fibers

MDPI

Article

Influence of Basalt Fiber on the Rheological and Mechanical Properties and Durability Behavior of Self-Compacting Concrete (SCC)

Ahmed Ashteyat [1,2,*], Ala' Taleb Obaidat [3], Rahaf Qerba'a [2] and Mu'tasim Abdel-Jaber [2,4]

1 Department of Civil Engineering, College of Engineering in Al-Kharj, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
2 Faculty of Engineering, Department of Civil Engineering, The University of Jordan, Amman 11942, Jordan; rahafqerbaa7@gmail.com (R.Q.); m.abduljaber@ju.edu.jo (M.A.-J.)
3 Civil Engineering Department, Philadelphia University, Amman 19392, Jordan; atobaidat@gmail.com
4 Member of Board of Trustees, Yarmouk University, P.O. Box 566, Irbid 21163, Jordan
* Correspondence: a.ashteyat@psau.edu.sa or a.ashteyat@ju.edu.jo

Abstract: This experimental study presents the influence of basalt fiber on the rheological and mechanical properties and the durability behavior of self-compacting concrete (SCC). In this study, a total of five self-compacting concrete mixtures were prepared: one as a control mix and the other mixes with 0.05%, 0.1%, 0.15%, and 0.2% basalt fibers. Slump flow and V-funnel flow tests were employed to assess the influence of basalt fibers on the rheological properties of fresh self-compacting concrete (SCC). Additionally, mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, were analyzed. Furthermore, the mechanical properties were assessed following exposure to elevated temperatures (400 °C and 600 °C) as well as 100 and 200 freeze-thaw (F/T) cycles. Additionally, water absorption and ultrasonic pulse velocity tests were conducted on the SCC mixes after 28 days of curing. The results revealed that the addition of fiber has a significant effect on the rheological properties of fresh SCC mixtures. As the volume of fibers increases, the reduction in rheological properties increases. Basalt fiber had no effect on the compressive strength, while the splitting and flexural strength were significantly enhanced by 33% using basalt fiber. As temperatures and freezing-thawing cycles escalated, the mechanical properties of SCC exhibited a decline. Experimental findings indicated that elevating the temperature to 600 °C resulted in a decrease of over 20% in both the tensile and compressive strengths of SCC. Moreover, the results demonstrated that the incorporation of basalt fibers substantially enhanced the mechanical properties of SCC when subjected to high temperatures and freezing-thawing cycles. In addition, water absorption increased slightly by the incorporation of basalt fiber.

Keywords: SCC; flexural strength; water absorption; basalt fiber; freezing and thawing; high temperature; UPV

Citation: Ashteyat, A.; Obaidat, A.T.; Qerba'a, R.; Abdel-Jaber, M. Influence of Basalt Fiber on the Rheological and Mechanical Properties and Durability Behavior of Self-Compacting Concrete (SCC). *Fibers* **2024**, *12*, 52. https://doi.org/10.3390/fib12070052

Academic Editor: Akanshu Sharma

Received: 20 April 2024
Revised: 1 June 2024
Accepted: 6 June 2024
Published: 24 June 2024

1. Introduction

Concrete is one of the most prominent materials that has been used in the construction industry for more than a century since it provides the appropriate strength at the lowest cost when compared to other materials available. Due to the inability to use vibrating tools, casting and compaction of concrete can be exceedingly challenging in some concrete buildings, such as those with dense reinforcing and complex molds. Consequently, this exerts a negative impact on both the performance and longevity of concrete. Self-compacting concrete (SCC), a type of non-compacted concrete, stands out as a pivotal advancement in concrete technology, enhancing both the quality and durability of concrete structures. SCC has been widely employed to elevate concrete properties, durability, and workability conditions.

SCC was initially created in Japan in 1988 to produce more durable concrete structures, and it was brought to Europe in the middle of the 1990s via Sweden [1]. Even in the presence of heavily reinforced, narrow, and deep sections [2–5], SSC is a new type of concrete mixture that can flow and fill every corner of the formwork by its own weight without requiring external vibration. In addition to these advantages, SCC offers the construction industry several other advantages, such as improved surface finish, decreased noise pollution, and health issues related to the use of vibration devices. SCC also decreases labor costs and construction time, which increases efficiency and effectiveness on site.

The ingredients for producing SCC mixtures are identical to those used in conventional concrete, comprising Portland cement, fine aggregate, coarse aggregate, water, and admixtures. However, SCC stands out due to the incorporation of supplementary fine components, such as filler materials like limestone powder and very fine sand, along with high water-reducing admixtures containing viscosity-modifying agents, which help regulate its rheological properties.

Concrete is generally known as a brittle, low ductility material that is strong in compression but weak in tension. In the field of concrete technology, incorporating fibers into self-compacting concrete creates a new composite material that combines the advantages of both SCC and fibers. The amount of fibers, length, aspect ratio, and shape all have a part in the improvement of concrete properties [3,6]. In general, fiber-reinforced self-compacting concrete (FRSCC) is a new construction material that combines the advantages of SCC with the positive benefits of fibers [2,4,7].

Numerous research studies have explored the properties of concrete with the incorporation of basalt fibers [8–18].

Shoaib et al. [8] studied the fresh and hardened properties of normal- and high-strength concrete (NSC and HSC) reinforced with basalt fibers (BF), ranging from 0.5 to 1.5% by volume. The findings revealed that the addition of BF decreased the workability of both NSC and HSC at a similar rate. An average maximum slump reduction of 78% was observed at 1.5% BF. The influence of BF on the compressive strength of NSC and HSC was found to be insignificant. However, significant enhancements were noted in the splitting tensile strength, ranging from 10 to 52% in NSC, and in flexural strength, ranging from 18 to 56%. Ref. [9] studied the impact of chopped basalt fibers, measuring 32 mm in length, on concrete properties. They observed a reduction in concrete slump ranging from 5 to 34% with varying volumes of basalt fibers (BF) between 0.04 and 0.11%. This decrease in concrete workability due to the addition of BF was attributed to the larger surface area requiring more cement paste, consequently reducing workability. Ref. [10] reported a minor improvement in the concrete compressive strength (up to 7%) by the addition of BF at 0.02 to 0.11%, while [11] reported no notable change in strength at 0.2% and 0.3%, and the highest flexural strength was achieved with a 0.1% volume of fibers.

Ref. [12] studied the use of basalt fiber in the production of self-compacting concrete (SCC). Basalt fibers of 3, 6, 12, and 24 mm in length were incorporated into the SCC mixtures at a replacement ratio of 0%, 0.1%, 0.3%, and 0.5% of concrete volume. Results show that the highest compressive strength result is obtained from the mixtures containing a fiber content of 0.1% for the fiber lengths of 12 mm and 24 mm. The highest flexural and splitting tensile strength results are obtained from the concrete mixtures incorporated with a content of 0.5% fibers having a length of 24 mm. The optimum volume fraction and basalt fiber length are determined as 0.49% and 21.12 mm. Ref. [13] added BF to SCC by a fraction of 0.1% to 0.5%. According to the research findings, BF has reduced the diameter of the flow (695–663 mm) and increased the time of the flow (3–5.6 s). Also, SCC containing 0.1–0.4% volume fraction of BF improve the compressive strength in ranged from 2.22% to 8.43% at 28 days. Ref. [14] examined various basalt fiber contents of 0.90, 1.35, and 1.80 kg/m^3, along with different fiber lengths of 24, 19, and 40 mm, respectively, in investigating SCC. Their findings indicated that the highest compressive and flexural strength values were achieved in SCC mixtures containing 0.1% and 0.5% BF by volume, with a fiber length of 24 mm, respectively. Compared to the control concrete, samples reinforced with basalt fiber showed an increase in compressive strength by 2.43%, 3.58%, and 4.20% for fiber contents of 0.90, 1.35, and 1.80 kg/m^3, respectively.

In the study conducted by [15], the behavior of SCC produced with basalt fiber was investigated using fiber amounts ranging from 0.6% to 2.0%. It was stated that the addition of fiber into SCC increases the 28-day splitting tensile and flexural strength by 5% to 50% and 30% to 48%, respectively. It was revealed that the 7-, 14-, and 28-day compressive strength, splitting tensile strength, and flexural strength results from SCC mixtures produced with basalt fibers become highest for the fiber utilization of 0.3%, 0.4%, and 1.4%, respectively.

Concrete's durability is a vital characteristic, irrespective of its compressive strength, as issues with concrete typically arise from durability failures rather than inadequate strength [19]. In order to maintain its ideal engineering properties, original shape, quality, and serviceability, concrete must be able to survive weathering, environmental factors, chemical attack, fire, abrasion, and any other deterioration process. Elevated temperatures represent a significant environmental factor that could potentially compromise the mechanical and physical properties of concrete. Conversely, heightened temperatures result in increased internal pressure, a primary factor contributing to the reduction in concrete strength [20,21]. According to previous studies on polypropylene fibers (PPF), utilizing PPF in conventional and self-compacting concrete can prevent spalling in the event of a fire [22,23]. PPF melts at 160–170 °C while spalls at 190–250 °C. As a result, as the fibers melt, vacuous channels emerge, creating a new pathway for gas escape [24].

Ref. [25] studied the compressive strength of self-compacting concrete under elevated temperatures. After 28 days of curing, the specimens were kept at 200 °C, 400 °C, 600 °C, and 800 °C temperatures for two hours. It was established that compressive capacity decreased with an increase in temperature. Also, there was a drastic reduction in strength at both 600 °C and 800 °C. The percent variation of resilience strength of self-packing concrete at 200 °C, 400 °C, 600 °C, and 800 °C was found to be 3.15%, 10.88%, 43.39%, and 51.36%, respectively, relative to the controlled concrete. Ref. [26] investigated the mechanical performance of self-compacting concretes (SCCs) under both room and high temperatures. Their findings revealed that the relative compressive strengths measured at 120 °C and 600 °C for all the SCCs studied were lower than those determined for conventionally vibrated concretes. Additionally, increasing the volume of cement paste resulted in a notable reduction in the relative compressive strength at 250 °C, 400 °C, and 600 °C. The water–binder ratio had minimal impact on the relative compressive strength of the SCCs studied at high temperatures.

Ref. [27] studied experimentally the influence of high temperatures on the characteristics of self-compacting concrete. All specimens were subjected to high temperatures (20, 200, 400, 600, and 800 °C). Mixes were categorized into three groups based on types of concrete: high-strength concrete (HSC), self-compacting concrete (SCC), and self-compacting concrete with polypropylene fiber (SCCPPF). Moreover, several parameters were studied: concrete compressive strength (30 MPa and 60 MPa), water–cement ratio (0.28 and 0.64), and polypropylene fiber content (0% and 1%). Based on experimental results, the hot compressive strength of SCC reduces as temperature rises, except for high-strength SCC, which rises at around 400 °C. On the other hand, concrete's strength loss is impacted by its strength grade, especially at temperatures under 400 °C. Another finding of the studies was that adding polypropylene fibers to the mix reduced the compressive strength and the possibility of explosive spalling as well as gave greater fire resistance than other HSC and good workability.

Ref. [28] investigated the effects of basalt fibers on the workability and strength of fresh self-compacting concrete (SCC). The properties of hardened concrete, such as compressive strength, splitting strength, and flexural strength, were examined at temperatures between 25 °C and 500 °C. The results showed that workability decreased significantly with an increase in basalt fiber content. An average strength reduction of 11.43% was observed when the fiber content was increased. This result is attributed to the reduction in the workability and density of SCC caused by fiber introduction. The splitting tensile strength of the SCC mixtures was increased by the addition of 0.25% basalt fibers. However, a decrease in splitting tensile strength occurred when more than 0.25% basalt fiber volume fraction was added. The experimental results revealed that increasing the temperature up to 500 °C reduced the tensile and compressive strengths of SCC by over 20%.

Based on the literature, there is limited research on the behavior of self-compacting concrete (SCC) containing basalt fiber after exposure to high temperatures and freezing-thawing cycles. Therefore, this study extensively investigates the rheological and mechanical properties and the durability of self-compacting concrete, incorporating basalt fiber in various proportions under the influence of exposure to high temperatures and freezing-thawing cycles, making it the focal point of this research.

2. Experimental Work

This section describes the material properties, details of the slab, procedure of thermal shock, test matrix, installation of CFRP, and test setup.

2.1. Material Properties

2.1.1. Cement

Ordinary Portland cement (OPC) Type I with 52.5 grade was used in the SCC mixes according to EN 197-1-2011 standards [29] with 3.15 specific gravity. Table 1 shows the chemical and physical properties of the OPC used in this study.

Table 1. Chemical and physical properties of the OPC used.

Chemical and Physical Properties	Percentages (%)
Silicon Oxide (SiO_2)	20.41
Aluminum Oxide ($Al2O_3$)	4.51
Ferric Oxide ($Fe2O_3$)	3.43
Calcium Oxide (CaO)	64.74
Magnesium Oxide (MgO)	1.99
Sulfur Trioxide (SO_3)	2.90
Potassium Oxide (K_2O)	0.52
Sodium Oxide (Na_2O)	0.32
Tricalcium Aluminate (C_3A)	7.50
Loss On Ignition (L.O.I)	1.15
Specific Service Area	3550 cm^2/g

2.1.2. Aggregate

The aggregate used in this study was selected based on the particle size, specific gravity, and original rocks as per the ASTM C33/C33M-18 standard [30]. The origin of the coarse aggregate used in this study is limestone with a maximum size of 16 mm. Two types of fine aggregate were used, limestone with a mean size between 3 and 6 mm and silica sand with a mean size between 0 and 3 mm. Table 2 summarizes the aggregate properties.

Table 2. Physical properties of aggregate.

Property	Coarse Aggregate	Fine Aggregate	
		Limestone	Silica Sand
Specific gravity (SSD)	2.66	2.66	2.62
Water absorption %	1.3%	0.9%	0.2%
Bulk Density	1410 kg/m^3		

2.1.3. Admixture

In this study, a high-performance superplasticizer (Hyperplast PC770) was used. It is based on polycarboxylate polymers supplied by the DCP Company (Amman, Jordan) and complies with ASTM C494-Type G [31]. Hyperplast PC 770 is a light-yellow liquid with a specific gravity of 1.06 ± 0.02.

2.1.4. Basalt Fiber

Basalt Concrete Fibers for Polymers and Concrete, a high-performing basalt fiber, was made available by the Globmarble Company. The basalt fiber used in this study has a length of 12 mm. The basalt fiber used in the concrete mix is seen in Figure 1. Table 3 lists the BF's chemical and physical properties.

Figure 1. Basalt fiber.

Table 3. Physical properties of basalt fiber.

Shape of Fiber	Straight
Density	2.67 (g/cm^3)
Length	12 mm
Diameter	16 micron
Melting Temperature	1450 °C
Tensile Strength	2600 MPa
Young's Modulus	≥65 GPa

2.2. Testing Program

Five types of SCC mixes with different ratios of basalt fibers were prepared: one as a control mix for comparison purposes and the other mixes with 0.05, 0.1, 0.15, and 0.2% basalt fiber by volume. The designation of the mixture is control, BF5, BF10, BF15, and BF20. For each mix, the test specimens consisted of 33 cylinders and 15 prisms, as shown in Table 4. The cylinders were subjected through testing for compressive strength, splitting tensile strength, and water absorption. Flexural strength testing and an ultrasonic pulse velocity test were performed on prisms. The previous tests were implemented on the specimens after exposure to three different levels of temperature (23 °C, 400 °C, and 600 °C) as well as freeze and thaw cycles (100 and 200).

Table 4. Experimental specimens' matrix and details.

Heat	23 °C	400 °C	600 °C
Compressive strength	3 Cylinder	3 Cylinder	3 Cylinder
Splitting tensile strength	3 Cylinder	3 Cylinder	3 Cylinder
Flexural strength	3 Prism	3 Prism	3 Prism
Freezing and thawing		100 Cycles	200 Cycles
Compressive strength	-	3 Cylinder	3 Cylinder
Splitting tensile strength	-	3 Cylinder	3 Cylinder
Flexural strength	-	3 Prism	3 Prism
Water absorption	3 Cylinder	-	-

2.3. Concrete Mix Design

The compressive strength of this mixture is designed to be C40/50 MPa (cylinder/cube) after 28 days through the proper ratios of cement, fine aggregates, and coarse aggregates. SCC with a water–cement ratio equal to 0.4 were prepared, 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), in addition to Superplasticizer at 2.5% (PC 770) by cement weight. After examining several mixtures of SCC, the mixture shown in Table 5 was used.

Table 5. Concrete mix design.

Cement (OPC 52.5)	420 kg/m^3
Coarse Aggregate (Limestone)	730 kg/m^3
Fine Aggregate (II) (Limestone)	438 kg/m^3
Fine Aggregate (I) (Silica Sand)	657 kg/m^3
Water absorbed by aggregate	16 kg/m^3
Superplasticizer (PC 770)	10.50 kg/m^3
Total Aggregate	1825 kg/m^3

2.4. Mixing and Casting Procedure

A tilting drum mixer of 0.25 m^3 was used for mixing the ingredients. In a dry state, coarse aggregates, fine aggregates (II), and fine aggregates (I) were blended for 2 min with one-third of the water quantity to give the aggregates their need for absorption. Then, cement was added, followed by another one-third of the water gradually, and mixing continued. Following that, superplasticizers were dissolved into the remaining water and mixed for 5 min. Fibers were added as the last ingredient in the mix, gradually dropping them into the mixer and mixing for approximately 4 min.

Thirty-three cylindrical samples (100 mm × 200 mm) and fifteen prismatic specimens (100 mm × 100 mm × 400 mm) were cast for each of the SCC mixes, both with and without fibers, without the application of any external vibration force. After each mold was filled up, the excess concrete was removed using a trowel to achieve a smooth surface. For 24 h, the casted specimens were kept in molds. The specimens were then removed out of their molds and submerged entirely for 28 days at a temperature of (23 °C) in a tank of water. Figure 2 illustrates the casting processes.

Figure 2. Casting of SCC specimens.

2.5. Testing Fresh SCC Concrete

Before casting specimens, two different types of tests were conducted on fresh self-compacting concrete mixtures to determine the impact of adding basalt fiber on their fresh qualities in accordance with EFNARC [32]. The tests that were conducted were the V-funnel test and the slump flow test. Figures 3 and 4 show the steps of the slump flow test and V-funnel test, respectively.

Figure 3. Steps of the slump flow test.

Figure 4. Steps of the V-funnel test.

2.6. Testing for Mechanical Properties of SCC

The mechanical properties of hardened SCC mixes containing basalt fibers were evaluated in the current study. These mechanical properties include compressive strength, splitting tensile strength, and flexural strength.

The compressive strength and splitting tensile strength of each SCC specimen were tested at 28 days at a load rate of 0.6 MPa/s in accordance with ASTM C39 [33] and ASTM

C496 [34], respectively. The specimens were tested using a compression testing machine with a capacity of 4000 kN. Flexural strength, commonly referred to as MOR (modulus of rupture), is an indirect way to measure tensile strength. As shown in Figure 5, a flexural strength test on prism-shaped specimens (100 mm × 100 mm × 400 mm) with a center-to-center span length of 300 mm was conducted utilizing a 150 kN capacity universal testing machine in accordance with the ASTM C293-16 [35] standard. The test was at a rate of 0.025 kN/min; the center point loading (vertical static loading) was gradually raised.

Figure 5. Flexural test of SCC specimens.

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 a sustainable concrete structure when exposed to harsh environmental conditions.

To assess the durability behavior of hardened SCC mixtures with different basalt fiber ratios, water absorption, freezing-thawing resistance, and heat resistance tests were used after 28 days of curing.

2.7.1. Water Absorption Test

A water absorption test serves as a means to gauge the pore structure within concrete material, providing a swift assessment of its durability. This test involves estimating the percentage of water absorption and voids present in cylindrical samples (100 mm × 200 mm) of self-compacting concrete. The saturated dry samples (W_{SSD}) were weighed after 28 days of curing. After that, the samples were put in the oven for 24 h at 105 ± 5 °C, and the dry samples' weights (W_{OD}) were measured, according to ASTM C642-13 [36]. The equation below is used to calculate the water absorption:

$$\text{Water Absorption} = \frac{W_{SSD} - W_{OD}}{W_{oOD}} \times 100\% \quad (1)$$

$$W_{SSD}\text{: weight saturated-dry sample (g)} \quad (2)$$

$$W_{OD}\text{: weight oven-dry sample (g)} \quad (3)$$

2.7.2. Freeze-Thaw Cycles

Over time, minor 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 experience permanent damage. According to ASTM C666-A [37], this test method assesses the resistance of concrete specimens to quickly repeated cycles of freezing and thawing in water (Procedure A). For each mixture, freeze-thaw resistance was assessed using cylinder specimens (100 mm × 200 mm) and prism specimens (100 mm × 100 mm × 400 mm). All specimens were placed in a freeze-thaw chamber after 28 days of curing and subjected to freeze-thaw cycles. The concrete specimens were frozen for two hours at (−18 ± 2) °C and thawed for one hour at +5 ± 2 °C. After being subjected to 100 and 200 cycles, compressive strength, splitting strength, and flexural strength tests were performed. Figure 6 shows the freeze-thaw chamber and the specimens inside the chamber.

Figure 6. Specimens before being subjected to freeze-thaw cycles.

2.7.3. Behavior under High Temperatures

This study investigates the behavior of self-compacting concrete mixtures with and without basalt fiber on the mechanical properties after being exposed to different temperatures: 400 °C and 600 °C. After a 28-day curing period, the samples (cylinders and prisms) were removed from the water tank.

Temperatures of 400 °C and 600 °C (high temperatures) were applied to the samples. As shown in Figure 7, the samples were placed in the furnace and heated from ambient temperature (23 °C) to a target temperature with an average increase rate of 5 °C/min; the specimens were subjected to a temperature of (400 °C or 600 °C) for 3 h. The specimens were then allowed to cool in the furnace until the following day. The furnace's interior temperature was digitally controlled using a display panel exterior. The samples were then cooled in the furnace without opening until the interior ambient temperature was reached. Subsequently, the specimens underwent testing for mechanical properties.

Figure 7. The samples before being subject to high temperatures in a furnace.

3. Results and Discussion

3.1. Results of SCC Fresh Properties

In this study, the slump flow test and the V-funnel test were chosen for testing the fresh properties of SCC mixes. The fresh properties of the mixes were evaluated within 30 min of mixing to control the workability of SCC. Table 6 shows the experimental results of the slump flow and V-funnel tests of fresh concrete mixtures.

Table 6. Experimental results of fresh properties of SCC mixtures.

Group of Mix	Slump Flow Test (mm)	V-Funnel Test (s)
Control	740	7.40
B5	665	10.90
B10	645	14.70
B15	550	16.90
B20	505	28

3.1.1. Slump Flow Test

The flowability of fresh concrete is assessed by the slump flow test. The effect of varying fiber ratios on the slump flow is shown in Table 6. According to EFNARC Standards, Specifications, and Guidelines for Self-Compacting Concrete [25], the slump flow value required for self-compacting concrete is 520 to 850 mm. All the mixtures satisfied these limits except the mixture containing 0.2% basalt fibers, which did not exhibit a slump flow value within the standard limits. The slump flow of the plain self-compacting concrete mixture was 740 mm. Figure 8 shows a significant reduction in the slump value when the fiber content increased. The reduction was 10%, 12.9%, 25.7%, and 31.7% at 0.05%, 0.10%, 0.15%, and 0.20% of basalt fibers, respectively, compared to the control sample. According to EFNARC standards, the utilization of a basalt fiber content of 0.1% marks the inflection point at which the flowability of SCC transitions from SF2 class to SF1. It can be observed that the flowability of SCC mixtures decreases as the fiber content increases; a similar trend was noticed by [8,10,14]. The reduction in the followability of SCC as the fiber volume increases can be due to the extensive surface area of the fibers and their high utilization content, which results in absorbing more cement paste to envelop them. Consequently, this diminishes the water–cement ratio and augments the viscosity of the mixture, ultimately resulting in slump loss [8,13,16].

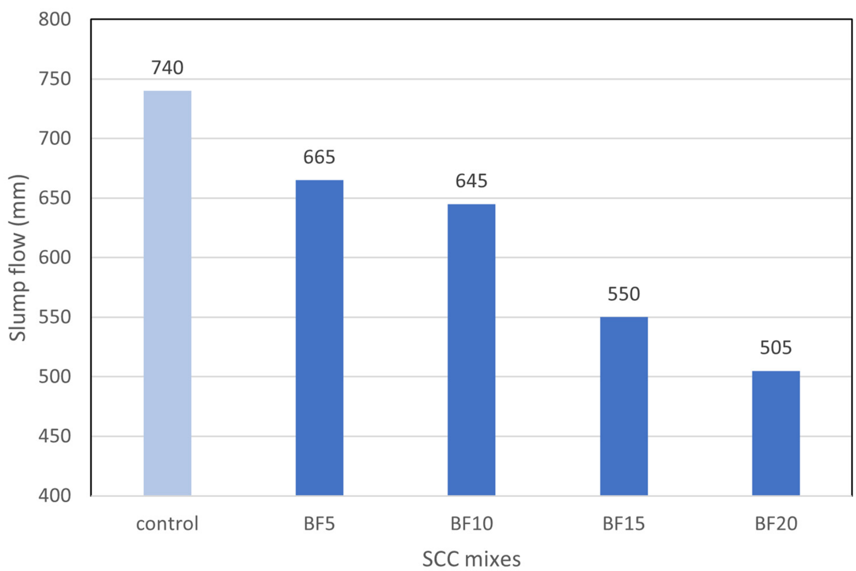

Figure 8. Slump flow test results for SCC mixtures with different basalt fiber contents.

3.1.2. V-Funnel Test

The V-funnel test is utilized to measure the filling ability of fresh SCC mixes. According to EFNARC standards, the V-funnel time required for self-compacting concrete is classified to VF1 (V-funnel flow time $\leq$ 8 s) and VF2 (V-funnel flow time 9 to 25 s). All SCC mixtures fulfill the permissible limit except the mixture that consists of 0.2% of basalt fiber, as shown in Table 6.

Table 6 and Figure 9 show that the V-funnel flow time gradually increases when the basalt fiber ratio in SCC mixes increases in comparison to the control mixture. Because fiber extends the amount of time required to flow mixes through the funnel, the V-funnel flow duration increases as the ratio of total volume of fibers increases. This was attributed to micro-scale particles of fibers absorbing some of the mixing water, enhancing the cohesiveness of fresh concrete as a result. It is clear that using BF at any ratio will cause SCC's viscosity class to move to VF2 according to EFNARC flow time standards. At 0.2% basalt fibers, the maximum V-funnel time was 28 s. BF5, BF10, BF15, and BF20 had V-funnel flow durations of 10.9, 14.7, 16.9, and 28 s, respectively. This finding is consistent with a prior investigation by [15,27].

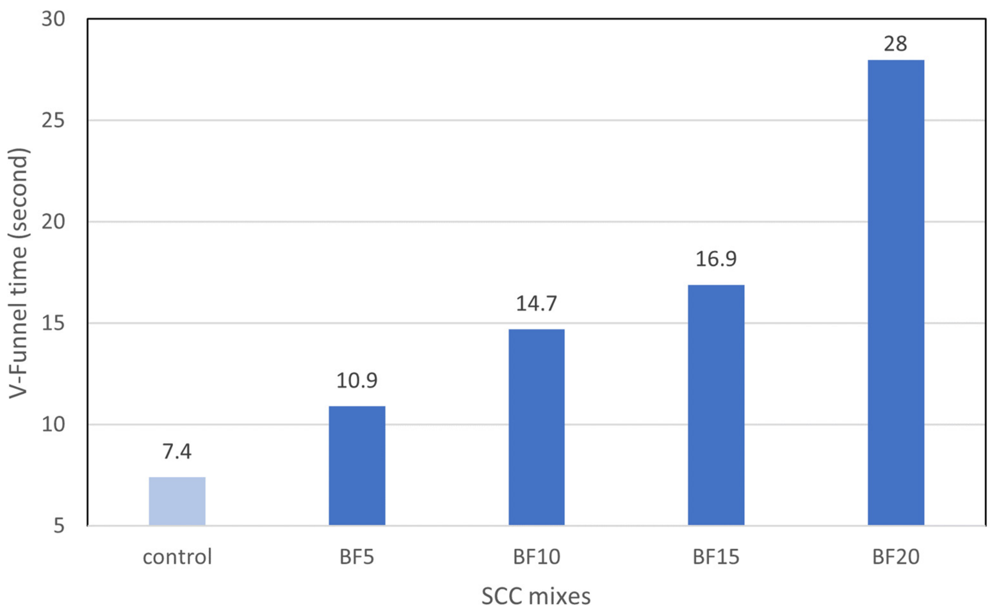

Figure 9. V-funnel test results for SCC mixtures with different basalt fiber contents.

3.2. Mechanical Properties of SCC

3.2.1. Compressive Strength at 23 °C

The results of the compressive strength of basalt fiber incorporation at different percentages are shown in Figure 10. As seen in Figure 10, adding basalt fibers did not considerably increase the compressive strength. In comparison to the control SCC specimen, the compressive strength of SCC at percentages of 0.05%, 0.1%, 0.15%, and 0.2% of basalt fibers increased by 2.6%, 3.9%, 4.4%, and 2.8%, respectively. The compressive strength decreased in the specimen with 0.2% of basalt due to the fact that the total surface area of the fibers significantly increases when the fiber content is extremely high. The bonding between cement pastes and aggregates deteriorates as a result of the requirement for additional cement pastes to surround the fibers [38]. This may possibly be because the introduction of fibers has reduced the density and workability of SCC. Similar results were reported by [11,13,14,18].

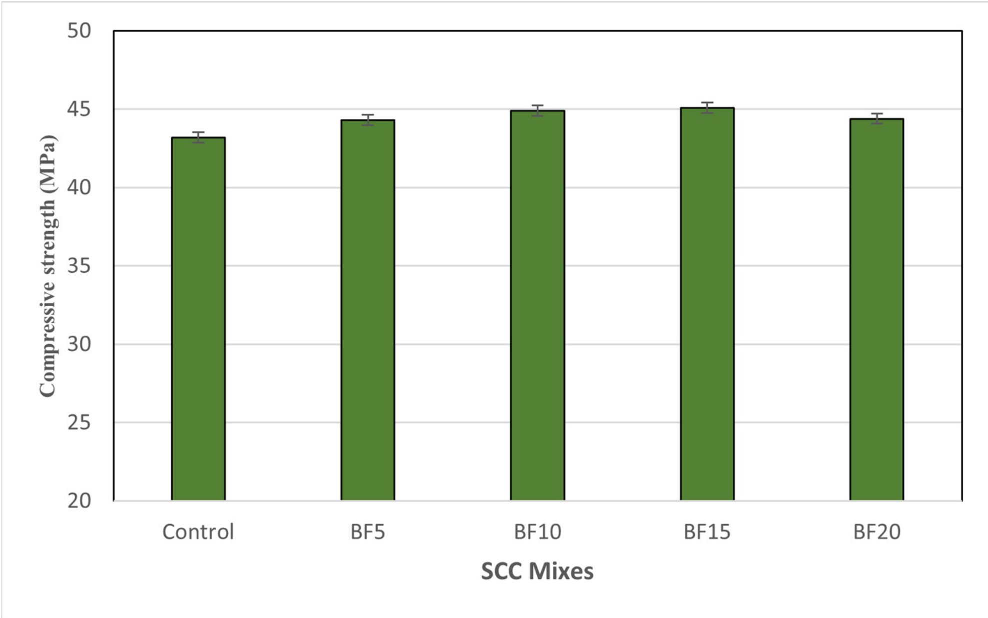

Figure 10. Compressive strength test results for SCC mixtures with different basalt fiber contents at ambient temperature.

3.2.2. Splitting Tensile Strength

In this investigation, splitting tensile and flexural strength tests were conducted to gather supplementary data regarding the impact of basalt fiber on the tensile behavior of the SCC mixtures. The outcomes of the splitting tensile strength tests for various basalt fiber ratios are depicted in Figure 11. The splitting tensile strength of SCC at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers was dramatically increased by 8.35%, 18.73%, 14.41%, and 10.95%, respectively, in comparison to the control specimen. This may be because basalt fibers have a high tensile strength, which restricts microcracks from spreading and hence increases tensile strength [12]. As depicted in Figure 9, the optimal proportion of basalt fibers for splitting tensile strength was found to be 0.1%. The splitting tensile strength of the SCC mixes exhibited improvement when utilizing 0.1% basalt fiber but declined with higher percentages of basalt fiber exceeding 0.1%.

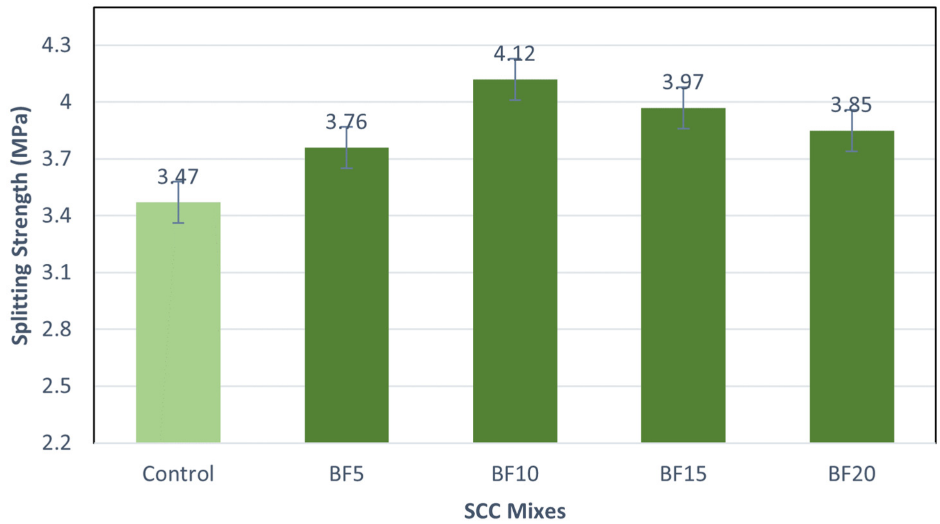

Figure 11. Splitting tensile strength test results for SCC mixtures with different basalt fiber contents at ambient temperature.

This could be because the basalt fibers are not evenly distributed throughout the cement matrix, causing agglomeration of basalt fiber particles to aggregate at high volume fraction values. According to [38], after 28 days, the addition of 0.05% basalt fiber increased the splitting tensile strength by 1.35%. When basalt fibers were introduced at 0.1%, 0.15%, and 0.20%, the strength decreased by 9.75%, 11.1%, and 11.92%, respectively, in comparison to the control sample. Ref. [28] discovered that adding 0.25% basalt fiber increased high-strength SCC's ability to split by 6%.

3.2.3. Flexural Strength

The flexural strength was determined in accordance with ASTM C293-16 [35]. Prismatic specimens measuring 100 mm × 100 mm × 400 mm were utilized for the test. At ambient temperature, the flexural strength of the SCC specimens ranged from 6.48 to 8.46 MPa. According to Figure 12, the value of flexural strength was significantly enhanced when the ratio of the total volume of fibers in SCC mixes increased. Flexural strength of SCC at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers was increased by 18.98%, 23.61%, 28.86%, and 30.56%, respectively, as compared to the control specimen. The results demonstrate that the control sample has the lowest flexural strength and that adding basalt fibers to concrete improves its flexural strength significantly. The BF20 specimen has a maximum flexural strength improvement of 30.56% over the control concrete specimen. This is due to the ability of fibers to limit crack extension and delay their growth rate. Ref. [12] showed that the flexural strength increases by 12% to 19%, depending on the length of the basalt fibers, while [13] reported an increase in the flexural strength, ranging from 3.30% to 13.61% with a volume fraction of 0.1–0.4% of BF compared to the control. Ref. [28] showed that at 0.28% basalt fiber, the flexural strength increased by 11%.

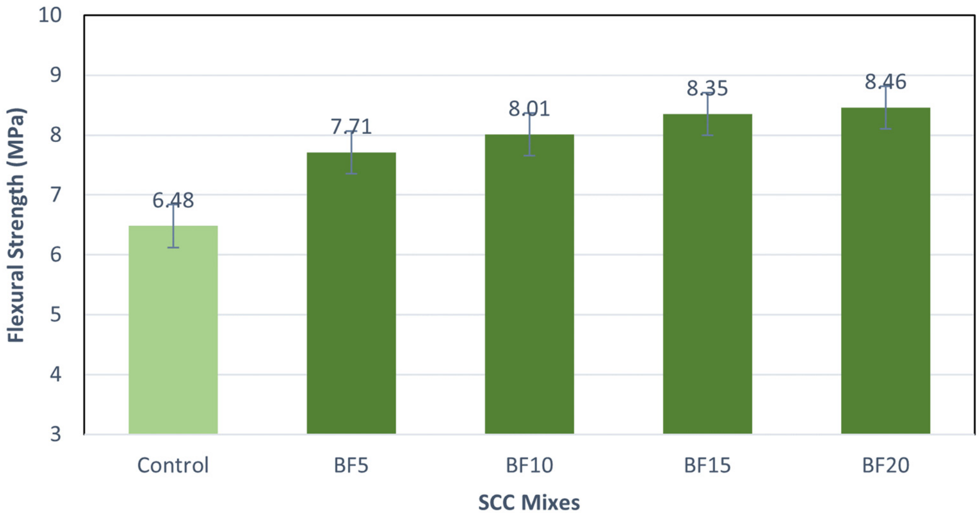

Figure 12. Flexural strength test results for SCC mixtures with different basalt fiber contents at ambient temperature.

3.3. Durability Performance

3.3.1. Effect of High Temperature

- Compressive Strength at High Temperature

The specimens were heated to 400 °C and 600 °C in an oven for three hours to assess the effect of high temperatures on the performance of SCC specimens with or without fibers. The results provided in Figure 13 reveal that compressive strength is reduced in SCC samples with or without fibers after 400 °C and 600 °C exposures compared to ambient temperature. The rate of loss in the compressive strength increases with increasing temperatures. At 400 °C, the compressive strength decreased by 14.12% in the control, 12.19% in the BF5, 9.58% in the BF10, 6.21% in the BF15, and 5.18% in the BF20 specimens, respectively, compared to the specimens subjected to 23 °C. On the other hand, after exposure to 600 °C, the compressive strength decreased by 15.97% in the control, 13.54% in the BF5, 14.25% in the BF10, 10.64% in the BF15, and 14.64% in the BF20 specimens, respectively.

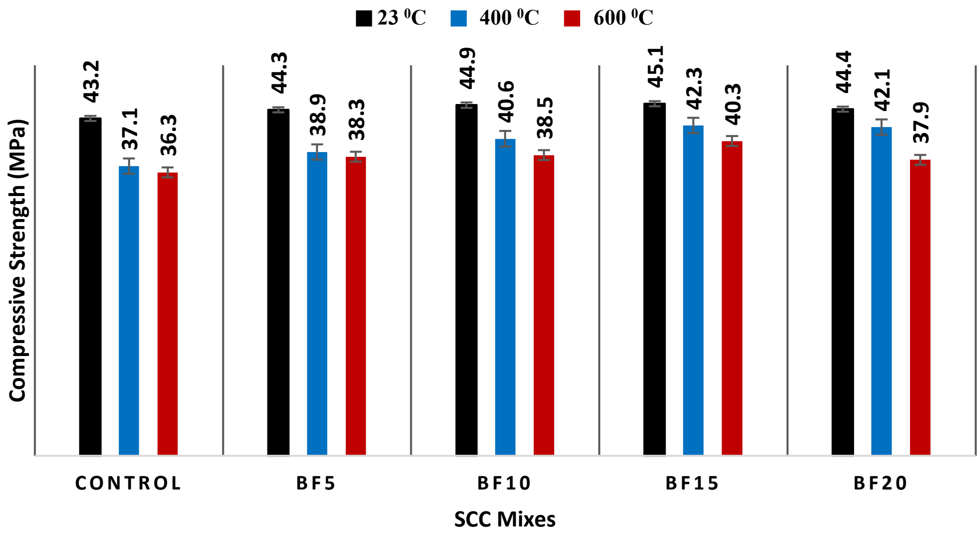

Figure 13. The effect of different temperatures (23 °C, 400 °C, and 600 °C) on compressive strength of SCC specimens.

The decrease in the compressive strength of the samples exposed to 400 °C and 600 °C can be attributed to the fact that the calcium silicate hydrate decomposes at exposure to high temperatures, and microcracks appear inside the concrete, which leads to a decrease in the compressive strength. Ref. [25] showed a reduction in the compressive strength of SCC specimens by 3.15%, 10.88%, 43.39%, and 51.36% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively, compared to the plain specimen. Figure 13 shows that the compressive strength was enhanced by incorporating basalt fibers. The compressive strength of SCC at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers increased by 4.85%, 9.43%, 14.02%, and 13.48%, respectively, as compared to the control SCC specimen. The optimum ratio of single basalt fibers was 0.15%. It can be seen that the use of fibers improves the performance of the samples in high-temperature resistance compared to the control samples.

- Splitting Tensile Strength at High Temperature

Fifteen-cylinder specimens were employed to examine the impact of temperature on the tensile behavior of SCC. Following exposure to high temperatures, the splitting tensile strength of the SCC specimens ranged from 3.07 to 3.99 MPa at 400 °C and from 2.4 to 3.4 MPa at 600 °C.

The results in Figure 14 demonstrate that, in comparison to ambient temperature, the splitting strength of SCC samples with or without fibers is significantly reduced after 400 °C and 600 °C exposures.

The splitting strength decreased by 11.5% after exposure to 400 °C in the control specimens, 3.5% in the BF5 specimens, 3.1% in the BF10 specimens, 2.7% in the BF15 specimens, and 2.9% in the BF20 specimens, as compared to specimens exposed to 23 °C. The control, BF5, BF10, BF15, and BF20 specimens' splitting tensile strength decreased by 18.2%, 5%, and 3.9%, respectively, after 600 °C, compared to the 23 °C specimens.

As the temperature increases, the splitting strength decreases, reaching an extreme level after exposure to 600 °C. SCC's splitting tensile strength increased by 18.2%, 29.2%, 25.7%, and 21.8%, respectively, at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers as compared to the control specimen at 400 °C. In comparison to the control specimen, the splitting tensile strength of SCC at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers increased by 25.7%, 28.5%, 34.1%, and 30.3%, respectively. The splitting tensile strength of SCC mixes showed an increase with the augmentation of basalt fiber content up to 0.1% yet declined with further increments beyond this threshold. These findings highlight the advantageous effect of incorporating basalt fiber on the splitting strength of concrete, particularly after exposure to high temperatures. At 500 °C, [28] showed that increasing the basalt fiber ratio by 0%, 0.2%, 0.5%, and 0.1% decreased the tensile strength of SCC.

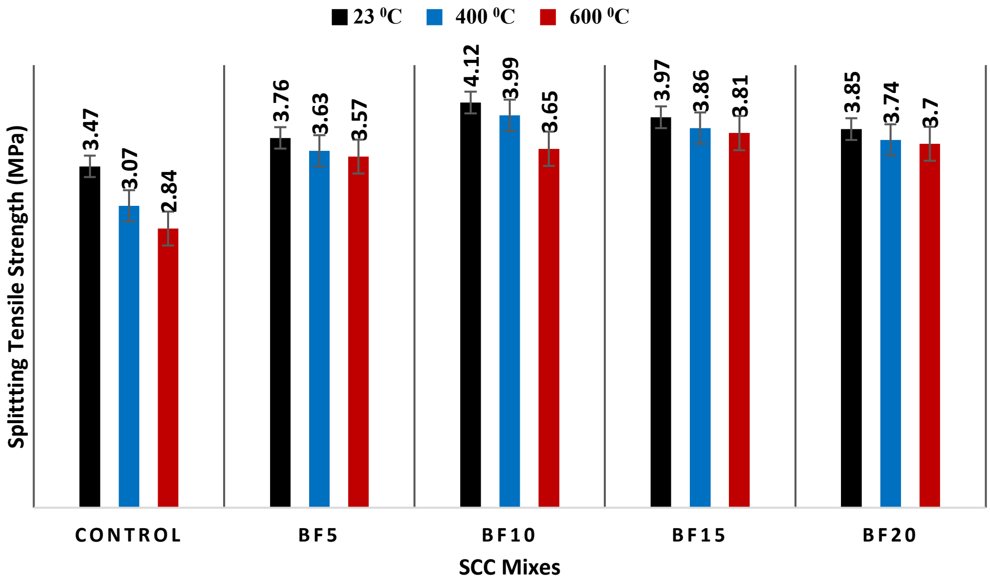

Figure 14. The effect of high temperatures (23 °C, 400 °C, and 600 °C) on the splitting tensile strength of SCC specimens.

- Flexural Strength at High Temperature

As depicted in Figure 15, after exposure to temperatures of 400 °C and 600 °C, the flexural strength of SCC specimens, with or without fibers, declines compared to those subjected to ambient temperature. The flexural strength decreases by 1.5% to 9.1% at 400 °C and by 1.2% to 12% following exposure to 600 °C. It is crucial to note that as temperature rises, flexural strength diminishes, with a significant decline observed after exposure to 600 °C due to concrete's susceptibility at high temperatures. The flexural strength decreased by 11.11% in the control specimens compared to those kept at ambient temperature.

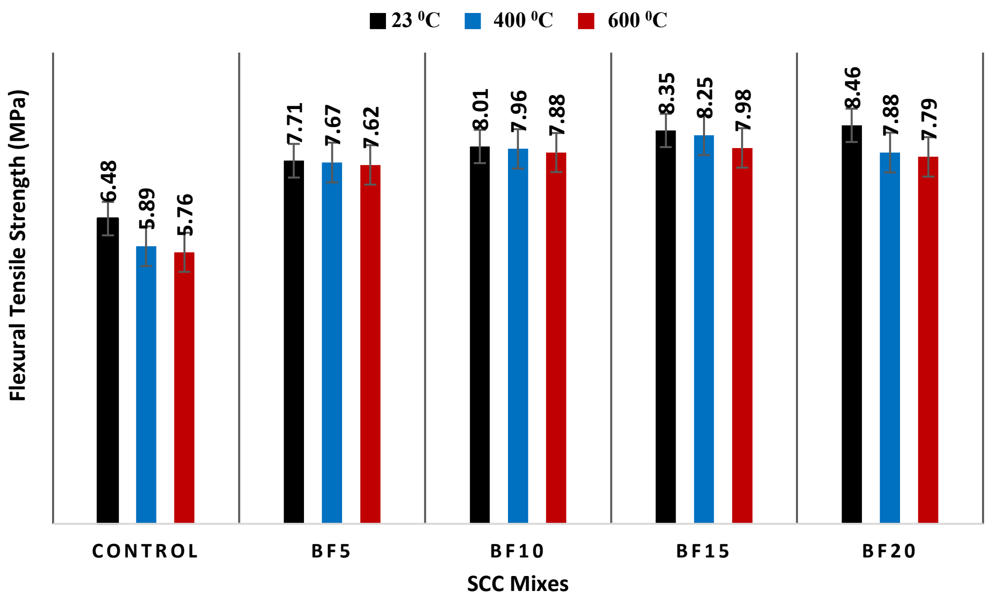

Figure 15. The effect of high temperatures (23 °C, 400 °C, and 600 °C) on the flexural tensile strength of SCC specimens.

After exposure to 400 °C, the flexural strength of basalt fibers at 0.05%, 0.1%, 0.15%, and 0.2% increased by 30.2%, 35.1%, 40%, and 33.8%, respectively, compared to the control specimen. However, when compared to the control specimen at 0.05%, 0.1%, 0.15%, and 0.2%, respectively, the flexural strength of basalt fibers increased by 27.5%, 31.3%, 32.8%, and 30%, respectively, at 600 °C. When the proportion of basalt fibers was increased to 0.15%, the flexural strength of SCC specimens increased, but it decreased with further addition of basalt fibers.

3.3.2. Freezing Thawing

- Compressive Strength

The compressive strength test was performed after subjecting cylindrical specimens (100 mm × 200 mm) to freeze and thaw cycles according to the ASTM C666-A [37] standard specification. Table 7 and Figure 16 show the maximum compressive strength of specimens following exposure to 100 and 200 freeze-thaw (F/T) cycles. All data in the table or figure below are the average of at least three test results for the same condition.

Table 7. Compressive strength test results of SCC specimens at 100 and 200 cycles.

Mixture Designation	Compressive Strength (MPa)	Compressive Strength (MPa) after 100 F/T Cycles	Compressive Strength (MPa) after 200 F/T Cycles
Control	43.2	40.2	37.8
BF5	44.3	42.8	40.8
BF10	44.9	43.6	42.7
BF15	45.1	44.4	39.2
BF20	44.4	41.9	36.7

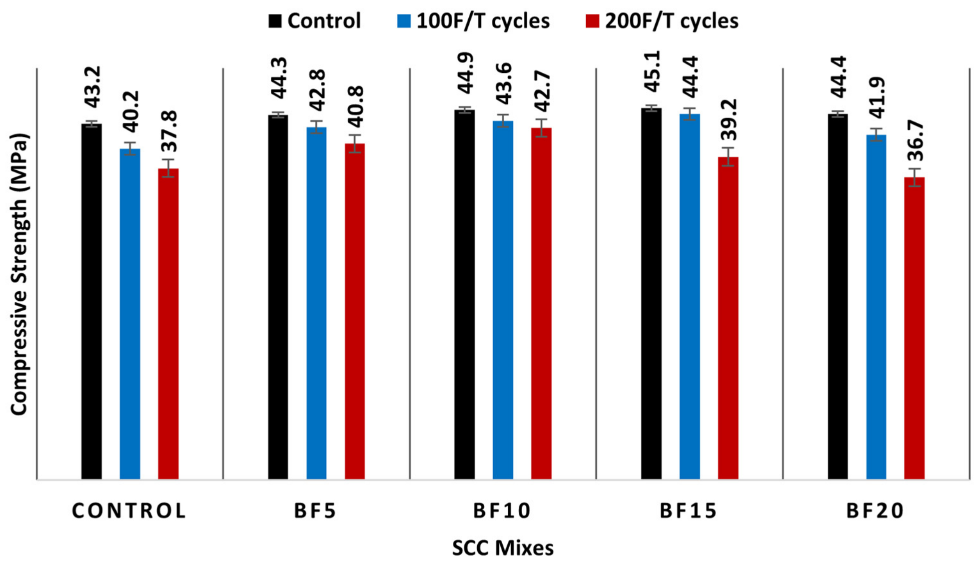

Figure 16. The effect of freeze-thaw cycles (0, 100, and 200) on compressive strength of SCC specimens.

Following 100 F/T cycles, the compressive strength of the SCC specimens ranged from 40.2 to 44.4 MPa. Table 7 illustrates that the compressive strength increased when fibers were utilized, compared to the control SCC. Figure 16 shows that after 100 and 200 cycles of freezing and thawing, the compressive strength of SCC samples with and without fibers is decreased, as compared to specimens before the freeze and thaw cycles. The rate of loss in compressive strength increases noticeably with increasing cycles of freezing and thawing. After 100 cycles of F/T, the compressive strength decreased by 6.9% in the control, 3.4% in the BF5, 2.9% in the BF10, 1.6% in the BF15, and 5.6% in the BF20 specimens, respectively, compared to the specimens at 0 cycles. The specimen containing 0.15% of basalt fibers showed the least reduction in compressive strength after 100 cycles of F/T, whereas the control specimen showed the greatest reduction. On the other hand, after exposure to 200 cycles of F/T, the compressive strength decreased by 12.5% in the control, 7.9% in the BF5, 4.9% in the BF10, 13.1% in the BF15, and 17.3% in the BF20 specimens, respectively.

The compressive strength was improved after introducing basalt fibers, as can be seen in Figure 16**.** The compressive strength of SCC at 0.05%, 0.1%, 0.15%, and 0.2% of basalt fibers increased by 6.47%, 8.46%, 10.45%, and 4.23%, respectively, as compared to the control SCC specimen. After being exposed to 200 F/T cycles, the specimens that contained 0.05%, 0.1%, and 0.15% of basalt fibers showed an increase in the compressive strength by 7.9%, 12.9%, and 3.7%, respectively. It is clear that the optimum fiber content is 0.1%. The increase in compressive strength can be explained by the ability of fibers to reduce crack extension and delay their growth rate [11,39]. The compressive strength of SCC specimens increased when the ratio of basalt fibers was raised to 0.1%, but it decreased when more than 0.1% of basalt fibers were used. As the basalt fiber content rises above 0.1%, the number of fibers in the unit volume of concrete increases, and the distance between the fibers decreases. As a result, contiguous fibers overlap, and this negatively affects the freezing and thawing durability of the concrete compounds.

- Splitting Tensile Strength

The splitting tensile strength of SCC samples with or without fibers was reduced after 100 and 200 cycles of F/T compared to samples at 0 cycles, as indicated in Figure 17. In comparison to specimens before freeze-thaw cycles, the splitting tensile strength was decreased by 7.8% in the control, 3.2% in the BF5, 1.5% in the BF10, and 3.38% in the BF20 specimens after 100 cycles, respectively. After 200 cycles, the splitting tensile strength of the control, BF5, BF10, BF15, and BF20 specimens decreased by 12.1%, 4.8%, 7.3%, 1.8%, and 4.2%, respectively, compared to the 0-cycle specimens.

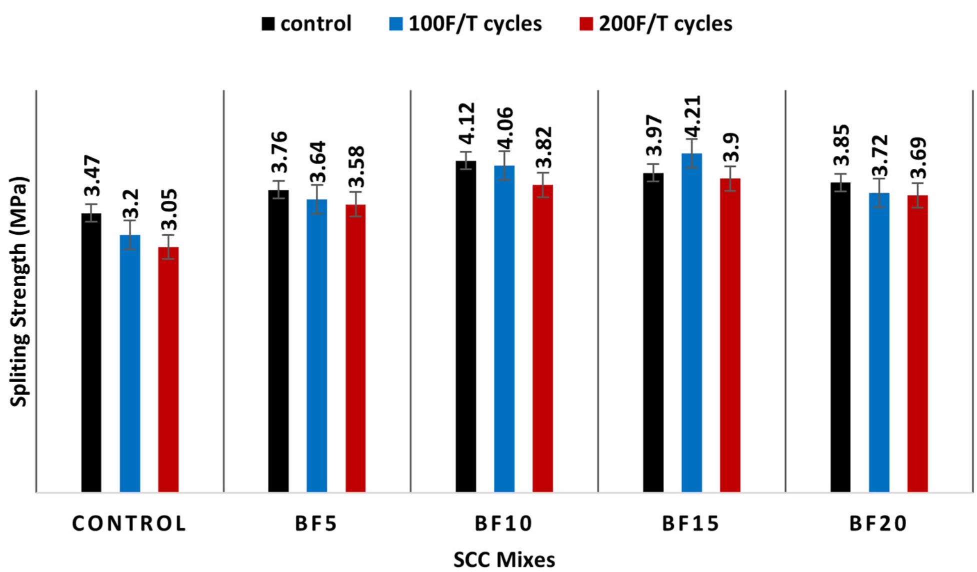

Figure 17. The effect of freeze-thaw cycles (0, 100, and 200) on splitting tensile strength of SCC specimens.

The splitting tensile strength of SCC with 0.05%, 0.1%, 0.15%, and 0.2% basalt fibers increased by 13.7%, 26.8%, 31.6%, and 16.3%, respectively. Following 200 F/T cycles, the splitting tensile strength of SCC with basalt fibers at 0.05%, 0.1%, 0.15%, and 0.2% increased by 17.4%, 25.3%, 27.9%, and 21%, respectively, compared to the control specimen. The splitting tensile strength of SCC specimens improved with an increase in the volume fraction of basalt fibers up to 0.15% but declined when basalt fibers exceeding 0.15% were used.

- Flexural Strength

As shown in Figure 18, the flexural strength of the SCC specimens ranged from 6.16 to 8.51 MPa after 100 cycles of freezing and thawing. According to Figure 18, the value of flexural strength improved when the ratio of the total volume of fibers in SCC specimens increased by 0.05%, 0.10%, 0.15%, and 0.2% compared to the control specimens.

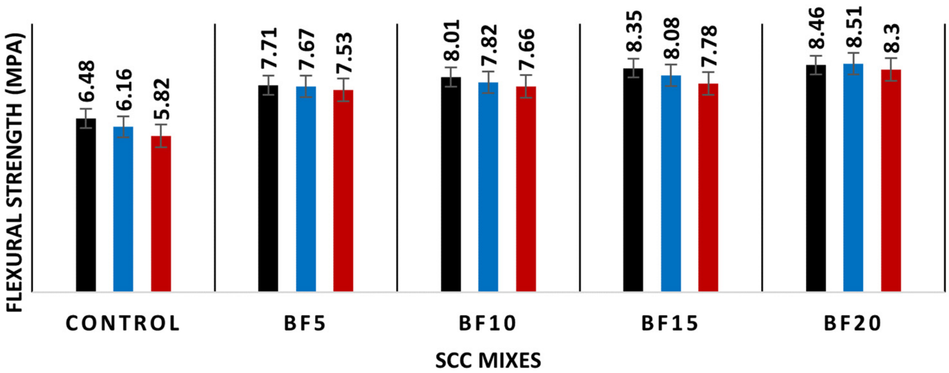

Figure 18. The effect of freeze-thaw cycles (0, 100, and 200) on flexural strength of SCC specimens.

Figure 18 compares the flexural strength of SCC samples with and without fibers after 100 and 200 F/T cycles to samples at 0 cycles. The rate of flexural strength loss was slight after 100 cycles. In comparison to specimens before freeze-thaw cycles, the flexural strength was decreased by 4.9% in the control, 2.4% in the BF10, and 3.2% in the BF15 after 100 cycles, respectively. After 200 cycles, the flexural strength of the control, BF5, BF10, BF15, and BF20 specimens decreased by 10.2%, 2.3%, 4.4%, 6.8%, and 1.9%, respectively, compared to the 0-cycle specimens.

Flexural strength of SCC at 0.05%, 0.10%, 0.15%, and 0.2% of basalt fibers was increased by 24.5%, 27%, 31.2%, and 38.2%, respectively, as compared to the control specimen. The incorporation of basalt fibers into SCC resulted in a considerable improvement in flexural strength due to its high tensile strength. In general, specimen B20 shows the best performance in freeze-thaw resistance after 200 cycles. The BF20 specimen had a maximum flexural strength of 38.15% higher than the control concrete specimen in this study.

3.3.3. Water Absorption Results of SCC

Water absorption was determined for both fiber-reinforced and non-fiber-reinforced SCC mixtures following 28 days of curing. Cylindrical specimens measuring 100 mm × 200 mm were subjected to a 24 h oven treatment at 105 ± 5 °C during the test process. The average water absorption for SCC specimens with and without fibers is shown in Figure 19. As shown in the figure, the water absorption of each of the concrete mixtures in this study was less than 3%, indicating that the SCC mixes are of acceptable quality.

The findings reveal that incorporating 0.1%, 0.15%, and 0.2% basalt fibers into SCC leads to an increase in water absorption by 8.6%, 10.9%, and 21.2%, respectively, compared to the control specimen. Conversely, the specimen containing 0.05% basalt fibers exhibited a reduction in water absorption by 27.6%. Specifically, specimen BF5 demonstrated the lowest water absorption, whereas specimen BF20 exhibited the highest. The observed outcomes can be attributed to the addition of an appropriate quantity of basalt fibers into the concrete, resulting in the introduction of numerous uniformly dispersed micro-bubbles. This phenomenon enhances the pore structure and reduces water absorption. However, when the fiber content is excessively high, the fibers are not evenly distributed, creating gaps between fibers, which in turn increases water absorption [38]. Niu et al. [38] showed the water absorption of specimens containing 0.05%, 0.1%, and 0.15% basalt fibers was reduced by 20.6%, 3.6%, and 2.6%, respectively, whereas specimens containing 0.2% increased by 19.1%, compared to the control sample.

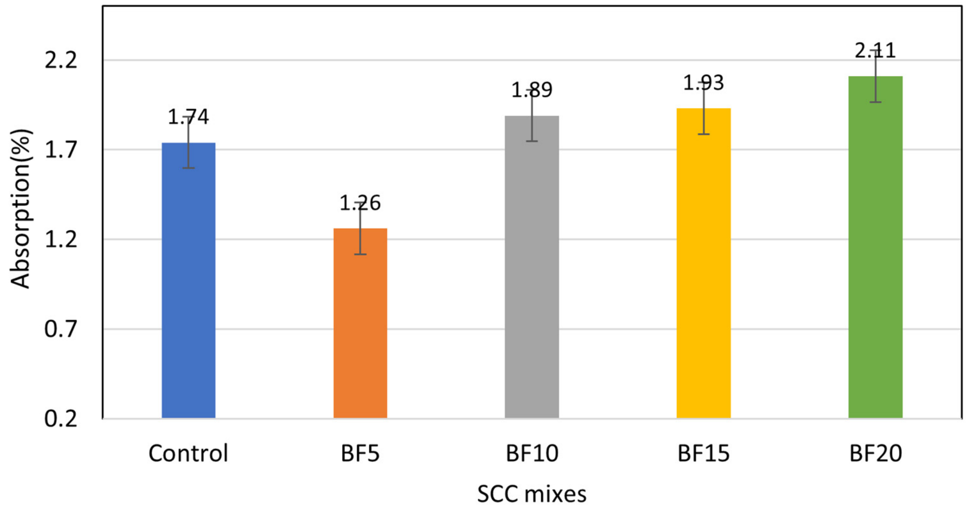

Figure 19. Water absorption test results for SCC mixtures with different basalt fiber contents.

3.3.4. Ultrasonic Pulse Velocity (UPV) Results of SCC

The ultrasonic pulse velocity test (UPV) serves as a non-destructive method to assess the quality and integrity of concrete. Following 28 days of curing, concrete prism specimens (100 mm × 100 mm × 400 mm) underwent an ultrasonic pulse velocity test to evaluate their properties.

The UPV is categorized as follows: excellent (above 4500 m/s), good (3500–4500 m/s), medium (3000–3500 m/s), and doubtful (below 3000 m/s). Figure 20 shows that the SCC specimens fall into two categories of UPV: above 4500 m/s and 3500–4500 m/s, which signal excellent and good quality conditions, respectively [40]. UPV values were enhanced after fibers were added to SCC mixtures by reducing the voids, but the enhancement was not significant, while it decreased at 0.2% of basalt fibers.

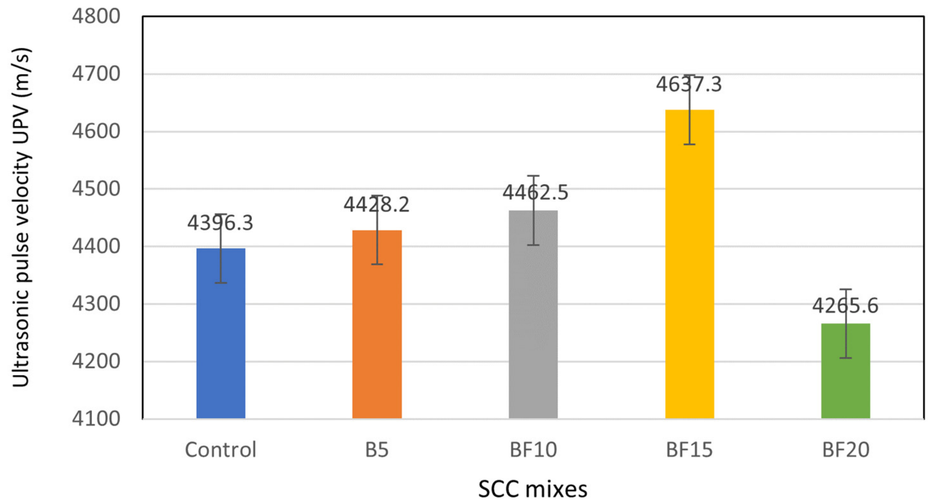

Figure 20. UPV test results for SCC mixtures with different basalt fiber contents.

In comparison to the control specimen, adding 0.05%, 0.1%, and 0.15% basalt fibers to SCC increases the UPV of concrete by 0.73%, 1.5%, and 5.5%, respectively. In the specimen containing 0.2% basalt fibers, UPV was reduced by 2.97%, compared to the control specimen. It can be concluded that with an increase in the content of basalt fibers to 0.15%, the speed of the pulses passing increases, but it decreases at 0.2%.

4. Conclusions

The test results lead to the following conclusions:

1. The addition of fibers negatively affected the rheological properties of fresh SCC mixtures. The slump flow value of SCC mixtures decreased as the fiber content increased, with an overall decrease ranging from 8.11% to 31.76%.
2. At ambient temperature (23 °C), using basalt fiber does not affect the compressive strength of the SCC specimens, while the splitting strength and flexural strength significantly enhanced with increasing the basalt fiber volume.
3. The addition of basalt fibers improved the mechanical properties of SCC specimens after being exposed to high temperatures (400 °C and 600 °C). The optimal basalt fiber ratio was found in the BF15 specimen, which increased flexural strength and splitting strength by 32.8% and 33.3%, respectively, over the reference SCC specimen.
4. After exposure to freeze-thaw cycles, the flexural strength and splitting strength of different SCC mixes increased as the ratio of the total volume of fibers increased. The optimum fiber content for SCC is 0.15% basalt fibers.
5. The incorporation of fibers into SCC had both a positive and negative effect on the water absorption of concrete. The specimen containing 0.075% BF exhibited the lowest water absorption. Water absorption increased by 8.62%, 10.92%, and 21.26%, respectively, for specimens BF1, BF15, and BF20, compared to the control specimen.
6. The UPV values were enhanced after fibers were added to SCC mixtures but decreased at 0.2% of fibers. The optimum fiber content was 0.15% of basalt fibers.

Author Contributions: Conceptualization, M.A.-J.; methodology, A.A.; validation, R.Q. and A.T.O.; formal analysis, M.A.-J.; investigation, R.Q.; resources, M.A.-J. and A.A.; data curation, R.Q.; writing—original draft preparation, R.Q.; writing—review and editing, A.A. and A.T.O.; visualization, A.A. and R.Q.; supervision, A.A.; project administration, R.Q. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The article includes all the research data.

Acknowledgments: The authors appreciate the support provided by the academic research deanship at the University of Jordan and support from Philadelphia University. Also, this study is supported via funding from Prince Sattam Bin Abdulaziz University project number (PSAU/2024/R/1445).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Goodier, C.I. Development of self-compacting concrete. *Proc. Inst. Civ. Eng.-Struct. Build.* **2003**, *156*, 405–414. [CrossRef]
2. Zeyad, A.M. Effect of fibers types on fresh properties and flexural toughness of self-compacting concrete. *J. Mater. Res. Technol.* **2020**, *9*, 4147–4158. [CrossRef]
3. Tabatabaeian, M.; Khaloo, A.; Joshaghani, A.; Hajibandeh, E. Experimental investigation on effects of hybrid fibers on rheological, mechanical, and durability properties of high-strength SCC. *Constr. Build. Mater.* **2017**, *147*, 497–509. [CrossRef]
4. Ashteyat, A.M.; Haddad, R.H.; Obaidat, Y.T. Case study on production of self compacting concrete using white cement by pass dust. *Case Stud. Constr. Mater.* **2018**, *9*, e00190. [CrossRef]
5. Ramees, M. Mechanical Properties of SCC Reinforced with Basalt Fiber and Polypropylene Fiber. *Int. J. Eng. Res.* **2020**, *V9*, 1046–1052. [CrossRef]
6. Aslani, F. Effects of specimen size and shape on compressive and tensile strengths of self-compacting concrete with or without fibres. *Mag. Concr. Res.* **2013**, *65*, 914–929. [CrossRef]
7. Ahmad, S.; Umar, A. Fibre-reinforced Self-Compacting Concrete: A Review. *IOP Conf. Series: Mater. Sci. Eng.* **2018**, *377*, 012117. [CrossRef]
8. Shoaib, S.; El-Maaddawy, T.; El-Hassan, H.; El-Ariss, B.; Alsalami, M. Fresh and Hardened Properties of Concrete Reinforced with Basalt Macro-Fibers. *Buildings* **2022**, *12*, 1136. [CrossRef]
9. Wang, Y.; Hughes, P.; Niu, H.; Fan, Y. A new method to improve the properties of recycled aggregate concrete: Composite addition of basalt fiber and nano-silica. *J. Clean. Prod.* **2019**, *236*, 117602. [CrossRef]

10. Arslan, M.E. Effects of basalt and glass chopped fibers addition on fracture energy and mechanical properties of ordinary concrete: CMOD measurement. *Constr. Build. Mater.* **2016**, *114*, 383–391. [CrossRef]
11. Zhang, J.; Zhao, Y.; Li, H. Effect of basalt fibres on mechanical properties of high-performance concrete containing supplementary cementitious materials. *RILEM Bookseries* **2018**, *15*, 181–187.
12. Algin, Z.; Ozen, M. The properties of chopped basalt fibre reinforced self-compacting concrete. *Constr. Build. Mater.* **2018**, *186*, 678–685. [CrossRef]
13. Vedhasakthi, K.; Chithra, R. Strength attributes and microstructural characterization of basalt fibre incorporated self-compacting concrete. *J. Build. Eng.* **2023**, *78*, 107592. [CrossRef]
14. Rohilla, C.; Sharma, K.; Kuldeep, A. A study on behavior of chopped fiber reinforced self-compacting concrete. *Eng. Technol. J.* **2016**, *1*, 33–38. [CrossRef]
15. Paulraj, S.; Balasundaram, N.; Sates Kumar, K.; Dharshna Devi, M. Experimental studies on strength and SCC characteristics of basalt fiber reinforced concrete. *Int. J. Civil Eng. Technol. (IJCIET)* **2017**, *8*, 704–711.
16. Çelik, Z.; Bingöl, A.F. Effect of basalt, polypropylene and macro-synthetic fibres on workability and mechanical properties of self-compacting concrete. *Chall. J. Struct. Mech.* **2019**, *5*, 35. [CrossRef]
17. Branston, J.; Das, S.; Kenno, S.Y.; Taylor, C. Mechanical behaviour of basalt fibre reinforced concrete. *Construct. Build. Mater.* **2016**, *124*, 878–886. [CrossRef]
18. Jiang, C.; Fan, K.; Wu, F.; Chen, D. Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. *Mater. Des.* **2014**, *58*, 187–193. [CrossRef]
19. Zhang, P.; Li, Q.-F. Effect of polypropylene fiber on durability of concrete composite containing fly ash and silica fume. *Compos. Part B Eng.* **2013**, *45*, 1587–1594. [CrossRef]
20. Anupama Krishna, D.; Priyadarsini, R.S.; Narayanan, S. Effect of elevated temperatures on the mechanical properties of concrete. *Procedia Struct. Integr.* **2019**, *14*, 384–394. [CrossRef]
21. Al Qadi, A.N.S.; Mustapha, K.N.B.; Nagathan, S.; Al-Kadi, Q. Effect of polypropylene fibres on fresh and hardened properties of self-compacting concrete at elevated temperatures. *Aust. J. Basic Appl. Sci.* **2011**, *5*, 378–384.
22. Behnood, A.; Ghandehari, M. Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures. *Fire Saf. J.* **2009**, *44*, 1015–1022. [CrossRef]
23. Al Qadi, A.N.; Al-Zaidyeen, S.M. Effect of fibre content and specimen shape on residual strength of polypropylene fibre self-compacting concrete exposed to elevated temperatures. *J. King Saud Univ.-Eng. Sci.* **2014**, *26*, 33–39. [CrossRef]
24. Hertz, K.; Sørensen, L. Test method for spalling of fire exposed concrete. *Fire Saf. J.* **2005**, *40*, 466–476. [CrossRef]
25. Surya, T.R.; Prakash, M.; Satyanarayanan, K.S.; Celestine, A.K.; Parthasarathi, N. Compressive strength of self compacting concrete under elevated temperature. *Mater. Today Proc.* **2021**, *40* (Suppl. S1), S83–S87. [CrossRef]
26. Pineaud, A.; Pimienta, P.; Rémond, S.; Carré, H. Mechanical properties of high performance self-compacting concretes at room and high temperature. *Constr. Build. Mater.* **2016**, *112*, 747–755. [CrossRef]
27. Tao, J.; Yuan, Y.; Taerwe, L. Compressive Strength of Self-Compacting Concrete during High-Temperature Exposure. *J. Mater. Civ. Eng.* **2010**, *22*, 1005–1011. [CrossRef]
28. Haido, J.H.; Tayeh, B.A.; Majeed, S.S.; Karpuzcu, M. Effect of high temperature on the mechanical properties of basalt fibre self-compacting concrete as an overlay material. *Constr. Build. Mater.* **2021**, *268*, 121725. [CrossRef]
29. EN 197-1:2011 - Cement - Part 1: Composition, Specifications and Conformity Criteria for Common. Available online: https://standards.iteh.ai/catalog/standards/cen/64d327b1-d5ac-45e3-8b04-fafec9e0698e/en-197-1-2011 (accessed on 21 April 2024).
30. *ASTM C33/C33M-18*; Standard Specification for Concrete Aggregates. ASTM International: West Conshohocken, PA, USA, 2023. Available online: https://www.astm.org/c0033_c0033m-18.html (accessed on 20 November 2022).
31. *ASTM C494/C494M-17*; Standard Specification for Chemical Admixtures for Concrete. ASTM International: West Conshohocken, PA, USA, 2020.
32. EFNARC. *Specifications and Guidelines for Self-Compacting Concrete*; EFNARC, Association House: Flums, Switzerland, 2005; pp. 1–32.
33. *ASTM C39/C39M-21*; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2021.
34. *ASTM C496/C496M-17*; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2017.
35. *ASTM C293/C293M-16*; Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading). ASTM International: West Conshohocken, PA, USA, 2016.
36. *ASTM C642-13*; Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International: West Conshohocken, PA, USA, 2013.
37. *ASTM C666/C666M-15*; Standard test method for resistance of concrete to rapid freezing and thawing. ASTM International: West Conshohocken, PA, USA, 2015.
38. Niu, D.; Su, L.; Luo, Y.; Huang, D.; Luo, D. Experimental study on mechanical properties and durability of basalt fiber reinforced coral aggregate concrete. *Constr. Build. Mater.* **2020**, *237*, 117628. [CrossRef]

39. Ashteyat, A.M.; Al Rjoub, Y.S.; Murad, Y.; Asaad, S. Mechanical and durability behaviour of roller-compacted concrete containing white cement by pass dust and polypropylene fibre. *Eur. J. Environ. Civ. Eng.* **2019**, *26*, 166–183. [CrossRef]
40. Whitehurst, E.A. Soniscope test concrete structure. *J. Am. Concr. Inst.* **1951**, *47*, 443–444.