Basalt Fiber Implication on Fresh and Mechanical Properties of Self-Compacting Concrete

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ABSTRACT

This research examined the effect of different percentages of chopped Basalt Fibers (BFs) on the workability and mechanical properties of Self-Compacting Concrete (SCC). Optimum fiber dosages of 0.2%, 0.4%, and 0.6% by volume of SCC were identified. SCC properties in the early stage were evaluated through slump flow, V-funnel, L-box, and sieve segregation index tests. In addition, compressive, tensile, and flexural strength values were obtained from cured SCC specimens at 7, 28, and 56 days. The results demonstrated that fiber insertion had a negative effect on the workability of fresh SCC. Tensile and flexural strength were benefited from the BF ratio increase, which also had a positive effect on the compressive strength. Adding 0.4% BF by volume improved compressive strength by 10.13%. However, the most significant effect of the aforementioned increase was on tensile and flexural strength, since a value of 0.6% improved splitting tensile and flexural strength by 27.05% and 35.15%, respectively. BF addition resulted in a 13.4% increase in water absorption in BF0.6 specimens after 28 days. It was concluded that BFs reduce workability and improve the mechanical properties of SCC.

Keywords-Self-Compacting Concrete (SCC); mechanical properties; basalt fiber; water absorption; compressive strength; tensile strength; flexural strength

I. INTRODUCTION

SCC does not require vibration to achieve distribution. Its ability to flow allows it to fill the forms and achieve full cohesion, even in the presence of crowded reinforcement. The resulting hardened concrete is dense and uniform, offering the same engineering properties and durability as conventional vibrated concrete [1-6]. A fresh concrete mixture can be formed when three properties are achieved, namely the ability to fill and pass in any form's shapes, resistance to segregation [7-10], and the ability to be easily molded and poured [11-13]. SCC provides improved construction quality, increased construction speed, and lower costs. It also enables obtaining high quality concrete on construction sites, reducing accidents, noise and vibration, and achieving a higher quality of the external concrete surface [14, 15]. Previous research has focused on improving SCC properties by using different types of fibers and volume fractions [16, 19]. Steel fiber utilization is a good option for SCC reinforcement. However, one of its potential drawbacks is its unsuitability for later ages due to the possibility of rusting and corrosion, which has led to alternative material employment for concrete reinforcement. BFs are used by combining their high chemical, mechanical and electrical properties [20, 21]. Among the available fiber types, glass fibers, with their high tensile strength and crack resistance, improve flexural properties. However, in the long run, their durability is compromised due to their weak resistance to alkaline environments, such as concrete [22]. The advantages of using BFs in SCC depend on the former's ability to maintain compressive strength at high temperatures. It has been proven that small BF concentrations improve concrete tensile and flexural strength, especially under high-temperature conditions. Adding BFs increases SCC's ductility while maintaining its compressive strength. Durability, an important characteristic for this type of concrete, has also been confirmed. Authors in [23] concluded that adding BFs to concrete mixes reduces their viscosity and increases their compressive strength. The addition of 1% BF has resulted in slightly lower compressive strength compared to samples without fiber. Concrete strengthened with very specific amounts of BF under certain conditions has exhibited better performance. SCC flowability and tensile strength are influenced by the type and content of fibers used [24]. Higher volume fractions improve the performance of self-compacting fiber-reinforced concrete in the hardened state, but may adversely affect its workability and fresh properties [25]. Therefore, it is crucial to optimize BF volume ratio to maintain concrete self-compacting ability. The current study aims to address this issue by investigating the best BF volume ratio for SCC to improve its mechanical characteristics. An experimental program involving four mixtures was carried out. The first (reference) mixture is without fibers, while the other three have BF contents of 0.2%, 0.4%, and 0.6%, respectively.

II. MATERIALS

A. Cement

ALMAS Ordinary Portland Cement (OPC) [CEM.I. 42.5 N], complying with IQS No. 5-2019 [26] was used in this experimental research. OPC chemical composition and physical properties are shown in Tables I and II, respectively.

TABLE I. OPC CHEMICAL PROPERTIES

Oxides	Content (%)	IQS, limits for CEM I-42.5 N
(CaO)	63.33	-
(SiO_2)	22.14	-
(Al_2O_3)	5.31	-
(Fe_2O_3)	2.89	-
(MgO)	3.39	Max (5) %
(SO_3)	2.13	[SO3 ≤ 2.8] If C_3A > 3.5
(L.O.I)	1.88	Max 4 %
(I.R)	0.92	Max 1.5 %
Calculated from Bogue's equations		
(C_3S)	49.68	
(C_2S)	25.86	
(C_3A)	9.18	
(C_4AF)	8.78	

TABLE II. OPC PHYSICAL PROPERTIES

Physical properties	Results	IQS, Limits for CEM.I. 42.5 N
Surface area (Blain method)	354	≥ 280
Setting time (Victa's Apparatus)		
Initial setting time (min)	155	≥ 45 min
Final setting time (hr)	3:47	≤ 10 hrs
Compressive strength (MPa)		
(2) Days	18.60	≥ 10 MPa
(28) Days	44.71	≥ 42.5 MPa
Autoclave expansion. %	0.19	≤ 0.8

B. Fine Aggregate (FA)

Table III presents the physical properties of local sand that underwent a 4.75-mm sieve analysis, while Table IV shows the sieve analysis results according to I.Q.S. No. 45-1984, Zone 2 [27].

C. Coarse Aggregate (CA)

CAs are characterized by nominal sizes of 10 mm. Their physical and chemical properties, as well as the sieve analysis, comply with I.Q.S. No. 45-1984 [27], as displayed in Tables V and VI.

TABLE III. FA PHYSICAL PROPERTIES

Physical properties	Results	I.Q.S No.45-1984
Specific gravity	2.59	-
Absorption ratio %	0.9	-
Sulphate amount	0.447	Max (0.5) %
Dry rodded density (kg/m^3)	1632	-

TABLE IV. FA SIEVE ANALYSIS

Sieve Opening (mm)	Passing (%)	I.Q.S No.45-1984 Zone 2
9.50	100	100
4.75	94	90 – 100
2.36	83	75 – 100
1.18	74	55 – 90
0.60	42	35 – 59
0.30	11	8 – 30
0.15	3	0– 10

TABLE V. CA PHYSICAL PROPERTIES

Properties	Results	I.Q.S No.45-1984
Specific gravity	2.68	-
Absorption ratio %	0.5	-
Sulphate content	0.068	≤ 0.5
Dry rodded density (Kg/m3)	1597	-

TABLE VI. CA SIEVE ANALYSIS

Sieve size (mm)	Passing (%)	I.Q.S No.45-1984 nominal size 10 mm
12.5	100	100
9.5	98	85-100
4.75	18	0-25
2.36	3	0-5

D. Silica Fume (SF)

All mixture samples incorporated SF as a partial replacement for cement, with a percentage of 6%. The SF samples satisfied the requirements of ASTM C1240-20 [28], as presented in Tables VII and VIII.

TABLE VII. SF PHYSICAL CHARACTERISTICS

Physical characteristics	Results	(ASTM/C-1240-20)
State	Amorphous	Sub-micron powder
Color	Grey	Grey
Specific surface area (m^2/g)	19	Min (15)
Strength activity index at 7-day,	119	Min (105)
Retained on 45 µm sieve (No.325), %	8	Max (10)

TABLE VIII. SF CHEMICAL ANALYSIS

Oxide	Content (%)	(ASTM/ C-1240-20)
SiO_2	92.14	Min (85) %
Al_2O_3	<0.03	-
Fe_2O_3	0.98	-
CaO	0.65	-
MgO	0.73	-
TiO_2	<0.11	-
SO_4	0.58	-
P_2O_5	0.17	-
K_2O	1.03	-
L.O.I.	3.56	Max (6) %

E. Limestone (LM)

LM powder utilization in SCC mixtures aims to enhance workability, density, and segregation resistance. LM powder addition, with particles measuring less than 0.125 mm, further optimizes these properties, as illustrated in Table IX.

TABLE IX. LM CHEMICAL COMPOSITION

Oxides	Content (%)
SiO_2	0.21
Fe_2O_3	3.33
Al_2O_3	0.03
CaO	48.28
MgO	3.94
SO3	0.07
L.O. I	43.12
IR	2.11

F. Basalt Fibers

BFs, also referred to as basalt rock fibers, depicted in Figure 1, possess a length of 10 mm, a diameter of 15 µm, and a density of 2.6 g/cm³. They are derived from volcanic rock and exhibit high elasticity, as evidenced by their modulus of elasticity (75 GPa), tensile strength (4.5 MPa), and elongation ratio (3.15%). These fibers were integrated as a volume fraction, constituting 0.2%, 0.4%, and 0.6% of the total concrete mixture volume.

G. Superplasticizer (SP)

The high-performance concrete SP, known as PC800, was used with a dosage of 1 L to 2.9 L per 100 kg of cementitious materials to achieve optimal workability, a critical attribute of SCC. Hyperplast PC800, composed of long-chain polycarboxylic polymers, enhances the efficiency of water content in concrete. Hyperplast functions as a high-range water-reducing SP and retarder, according to ASTM C494-05 type A and G specifications [29]. Table X provides a list of Hyperplast properties.

H. Water

The experiment was conducted using potable water, in accordance with the provisions of ISO 1703-18 [30].

I. Mix Proportions

The specific mixture proportions are presented in Table XI and Figure 2, which details the methodology employed for sample preparation. This approach was undertaken to accomplish the requisite strength properties. The mixture composition was developed to achieve an SCC that complied with the specifications of EFNARK (2005) [7]. The mixture contained 2.9 L/100 kg of cementitious material PC800, 6% SF of cement weight (partial replacement of cement), and 60 kg/m³ of LM as a filler. The SSC evaluated the effects of BF reinforcement, present in proportions of 0.2%, 0.4%, and 0.6% by volume of the concrete mix. The compressive strength for the reference specimens was measured at 57.13 MPa after 28 days of curing.

Fig. 1. BF.

TABLE X. PROPERTIES OF PC800

Properties	Description
Form	Viscous liquid
Appearance/Color	Light yellow
Chemical base	Modified polycarboxylates based polymer
Specific gravity	(1.06 ±0.02 g/cm^3)
Dosage	(1 - 2.9) L/100 kg of cementitious materials in the mix

TABLE XI. MIX PROPORATIN/PROPORTION FOR SCC ACCORDING TO (EFNARC, 2005)

Specimen	Cement (kg/m^3)	SF (kg/m^3)	LM (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	SP L/100 kg of cementitious materials	w/cm	BF by volume fraction (%)
M	510	30.6	60	779	870.6	156.6	2.9	0.29	0
$BF_{0.2}$	510	30.6	60	779	870.6	156.6	2.9	0.29	0.2
$BF_{0.4}$	510	30.6	60	779	870.6	156.6	2.9	0.29	0.4
$BF_{0.6}$	510	30.6	60	779	870.6	156.6	2.9	0.29	0.6

III. RESULTS AND DISCUSSION

A. Fresh Properties of Self-Compacting Concrete

In this study, a total of four mixes were prepared for the fresh SCC mix. One of the samples is regarded as the reference mix without fibers, and the remaining three samples contain varying proportions of BF. The workability exhibited an inverse relationship with the BF ratio due to the interference and friction between the fibers and the other mix components. However, the most significant decline in workability was observed at a fiber content of 0.6% in the mix. As shown in Table XII, the slump flow test results exhibited a decline from 790 mm to 672 mm, with a percentage of 6%. The values of the slump flow time, T500, exhibited a gradual increase with the fiber incorporation, ranging from 4 s to 17 s. The V-funnel test results ranged from 6 s to 23 s, while the L-box test values varied from 0.96 to 0.83, with a decrease observed as the ratio of BF addition to the mixture increased. In a similar manner, the sieve Segregation Index (SI) values ranged from 19.31% to 6.72%. The obtained results are in accordance with the SCC specifications outlined in ENARKO-2005 [7].

TABLE I. FRESH PROPERTIES OF SCC ACCORDING TO (EFNARC,2005)

Mix ID	Slump flow (mm)	T_{500} (s)	V – funnel (s)	L – box (h_2/h_1)	SI (%)
M	790	4	6	0.96	19.31
$BF_{0.2}$	763	6	10	0.92	16.21
$BF_{0.4}$	716	9	15	0.88	11.76
$BF_{0.6}$	672	17	23	0.83	6.72
EFNARC, 2005 limits	SF_1 550-650, SF_2 660-750, SF_3 760-850	$VS_1 \leq 2$, $VS_2 > 2$	$VF_1 \leq 8$, VF_2 9- 25	$PA_1 \geq 0.8$, $PA_2 \geq 0.8$	$SR_1 \leq 20$, $SR_2 \leq 15$

Fig. 2. Preparing and casting molds.

B. Hardening Properties of Self-Compacting Concrete

1) Oven Dry Density of Self-Compacting Concrete

This research uses a cube-shaped BF-reinforced SCC specimen with dimensions of 100 mm × 100 mm × 100 mm at 28 days, complying with ASTM C642-13 [31]. The oven-dry density results are shown in Table XIII and Figure 3. The findings indicate that including 0.2% volume fraction of fibers at $BF_{0.2}$ mix slightly increases the density of concrete specimens by 0.83% and the $BF_{0.4}$ to 1.29%, explained by the higher density of the BF relative to that of concrete [32]. However, in $BF_{0.6}$, fiber increase was followed by a 0.75% reduction in density, which can be attributed to the void formation caused by a decrease in workability [23, 33, 34].

TABLE II. OVEN DRY DENSITY(kg/m^3)

Mixes	At 28 days
M	2390
$BF_{0.2}$	2410
$BF_{0.4}$	2421
$BF_{0.6}$	2408

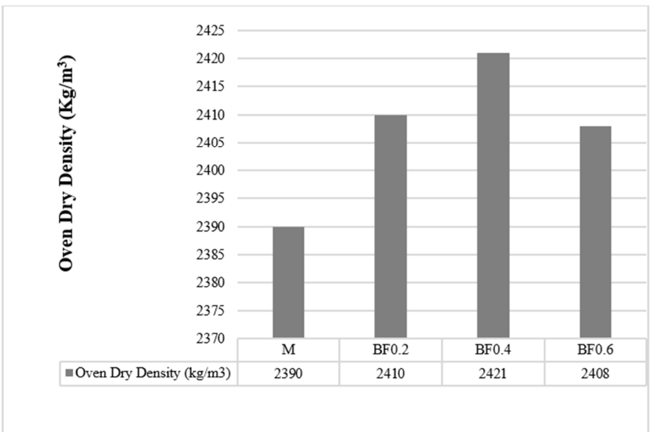

Fig. 3. Oven dry density of SCC.

A higher BF dosage results in an increase in the specific surface area, necessitating a greater quantity of mortar to ensure that the whole fiber surface is covered, maintaining a constant water-cement ratio [34]. This process leads to void formation, thereby increasing concrete porosity and decreasing density.

2) Water Absorption

The water absorption test was conducted according to ASTM C642-13 [31], using a cube sample of 100 mm × 100 mm × 100 mm, as shown in Table XIV and Figure 4. The high BF ratio exhibited a faster absorption rate than other available fibers [35]. The water absorption values of the $BF_{0.2}$, $BF_{0.4}$, and $BF_{0.6}$ specimens increased compared to those of the reference sample. The $BF_{0.6}$ specimen exhibited the highest water absorption value, 1.956%, which is 6.13% higher than that of the reference. This is due to the higher fiber ratios leading to an increase in concrete porosity and water absorption [36, 37].

TABLE III. ABSORPTION VALUE IN HARDENED SCC (%)

Mixes	At 28 days
M	1.843
$BF_{0.2}$	1.899
$BF_{0.4}$	1.914
$BF_{0.6}$	1.956

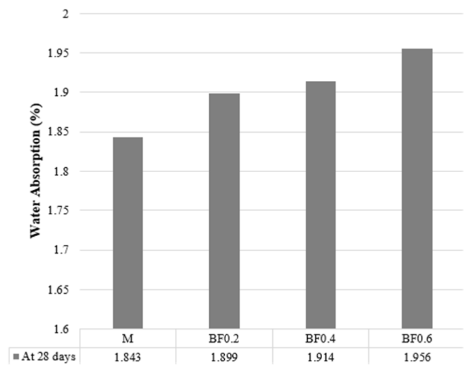

Fig. 4. Water absorption rate.

3) Thermal Conductivity

As portrayed in Table XV and Figures 5, 6, the relationship between thermal conductivity (K) and increasing fiber dosage is inverse [36, 38]. The K value ranges from 1.289 W/(m·K) to 0.913 W/(m·K). The highest reduction occurred at $BF_{0.6}$, with a 29.17% value compared to that of the reference specimen, due to the superior insulation features of the basalt material [38].

TABLE IV. THERMAL CONDUCTIVITY (W/m.K)

Design mix	At 28 days
M	1.289
$BF_{0.2}$	1.17
$BF_{0.4}$	1.061
$BF_{0.6}$	0.913

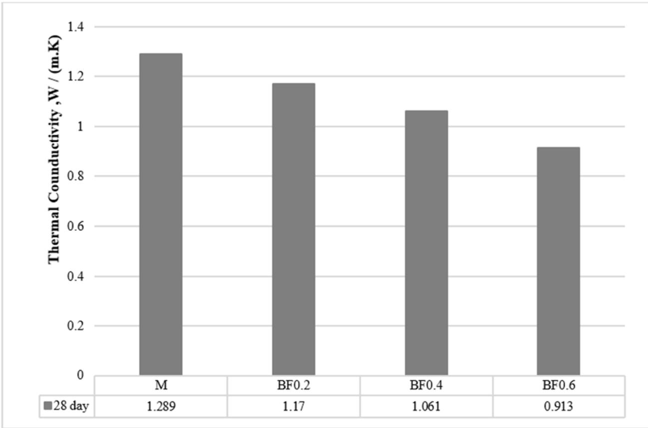

Fig. 5. Thermal conductivity.

Fig. 6. Thermal conductivity test.

4) Compressive Strength

The compressive strength of SCC cube samples (100 mm × 100 mm × 100 mm) was tested at 7, 28, and 56 days of curing according to BS EN 12390-3, 19 [39]. Table XVI and Figure 7 present the effect of various fiber dosages on compressive strength. The $BF_{0.4}$ specimen had the highest value, 62.92 MPa, which is approximately 10.13% higher than that of the reference concrete at 28 days. BF addition to the SCC increases the latter's compressive strength [40]. However, an excessive ratio reduces the compressive strength values by 5.46% in the $BF_{0.6}$ mix [23, 41, 42]. A reduction in concrete workability due to higher fiber dosage, generates difficulty in mixing and improper distribution, which is responsible for entrapped air, increasing SCC porosity and reducing compressive strength [43, 44].

5) Splitting Tensile Strength

The tensile strength test, which included preparing cylindrical specimens measuring 100 mm by 200 mm, was performed at 7, 28, and 56 days after curing. The procedure was conducted in accordance with the ASTM C496-2017 standard [45]. As illustrated in Table XVII and Figure 8, the tensile strength increased by 5.71% and 22.01% at 28 days for the $BF_{0.2}$ and $BF_{0.4}$ mixes, respectively, compared with the reference mixture. The maximum increase occurred when 0.6% BF was incorporated into the $BF_{0.6}$ mix, improving ductility by 27.05% at 28 days compared with the reference mixture, and strengthening the interaction between its surface and the SCC mortar [46].

TABLE V. COMPRESSIVE STRENGTH (MPa)

Design mix	At 7 days	At 28 days	At 56 days
M	42.9	57.13	63.41
$BF_{0.2}$	44.58	59.45	66.58
$BF_{0.4}$	47.19	62.92	68.84
$BF_{0.6}$	40.61	54.15	57.94

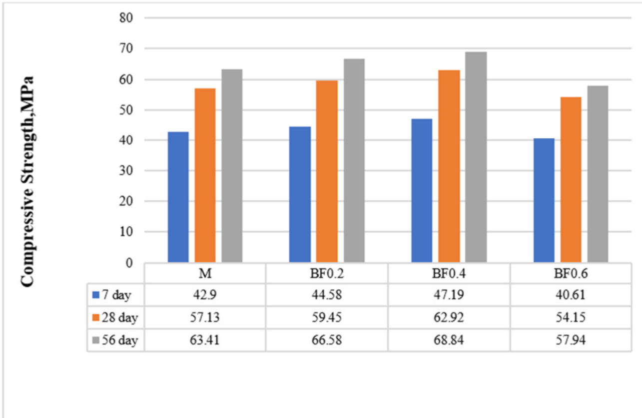

Fig. 7. Compressive strength results.

TABLE VI. SPLITTING TENSILE STRENGTH (MPa)

Design mix	At 7 days	At 28 days	At 56 days
M	4.47	5.95	6.59
$BF_{0.2}$	4.79	6.29	6.98
$BF_{0.4}$	5.46	7.26	7.98
$BF_{0.6}$	5.67	7.56	8.53

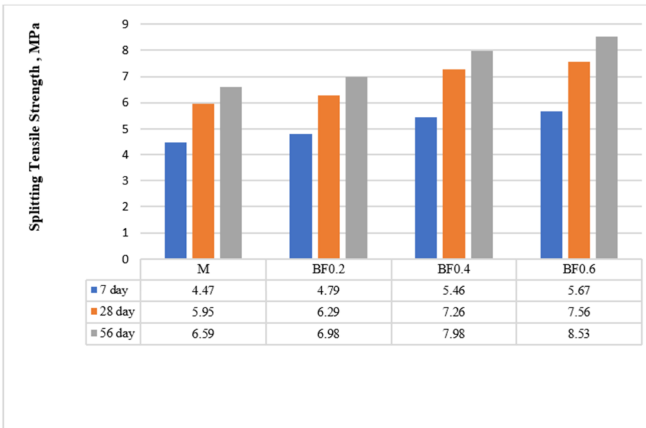

Fig. 8. Splitting tensile strength.

6) Flexural Strength

The test was performed according to ASTM C293/C293M-16 [47], using prism specimens measuring 75 mm × 75 mm × 380 mm. At room temperature, the results ranged from 7.14 MPa to 9.65 MPa, as shown in Table XVIII and Figure 9. The flexural strength rose with an increasing BF dosage in SCC mixes. The respective rates of increase were 8.26%, 28.29%, and 35.15% at 28 days for the $BF_{0.2}$, $BF_{0.4}$, and $BF_{0.6}$ mixes. The $BF_{0.6}$ specimen exhibited a maximum flexural strength improvement of 35.15% and 30.03% at 28 and 56 days, respectively, compared to the reference SCC specimen. This is due to the ability of BF to lower crack extension and retard their growth rate, which enhances the cohesion force between fibers and SCC (interfacial adhesion) [46].

TABLE VII. FLEXURAL STRENGTH (MPa)

Design mix	At 7 days	At 28 days	At 56 days
M	5.36	7.14	7.99
$BF_{0.2}$	5.79	7.73	8.49
$BF_{0.4}$	6.87	9.16	10.08
$BF_{0.6}$	7.24	9.65	10.39

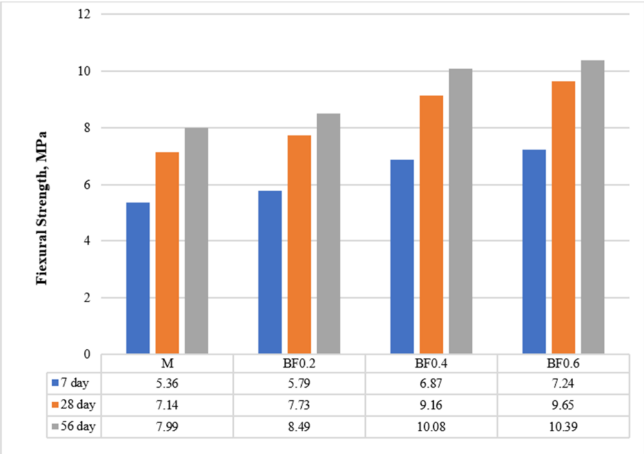

Fig. 9. Flexural strength.

IV. CONCLUSIONS

The primary objective of this experimental study is to examine the influence of Basalt Fibers (BFs) on rheological and mechanical properties of Self-Compacting Concrete (SCC). The experimental test findings led to the following conclusions:

- BF addition increased mixture density, with the highest value observed at 1.29% in $BF_{0.4}$ specimen. However, further addition beyond 0.6% BF resulted in a decrease in density.
- BF addition increases SCC water absorption; the $BF_{0.6}$ specimen had the highest water absorption ratio, at 6.13% of water.
- Thermal conductivity decreased due to the BF addition to the SCC.
- BF addition reduced the flowability properties of fresh SCC mixtures. The slump flow values of concrete decreased as the volume fraction of BF increased.
- Compressive strength improved by 10.13% in $BF_{0.4}$ specimen with BF usage.
- The most appropriate BF ratio was found in the $BF_{0.6}$ specimen, which demonstrated improvements of 27.05% and 29.44% in splitting tensile strength at 28 days, respectively, compared to the reference specimen.
- The acceptable BF ratio was determined in the $BF_{0.6}$ specimen, which demonstrated enhancements of 35.15% and 30.03% in flexural strength at 28 and 56 days, respectively.

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