinct types of fibers—hooked end steel and polypropylene fibers—at different dosages. The specimens' rheological, robustness, and mechanical qualities were examined. The findings showed that adding steel and polypropylene fibers might reduce workability while also enhancing tensile strength and flexural stiffness. Polypropylene may also cause an increase in Electrical resistivity.

Regardless of the compressive strength of the concrete, durability is a crucial component since durability issues frequently result in problems rather than insufficient strength.[29] The term "durability" refers to a material's capacity to survive a variety of degradation processes while keeping acceptable engineering characteristics, the original shape, quality, and serviceability over an extended period of time. The durability of the concrete is influenced by its strength, the quality of the aggregates, the curing time, the water's quality, the cement concentration, and the level of exposure.

Particularly when concrete is used in cold climates like the Arctic, China, and North China, freezing and thawing durability is of utmost importance in concrete design and application since it significantly affects the life and service quality of concrete buildings. One of the worst things that can happen to concrete is a quick shift in temperature (freezing and thawing cycles). A change in the water's condition can reduce the internal pressure that develops in concrete. This is accomplished by, air-entraining chemicals are added to the cement mixture to produce air bubbles. The use of fiber enhances air entrainment in concrete and decreases porosity as compared with conventional concrete. Therefore, adding different kinds of fibers to concrete and SCC can significantly increase its capacity to withstand freeze-thaw cycles.[30,31]

One of the environmental factors that might have a negative effect on the mechanical and physical properties of concrete is high temperatures. Fire resistance is thus one of the most crucial factors in the construction of concrete structures. The primary impacts of high temperatures on concrete are dehydration of the cement paste, increased internal pressure, loss of resilience, changes in moisture content, thermal expansion, structural cracking, increased porosity, and thermal spalling. The main factor causing lower concrete strength is increased internal pressure, which is brought on by increased temperature.[32,33] According to,[34] the fire resistance of concrete buildings is generally determined by the caliber of the materials used to produce the concrete, the rate of heat increase, the maximum temperature, and the length of time exposed to fire.[35] A fire won't cause conventional and self-compacting concrete to spall, according to earlier research on polypropylene fibers (PPF).[24,36,37]

Tao *et al*. in 2010[38] conducted an Experimental research on the impact of high temperatures on the properties of self-compacting concrete. High temperatures (at 20, 200, 400, 600, and 800 °C) were applied to all specimens. Depending on the type of concrete used, mixes were divided into three groups: self-compacting concrete (SCC), self-compacting concrete with polypropylene fiber (SCCPPF), and high-strength concrete (HSC). According to experimental findings, SCC's hot compressive strength decreases with increasing temperature, with the exception of high-strength SCC, which increases at about 400 °C. On the other side, the strength grade of concrete affects how much strength it retains, particularly at temperatures below 400 °C. The addition of polypropylene fibers to the mixture decreased compressive strength and the potential for explosive spalling, as well as provided stronger fire resistance than previous HSC and improved workability, according to another study conclusion. Tuyan *et al*.,[39] investigated the freeze-thaw resistance and mechanical properties of SCC with coarse recycled concrete aggregate. Recycled concrete aggregate (RCA) was used in place of coarse limestone aggregate in amounts of 0%, 20%, 40%, and 60% by weight. According to test results, passing ability remained unchanged but the viscosity of SCC mixes was increased in mixes that contained RCA. For the same slump flow value, the superplasticizer content slightly increased as the RCA content increased. When the coarse RCA percentage was increased to 40%, the compressive strength of SCC mixes increased. Additionally, adding RCA to SCC mixes decreased concrete's tensile strength, water absorption, unit weight, and freeze-thaw resistance, while increasing chloride-ion penetration and water absorption.

Berkowski and Kosior-Kazberuk[30] investigated the influence of various types of polypropylene fibers and steel fibers on concrete's resistance to surface scaling exposed to freeze-thaw cycles. The test's parameters were fiber type (steel microfibers A, steel macro fibers B, polypropylene smooth fibers C, polypropylene extruded fibers D), fiber volume (steel fibers were 0.38% and 0.76% and polypropylene fibers were 0.5% and 0.1%), and concrete surface type. According to the results of the experiments, steel fibers were more effective than polypropylene fibers at improving scaling resistance.

Steel fibers may be able to prevent cracks from spreading further and stop concrete's performance from degrading. On the other hand, the effectiveness of fibers was correlated with their shape and size.

Khan *et al*.[40] conducted an experimental study to see how different lengths and ratios of basalt fibers would affect a hybrid fiber reinforced concrete (HFRC) subjected to high temperatures. Basalt fiber proportions (0.6%, 0.45%, 0.3%, and 0.5%), basalt fiber lengths (50, 37, 25, and 12 mm), and a constant content of steel fiber, fly ash, and CaCO3 whisker of 0.35%, 0.3%, and 1% by volume fraction were the main factors investigated in this study. The experimental behavior of all mixes was investigated at room temperature and 850 °C. The findings demonstrated that basalt fibers improved the toughness, stress-strain response, peak strain, peak stress, ultimate strain, elastic modulus, and strain capacity of hybrid fiber reinforced concrete. Additionally, basalt fibers added to HFRC demonstrated less spalling of concrete after being exposed to high temperatures than the control combination. The use of these materials in the construction of structures under high temperatures may be beneficial based on the successful results of using basalt fibers in HFRC mixes.

It may draw the conclusion that despite the fact that several research on the properties of SCC with various types and amounts of fibers have been conducted, there is a lack of knowledge about the properties of SCC that incorporate hybrid fibers that have been exposed to high temperatures and freeze-thaw cycles. Examining the rheological, mechanical, and durability behavior of self-compacted concrete containing hybrid fibers (basalt fiber, steel fiber, and polypropylene fiber) is the goal of this study. Seven SCC mixes were produced with varying fiber levels (0%, 0.05%, 0.1%, and 0.15%). The workability and compressive strength, splitting tensile strength, and flexural strength of a total of 528 specimens were tested after being subjected to high temperatures (23 °C, 400 °C, and 600 °C), freezing-thawing conditions (200 cycles), water absorption, and ultrasonic pulse velocity tests.

2. Experimental program

2.1 Material properties

The SCC mixes were made in accordance with EN 197-1-2011 standards, using ordinary Portland cement (OPC) Type I with a 52.5 grade and a 3.15 specific gravity. According to the ASTM C33/C33M-16[41] standard, the aggregate was selected based on the original rocks, specific gravity, and particle size. Limestone with a maximum size of 16 mm, which was retained on filter No. 4, is the origin of the coarse aggregate used in this investigation. Water absorption and specific gravity were 2.66 and 1.3%, respectively. Two types of fine aggregate were used, limestone with a mean size between 3-6 mm and silica sand with a mean size between 0-3 mm. The features of fine aggregate are summarized in Table 1. A high-performance superplasticizer (Hyperplast PC770) was used in this investigation. It adheres to ASTM C494-Type G[42] and is based on polycarboxylate polymers provided by DCP Company. Hyperplast PC 770 has a specific gravity of 1.060.02 and is a light-yellow liquid.

Table 1. Physical properties of fine aggregate.

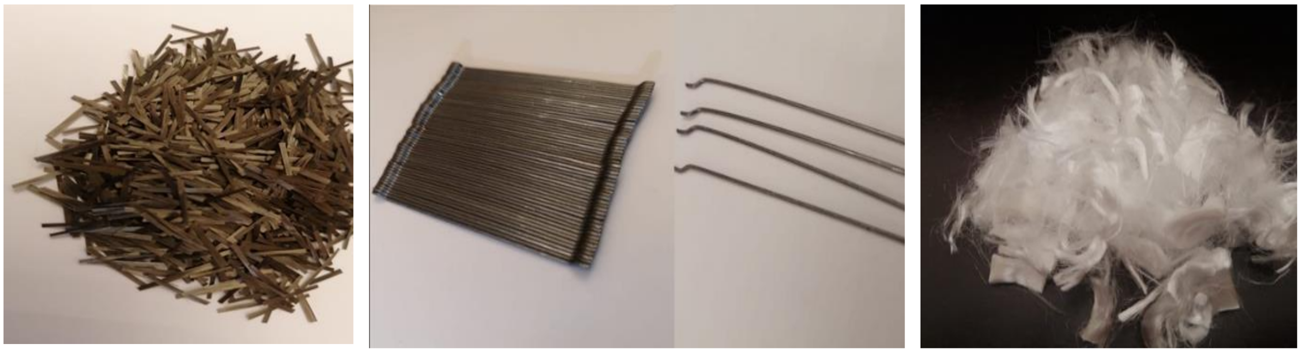
Property	Limestone Fine Aggregate(II)	Silica Sand Fine Aggregate(I)
The specific gravity of saturated surface dry aggregate (SSD)	2.66	2.62
The specific gravity of oven-dried aggregate (OD)	2.62	2.61
Water Absorption	0.9 %	0.2 %
Bulk Density	1410 (kg/m^3)	1370 (kg/m^3)

2.2 Fiber reinforced polymers

Basalt fiber having high performance was provided by Globmarble Company, America with the commercial name Basalt Concrete Fibers for Polymers and Concrete. The basalt fiber used in this investigation is 12 mm long. The used basalt fiber is seen in Fig. 1 and its parameters are listed in Table 2. Wire filaments that have been bent and clipped to the proper length for use in concrete reinforcement are known as steel fibers (SF). This study uses the steel fiber Dramix 3D 80/60 BG, which was provided by BEKAERT and complies with ISO 13270 Class A, EN 14889-1, and ASTM A820. The steel fiber used to create self-compacting concrete is seen in Fig. 1. The steel fiber's characteristics are listed in Table 2. The polypropylene fibers utilized in this study go by the brand name MasterFiber012 and were created by the MASTER BUILDERS SOLUTIONS company in accordance with ISO 9001, ISO 14001, and ISO 45001. The polypropylene fiber used in the concrete mix is seen in Fig. 1. Table 2 lists the physical and chemical characteristics of PPF.

2.3 Testing program

In this study, seven different types of SCC mixes with various fiber ratios were prepared. One mix served as a control for comparison, while the other mixes contained steel, basalt, and polypropylene hybrid fibers in amounts of 0.05%, 0.1%, and 0.15%, respectively. Two mixes for each amount of fiber. According to the total volume of fiber ratios in the SCC mixes (P-0%, P-0.05%, P-0.1%, and P-0.15%), the mixtures were divided into four groups. The test specimen for each mixture was made up of 12 prisms and 27 cylinders, as indicated in



Basalt fiber (BF) Steel fiber (SF) Polypropylene fiber (PPF)

Fig. 1 The fibers used in SCC.

Table 2. properties of fiber used.

Fiber Type	Basalt Fibers	Steel Fibers	Polypropylene Fibers
Shape of Fiber	Straight	Hooked-end	straight
Density	2.67 (g/cm^3)	7.85 (g/cm^3)	0.91 (g/cm^3)
Chopped Length	12 mm	60 mm	12 mm
Diameter	16 micron	0.75 mm	18 micron
Color	Dark grey /Smoked		White
Melting Temperature	1450 °C		160 °C
Tensile Strength		1225 MPa	350 MPa
Elongation	≥ 1.5 %		
Elastic modulus	≥ 65 GPa	200GPa	3500-3900 MPa

Table 3. The cylinders have undergone through testing for compressive strength, splitting tensile strength, and water absorption. Flexural strength testing and an ultrasonic pulse velocity test were carried out on prisms. A number of specimens were tested after being subjected to various temperatures (23°C, 400°C, and 600 °C), as well as 200 cycles of freezing and thawing.

After 28 days, this mixture is intended to have a compressive strength of C40/50 MPa (Cylinder/Cube) due to the right proportions of cement, fine aggregates, and coarse aggregates. Using Type I Ordinary Portland cement (OPC 52.5), coarse aggregates with a maximum size of 16 mm, a mixture of fine aggregates (II) (limestone) and fine aggregates (I) (silica sand), as well as Superplasticizer at 2.5% (PC 770) by cement weight, seven concrete mixtures with various ratios of the three fibers (basalt, steel, and polypropylene) were created. Following the examination of many SCC mixes, the mixture depicted in Table 4 was used.

2.4 Mixing and casting Procedures

The components of SCC concrete were mixed in a 0.25 m^3 tilting drum mixer. To provide the aggregates their requirement for absorption, coarse aggregate, fine aggregate (II), and fine aggregate (I) were mixed for two minutes in a dry condition with one-third of the water quantity. After that, cement was added, and mixing proceeded while another third of the water was gradually added. The remaining water was then combined for 5 minutes with the addition of superplasticizers. The final component to be added is fibers, which are slowly poured into the mixer and mixed for around 4 minutes. The mixing took place at room temperature (23 °C). Without utilizing any external vibrational forces, each SCC

Table 3. Test matrix of Experimental specimens.

Heat	23 °C	400 °C	600 °C	Total
Compressive strength	3 Cylinder	3 Cylinder	3 Cylinder	9 Cylinder
Splitting tensile strength	3 Cylinder	3 Cylinder	3 Cylinder	9 Cylinder
Flexural strength	3 Prism	3 Prism	3 Prism	9 Prism
Freezing and thawing		200 Cycles		Total
Compressive strength	-	3 Cylinder		3 Cylinder
Splitting tensile strength	-	3 Cylinder		3 Cylinder
Flexural strength	-	3 Prism		3 Prism
Water absorption	3 Cylinder	-	-	3 Cylinder
				27 Cylinders + 12 prisms

Table 4. Concrete mix design.

Cement (OPC 52.5)	420 kg/m^3
Coarse Aggregate (Lime Stone)	730 kg/m^3
Fine Aggregate (II) (Lime Stone)	438 kg/m^3
Fine Aggregate (I) (Silica Sand)	657 kg/m^3
Water absorbed by aggregate	16 kg/m^3
Superplasticizer (PC 770)	10.5 kg/m^3
W/C (Effective)	0.40
W/C (Total)	0.44
Total Aggregate	1825 kg/m^3
Aggregate/Cement ratio	4.35

mix, both with and without fibers, was cast into twelve prismatic specimens (100 mm × 100 mm × 400 mm) and twenty-seven cylinder samples (100 × 200 mm). Each mold was filled to capacity, and the extra concrete was scraped away with a trowel to create a flat surface. The cast specimens were stored in molds for 24 hours. Afterward, the specimens were removed off of their molds and submerged entirely for 28 days at a temperature of (23 °C) in a tank of water. The steps of casting and curing are shown in Fig. 2.

2.5 Testing fresh properties

According to the European Federation dedicated to Specialist Construction Chemicals and Concrete Systems (EFNARC),[43] two types of tests, including slump flow test and V-Funnel Test, were conducted on self-compacting concrete mixes to evaluate the impact of adding fibers (basalt, steel, and polypropylene) on their fresh qualities before casting specimens.

2.5.1 Slump flow test

One of the most popular techniques for determining SCC's free horizontal flow in the absence of impediments is the slump flow test. The test was conducted according to ASTMC1611.[44] The base plate is wetted prior to the test, and the cone is then focused in the center of the plate while it is placed on a solid, level surface. Concrete that self-compacts without being compacted is used to fill the cone. The base of the slump cone and its surroundings were cleaned of any remaining concrete. The cone was then elevated vertically to allow the concrete for flow and spreading. The average diameter of the concrete spread in two perpendicular directions is measured to obtain a slump flow value. The slump flow test's steps are shown in Fig. 3.

Figure 4 displays the impact of various fiber ratios on slump flow. The slump flow value necessary for self-compacting concrete is 550 to 850 mm, as per EFNARC standards, specifications, and guidelines for self-compacting concrete. All of the mixes met these requirements. The ordinary self-compacted concrete mixture had a maximum slump value of 740 mm. It can be seen that when the fiber content increases, the SCC mixes' flowability significantly decreases. In comparison to the control specimen, the slump value decreased by 23.6%, 12.2%, and 9.5% at 0.15, 0.1, and 0.05 fiber volumes, respectively. This is explained by the fibers in the fresh concrete mix, which form a dense network structure and prevent the cement paste from flowing.[29,45]

As seen in Fig. 4, the BFI-SF3-PPF1 combination decreases slump flow more than the BF2-SF3 mixture when basalt fibers are replaced by polypropylene fibers with a constant steel fiber ratio. This may be explained by the fact that basalt fibers with polypropylene fibers present absorb more water than basalt fibers with a fixed percentage of steel fibers.[28] As can be observed, mixes with three different types of fiber have lower slump flow than mixes with basalt and steel at all volumetric ratios.[21] found that the addition of basalt microfiber significantly reduced the concrete workability of both NSC and HSC at almost the same rate.

Fig. 2 Procedures for casting and curing specimens.

Fig. 3 Steps of the slump flow test.

2.5.2 V-Funnel test

The filling ability of self-compacting concrete mixtures without segregation or obstruction is assessed using the V-funnel test. The inside surface of the V-funnel was wet after mixing, and the trap door had been locked while a container was stored underneath. The V-funnel was then filled with about 12 liters of SCC without tamping, and after leveling the top and waiting for 10 seconds, the trap door was opened to allow the concrete flow out. This time was then recorded to determine how long it took the mixture to flow through the funnel until it was empty, as shown in Fig. 5.

The V-funnel time required for self-compacting concrete is divided into two categories by EFNARC standards: VF1 (V-funnel flow time 8 sec) and VF2 (V-funnel flow time 9 to 25 sec). All SCC mixes meet the permissible limit as displayed in Fig. 5. Because fiber lengthens the amount of time required for passing mixtures through the funnel, the V-funnel flow duration grows as the ratio of the total volume of fibers.

The results of the V-funnel test of the V-funnel flow times of group p-0.05% are shown in Fig. 6. BF1-SF3-PPF1 and BF2-SF3 had flow times of 12.1 and 12.9 seconds, respectively. Both hybrid mixes' flow times were lengthened by the steel fibers. The BFI-SF3-PPF1 mixture flows through the V-funnel faster than the BF2-SF3 mixture due to the presence of 10% polypropylene fibers and 10% basalt fibers at a constant steel fiber ratio. Group P-0.1% has the similar

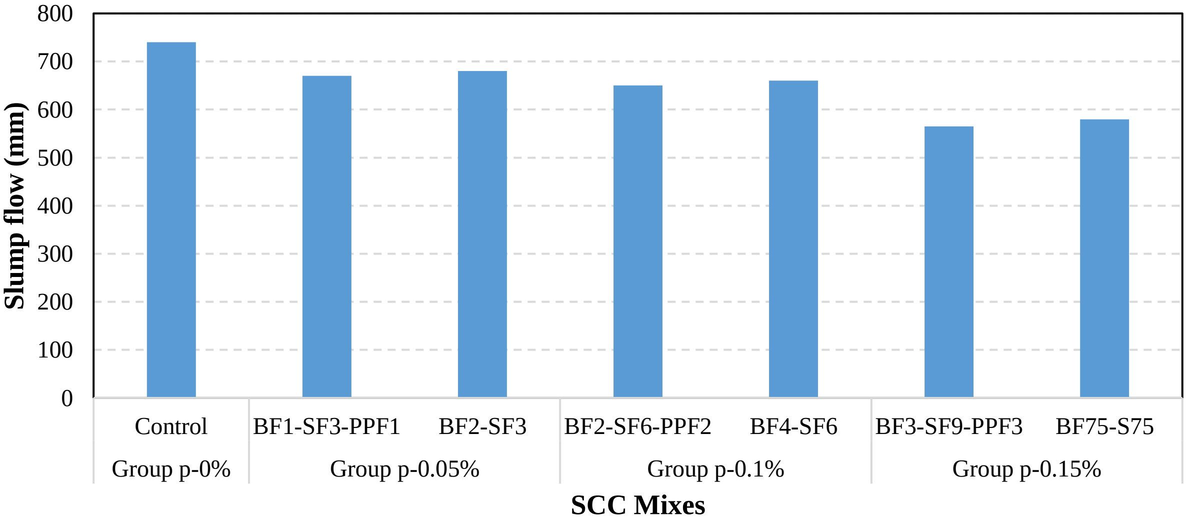


Fig. 4 Slump flow results for all mixes.

Fig. 5 Steps of the V-funnel test.

pattern, with all of the mixes having longer V-funnel flow durations than the control mix. The V-funnel flow times for the mixtures BF2-SF6-PPF2 and BF4-BF6 were 15.8 and 17.3 seconds, respectively. When the impact of fibers on SCC mixtures was investigated, the BF4-SF6 mixture performed worse than the BF2-SF6-PPF2 mixture in terms of flow time via the V-funnel. The V-funnel flow times for BF3-SF9-PPF3 and BF75-SF75 for group p-0.15% were respectively 20.1 and 18.6 seconds. The findings show that using 20% basalt fibers, 60% steel fibers, and 20% polypropylene fibers (BF3-SF9-PPF3) considerably enhanced the V-funnel flow time as compared to using 50% basalt fibers and 50% steel fibers (BF75-SF75). The delay in the flow of the mixture was more affected by increasing the quantity of steel fibers. Tabatabaeian *et al*.[28] found that the effect of polypropylene fibers on increasing viscosity was significantly higher than steel fibers.

2.6 Testing mechanical properties

In the current investigation, the hardened SCC samples were divided into two groups; one group was subjected to high temperatures, and the other group underwent repeated freezing and thawing cycles. Then tests for compressive strength, splitting tensile strength, and flexural strength were used to evaluate the mechanical characteristics.

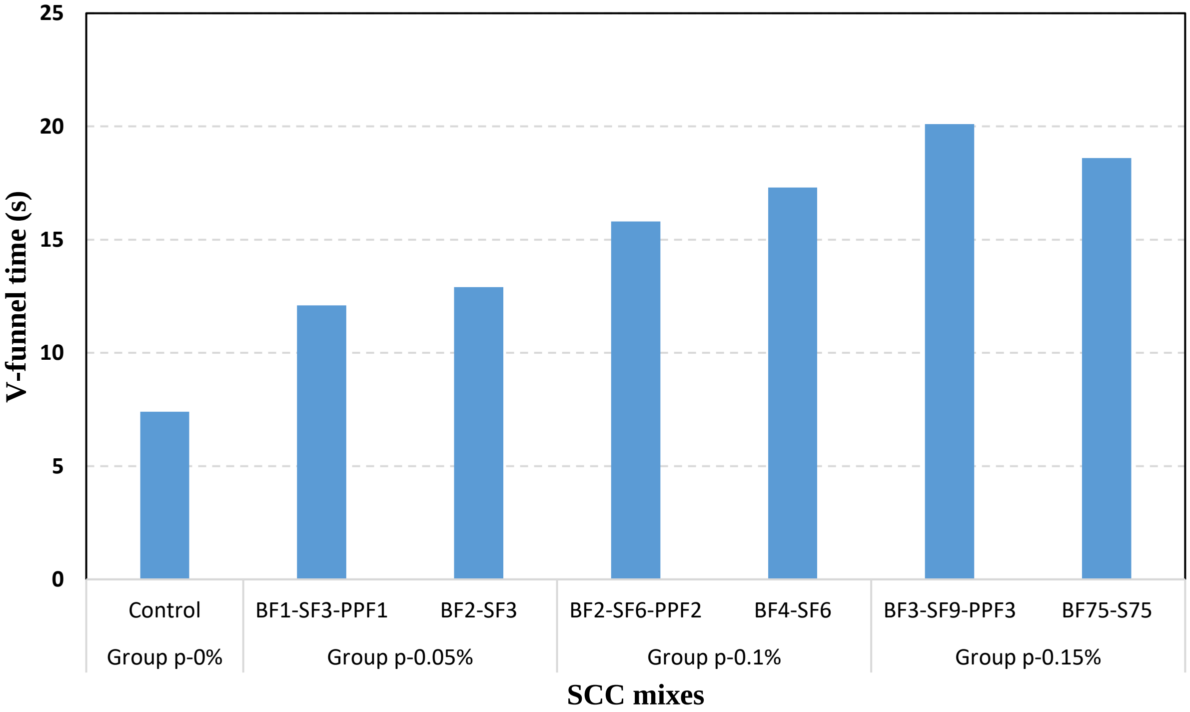


Fig. 6 V-funnel test results for SCC mixtures with different fiber contents.

2.6.1 Compressive strength test

in this study, (100 mm × 200 mm) cylinders were taken in and capped in accordance with ASTM guidelines after the specimens had been subjected to high temperatures and freezing and thawing cycles. The cylinders for each SCC mixture were tested in accordance with ASTM C39[45] using a compression testing machine with a capacity of 4000 kN at a load rate of 0.6 MPa/sec. Fig. 7 depicts the Universal Testing Machine for Compression Strength Tests.

2.6.2 Splitting tensile strength test

The length and size of cracks in concrete are a critically important characteristic and significantly influenced by the splitting tensile strength. With this test method, a continuously diametral compressive force is applied throughout a cylindrical concrete specimen's dimensions (100mm × 200mm) until a failure occurs. Concrete's tensile strength may be calculated indirectly using the splitting method. As shown in Fig. 8, the testing was done utilizing a Universal testing machine with a 4000 kN capacity and a 0.6 MPa/sec load rate, then ASTM C496.[46]

2.6.3 Flexural strength test

Flexural strength, sometimes referred to as modulus of rupture (MOR), is an indirect way to measure of tensile strength. As illustrated in Fig. 9, a flexural strength test on prism-shaped specimens (100 mm × 100 mm × 400 mm) with a clear span length of 300 mm (center to center) was conducted utilizing a 150 kN capacity universal testing machine in accordance with ASTM C293-16[47] standard. Up until the specimen reached the maximum load and started to fall, resulting in specimen failure, the vertical static loading (central point loading) was gradually increased at a rate of 0.025 kN/min.

2.7 Testing durability properties

Durability is the ability of concrete to maintain its desirable engineering properties without damage or deterioration as well as to obtain sustainable concrete structure when exposed to harsh environmental conditions.

Water absorption, freezing-thawing resistance, and mechanical characteristics during high temperature exposure were studied to determine the durability behavior of hardened SCC mixes with various fiber ratios (basalt fiber, steel fiber, and polypropylene fiber).

Fig. 7 Compressive strength test machine.

Fig. 8 Splitting Tensile strength test machine.

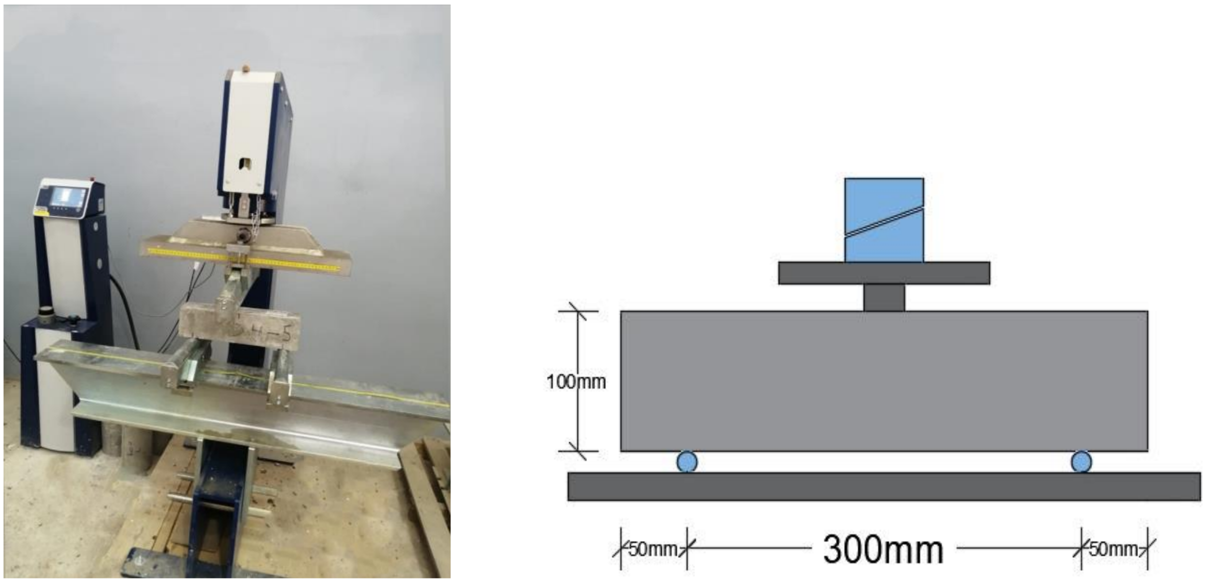


Fig. 9 Flexural strength test machine and Schematic diagram of specimen.

2.7.1 Water absorption test

A quick test to determine the durability of a material is the water absorption test, which is used to evaluate the pore structure in concrete material. In this test, the percentages of voids and water absorption in cylindrical samples of self-compacting concrete measuring 100 mm by 200 mm are determined. After 28 days of curing, the saturated dry samples (WSSD) were weighed. The samples were then heated to 105 °C for 24 hours, as illustrated in Fig. 10, and their weights (WOD) were recorded for the dry specimens. based on ASTM 642-13.[48]

The water absorption is calculated using the equation below:

$$\text{Water Absorption}=\frac{\text{WSSD}-\text{WOD}}{\text{WOD}}\times 100\% \qquad (1)$$

Where, the WSSD: weight saturated -dry sample (g) and WOD: weight oven-dry sample (g)

2.7.2 Ultrasonic pulse velocity (UPV)

One of the non-destructive tests used in the field of concrete to ensure its quality and reliability is the ultrasonic pulse velocity test (UPV). In order to measure the ultrasonic pulse transmission time by the most accurate method, direct transmission, an ultrasonic pulse velocity test was carried out at 28 days on concrete prism specimens (100 mm × 100 mm × 400 mm). Using the portable ultrasonic nondestructive digital indicator tester (PUNDIT), as seen in Fig. 11.

The device complies with ASTM C597[49] and contains two transducers (a transmitter and a receiver), both of which are wired to a box that also has a screen, an electronic timing circuit, and an electrical pulse generator. In order to facilitate effective energy transfer and air removal between the concrete and the transducers, grease was further put as a coupling agent on the concrete surfaces in contact with the transformers. After calibration, as shown in Fig. 11, the transducers are positioned on either side of the specimen. To determine the pulse velocity (V), the measured distance between the transducer sides' centers (L) is divided by the time the ultrasonic pulse took to pass through the concrete samples. The velocity criterion for grading concrete quality is shown in Table 5.

Fig. 10 Placing the samples in the oven.

Table 5. Velocity criterion for concrete quality grading.

Ultrasonic Pulse Velocity (km/s)	Concrete Quality Grading
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

(a) (b)

Fig. 11 Ultrasonic pulse velocity (UPV): (a) Ultrasonic pulse velocity testing apparatus and (b) measuring details for prism specimen.

2.7.3 Freeze-Thaw cycles

Over time, small cracks in concrete elements become wider due to freezing and thawing in water. If the use of additives in the concrete mix is not stopped, the structure will suffer irreversible damage. The ASTM C666-A[50] test technique evaluates concrete specimen resistance to rapidly repeated cycles of freezing and thawing in water (Procedure A). Cylinder specimens of (100 mm × 200 mm) and prism specimens of (100 mm × 100 mm × 400 mm) were used to assess the freeze-thaw resistance of each mixture. After 28 days of curing, all specimens were placed in a freeze-thaw chamber and subjected through freeze-thaw cycles. The specimens of concrete were frozen at (-18) °C for two hours and thawed at (+5 °C) for one hour. Compressive strength, splitting strength, and flexural strength tests were carried out after 200 cycles. Specimens in a freeze-thaw chamber are shown in Fig. 12 together with the chamber itself.

2.7.4 Behavior under high temperatures

This study investigates the effects of several temperature treatments (23 °C, 400 °C, and 600 °C) on self-compacting concrete mixes with and without fibers (basalt, steel, and polypropylene). The specimens (cylinders and prisms) were taken out of the water tank after a 28-day curing period. The samples were exposed to temperatures of 23 °C (ambient temperature), 400 °C, and 600 °C (high temperatures). As depicted in Fig. 13, the specimens were put into the furnace and heated with an average increase rate of 5 °C/min from the starting temperature of 23 °C to the target temperature. Once the target temperature was reached, the specimens were held there for three hours before the specimens were gradually cooled to the ambient temperature. The furnace's internal temperature was digitally managed using an outside display screen, as seen in Fig. 13. After that, the specimens were cooled in the furnace without being opened until the internal

Fig. 12 Freeze-Thaw chamber and Specimens before being subjected to freeze-thaw cycles.

Fig. 13 The samples before being subject to the high temperatures in a furnace and the external display shows the target temperature (400 °C and 600 °C).

temperature approached ambient. The specimens were then subjected to tests for compressive strength, splitting tensile strength, and flexural strength.

3. Results and discussion

3.1 Effect of high temperature on SCC

Spalling and the degradation of structural strength are primarily influenced by factors such as temperature, exposure duration, cooling rate, and the characteristics of the structural elements. Additionally, the compressive strength of the concrete plays a significant role in determining its behavior during a fire. A greater compressive strength is associated with reduced porosity and enhanced compaction, which can result in elevated pore pressure and the potential for spalling when subjected to high temperatures.[51] In this study no explosion was noticed for the SCC samples with or without fibers during exposure to the high temperatures, which demonstrates good performance and the ability to withstand high temperatures. Similar results found by Ref. [17] even at 800°C SCC specimens exhibited no important spalling. The color of the surfaces of the samples changed after exposure to high temperature. At 400 °C, the color of the concrete turned gray with a light red, and no cracks or damage were observed on the surfaces of the samples as shown in Fig. 14a. Also, the concrete color turned red with some microcracks at a temperature of 600 °C, as shown in Fig. 14b.


(a)

(b)

Fig. 14 Samples after exposure to 600 °C.

3.2 Mechanical properties results of SCC

3.2.1 Compressive strength test of the specimens

According to ASTM C39, the compressive strength test was conducted. Concrete cylinders measuring 100 mm by 200 mm were used as test specimens. After 28 days, the maximum compressive strength at 23 °C, 400 °C, and 600 °C for specimens was computed. A minimum of three test results for the same condition were averaged for each value mentioned in figures below.

3.2.1.1 Compressive strength at ambient temperature (23 °C)

At ambient temperature, the SCC specimens' compressive strengths varied from 43.3 to 51.2 MPa. The compressive strength value increased at all fiber ratios with varying percentages, as shown in Fig. 15. The ability of fibers to reduce crack extension and slow down their rate of expansion can be used to explain this improvement in compressive strength.[17,52] When compared to the control specimen, using hybrid fiber increases compressive strength. Also, compressive strength increases as fiber volume increase. The increase in compressive strength was 8.6%, 12.3%, and 18.5% for 0.05, 0.1, and 0.15, respectively.

The findings of group p-0.05% show that, in comparison to the control SCC, the compressive strength increased when various fiber contents, shapes, and types were utilized. In comparison to the control SCC specimen, the mixes BF1-SF3-PPF1 and BF2-SF3 increased compressive strength by 7.4% and 8.6%, respectively. As can be shown, increasing the amount of basalt fibers by 40% had a greater impact on compressive strength than increasing the amount of polypropylene and steel fibers by 20% and 20%, respectively, of the total volume of fiber. This may be explained by the fact that basalt fibers used with steel work better than polypropylene fibers in reducing cracks, preventing their spread, and increasing compressive strength. The same trend was observed for group p-0.1%, where the combinations BF2-SF6-PPF2 and BF4-BF6 increased strength by 12.7% and 15.3%, respectively. The specimen in this group with the highest compressive strength (BF4-SF6) had 40% basalt fibers and 60% steel fibers as a percentage of the total volume of fiber. In comparison to the control specimen, the compressive strength of the BF3-SF9-PPF3 and BF75-SF75 specimens increased by 18.5% and 17.4%, respectively. The findings of group p-0.15% show that the addition of 20% basalt fibers, 60% steel fibers, and 20% polypropylene fibers (BF3-SF9-PPF3) to the mixture enhances the compressive strength of concrete to 18.5%. However, compared to BF3-SF9-PPF3, it can be seen that using 50% basalt fiber and 50% steel fiber (BF75-SF75) resulted in a slight reduction in strength. Fu *et al*.[53] demonstrated that the compressive strength of concrete can be significantly improved when the basalt fibers and polypropylene fibers are each 0.1%. According to Ref. [54], the compressive strength of concrete increases when the hybrid fiber concentration is between 0.05% and 0.1%, and decreases when it is between 0.15 and 0.2%. According to Ref.

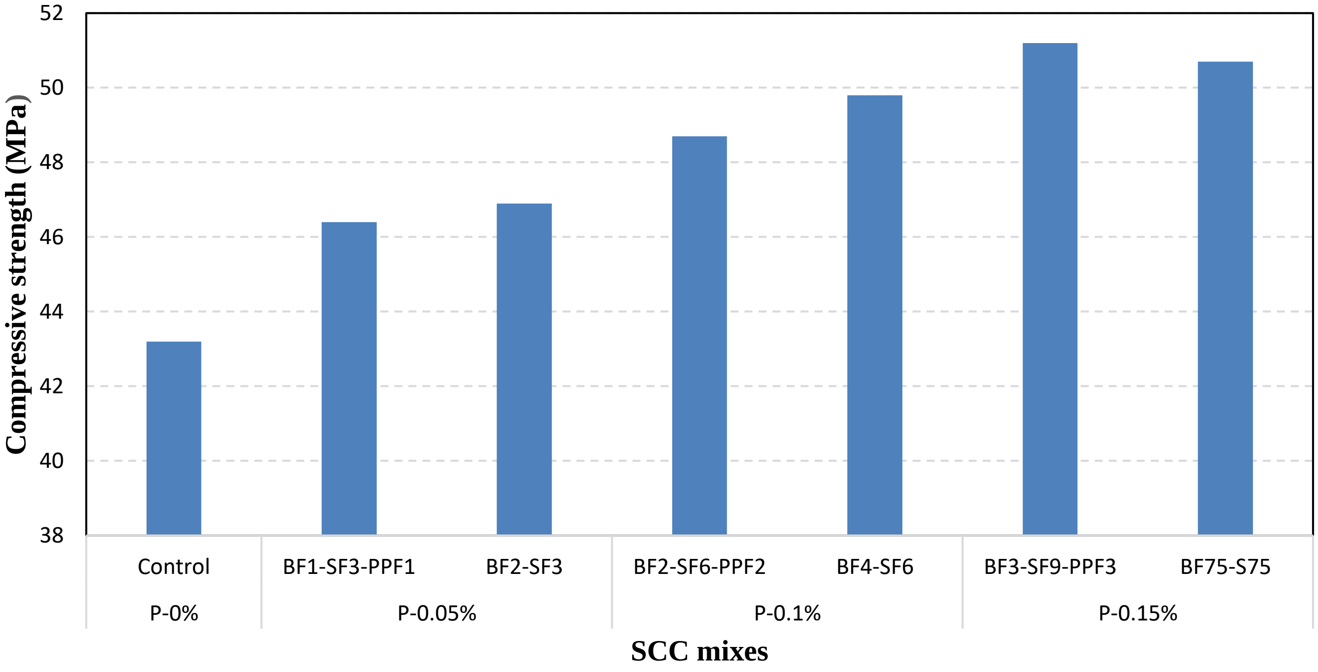


Fig. 15 Compressive strength test results for all mixes at ambient temperature.

[25], the compressive strength improved by 14.1% when basalt fiber content was 0.15 % and polypropylene fiber content was 0.03% when compared to HPC without fibers. According to,[26] hybrid steel fiber and polypropylene fiber self-compacting concrete had greater compressive strength and modulus of elasticity at the same age than steel and polypropylene fiber self-compacting concrete.

3.2.1.2 Compressive strength at high temperature 400°C and 600 °C

The compressive strength of SCC specimens with or without fibers was measured after they had been heated to temperatures of 400 °C and 600 °C in an oven. The SCC specimens' compressive strengths at 400°C varied from 37.1 to 47.9 MPa. According to Fig. 16, the value of compressive strength increased for all fiber ratios when the total volume of fibers in SCC specimens increased by 0.05%, 0.10%, and 0.15% in comparison to the control specimens. As can be shown, the specimens perform better than the control samples in terms of high-temperature resistance when fibers are used.

According to the findings shown in Fig. 16, compressive strength in SCC specimens with or without fibers decreases at 400 °C and 600 °C in comparison to ambient temperature. With increasing temperatures, compressive strength decreases more quickly comparing the specimens heated to 400°C to those heated to 23°C, the compressive strength decreased by 14.1% in the control, 4.7% in the BF1-SF3-PPF1, 6.6% in the BF2-SF3, 2.5% in the BF2-SF6-PPF2, 6.6% in the BF4-SF6, 6.2% in the BF15, 6.45% in the BF3-SF9-PPF3, and 10.3% in the BF75-SF75. The specimens with three different types of fibers have the least loss in compressive strength after exposure to 400 °C, whereas the control sample exhibits the most decrease. On the other hand, after exposure to 600 °C, the compressive strength decreased by 16% in the control, 9.3% in the BF1-SF3-PPF1, 11.9% in the BF2, BF3, 5.1% in the BF2-SF6-PPF2, 12.9% in the BF4-SF6, 9% in the BF3-SF9-PPF3. The greatest decrease in compressive strength may be seen after 600 °C in specimens that are 50% BF and 50% SF. The calcium silicate hydrate decomposes when exposed to high temperatures and causes microcracks to form inside the concrete, which causes a reduction in compressive strength. This is the likely cause of the decrease in compressive strength of the specimens that were treated to 400 °C and 600 °C. In contrast, adding 20% polypropylene and 20% basalt fibers enhanced the compressive strength more than adding 40% basalt fibers, although the amount of steel fibers in both mixes remained unchanged. The presence of polypropylene fibers, which have demonstrated effectiveness in fire resistance, is attributed with playing the largest influence. Polypropylene fibers dissolve around 160 °C, creating pores in the concrete that allow water escape and reducing its internal pressure. Surya *et al.*,[55] show that, in comparison to the plain specimen, SCC specimens' compressive strength decreased by 3.2%, 10.9%, 43.4%, and 51.4% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively. [17] reported decrease in compressive strength of fiber SCC between 22.4% to 32.3% when temperature rose to 600 °C.

3.2.2 Splitting tensile strength test of the specimens

The results of splitting tensile strength for specimens after 28 days is shown in Fig. 17 and Fig. 18 at 23 °C, 400 °C, and 600 °C. The average of at least three outcomes for the same situation is used to calculate each result.

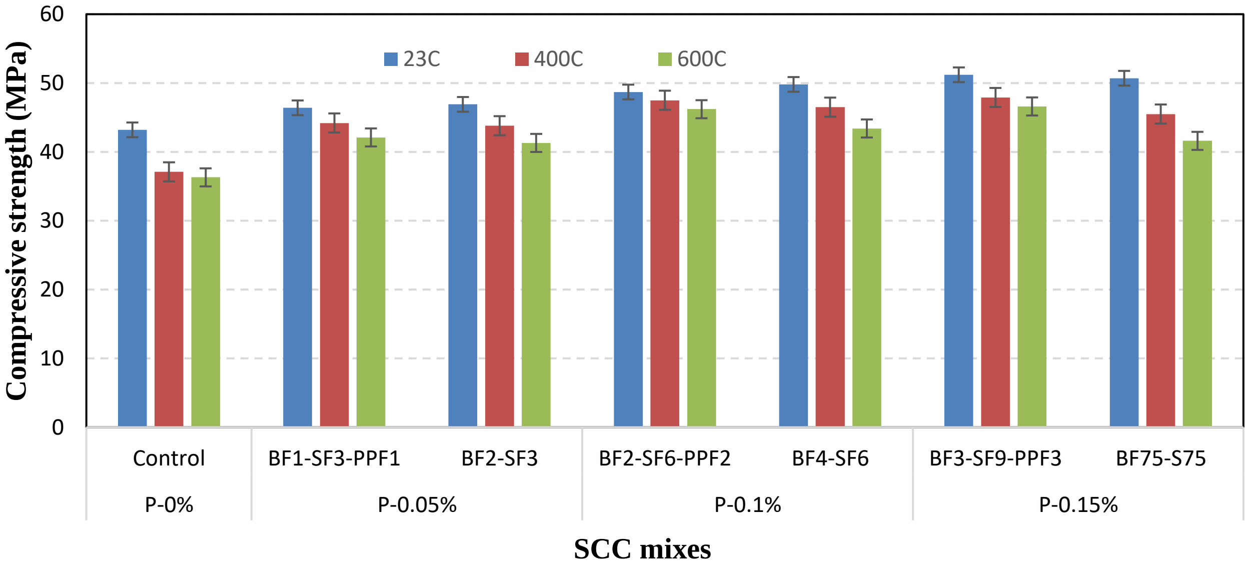


Fig. 16 Compressive strength results for SCC mixes at different temperatures.

3.2.2.1 Splitting tensile strength at ambient temperature (23 °C)

The control SCC specimen's splitting tensile strength is 3.47 MPa at ambient temperature. Fig. 17 shows that the SCC groups with included fibers have stronger splitting tensile strength than the control group. The splitting strength of the fiber increased with fiber volume.

The results of the splitting tensile strength test for group p-0.05% are shown in Fig. 17. The outcomes show that, in comparison to the control specimen, the use of fibers in SCC enhanced splitting tensile strength. The splitting tensile strength of the BF1-SF3-PPF1 and BF2-SF3 mixtures increased by 1.2% and 4.9%, respectively. It is noticeable that there was a modest increase once the hybrid fibers were added. Accordingly, with a fixed steel fibers ratio in both hybrid specimens (BF2-SF3 and BF1-SF3-PPF1), the splitting tensile strength was better when the basalt fiber was utilized by 0.02% than when 0.01% basalt fibers and 0.01% polypropylene fibers were used. It has been demonstrated that specimens with any ratio and any type of fibers exceeded the control for group p-0.1%. Combinations of BF4-BF6 and BF2-SF6-PPF2 increased strength by 4.2% and 7.2%, respectively. In comparison to the control specimen, the splitting tensile strength of the BF3-SF9-PPF3 and BF75-SF75 specimens increased by 4.3% and 10.1%, respectively. Comparing the hybrid fiber samples, it was found that the sample with 50% steel and 50% basalt fibers increased strength more than the sample with 20% basalt, 60% steel, and 20% polypropylene fibers (of the total volume of fiber). According to,[28] the splitting tensile strength decreased as the percentage of polypropylene fiber decreased in comparison to steel fiber. Sohib *et al*.[21] found that SC with basalt micro fiber exhibited significant improvements in splitting strength about 10–52%.

3.2.2.2 Splitting tensile strength at high temperature (400 °C and 600C)

The findings shown in Fig. 18 demonstrate that, in comparison to ambient temperature, the splitting tensile strength of SCC samples with or without fibers reduced after 400 °C and 600 °C exposures. Splitting tensile strength reduced for specimens exposed to 400 °C in comparison with specimens exposed to 23 °C by 11.5% in the control, 4.6% in the BF1-SF3-PPF1, 2.2% in the BF2-SF3, 3.2% in the BF2-SF6-PPF2, 3.5% in the BF4-SF6, and 14.1% in the BF3-SF9-PPF3, and 3.9% in the BF75-SF75, respectively. After 400 °C, the splitting tensile strength of the BF2-SF3 sample is reduced the least, while that of the BF3-SF9-PPF3 specimen is reduced the most. It is important to remember that the loss of splitting tensile strength increases with temperature, reaching high levels after exposure to 600 °C. As a result, when concrete is exposed to high heat, the calcium hydroxide starts to break down and small cracks start to appear inside the material. This causes the splitting tensile strength of the concrete to significantly decrease. In comparison to the 23°C specimens, the splitting tensile strength of the control, BF1-SF3-PPF1, BF2-SF3, BF10, BF2-SF6-PPF2, BF4-SF6, BF3-SF9-PPF3, and BF75-SF75 specimens decreased by 18.2%, 5.8%, 3.9%, 6.7%, 4.3%, 19.1%, and 5.8%, respectively, after 600 °C.

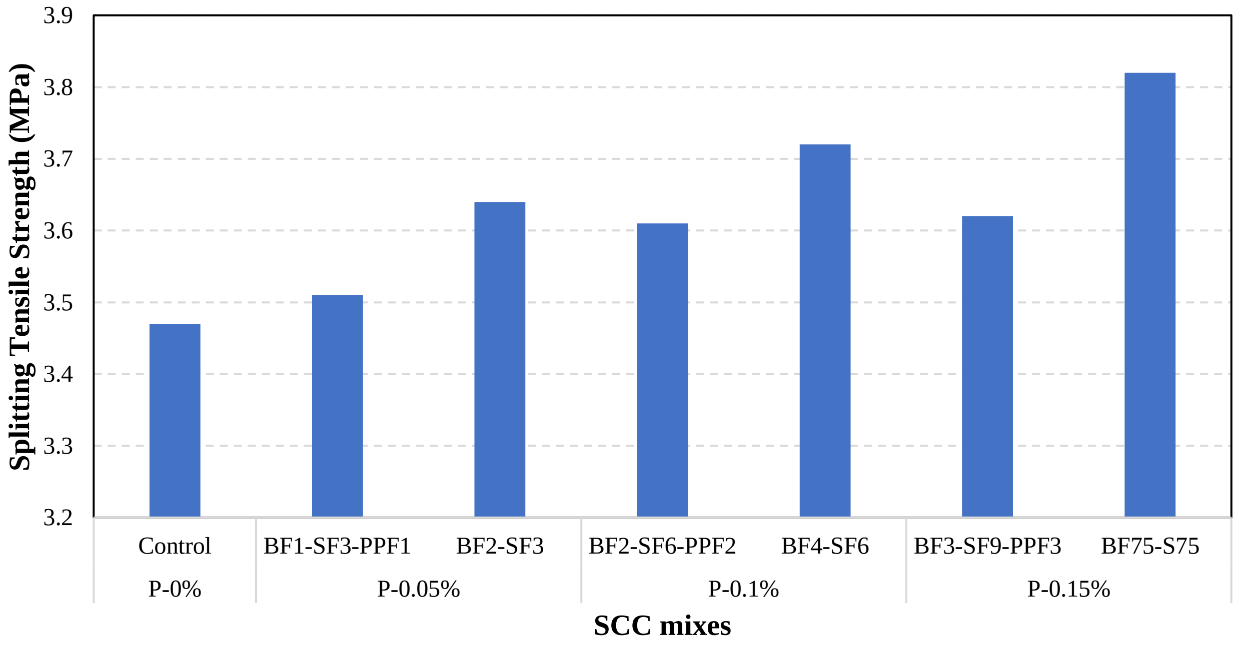


Fig. 17 Splitting tensile strength test results for group p-0.05% at ambient temperature.

At 400 °C and 600 °C, every specimen exceeded the control specimens in terms of splitting tensile strength. At 400°C, the increase in splitting strength relative to the control specimen ranged from 1.3% to 20%, while at 600°C, it ranged from 3% to 27%. The strength of the BF3-SF9-PPF3 and BF75-SF75 specimens was increased by 1.3% and 20%, respectively. According to Fig. 18, SCC specimens with a BF75-S75 content—50% basalt fiber and 50% steel fiber—have the maximum splitting tensile strength. The results showed that adding double hybrid fibers (BF4-SF6) to SCC significantly improved splitting tensile strength. Additionally, compared to previous fiber mixtures, the addition of triple hybrid fibers (BF2-SF6-PPF2) produced a small increase.

The proportion of steel fibers remained steady in both mixtures, however adding 40% basalt fibers increased strength more than adding 20% basalt fibers and 20% polypropylene fibers. Steel fibers in hybrid specimens significantly increase tensile strength. In order to minimize the temperature gradient and avoid cracks, steel fibers with a high thermal conductivity enable more heat to enter the concrete.[56]

3.2.3 Flexural Strength test of the specimens

According to ASTM C293-16, the test was conducted to determine the flexural strength. The prisms that were utilized have dimensions of 100 mm × 100 mm × 400 mm. The flexural strength for specimens after 28 days was tested at 23 °C, 400 °C, and 600 °C. The average of at least three findings for the same condition is used to calculate each result in Figs. 19 & 20.

3.2.3.1 Flexural strength at ambient temperature (23 °C)

The flexural strength of the SCC specimens varied from 6.48 to 7.7 MPa at ambient temperature. According to Fig. 19, as the ratio of the total volume of fibers in SCC mixes increased by 0.05%, 0.1%, and 0.15%, respectively, the flexural strength increased as compared to the value without fibers. Fig. 19 display the results of the flexural strength test for the group p-0.05%. The mixtures of BF1-SF3-PPF1 and BF2-SF3 enhanced the flexural strength by 13% and 17%, respectively, as compared to the control SCC mixture. As can be seen, the specimen BF2-SF3 exhibited more flexural strength than the specimens BF1-SF3-PPF1. Flexural strength increased for the group p-0.10% BF2-SF6-PPF2 and BF4-BF6 combinations by 14.5% and 18.2%, respectively. In contrast to the control specimen, the flexural strength of the BF3-SF9-PPF3 and BF75-SF75 specimens for group p-0.15% increased by 15.1% and 18.7%, respectively. Therefore, this improvement in flexural strength may be explained by fibers' capacity to limit cracks extension and slow their rate of expansion. The enhancement in the flexural strength was due to the bridging effect of the fibers that allowed the specimens to withstand additional tensile forces.[57] Basalt fibers mixed with steel have allowed hybrid fiber specimens more successfully prevent large cracks in the concrete because of their high tensile strength. When polypropylene fibers were used to replace 20% of the basalt fibers, the flexural strength of SCC decreased according to Mastali *et al*..[58] Sohib *et al*.[21] found that the addition of basalt micro fiber to NSC at 0.5 and 1.0% increased the flexural strength by18 and 24%.

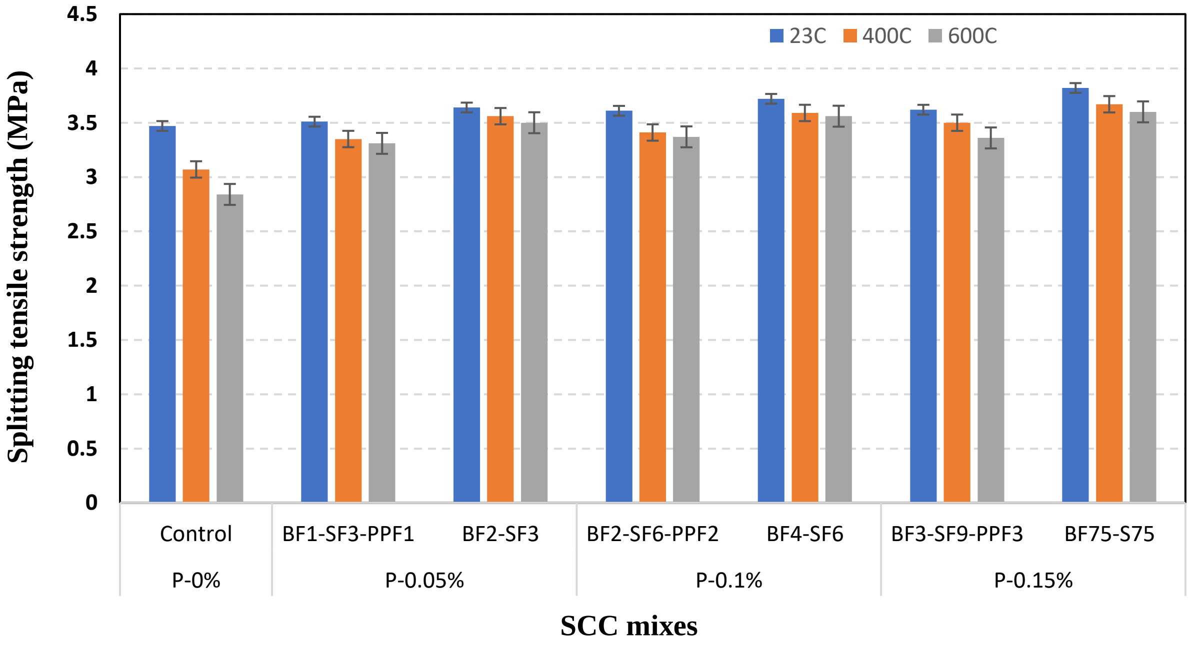


Fig. 18 The effect of high temperatures (23°C, 400°C and 600°C) on the splitting tensile strength of SCC specimens.

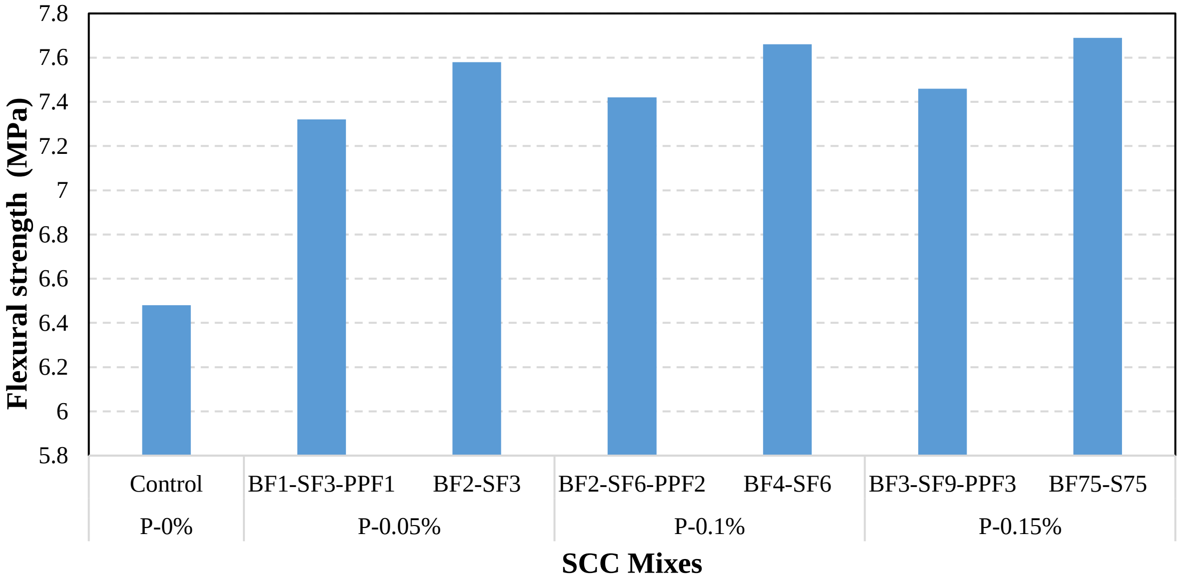


Fig. 19 Flexural strength test results for SCC mixes at ambient temperature.

3.2.3.2 Flexural strength of the specimens at high temperature (400 °C and 600 °C)

The effect of high temperature (400 °C) and fiber amount on the flexural strength of SCC specimens is shown in Fig. 20. The SCC specimens' flexural strengths at 400 °C varied from 5.9 to 8.3 MPa. The use of fibers in SCC enhances the flexural strength after being subjected to high temperatures in comparison to the control specimen, as shown in Fig. 20.

The results of the flexural strength test of group p-0.05% at 400 °C are shown in Fig. 20. In comparison to the control SCC specimen, the mixes BF1-SF3-PPF1 and BF2-SF3 both enhanced flexural strength by 10.5% and 25.8%, respectively. Additionally, substituting polypropylene with basalt fibers significantly reduced flexural strength more than using basalt, steel, and polypropylene fibers in the same sample (BF1-SF3-PPF1). This is due to the fact that basalt and steel fibers, which have high tensile strength, increase flexural strength more efficiently than polypropylene fibers, which have low tensile strength. For group p-0.1%, the flexural strength of the BF2-SF6-PPF2 and BF4-BF6 specimens increased by 22.4% and 28.4%, respectively. The flexural strength increased by 26% and 16.6%, respectively, in the BF3-SF9-PPF3 and BF75-BF75 specimens at group p- 0. 15%. The BF3-SF6-PPF3 displays better improvement in flexural strength values when compared to hybrid fiber specimens than the BF75-SF75. This may be because the percent of basalt fibers produced and a

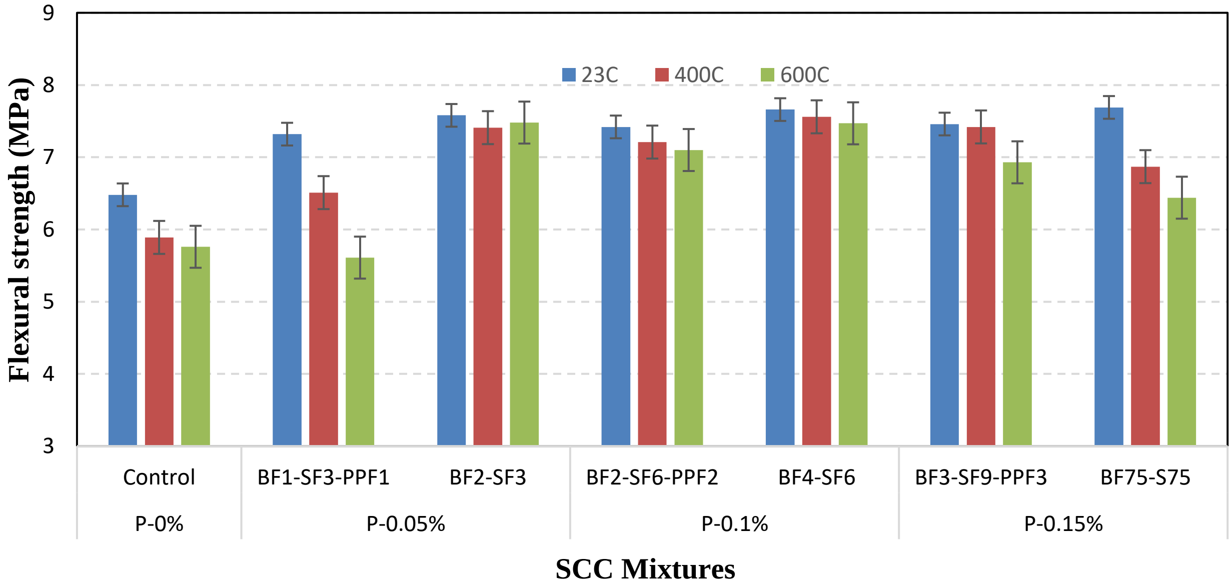


Fig. 20 The effect of high temperatures (23°C, 400°C and 600°C) on the flexural strength of SCC specimens.

percentage of steel fibers decreased which lowered the flexural strength. The outcome indicated that 0.1% fiber volume is optimal. All specimens exposed to 600C showed the same trend. In comparison to the control specimen, the use of fibers in SCC enhances flexural strength when heated to high temperatures, as seen in Fig. 20. In comparison to the control specimen, the increase in flexural strength was 30%. Fig. 20 illustrate the results of the flexural strength test for group p-0.1%. The strength of the specimens BF4-BF6 and BF2-SF6-PPF2 increased by 25.3% and 19.8%, respectively. This increase in strength is a result of fibers' increased resistance to high temperatures. Additionally, it should be highlighted that using specimens reinforced with double hybrid fibers (BF4-SF6) rather than triple hybrid fibers (BF2-SF6-PPF2) increases flexural strength more. Results from the flexural strength test for group p-0.15% revealed a decrease when compared to p-0.1%. In comparison to the control specimen, the flexural strength increased 17.31% in the BF3-SF9-PPF3 specimen and 10.06% in the BF75-BF75 specimen. The BF3-SF6-PPF3 exhibits a greater improvement in flexural strength values than the BF75-SF75 when compared to hybrid fiber specimens.

3.3 Effect of Freezing Thawing on mechanical properties

To investigate how the mechanical characteristics of SCC concrete are affected by freeze-thaw cycles, after undergoing freeze and thaw cycles in accordance with ASTM C666-A standard standard, cylindrical specimens (100 mm × 200 mm) were put through the compressive strength, splitting tensile test, and flexural test. The maximum compressive strength, splitting tensile strength, and flexural strength of specimens after exposure to 200 freeze-thaw (F/T) cycles are shown in Figs. 21, 22, and 23. A minimum of three test results for the same condition were used to average each set of data in the tables or Figures below.

3.3.1 Compressive strength test after 200 Cycles

The compressive strength of the SCC specimens ranged from 37.8 to 48.6 MPa after 200 F/T cycles. As indicated in Fig. 21, when varied fiber content, types, and shapes were used as compared to the control SCC, the compressive strength increased. The capacity of fibers to reduce cracking extension and slow their rate of propagation can be used to explain the improvement in compressive strength. Additionally, the presence of fibers makes SCC more resistant to freezing conditions.[29,59]

The findings seen in Fig. 21 show that, in comparison to the control SCC specimen, the use of fibers enhanced compressive strength. When compared to the control sample, the increases in compressive strength were (12–18%), (23.8–25%), and (20–29%) at p-05, p-0.1%, and p-0.15%, respectively. The ratio of steel fibers in both specimens remained unchanged, hence it can be observed that adding 40% basalt fibers enhanced compressive strength more than adding 20% basalt fibers and 20% polypropylene fibers. This can be explained by the fact that basalt fibers work better with steel than polypropylene fibers to reduce cracks, close thespace between cement particles, and increase compressive

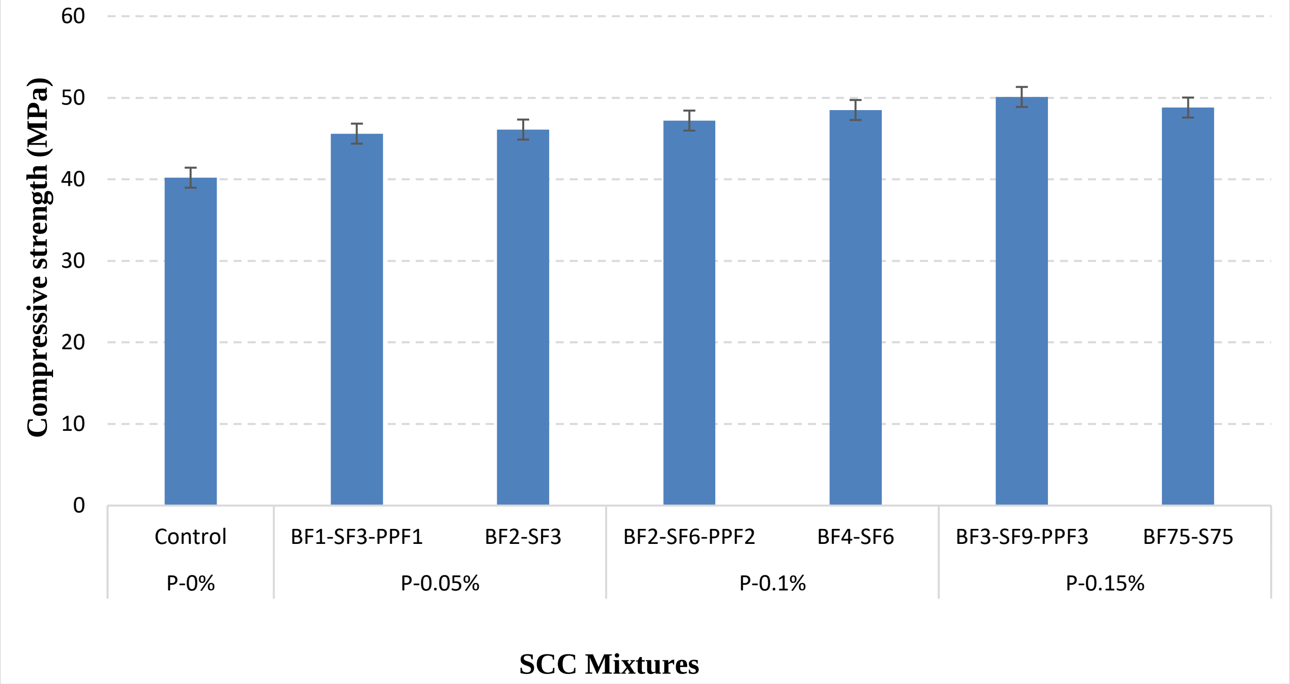


Fig. 21 The effect of freeze-thaw cycles (200) on compressive strength of SCC specimens.

strength. The compressive strength was more affected by increasing a percentage of steel fibers than by increasing a percentage of basalt fibers. The ideal fiber ratio for the compressive strength of SCC was determined to be 0.03% BF, 0.09% SF, and 0.03% PPF (BF3-SF9-PPF3) after 200 freeze-thaw cycles. In samples containing polypropylene fibers, Zhang[20] demonstrated that the resistance to freezing and thawing increased with the percentage of fibers up to 0.08%, but thereafter decreased. In comparison to the control specimen, the compressive strength of the BF3-SF9-PPF3 and BF75-SF75 specimens rose by 28.57% and 19.84%, respectively. The findings of group p-0.15% show that adding 20% basalt fibers, 60% steel fibers, and 20% polypropylene fibers to the mix increases concrete's compressive strength to 48.6 MPa, while using 50% basalt fiber and 50% steel fiber reduces it to 45.3 MPa. As a result, adding fibers in the right amounts could increase the concrete composite's durability.

3.3.2 Splitting Tensile Strength Test after 200 F/T Cycles

The splitting tensile strength of the SCC exhibits the similar trend as compressive strength after 200 freeze-thaw cycles. The specimens' splitting tensile strengths varied from 3.05 to 3.72 MPa. The findings show that after 200 cycles of freezing and thawing, SCC specimens with included fibers had better splitting tensile strength than the control specimen. Therefore, the reason for the increase in splitting tensile strength may be attributed to fibers' capacity to reduce the number of microcracks in concrete components and delay their rate of expansion. The results of the splitting tensile strength test for group p-0.05% are displayed in Fig. 22.

Results show that, after 200 F/T cycles, the use of fibers in SCC enhanced splitting tensile strength in comparison to the control specimen. The BF1-SF3-PPF1 and BF2-SF3 specimens both experienced increases in splitting tensile strength of 12.13 % and 14.1%, respectively. At p0.1%, there was a slight improvement in splitting tensile strength, with improvements of 12.46% and 15.08% for the BF2-SF6-PPF2 and BF4-SF6 specimens, respectively. Fig. 22 display the splitting tensile strength test results for group p-0.15%. After 200 cycles of freezing and thawing, the splitting tensile strength of the BF3-SF9-PPF3 and BF75-SF75 specimens was 22% higher than the control specimen's.

3.3.3 Flexural strength test at 200 Cycles

Figure 23 lists the maximum flexural strength that was measured for specimens after 200 cycles of freezing and thawing. After 200 cycles of freezing and thawing, the flexural strength of the SCC specimens varied from 5.82 to 7.72 MPa. According to Fig. 23, as the ratio of the total volume of fibers in SCC specimens increased by 0.05%, 0.10%, and 0.15% in comparison to the control specimens, the value of flexural strength increased. It is evident that, as compared to control samples, specimens including fibers of any type or percentage perform better in terms of freeze-thaw resistance. Fig. 23 display the results of the flexural strength test for group p-0.05%. The flexural strength of the specimens BF1-SF3-PPF1 and BF2-SF3 increased by 17.5% and 22%, respectively, as compared to the control SCC specimen. When the basalt fiber was increased by 0.02% compared to 0.01% basalt and 0.01% polypropylene fibers, with a consistent steel fiber ratio in both

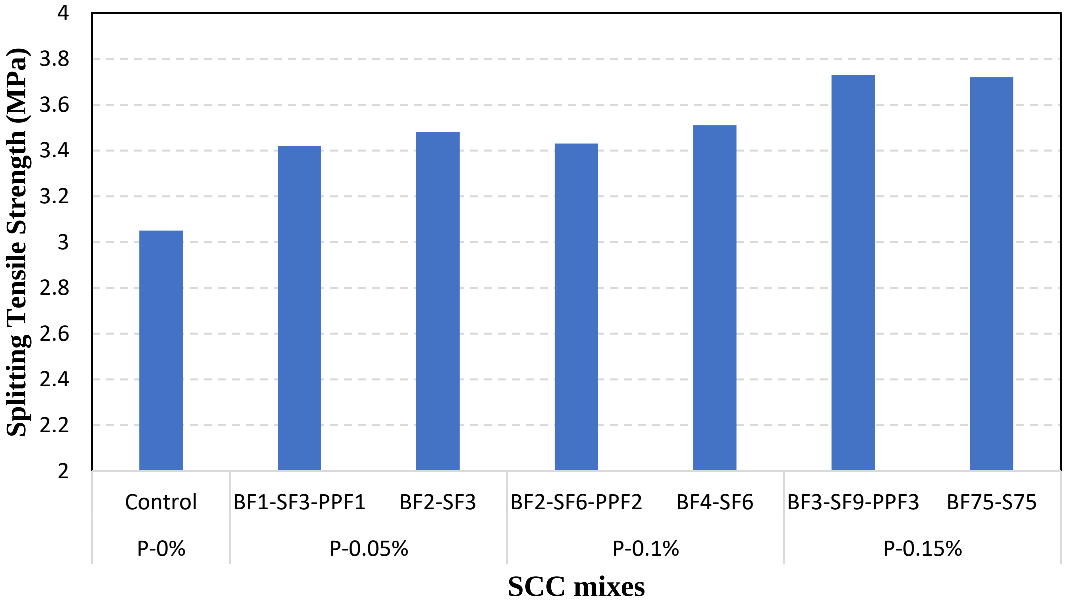


Fig. 22 The effect of freeze-thaw cycles on splitting tensile strength of SCC specimens.

specimens, the flexural strength was higher. Fig. 23 display the results of the flexural strength test for group p-0.10%. All of the specimens exceeded the control specimens in terms of flexural strength. The strength of the BF2-SF6-PPF2 and BF4-BF6 specimens increased by 19.7% and 25.7%, respectively. Adding double hybrid fibers (BF4-SF6) with SCC significantly increased flexural strength. Additionally, a modest increase was produced by the addition of triple hybrid fibers (BF2-SF6-PPF2). A similar trend is visible for group p-0.15%, as illustrated in Fig. 23. In comparison to the control specimen, flexural strength increased in the BF3-SF9-PPF3 and BF75-BF75 specimens by 28.7% and 32.6%, respectively. The hybrid fiber specimen with the biggest improvement in flexural strength is the BF75-SF75, which shows a larger improvement in flexural strength values than the BF3-SF6-PPF3.

3.4 Water absorption results of SCC

After 28 days of cure, the water absorption for SCC mixes with and without fibers was determined. In the test, cylindrical specimens measuring 100 mm × 200 mm were placed in an oven set at 105 °C for 24 hours. Fig. 24 summarizes and displays the average water absorption for SCC specimens with and without fibers. Each of the concrete mixtures tested in this study had a water absorption rate of less than 3%, as indicated in Fig. 24, suggesting that the mixes are of acceptable quality. All hybrid fibers tested for water absorption shown a considerable decrease in water absorption as fiber volume was increased. In comparison to the control specimens, there was a reduction in water absorption of 16.6%, 18%, and 31% at p-0.05%, p-0.1%, and p-0.15%, respectively. The results of adding fibers to SCC mixes show that fibers have a positive impact on lowering concrete's water absorption. In Fig. 24, the results of the water absorption test for group p-0.1% are displayed. The findings show that when compared to the control specimen, the hybrid fiber specimens BF2-SF6-PPF2 and BF4-BF6 have reduced water absorption by 16.64% and 12.64%, respectively. As can be observed, adding 40% basalt fibers reduced the water absorption more than adding 20% polypropylene and 20% basalt fibers, although the amount of steel fibers remained stable in both mixes. The findings of group p-0.15%'s water absorption test are shown in Fig. 24. In comparison to the control specimen, the water absorption was decreased by 23.6% and 30.5% for the BF3-SF9-PPF3 and BF75-SF75, respectively. As a result, among all the hybrid fiber SCC specimens, the lowest water absorption was achieved by the BF75-SF75 hybrid fiber specimen, which had 0.075% basalt fiber and 0.075% steel fiber. Sohaib *et al*.[21] The water absorption tended to decrease with an increase in the BMF volume up to 1.0%. The presence of BMF may have blocked some routes inside the concrete thus slowing migration of water.[21]

3.5 Ultrasonic pulse velocity (UPV) Results of SCC

A non-destructive test that is used for evaluating concrete's quality and integrity is the ultrasonic pulse velocity test (UPV). After 28 days, concrete prism specimens (measuring 100 mm × 100 mm × 400 mm) underwent an ultrasonic pulse velocity test. At room temperature, Fig. 25 displays the impact of various fiber types and amounts on the ultrasonic pulse velocities for SCC specimens.

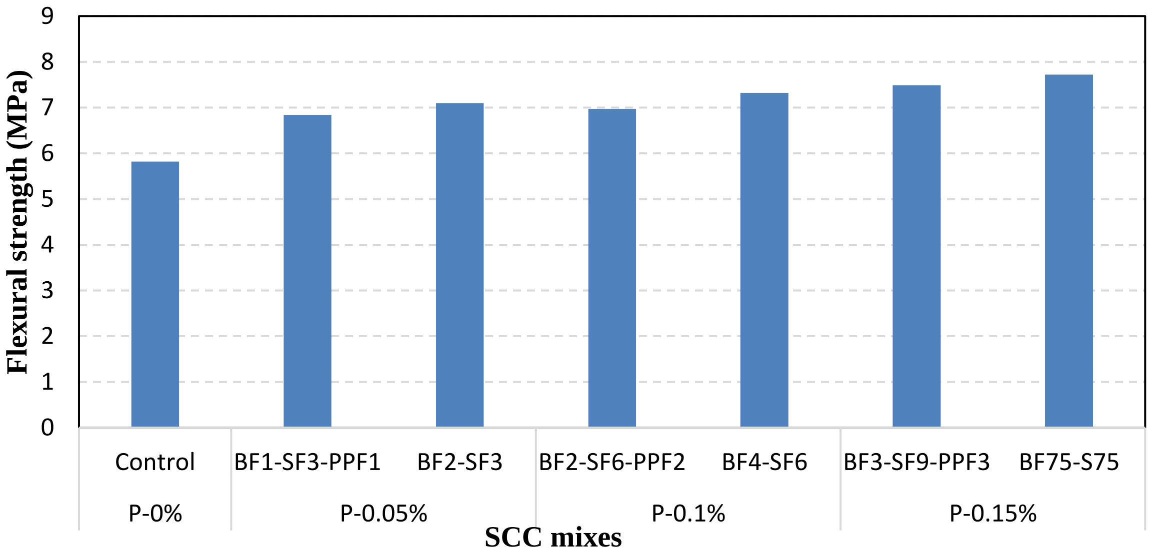


Fig. 23 Flexural strength test for SCC mixes.

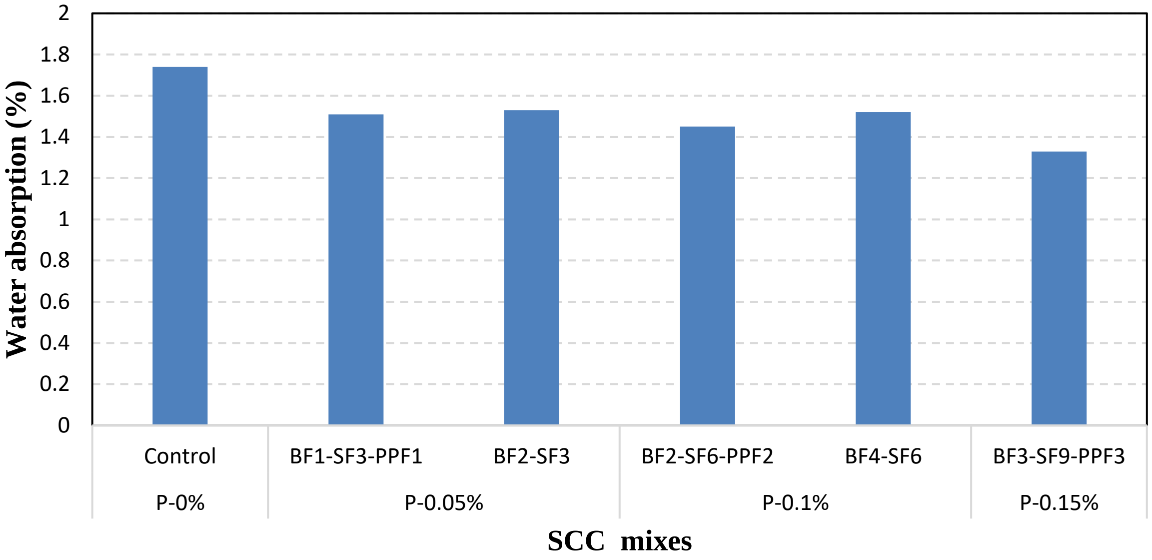


Fig. 24 Water absorption Results of SCC.

UPV is categorized into four categories Excellent (over 4500 m/s), good (3500-4500 m/s), medium (3000-3500 m/s), and doubtful (below 3000 m/s).[60] As seen in Fig. 25, the FRSCC specimens fall into two UPV categories: above 4500 m/s and 3500 m/s-4500 m/s, which respectively signal excellent and good-quality conditions. After fibers were introduced to SCC mixes, the UPV values were improved by minimizing the voids, but the improvement was not significant. In Fig. 25, the results of the UPV test for group p-0.15% are displayed. The UPV value increased by 1.5% and 4.5%, respectively, when BF3-SF9-PPF3 and BF75-BF75 specimens were compared to control specimens. Using specimens reinforced with double hybrid fibers (BF75-SF75) enhances the UPV more than using samples reinforced with triple hybrid fibers (BF3-SF9-PPF3). The specimens with the highest UPV for groups p-0.05%, p-0.1%, and p-0.15% were BF2-SF3 (4544.7 m/s), BF4-SF6 (4565.5 m/s), and BF75-SF75 (4637.3 m/s), respectively.[21] found that the addition of BMF had almost no effect on UPV values of normal SC.[57] noticed no significant decrease in UPV value of NSC with using polypropylene fiber. While Ref. [61] reported an increase in UPV by 7-11% with using nonmetallic fiber.

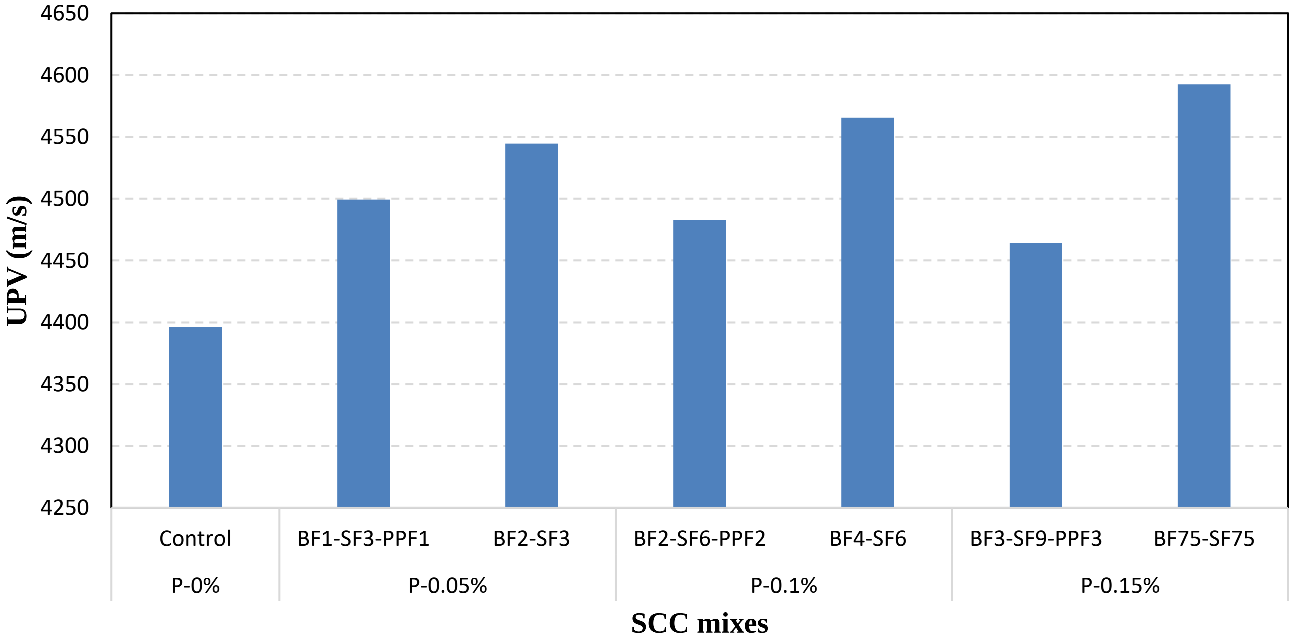


Fig. 25 Impact of various fiber types and amounts on the ultrasonic pulse velocities for SCC specimens.

4. Conclusions

To investigate rheological, the mechanical, and durability characteristics of self-compacted concrete including hybrid fibers (basalt fiber, steel fiber, and polypropylene fiber), seven SCC mixes were created with various fiber amounts (0%, 0.05%, 0.1%, and 0.15%). A total of 528 specimens were tested for workability, compressive strength, splitting tensile strength, and flexural strength after undergoing tests for water absorption, ultrasonic pulse velocity, high temperatures (23 °C, 400 °C, and 600 °C), and freezing-thawing conditions (200 cycles). The following conclusion may be drawn based on the findings of the experimental work:

1. The rheological characteristics of fresh SCC mixes were adversely impacted by the addition of fibers. As the amount of fiber in SCC mixes increased, the slump flow value decreased with a range of decreases from 8.11% to 31.76%. The best mixes for groups p-0.05%, p-0.1%, and p-0.15% were (BF2-SF3), (BF4-SF6), and (BF75-S75).
2. The compressive strength of the SCC specimens with fibers is higher than the control specimen at ambient temperature (23°C). Additionally, it was found that the specimens' compressive strength increased when the volume ratio of the fibers increased to 0.15%. The optimum fiber mix for SCC compressive strength is 0.03% BF, 0.09% SF, and 0.03% PPF (BF3-SF9-PPF3), which is almost 18.52% more than the control specimen.
3. When fibers were utilized, the specimens exceeded the control samples in terms of high-temperature resistance at 400°C and 600 °C. In comparison to the control group, the mechanical properties of SCC groups including fibers subjected to high temperatures were greater. Adding fibers to SCC specimens will thereby increase their ability to resist fire.
4. Fibers added to SCC had a beneficial impact on concrete's ability to absorb water. The specimen with the lowest water absorption was the one with 0.075% BF and 0.075% SF.

It can be noted that using specimens reinforced with double hybrid fibers (BF75-SF75) improves the UPV more than using specimens reinforced with triple hybrid fibers (BF3-SF9-PPF3). The UPV values increased whenever fibers were added to SCC mixtures.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] A. B. Kizilkanat, N. Kabay, V. Akyüncü, S. Chowdhury, A. H. Akça, Mechanical properties and fracture behavior of basalt and glass fiber reinforced concrete: an experimental study, *Construction and Building Materials*, 2015, **100**, 218-224, doi: 10.1016/j.conbuildmat.2015.10.006.

[2] C. Jiang, K. Fan, F. Wu, D. Chen, Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete, *Materials & Design*, 2014, **58**, 187-193, doi: 10.1016/j.matdes.2014.01.056.

[3] T. Uygunoğlu, Investigation of microstructure and flexural behavior of steel-fiber reinforced concrete, *Materials and Structures*, 2008, **41**, 1441-1449, doi: 10.1617/s11527-007-9341-y.

[4] M. Karatas, A. Benli, F. Arslan, The effects of Kaolin and calcined Kaolin on the durability and mechanical properties of self-compacting mortars subjected to high temperatures, *Construction and Building Materials*, 2020, **265**, 120300, doi: 10.1016/j.conbuildmat.2020.120300.

[5] A. Pineaud, P. Pimienta, S. Rémond, H. Carré, Mechanical properties of high performance self-compacting concretes at room and high temperature, *Construction and Building Materials*, 2016, **112**, 747-755, doi: 10.1016/j.conbuildmat.2016.02.132.

[6] M. Sahmaran, A. Yurtseven, I. Ozgur Yaman, Workability of hybrid fiber reinforced self-compacting concrete, *Building and Environment*, 2005, **40**, 1672-1677, doi: 10.1016/j.buildenv.2004.12.014.

[7] A. Benli, K. Turk, C. Kina, Influence of silica fume and class F fly ash on mechanical and rheological properties and freeze-thaw durability of self-compacting mortars, *Journal of Cold Regions Engineering*, 2018, **32**, doi: 10.1061/(asce)cr.1943-5495.0000167.

[8] V. Corinaldesi, G. Moriconi, Durable fiber reinforced self-compacting concrete, *Cement and Concrete Research*, 2004, **34**, 249-254, doi: 10.1016/j.cemconres.2003.07.005.

[9] A. M. Zeyad, Effect of fibers types on fresh properties and flexural toughness of self-compacting concrete, *Journal of Materials Research and Technology*, 2020, **9**, 4147-4158, doi: 10.1016/j.jmrt.2020.02.042.

[10] A. Benli, M. Karatas, H. Anil Toprak, Mechanical characteristics of self-compacting mortars with raw and expanded vermiculite as partial cement replacement at elevated temperatures, *Construction and Building Materials*, 2020, **239**, 117895, doi: 10.1016/j.conbuildmat.2019.117895.

[11] A. Benli, M. Karataş, Y. Bakir, An experimental study of different curing regimes on the mechanical properties and sorptivity of self-compacting mortars with fly ash and silica fume, *Construction and Building Materials*, 2017, **144**, 552-562, doi: 10.1016/j.conbuildmat.2017.03.228.

[12] M. Karataş, A. Benli, A. Ergin, Influence of ground pumice powder on the mechanical properties and durability of self-compacting mortars, *Construction and Building Materials*, 2017, **150**, 467-479, doi: 10.1016/j.conbuildmat.2017.05.220.

[13] F. Arslan, A. Benli, M. Karatas, Effect of high temperature on the performance of self-compacting mortars produced with calcined Kaolin and metakaolin, *Construction and Building Materials*, 2020, **256**, 119497, doi: 10.1016/j.conbuildmat.2020.119497.

[14] J. H. Haido, S. S. Majeed, M. Karpuzcu, Flowability, strength and permeability characteristics of self-compacted concrete made with basalt fibers, *Academic Journal of Nawroz University*, 2020, **9**, 194, doi: 10.25007/ajnu.v9n1a589.

[15] A. M. Ashteyat, R. H. Haddad, Y. T. Obaidat, Case study on production of self compacting concrete using white cement by pass dust, *Case Studies in Construction Materials*, 2018, **9**, e00190, doi: 10.1016/j.cscm.2018.e00190.

[16] S. Ahmad, A. Umar, Fibre-reinforced self-compacting concrete: a review, *IOP Conference Series: Materials Science and Engineering*, 2018, **377**, 012117, doi: 10.1088/1757-899x/377/1/012117.

[17] M. Karatas, M. Dener, A. Benli, M. Mohabbi, High temperature effect on the mechanical behavior of steel fiber reinforced self-compacting concrete containing ground pumice powder, *Structural Concrete*, 2019, **20**, 1734-1749, doi: 10.1002/suco.201900067.

[18] S. Shoaib, T. El-Maaddawy, H. El-Hassan, B. El-Ariss, M. Alsalami, Characteristics of basalt macro-fiber reinforced recycled aggregate concrete, *Sustainability*, 2022, **14**, 14267, doi: 10.3390/su142114267.

[19] C. T. Mohammed Ramees, College, Mechanical properties of SCC reinforced with basalt fiber and polypropylene fiber, *International Journal of Engineering Research and Technology*, 2020, **V9**, doi: 10.17577/ijertv9is070411.

[20] S. Paulraj, N. Balasundaram, K. Sates Kumar, M. Dharshna Devi, Experimental studies on strength and SCC characteristics of basalt fiber reinforced concrete, *International Journal of Civil Engineering and Technology*, 2017, **8**, 704-711.

[21] S. Shoaib, T. El-Maaddawy, H. El-Hassan, B. El-Ariss, M. Alsalami, Fresh and hardened properties of concrete reinforced with basalt macro-fibers, *Buildings*, 2022, **12**, 1136, doi: 10.3390/buildings12081136.

[22] S. K. Kirthika, S. K. Singh, Experimental investigations on basalt fibre-reinforced concrete, *Journal of the Institution of Engineers (India): Series A*, 2018, **99**, 661-670, doi: 10.1007/s40030-018-0325-4.

[23] V. Afroughsabet, T. Ozbakkaloglu, Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers, *Construction and Building Materials*, 2015, **94**, 73-82, doi: 10.1016/j.conbuildmat.2015.06.051.

[24] A. N. S. Al Qadi, S. M. Al-Zaidyeen, Effect of fibre content and specimen shape on residual strength of polypropylene fibre self-compacting concrete exposed to elevated temperatures, *Journal of King Saud University - Engineering Sciences*, 2014, **26**, 33-39, doi: 10.1016/j.jksues.2012.12.002.

[25] D. Wang, Y. Ju, H. Shen, L. Xu, Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber, *Construction and Building Materials*, 2019, **197**, 464-473, doi: 10.1016/j.conbuildmat.2018.11.181.

[26] F. Aslani, S. Nejadi, Self-compacting concrete incorporating steel and polypropylene fibers: Compressive and tensile strengths, moduli of elasticity and rupture, compressive stress–strain curve, and energy dissipated under compression, *Composites Part B: Engineering*, 2013, **53**, 121-133, doi: 10.1016/j.compositesb.2013.04.044.

[27] B. Akcay, M. Ali Tasdemir, Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete, *Construction and Building Materials*, 2012, **28**, 287-293, doi: 10.1016/j.conbuildmat.2011.08.044.

[28] M. Tabatabaeian, A. Khaloo, A. Joshaghani, E. Hajibandeh, Experimental investigation on effects of hybrid fibers on rheological, mechanical, and durability properties of high-strength SCC, *Construction and Building Materials*, 2017, **147**, 497-509, doi: 10.1016/j.conbuildmat.2017.04.181.

[29] P. Zhang, Q.-F. Li, Effect of polypropylene fiber on durability of concrete composite containing fly ash and silica fume, *Composites Part B: Engineering*, 2013, **45**, 1587-1594, doi: 10.1016/j.compositesb.2012.10.006.

[30] P. Berkowski, M. Kosior-Kazberuk, Effect of fiber on the concrete resistance to surface scaling due to cyclic freezing and thawing, *Procedia Engineering*, 2015, **111**, 121-127, doi: 10.1016/j.proeng.2015.07.065.

[31] H. Yazıcı, The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze–thaw resistance of self-compacting concrete, *Construction and Building Materials*, 2008, **22**, 456-462, doi: 10.1016/j.conbuildmat.2007.01.002.

[32] D. A. Krishna, R. S. Priyadarsini, S. Narayanan, Effect of elevated temperatures on the mechanical properties of concrete, *Procedia Structural Integrity*, 2019, **14**, 384-394, doi: 10.1016/j.prostr.2019.05.047.

[33] A. N. S. AL Qadi, K. N. B. Mustapha, S. Naganathan, Q. N. S. AL-Kadi, Effect of polypropylene fibres on fresh and hardened properties of self-compacting concrete at elevated temperatures, *Australian Journal of Basic and Applied Sciences*, 2011, **5**, 378-384.

[34] D. N. Crook, M. J. Murray, Regain of strength after firing of concrete, *Magazine of Concrete Research*, 1970, **22**, 149-154, doi: 10.1680/macr.1970.22.72.149.

[35] K. D. Hertz, L. S. Sørensen, Test method for spalling of fire exposed concrete, *Fire Safety Journal*, 2005, **40**, 466-476, doi: 10.1016/j.firesaf.2005.04.001.

[36] A. Karimipour, M. Edalati, J. de Brito, RETRACTED: Biaxial mechanical behaviour of polypropylene fibres reinforced self-compacting concrete, *Construction and Building Materials*, 2021, **278**, 122416, doi: 10.1016/j.conbuildmat.2021.122416.

[37] A. Behnood, M. Ghandehari, Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures,

Fire Safety Journal, 2009, **44**, 1015-1022, doi: 10.1016/j.firesaf.2009.07.001.

[38] J. Tao, Y. Yuan, L. Taerwe, Compressive strength of self-compacting concrete during high-temperature exposure, *Journal of Materials in Civil Engineering*, 2010, **22**, 1005-1011, doi: 10.1061/(asce)mt.1943-5533.0000102.

[39] M. Tuyan, A. Mardani-Aghabaglou, K. Ramyar, Freeze–thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate, *Materials & Design*, 2014, **53**, 983-991, doi: 10.1016/j.matdes.2013.07.100.

[40] M. Khan, M. Cao, C. Xie, M. Ali, Experimental and analytical study of hybrid fiber reinforced concrete prepared with basalt fiber under high temperature, *Fire and Materials*, 2022, **46**, 205-226, doi: 10.1002/fam.2968.

[41] ASTM C33/C33M-18 Standard Specification for Concrete Aggregates, ASTM International, West Conshohocken, 2023. doi: 10.1520/C0033_C0033M-23.

[42] ASTM C494/C494M-17 Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, 2020, doi: 10.1520/C0494_C0494M-19E01.

[43] Specifications and guidelines for self-compacting concrete, EFNARC, Association House, Surrey, UK, 2005.

[44] STM C1611. Standard test method for Standard Test Method for Slump Flow of Self-Consolidating Concrete. ASTM International. West Conshohocken, 2021, doi:10.1520/C1611_C1611M-21.

[45] ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, 2021, doi: 10.1520/C0039_C0039M-23.

[46] ASTM C496/C496M-17; Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimen ASTM International: West Conshohocken, PA, USA, 2017, doi:10.1520/C0496_C0496M-17.

[47] ASTM C293-M16; Standard Test Method for Flexural Strength of Concrete. ASTM International: West Conshohocken, PA, USA, 2016, doi: 10.1520/C0293_C0293M-16.

[48] ASTM C642-13, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken, 2013, doi: 10.1520/C0642-21.

[49] ASTM C597; Standard Test Method for Pulse Velocity Through Concrete. ASTM International: West Conshohocken, PA, USA, 2016, doi: 10.1520/C0597-22.

[50] ASTM C666/C666M-15. Standard test method for resistance of concrete to rapid freezing and thawing. ASTM International. West Conshohocken, 2015, doi: 10.1520/C0666_C0666M-15.

[51] S. Bakhtiyari, A. Allahverdi, M. Rais-Ghasemi, A. Ramezanianpour, T. Parhizkar, B. Zarrabi, Mix design, compressive strength and resistance to elevated temperature (500°C) of self-compacting concretes containing limestone and quartz fillers, *International Journal of Civil Engineering*, 2011, **9**, 215-222.

[52] H. Yan, W. Sun, H. Chen, The effect of silica fume and steel fiber on the dynamic mechanical performance of high-strength concrete, *Cement and Concrete Research*, 1999, **29**, 423-426, doi: 10.1016/S0008-8846(98)00235-X.

[53] Q. Fu, W. Xu, M. Bu, B. Guo, D. Niu, Effect and action mechanism of fibers on mechanical behavior of hybrid basalt-polypropylene fiber-reinforced concrete, *Structures*, 2021, **34**, 3596-3610, doi: 10.1016/j.istruc.2021.09.097.

[54] Y. Liu, L. Wang, K. Cao, L. Sun, Review on the durability of polypropylene fibre-reinforced concrete, *Advances in Civil Engineering*, 2021, **2021**, 6652077, doi: 10.1155/2021/6652077.

[55] T. Rajah Surya, M. Prakash, K. S. Satyanarayanan, A. Keneth Celestine, N. Parthasarathi, Compressive strength of self compacting concrete under elevated temperature, *Materials Today: Proceedings*, 2021, **40**, S83-S87, doi: 10.1016/j.matpr.2020.03.746.

[56] D. Gao, D. Yan, X. Li, Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures, *Fire Safety Journal*, 2012, **54**, 67-73, doi: 10.1016/j.firesaf.2012.07.009.

[57] C. S. Das, T. Dey, R. Dandapat, B. B. Mukharjee, J. Kumar, Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete, *Construction and Building Materials*, 2018, **189**, 649-659, doi: 10.1016/j.conbuildmat.2018.09.036.

[58] M. Mastali, A. Dalvand, Use of silica fume and recycled steel fibers in self-compacting concrete (SCC), *Construction and Building Materials*, 2016, **125**, 196-209, doi: 10.1016/j.conbuildmat.2016.08.046.

[59] A. M. Ashteyat, Y. S. Al Rjoub, Y. Murad, S. Asaad, Mechanical and durability behaviour of roller-compacted concrete containing white cement by pass dust and polypropylene fibre, *European Journal of Environmental and Civil Engineering*, 2022, **26**, 166-183, doi: 10.1080/19648189.2019.1652694.

[60] A. M. Neville, J. J. Brooks, Concrete Technology, 2nd ed.; Pearson: Essex, UK, 2010.

[61] S. Lee, Effect of nylon fiber addition on the performance of recycled aggregate concrete, *Applied Sciences*, 2019, **9**, 767, doi: 10.3390/app9040767.