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ORIGINAL ARTICLE

Flexural behavior of high-strength reinforced concrete beam with hybrid fiber under normal and high temperature

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Abstract: The low cost of basalt and steel fibers makes their use in enhancing concrete properties very attractive, this paper presents experimental research on the use of Basalt Fibers (BF) and Steel Fibers (SF) and their effect on compressive, tensile, and flexural behavior of reinforced concrete beams under normal and elevated temperatures. Nineteen beams, 114 cubes, and 114 cylinders were tested to find the optimum percentage of fibers. The percentages of BF used were 1%, 2%, and 3.5% by cement weight, while the percentages of SF were 0%, 0.5%, 1%, and 1.5%. Heated samples were subjected to 600 ℃ for 3 hours and left to cool off naturally before testing. The test results show that using BF and SF significantly increased the tensile strength of unheated cylinders, with the optimum fiber content of 1% BF - 1.5% SF achieving an increase of 163% over the control. For heated cylinders, the optimum fiber content was (2% BF - 1.5% SF) achieving an increase of 175%. For compressive strength, enhancement was more modest for most of the fiber content ratios used, and the optimum mix of (1% BF - 1% SF) achieved an enhancement for unheated and heated conditions of 27% and 44%, respectively. Flexural results show that beams employing a mix of 2% BF and 1% SF yielded the most favorable result at normal temperature, enhancing the capacity by 27% compared to the control. While at high temperatures, using an optimum mix of 1% BF and 1.5% SF achieved a 27.2% increase compared to control. The use of BF and SF in concrete has also been proven to increase the ductility of the beams and has moved the failure mode from shear to flexural failure.

Keywords: Flexural behavior; Reinforced Concrete (RC) beams; Steel Fibers (SF), Basalt Fibers (BF); Fiber Reinforced Concrete (FRC); Elevated temperatures.

1 Introduction

Concrete is the world’s most popular building material due to its affordability, durability, and versatility, however, it is much weaker in tensile strength. Researchers have explored adding reinforcing fibers to improve concrete properties, which include two types of fibers available: organic and inorganic. Adding fibers to concrete improves its mechanical properties, such as bending, tensile, and fatigue forces. This enhancement of concrete's toughness, ductility, and nonlinear behavior has been

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demonstrated in various studies [1-4]. By increasing the crushing capacity of structural components and preventing micro-cracks from forming, fibers enhance the overall integrity of the concrete structure.

Basalt, an igneous rock formed from volcanic lava, has emerged as a strong contender for use as a composite fiber reinforcement due to its inorganic and natural composition, high strength, thermal resistance, low environmental impact, and affordability.

The production of Basalt Fibers (BF) involves the extrusion of molten basalt heated to approximately 1500 ℃ and then formed into continuous or chopped fibers. In many ways, the manufacturing process for BF is comparable to that used for glass fiber [5, 6].

When it comes to reinforcing concrete using fiber additives, Steel Fiber (SF) is a conventional and popular choice. Studies have shown that adding SF to concrete can improve its strength, durability, and resistance to cracking, as well as make it more flexible and ductile before failure [7]. While steel has traditionally been used for reinforcement, fibers offer a different approach. These thin, short pieces of steel are randomly placed throughout the concrete, rather than concentrated in specific areas like traditional bars. While this random distribution may reduce efficiency, the fibers still improve the concrete's tensile qualities and help with crack management. For best results, combining fiber reinforcement with traditional steel reinforcement is often recommended [8]. Adding SF to High Strength Concrete (HSC) beams can significantly increase their strength [9]. Hybrid use of different fiber types is a recent and popular approach that has garnered significant attention. By combining different types of fibers at specific ratios, a hybrid composite can be created that benefits from each of the original fibers and displays better results than using each type separately [10]. For instance, incorporating a high-strength synthetic fiber like Polyethylene fibers, BF, or SF into concrete can improve its HSC tensile behavior [11].

Another area of concern is concrete durability, which is a crucial factor irrespective of its compressive strength, as durability issues create more problems than insufficient strength [12]. Concrete's ability to resist chemical attacks, abrasion, weathering, or any other form of wear and maintain its original shape and functionality when exposed to the environment determines its durability. Achieving durable concrete requires meticulous design, proportioning, placement, finishing, testing, inspection, and curing [13]. Elevated temperatures due to fires can cause a range of effects on concrete, including dehydration of the cement paste, loss of durability, and structural cracking. To ensure concrete structures can withstand fires, it is important to study the behavior of newer reinforcement techniques under these conditions. A recent study by Khan et al [14] found that adding BF of various lengths and contents significantly improved the fracture and compressive characteristics of hybrid fiber-reinforced concrete. Shorter fibers of 12 and 25 mm had a bigger influence on the properties compared to longer fibers of 37 and 50 mm. The study concluded that adding multi-scale fibers led to high-quality concrete with superior properties.

Khan et al also found in a different study [15] that adding BF to a hybrid fiber concrete composite improved its toughness, specific toughness, stress-strain response, elastic modulus, peak strain, peak stress, and ultimate strain at 850 ℃ and normal temperature. Bheel et al [16] found that adding BF changes the properties of concrete, where workability decreases as the quantity and length of fibers increase due to reduced liquidity caused by water absorption. Alnahhal et al [17] conducted a study on the effects of incorporating recycled concrete aggregates (RCA) leftover from demolition and construction combined with BF in RC beams. The study found that BF improved the beams' flexural capacity, while RCA had no significant impact on the beams' flexural strength.

Two independent studies by Hannawi et al and Sadrmomtazi et al [18, 19] were conducted on the effects of fiber and silica fume addition on cementitious composites. The first study focused on the impact of different types of fibers on microstructure and mechanical properties and found that SF increased strength due to its stiffness, but the effect on elastic modulus and compressive strength was small by other types of fibers. The second study showed that BF improved toughness and flexural strengt, but decreased compressive strength, while silica fume enhanced bond quality and mechanical strength.

Afroughsabet et al [20] conducted a study to examine the effects of adding polypropylene fibers and steel on HSC. The study utilized different fiber volume fractions and found that adding silica fume and fibers improved the durability and mechanical characteristics of the concrete mixes. The study also found that adding 1% SF significantly improved the concrete's flexural and splitting tensile strength. In another study by Santarelli et al [21], the impact of three types of BF on compressive strength and water absorption of fiber-reinforced mortars was examined. Results showed that the type of matrix and BF used had a significant impact on the performance of the mortars. The study highlighted the importance of optimizing the surface treatment and fiber concentration for masonry repair.

Jiang et al [22] found that adding BF to concrete improves flexural strength, tensile strength, and toughness index. The study showed that the mixture with 0.3% BF by volume had the highest flexural and tensile strength. Results show that BF of 22mm in length had the highest toughness enhancement capacity efficiency.

To examine the use of more than one type of fiber, a study by Larsen et al [23] examined various fiber types and found that fibers could increase HSC's tensile strength. However, the effect varies depending on fiber type, amount, and hybridization. The study suggests that the choice of ideal fiber type is more likely to be influenced by the fiber volume percentage. Another study by Banerji et al [24] investigated the behavior of HSC beams under structural loads and fire exposure. The study found that the beams were susceptible to catastrophic spalling in the compression zone, but the inclusion of polypropylene fibers reduced fire-induced spalling and increased fire resistance. Thanaraj et al [25] conducted an experimental study to investigate the impact of various parameters on the structural behavior of RC beams under the ISO standard fire curve of different strength grades. The study found that lower grade concretes suffer greater damage from fires up to 120 minutes where the reduction in moment of resistance and yield strength were 56% and 40%, respectively, but for 180–240-minute fires, the difference in moment of resistance and yield strength loss between lower strength and higher strength concretes is minimal. In the same vein, Kodur et al [26] tested five different types of reinforced concrete columns to determine their fire resistance and found that normal-strength concrete has more fire resistance than HSC. Polypropylene fibers and carbonate aggregates can be used to increase fire resistance in concrete columns.

Basalt fiber reinforcement has shown promise in improving the mechanical properties and performance of RCA. Zhang et al. [27] proposed using Basalt Fiber-Reinforced Recycled Aggregate Concrete (BFRRAC) to fill tubular square steel columns, combining the modification methods of steel tube and fiber reinforcement to enhance RCA mechanical properties. Their axial compression tests on BFRRAC-filled columns with varying recycled coarse aggregate replacement ratios and basalt fiber contents demonstrated that while the peak load was not significantly affected, the ductility coefficients and dissipation factor increased by 5.6% and 10.2%, respectively, with the addition of 4 kg/m3 of basalt fibers.

In a separate study, Hassan et al. [28] investigated the use of basalt fiber reinforced polymer (BFRP) bars to improve the shear strength of concrete haunched beams with varying tapered angles. They found a direct relationship between expanding tapered angles and enhanced shear capacity. The promising results from these studies indicate that basalt fiber reinforcement, whether in the form of discrete fibers or continuous bars, has the potential to mitigate performance weaknesses of RAC and enable its expanded use in structural applications.

The existing literature highlights the benefits of using fiber reinforcements, such as steel and basalt fibers, to improve concrete's mechanical properties, fire resistance, and durability. However, gaps remain in understanding concrete's behavior and the flexural performance of RC beams exposed to high temperature.

This study aims to address these gaps by investigating the combined effects of different fiber types on the flexural response of high-strength concrete beams under both normal and elevated temperature conditions. This research can provide valuable insights for the design and performance of concrete structures exposed to high temperatures, an area that requires further exploration through experimental, analytical, and field-based studies.

2 Structure

2.1 Concrete Formulations and Materials

Type I cement was used in the HSC mixes complying with EN 197-1-2011 standards [29], the specific gravity of cement was 3.15 g/cm3. **Table 1** shows the cement chemical properties.

Table 1. Properties of cement

Chemical Composition	By Mass%
SiO_2	20.41
Al_2O_3	4.51
Fe_2O_3	3.43
CaO	64.74
MgO	1.99
SO_3	2.9
K_2O	0.52
C_3A	7.5

Aggregate selection was per the ASTM C33/C33M-16 standard [30] and was supplied locally. For the coarse aggregate, limestone was utilized with a maximum size of 15.5 mm (5/8 in.) and retained on sieve No. 4 (4.75 mm). **Table 2** provides details about the coarse aggregate properties. Fine aggregate consisted of silica sand with an average size of 0-3 mm and limestone with an average size of 3-6 mm. **Table 3** summarizes the properties of the fine aggregate.

Table 2. Coarse aggregate properties

Property	Limestone Coarse Aggregate (I)
Specific gravity of saturated surface dry aggregate (SSD)	2.66
Specific gravity of oven-dried aggregate (OD)	2.63
Water Absorption	1.3%
Bulk Density	1460(kg/m^3)

Table 3. Fine aggregate properties

Property	Limestone Coarse Aggregate (I)	Silica Sand Fine Aggregate (I)
Specific gravity of saturated surface dry aggregate (SSD)	2.66	2.62
Specific gravity of oven-dried aggregate (OD)	2.63	2.61
Water Absorption	1.3%	0.2%
Bulk Density	1460(kg/m^3)	1370(kg/m^3)

Grade 60 reinforcement steel bars with a yield stress of 420 MPa were employed. Longitudinal steel reinforcement was used with diameters of 12 and 10 mm, while 8 mm diameter stirrups were used.

To achieve high strength for concrete mixes, Hyperplast superplasticizer was utilized. This product is based on polycarboxylic polymers supplied by DCP Company and conforms to [31]. Specific gravity of the Hyperplast PC 7110 liquid was 1.1 ± 0.1.

Fig. 1. Basalt fibers.

The US-based company Globmarble provided the high-performance basalt fibers, the BF used in this study was 24mm in length, as shown in **Fig. 1**, and its properties are outlined in **Table 4**.

Table 4. Characteristics of Basalt Fibers

Shape	Straight
Density	2.67(g/cm^3)
Chopped Length	24 mm
Diameter	16 microns
Color	Dark grey/Smoked
Melting Temperature	1450 ℃
Moisture Content	≤0.2 ℃
Elongation	≥1.5%
Elastic modulus	≥65GPa

Corrugated and flattened wire fiber was used in this study as steel fibers, Dramix 3D 45/50 BL, which was supplied by the company BEKAERT, conforming to various standards such as ASTM A820, EN 14889-1, ISO 9001, and ISO 14001 [32-34]. **Fig. 2** shows the shape of the SF used, while **Table 5** details their properties.

Fig. 2. Steel fibers.

Table 5. Properties of steel fibers

Shape of Fiber	Hooked end
Density	7.85(g/cm^3)
Length	50 mm
Diameter	1.05 mm
Aspect Ratio	45
Tensile Strength	1115 MPa
Young's Modulus	200 GPa
Strain at Ultimate Strength	0.8%

After experimenting with various ratios of cement, fine aggregate, and coarse aggregate to achieve compressive strengths of 60 MPa after 28 days, the water/cement ratio for the mixture was set at 0.39 and the proportions specified in **Table 6** were deemed suitable. Thirteen mixes, each containing different ratios of basalt and steel fiber, were meticulously prepared.

Table 6. Concrete mix design

Components	Over dry weight
Cement	510 kg/m^3
Limestone Aggregate (Coarse)	866.7 kg/m^3
Limestone Fine Aggregate (II)	489 kg/m^3
Fine Silica Sand Aggregate (I)	467 kg/m^3
Absorbed Water in Aggregate	199 kg/m^3
Superplasticizer (PC 711)	7 kg/m^3
W/C (Total)	0.39
Total Aggregate	1822.7 kg/m^3
Aggregate/Cement ratio	3.57
Steel fiber	39 kg/m^3

2.2 Test Specimens

Beams were designed per ACI 318-19 [35] equations for flexural failure as detailed in **Fig. 3**. A drum mixer was used to mix the ingredients, and concrete was cast into the beam molds and cylinders, and an electric vibrator was used to ensure adequate compaction, according to [36], and as shown in **Fig. 4**. Water immersion was used to cure the cylinders for 28 days (at 20 ℃ ±2 ℃), while wetted burlap was used to cure the beams for the same period.

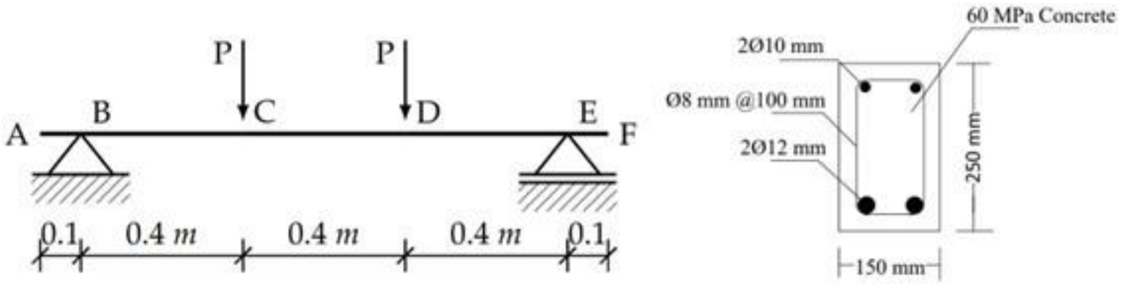


Fig. 3. Beam details.

Fig. 4. Beam construction.

Table 7. Test matrix and sample designation.

Group	Mix	Mix Details	Beam Designation	Temperature
B-Control	Mix 1	Control	B1	Heated
		Control	B2	Unheated
B-0%	Mix 2	1%BF	B3	Heated
		1%BF	B4	Unheated
	Mix 3	2%BF	B5	Heated
		2%BF	B6	Unheated
	Mix 4	3.5%BF	B7	Heated
		3.5%BF	B8	Unheated
B-0.5%	Mix 5	1%BF 0.5%SF	B9	Heated
	Mix 6	2%BF 0.5%SF	B10	Unheated
		2%BF 0.5%SF	B11	Heated
	Mix 7	3.5%BF 0.5%SF	B12	Heated
B-1%	Mix 8	1%BF 1%SF	B13	Heated
	Mix 9	2%BF 1%SF	B14	Unheated
		2%BF 1%SF	B15	Heated
	Mix 10	3.5%BF 1%SF	B16	Heated
B-1.5%	Mix 11	1%BF 1.5%SF	B17	Heated
	Mix 12	2%BF 1.5%SF	B18	Unheated
		2%BF 1.5%SF	B19	Heated

Note: Letter **B** denotes the percentage of basalt fibers.

A total of 19 beams, 114 cubes (150×150×150 mm), and 114 cylinders (H: 300 mm, D: 150 mm) were tested. Utilizing ratios of only BF (1%, 2%, 3.5%), and several containing hybrid fibers (a combination of basalt and steel). The beams were classified into five groups based on the SF ratios in the HSC mixtures. Each group contained varying percentages of fiber types. **Table 7** details each group of specimens and its designation.

2.3 Heat Treatment

To examine the mechanical properties of HSC mixes with and without fibers, exposed to temperatures ranging from 23 ℃ to 600 ℃. The samples, consisting of beams, cubes, and cylinders, are heated in an electric furnace (L=2.2m, W=1.8m, H=0.8m) as shown in **Fig. 5**. After reaching the required temperature (600 ℃) at a rate of 1.67 ℃/min, the samples were kept there for three hours before being gradually cooled to room temperature.

Fig. 5. Heat treatment using an electric furnace.

2.4 Test Setup

To determine splitting tensile and compressive strength, six cylinders and six cubes were tested using a 4000 kN hydraulic semi-automated testing setup, the loading rate used was 0.60 MPa/sec, adhering to [37] as shown in **Fig. 6**.

The splitting tensile test for the cylinders was conducted by placing the specimen horizontally in the test setup then applying loading at a constant rate until failure, recording the failure load.

Fig. 6. Compression and tensile test setup.

Fig. 7. Flexural test setup.

Additionally, the four-point flexural strength test was conducted on the beam samples using a hydraulic jack machine (depicted in **Fig. 6**). The loading rate was a constant 3 kN/s, as per [38]. Linear Variable Displacement Transducers (LVDTs) were installed at midspan to record the load-displacement data using the machine's logger.

3 Results and Discussions

3.1 Compressive Strength

According to the results presented in **Fig. 8**, the 28-day compressive strength of the control mix at normal temperature was 53.3 MPa, and specimens not containing SF with 1% BF was 56 MPa, while the 2% and 3.5% achieved lower capacity at 52.2 and 51.2 MPa. For the hybrid mixes containing varying percentages of SF and BF, the highest strength was achieved by the 1% SF - 1% BF mix at 71.7 MPa, while the lowest result was achieved by the 1% SF - 2% BF at 45.6 MPa. Kizilkanat et al [39] found that for BF at 0.50% dosage, the increase in strength was 5.1%, Ayub et al [40] found that the addition of 1% BF to HSC increased the strength by only 3% and decreased after 2% BF, where 0.50% SF inclusion resulted in 7.1% increase in strength [41]. Dawood et al [42] showed that the use of 1.0 % of SF increases the compressive strength by about 13%. High et al [43] observed that the addition of BF increased the compressive strength at 28 days slightly. Wang et al [44] found using hybrid fiber of BF content (0.15%) and polypropylene fiber content (0.033%) increases the compressive strength by 14%. While the mix with ternary fibers yielded a 14% increase in compressive strength as well [45].

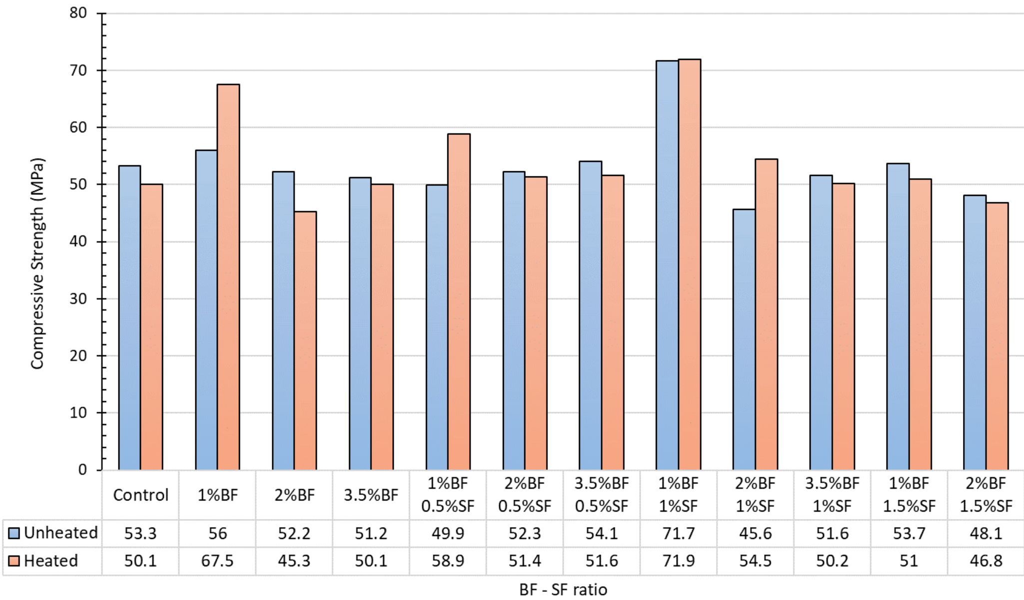


Fig. 8. Compressive test results.

At elevated temperatures (600 °C), the heated control mix achieved a compressive strength of 50.1 MPa (a 6% decrease compared to the unheated control). The mixes containing only 1% BF achieved 67.5 MPa (a 26% increase over the heated control), while 2% BF achieved the lowest strength value of all mixes heated or unheated at 45.3 MPa, and 3.5% BF achieved 50.1 MPa. In a study by Mubarak et al [46] it was found that exposure to high temperatures (800 ℃), the residual compressive strength with 1% steel fiber was 15%. In contrast, long PP fiber demonstrated notably superior strength.

Hybrid mixes containing SF and BF and subjected to heat varied significantly, where the 1% SF - 1% BF mix again achieved the highest strength capacity under heated conditions at 71.9 MPa (a 39% increase compared to heated control), and the 1.5% SF - 2% BF mix achieved the lowest result at 46.8 MPa. Hussein et al. [47] found that the greatest increase in compressive strength was achieved with a hybridization ratio of 70% steel fibers and 30% polypropylene fibers, resulting in an increase of 14.54%. 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 [48].

The observed variations in compressive strength of concrete incorporating BF at elevated temperatures can be attributed to several interrelated factors. At lower BF contents, such as 1% BF, the fibers may enhance the concrete matrix's structural integrity, leading to improved load-bearing capacity even at high temperatures. This enhancement is likely due to the fibers' ability to bridge cracks and improve the overall ductility of the concrete, which can help maintain strength under thermal stress. However, as the BF content increases to 2% and 3.5%, the concrete's performance appears to decline at high temperatures. This phenomenon may be linked to the increased brittleness and reduced workability of the mix, which can lead to inadequate bonding between the fibers and the cement matrix. Additionally, at elevated temperatures, the thermal degradation of the fibers and the potential for microcracking within the concrete can result in a loss of compressive strength.

In general, it can be observed that all concrete mixes experienced compressive strength reduction with increasing BF percentage at the same SF content, where it can be concluded that 1% BF is the optimum percentage for basalt fibers. As for the SF, the optimum percentage was 1% SF which achieved better results than both 0.5% and 1.5%. It is noteworthy that all concrete mixes generally exhibited a compressive strength close to or exceeding control in heated and unheated conditions with few exceptions such as the 1.5% SF - 2% BF mix, which confirms the feasibility of using SF and BF in reinforced concrete.

3.2 Tensile Strength

Splitting tensile test results at normal temperatures shown in **Fig. 9** describes the effect of various SF - BF percentages, where samples utilizing 0% SF combined with 1%, 2%, and 3.5% BF achieved similar (within 5%) tensile capacity compared to control (which achieved 3.76 MPa). Increasing the SF percentage to 0.5% increased the strength by 24.9% for 1% BF, 36.7% for 2% BF, and 41.5% for 3.5% BF compared to control. At 1% SF, a similar pattern appeared where increasing the BF percentage increased the strength by 143.5%, 83%, and 148.1% while using 1.5% SF increased the strength by 163.3% for 1% BF and 132.7% for 2% BF. Kizilkanat et al [39] observed that the highest splitting tensile strength achieved with BF occurred at a fiber inclusion rate of 1%, reaching 40%. According to Jiang et al [22], the rise in BF content correlated with a boost in the splitting tensile strength of concrete, reaching approximately 24%. This enhancement was credited to the fibers' bridging effect, which curbed the spread of microcracks primarily during their formation. In their study, Mubarak et al [46] discovered a substantial 105% increase in the split tensile strength of concrete with the addition of steel fibers compared to the control sample. This improvement was credited to the anchoring effect provided by the triple-end hooks, which elevated the bond strength of the fibers, consequently boosting the concrete's tensile strength.

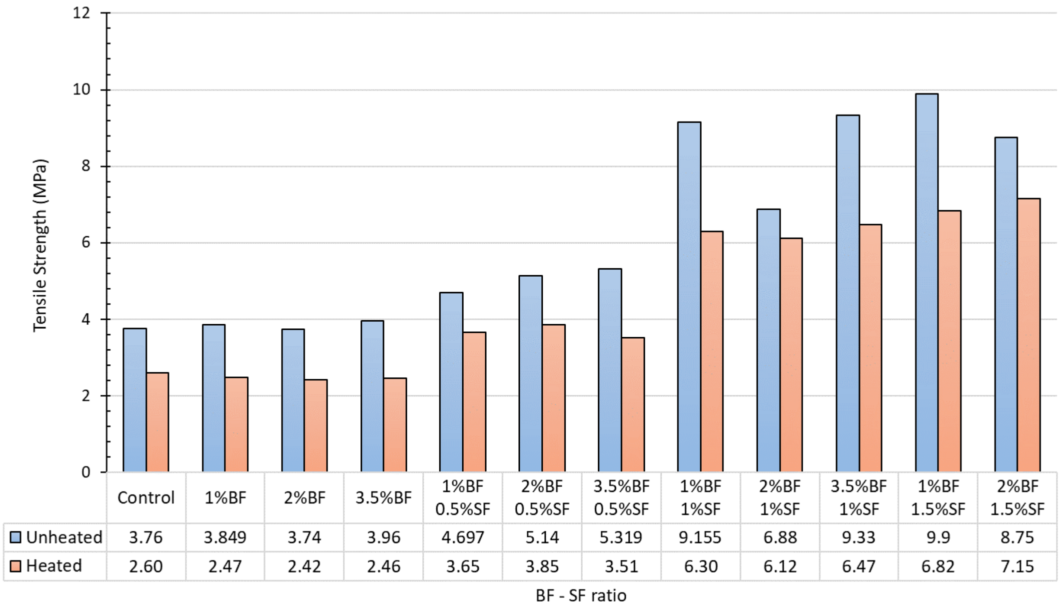


Fig. 9. Tensile strength results.

For heated specimens, the control achieved a tensile strength of 2.6 MPa (a 30% reduction compared to the unheated control). At 0% SF, the various BF percentages achieved a similar reduction of strength compared to the heated control of about 5-6%. Increasing SF to 0.5% increased strength by 40.7% (1% BF), 48.2% (2% BF), and 35.2% (3.5% BF) compared to heated control. At 1% SF, the strength increased substantially, 142.6% for 1% BF, 135.5% at 2% BF, and 149% for 3.5% BF, and at 1.5% SF, the strength increased even more compared to control by 162.8% (1% BF) and 175.4% (2% BF). Mubarak et al [46] found that the residual splitting strength was 26% at a high temperature of 800 °C. Wang et al [44] found that in HPC when the basalt fiber content is 0.15% and polypropylene fiber content is 0.033%, simultaneously splitting tensile strength increased by 14.1% and 22.8%.

Based on these results, it can be deduced that increasing the SF percentage increased the tensile strength of heated or unheated concrete regardless of the BF percentage. Increasing the BF percentage at the same SF level generally increased the strength, with the notable exception of 2% BF in unheated concrete. The tensile strength gains by incorporating SF and BF in concrete were higher than in compressive strength. This is likely due to the bridging effect provided by the fibers [39], which helps transfer stresses across cracks in the concrete. Concrete is much weaker in tension than compression, and the high-tensile strength and bridging action of fibers like SF and BF have a more appreciable effect on tensile strength compared to compressive strength [40].

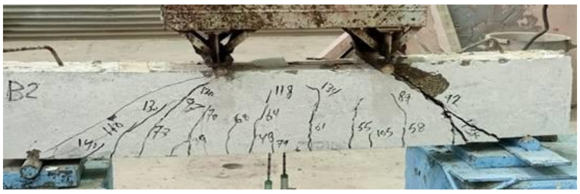
3.3 Flexural Strength of RC Beams

Flexural capacity results are summarized in **Table 8**, while the crack pattern, failure mode, and load-deflection curves are shown in **Fig. 10** to **15**.

Table 8. Flexural results

Specimen	Treatment	Temperature	Pu (KN)	ΔU (mm)	Enhancement ratio %	First crack	Failure mode
B1	Control	Heated	147	8.94	–	33	Shear & Flexural
B2	Control	Unheated	160.1	13.9	–	39	Shear
B3	1%BF	Heated	176.5	21.01	20%	45	Flexural
B4	1%BF	Unheated	170.9	5.69	6.8%	42	Shear
B5	2%BF	Heated	149.7	13.92	1.9%	40	Shear
B6	2%BF	Unheated	157.7	22.67	-1.5%	48	Flexural
B7	3.5%BF	Heated	145.8	15.76	-0.8%	45	Shear & Flexural
B8	3.5%BF	Unheated	154.2	13.50	-3.7%	56	Shear & Flexural
B9	1%BF 0.5%SF	Heated	164.6	26.07	12.1%	50	Flexural
B10	2%BF 0.5%SF	Unheated	167.6	22.33	4.7%	56	Flexural
B11	2%BF 0.5%SF	Heated	163.7	19.12	11.4%	45	Flexural
B12	3.5%BF 0.5%SF	Heated	175.1	31.23	19.1%	38	Flexural
B13	1%BF 1%SF	Heated	162.4	20.85	10.4%	54	Flexural
B14	2%BF 1%SF	Unheated	203.7	27.24	27.3%	40	Flexural
B15	2%BF 1%SF	Heated	173.2	34.85	17.9%	50	Flexural
B16	3.5%BF 1%SF	Heated	166.3	20.85	13.9%	70	Flexural
B17	1%BF 1.5%SF	Heated	187.1	33.21	27.2%	43	Flexural
B18	2%BF 1.5%SF	Unheated	189.4	8.104	18.3%	65	Flexural
B19	2%BF 1.5%SF	Heated	165.8	20.80	12.8%	68	Flexural

(a) B1



(b) B2

(c) B3

(d) B4

(e) B5

(f) B6

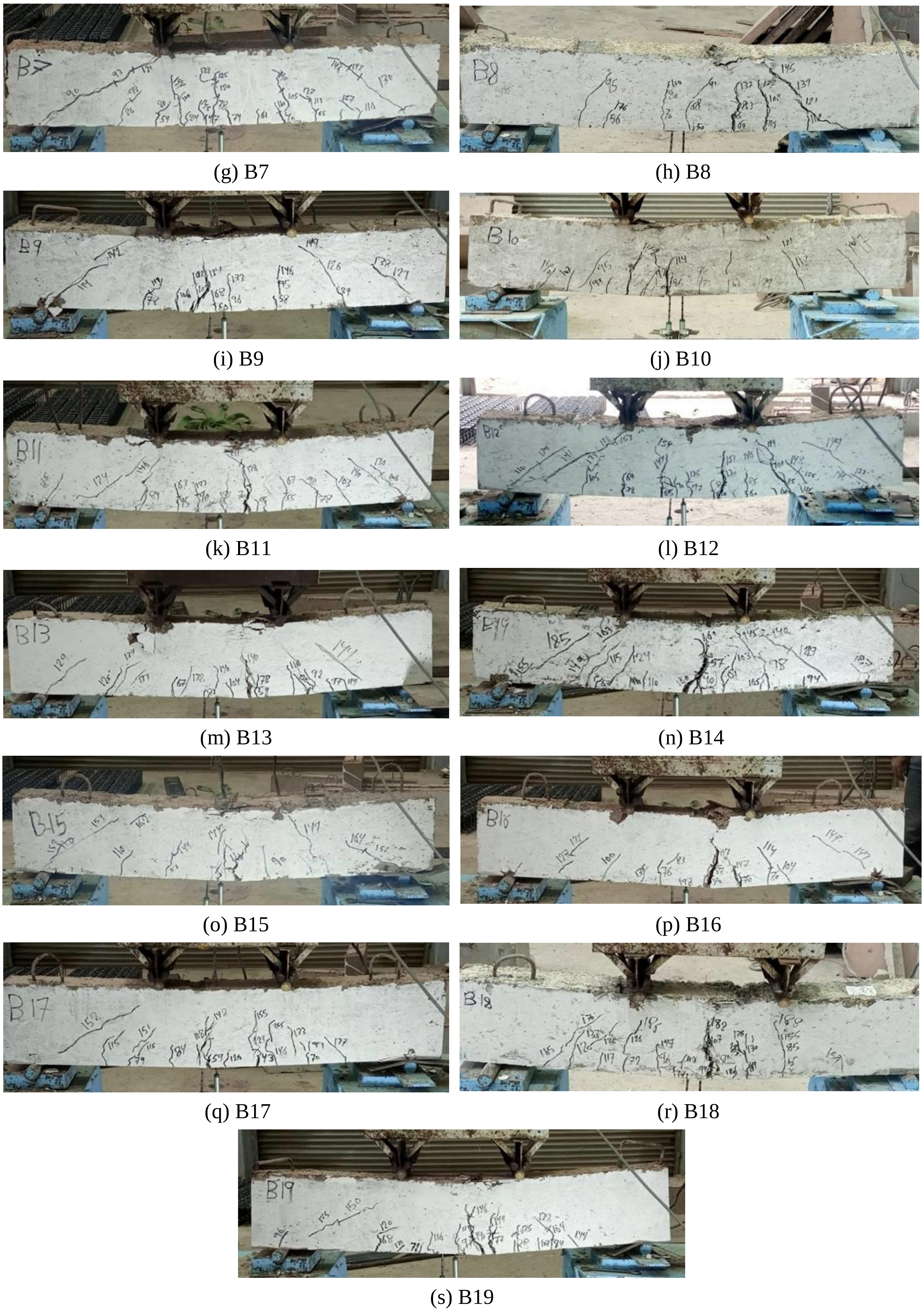


Fig. 10. Beams after flexural testing.

Results for beams tested under normal temperatures are summarized in **Fig. 16**, the sample containing only 1% BF (B4) achieved an ultimate load of 170.9 kN, enhancing the flexural strength by 6.8% compared to the unheated control (at 160.1 kN), while B6 (2% BF), and B8 (3.5% BF) achieved 1.5% and 3.7% lower capacity compared to control, respectively. In this experimental study, the reinforced beam B4 (1% BF) exhibited the most notable strengthening outcomes, demonstrating an enhancement ratio of 6.75% at ambient temperature. Mertol et al [49] found that the use of SFRC increases the ultimate load of the beams by up to 18% compared to that of control specimens, depending on the steel ratio. Biolzi et al. [9] found that incorporating SF into high-performance concrete beams significantly enhances both shear and bending strength. In their tests, they suggested that SF could serve as an alternative to traditional shear reinforcement at a volume of 1%. Yoo et al [50] found that the flexural strength capacity increased with increasing steel fiber content and concrete strength, at 1%steel fiber the increase in flexural strength for HSC was 20%.

For hybrid fiber use of BF and SF at a fixed 2% BF and three percentages of SF (0.5%, 1%, and 1.5% SF), results show that using 0.5% SF achieved a flexural capacity of 167.6 (a 4.7% increase over control). Increasing the SF to 1% increased the capacity to 203.7 kN (27% over control) but increasing the SF percentage again to 1.5% did not increase the strength again, achieving 189.4 kN (18.3% over control).

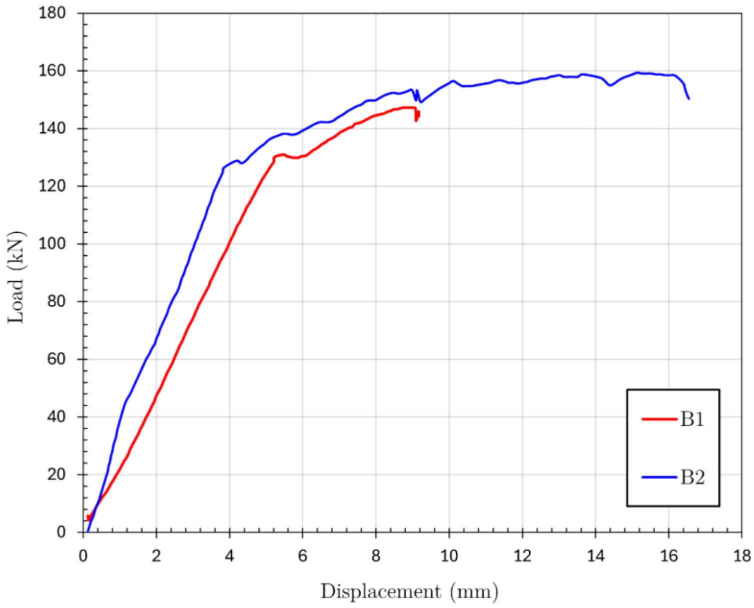


Fig. 11. Load-displacement of heated and unheated controls.

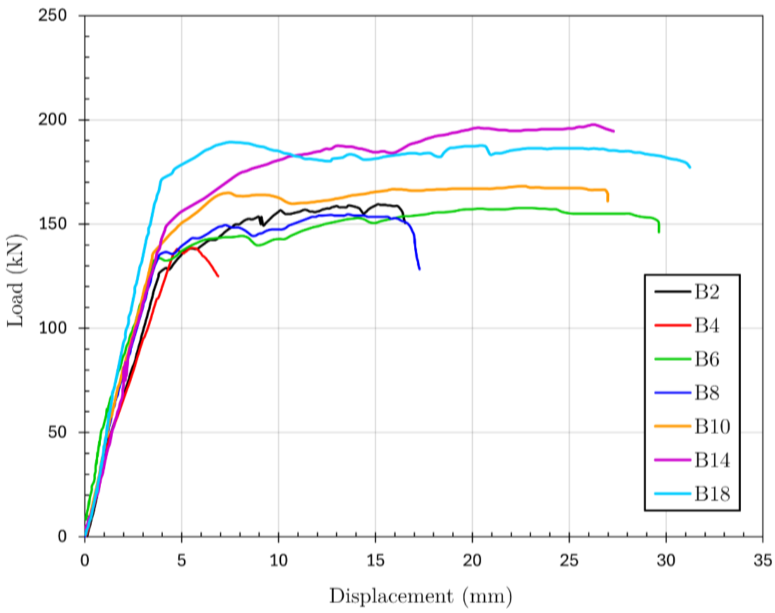


Fig. 12. Load-displacement of unheated beams.

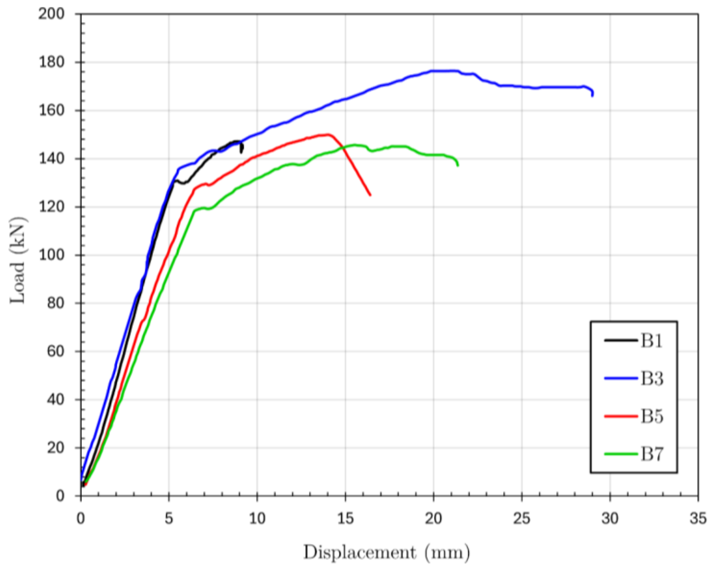


Fig. 13. Load-displacement of heated beams reinforced with BF.

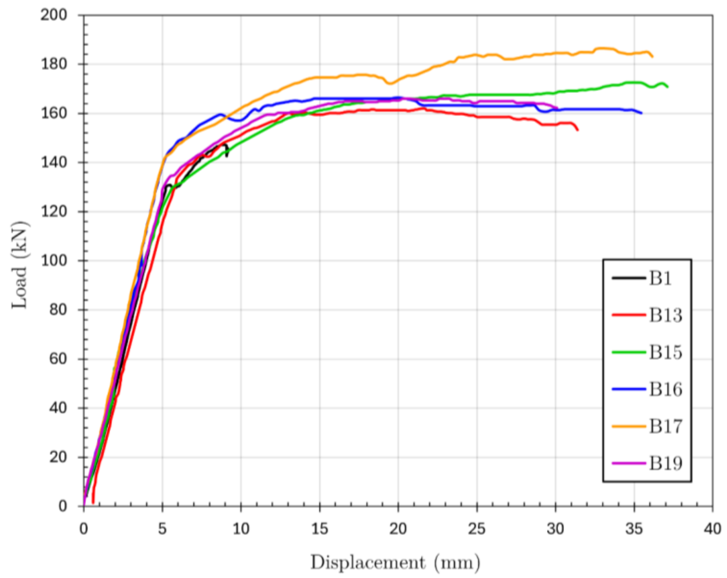


Fig. 14. Load-displacement of heated beams reinforced with SF and BF.

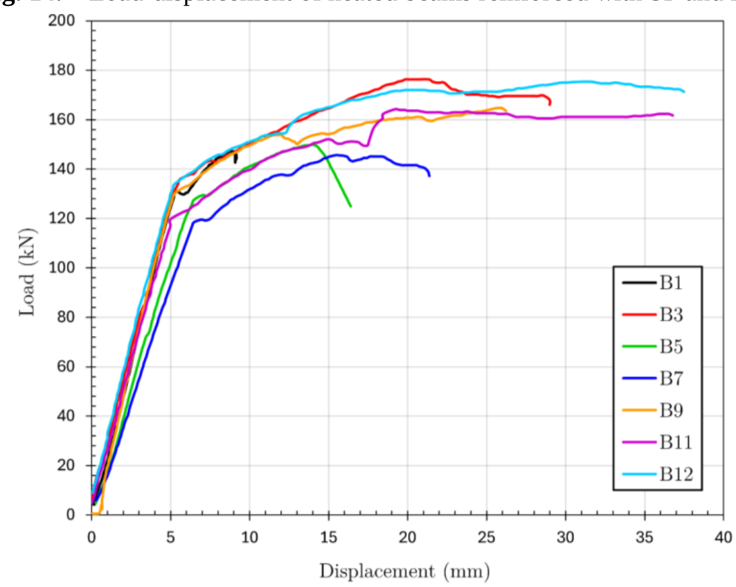


Fig. 15. Load-displacement of heated beams reinforced with SF and BF.

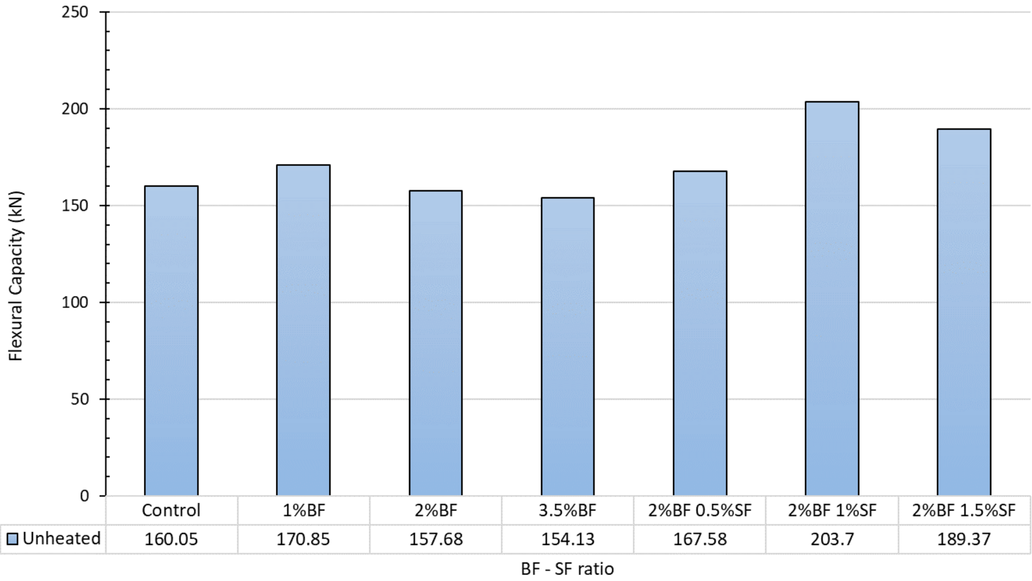


Fig. 16. Flexural capacity of beams under normal temperature.

Flexural results at normal temperatures show that using a 2% BF and 1% SF mix achieved the best results enhancing the capacity by 27% over control. It can be observed that using solely BF to reinforce the beams resulted in a reduced capacity as the BF percentage increased. Using hybrid fiber with basalt fiber content of 0.15% and polypropylene fiber content of 0.033% increases the flexural strength of plain concrete by 22.8% [44]. Mubarak et al [46] found that mixing with ternary fibers yielded an increase in flexural strength of plain concrete by 43.66%–22.16%.

The observed decrease in flexural capacity of RC beams with increasing BF content at normal temperatures can be attributed to several factors. As the BF percentage increases, the concrete matrix becomes more densely packed with fibers, which can lead to a reduction in workability and compaction. This can result in the formation of voids and air pockets within the concrete, particularly around the fibers, leading to a weakened interfacial transition zone (ITZ) between the fibers and the cement paste. The reduced ITZ strength can compromise the load transfer mechanism, limiting the fibers' ability to effectively bridge cracks and enhance the flexural performance of the beams. Additionally, the increased fiber content may cause fiber balling or clumping, leading to uneven fiber distribution and stress concentrations within the concrete. This uneven distribution can create localized weak points, further reducing the flexural capacity of the beams.

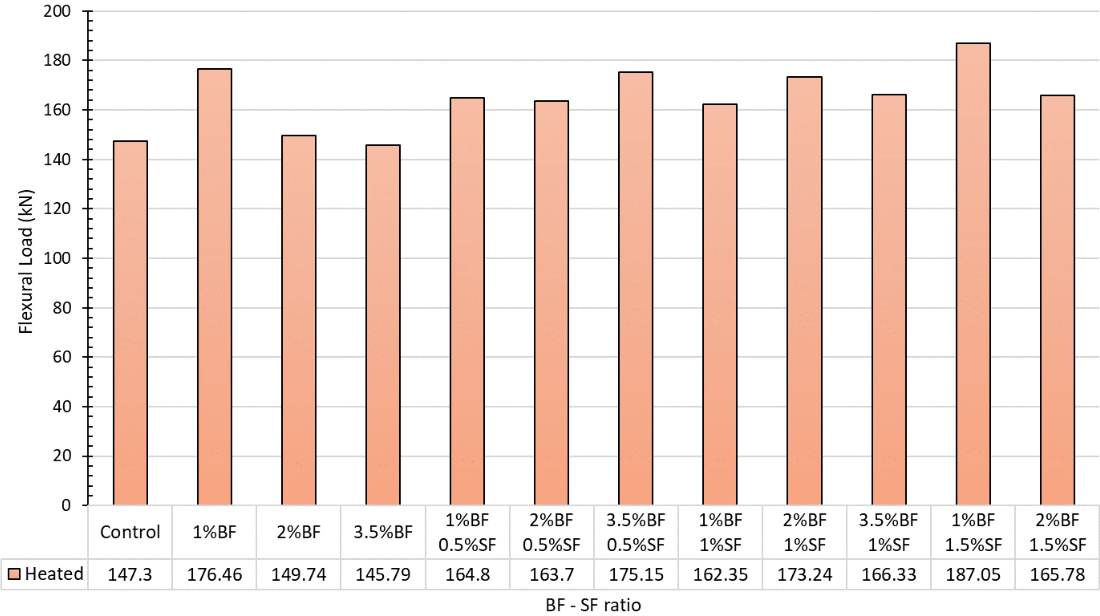


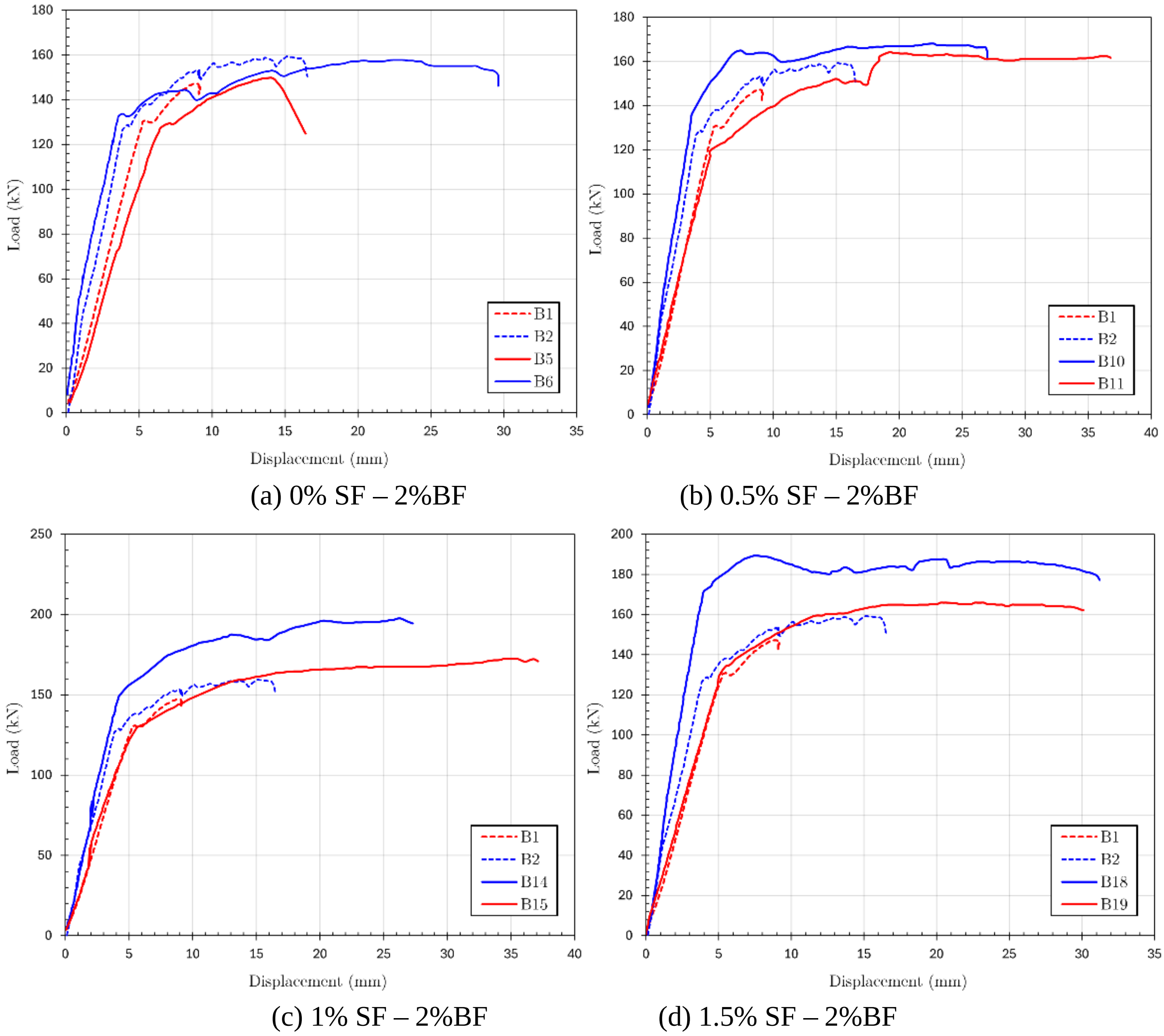
Fig. 17. Flexural capacity of beams under elevated temperatures.

At elevated temperatures, the heated control beam achieved an ultimate load of 147.3 kN as shown in **Fig. 17** (an 8% reduction compared to unheated control). Beams containing 1% BF only achieved a significantly higher flexural capacity over the heated control (20% increase), while 2% BF had a smaller enhancement of 1.9% over the heated control. Increasing the BF percentage to 3.5%, however, caused a small reduction of 0.8% over the heated control. Adding SF to the mix generally increased flexural capacity at high temperatures, where the best result was achieved by B17 (1% BF and 1.5% SF) at 187.1 kN (a 27.2% increase over the heated control). Increasing the BF percentage to a set SF percentage generally increased the capacity (with the exception of B19), however, increasing the SF percentage at a set BF percentage did not. In the study conducted by Kodur [26], it was observed that the presence of polypropylene fibers in UHPFRC leads to a reduction in fire-induced spalling, thereby increasing its fire resistance.

It can be concluded that in a hybrid use of BF and SF at high temperatures, increasing BF and SF increased the flexural capacity, however, when only using BF as fiber reinforcement, increasing the BF percentage caused a lower capacity enhancement similar to the pattern observed at normal temperatures.

3.4 Temperature's Impact on Flexural Performance

Elevated temperature treatment of 600 °C for 3 hours had an adverse effect on the flexural capacity of beams as can be seen in **Fig. 18-19**. The heated control specimen achieved an 8% lower capacity than its unheated counterpart, and most of the fiber-reinforced beams achieved a reduction as well ranging from 2% to 14%.



(a) 0% SF – 2%BF (b) 0.5% SF – 2%BF

(c) 1% SF – 2%BF (d) 1.5% SF – 2%BF

Fig. 18. Heated (red) vs. unheated (blue) flexural response compared to control (dashed).

It can be noted that beams incorporating both BF and SF have a more significant impact due to heating, where the lowest reduction in strength was suffered by B15 (2% BF–1%SF), a 15% decrease compared to its unheated counterpart B14.

At lower BF contents, such as 1% and 2%, the fibers may help maintain the concrete matrix' structural integrity under thermal stress, leading to improved flexural performance. The fibers' ability to bridge cracks and enhance ductility can contribute to this enhancement. However, as the BF content increases to 3.5%, the flexural capacity appears to decrease at elevated temperatures. This phenomenon may be linked to the increased brittleness and diminished workability of the mix, which can lead to inadequate bonding between the fibers and the cement matrix. Additionally, at high temperatures, the thermal degradation of the fibers and their potential for bridging micro-cracks within the concrete resulting in a loss of flexural strength.

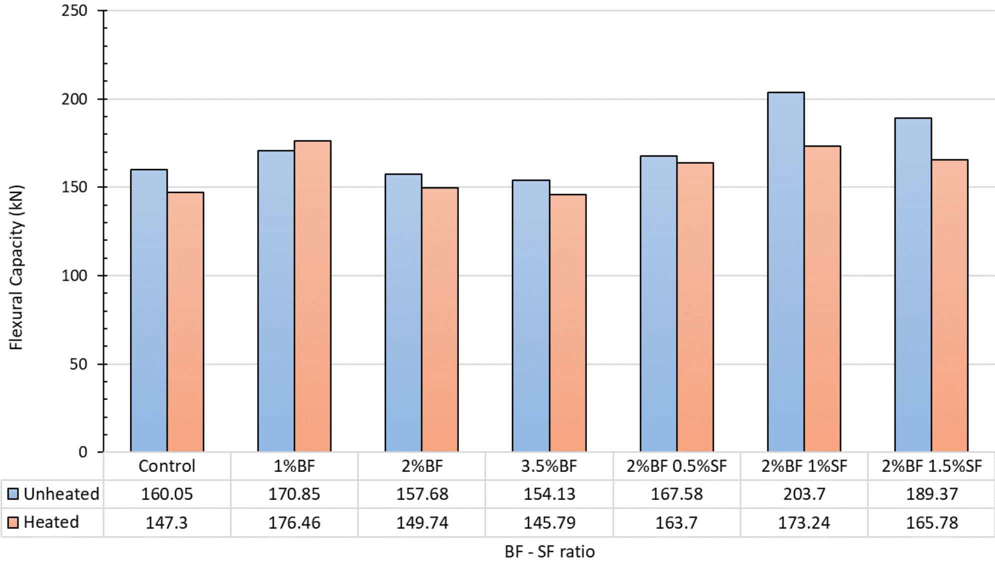


Fig. 19. Effect of high temperature on flexural capacity.

Heated beams containing only BF decreased in flexural strength with higher BF percentages, while beams incorporating both SF and BF increased in flexural strength with the higher SF percentages.

An interesting result was achieved by the beam B3 incorporating 1% BF, which was the only mix that had a higher capacity at elevated temperatures than at normal temperature (a 3.3% increase), this result agrees with the material compressive strength results illustrated in **Fig. 8**.

Slope deflection curves shown in **Fig. 18** indicate that the stiffness (slope of the linear portion) in heated beams was not affected by the addition of SF, while unheated beams displayed higher stiffness with addition of SF to concrete. On the other hand, the addition of only BF decreased the stiffness for heated beams and increased it for unheated beams.

Fig. 20. Beams thermal cracks.

3.5 Crack Pattern, First Cracks, and Failure Modes.

Beams subjected to 600 °C before loading suffered from small hairline cracks as shown in **Fig. 20**, those cracks were caused by the increased temperature expanding the concrete material and drying it at the same time, followed by a cooling period shrinking the material exacerbating the effect even more. This caused most of the test samples to lose strength as expected due to heat.

Under the 4-point flexural tests, the first cracks appeared at 33 kN for the unheated control beam, and 39 kN for the heated control, adding reinforcement fibers to concrete delayed the appearance of first cracks for almost all samples, ranging from 40 kN for B5 to 70 kN for B17, where the higher the BF and SF percentages, the higher the first cracking load, as detailed in **Table 9**.

Table 9. First crack and failure modes.

Specimen	Treatment	Temperature	First crack	Failure mode
B1	Control	Heated	33	Shear & Flexural
B2	Control	Unheated	39	Shear
B3	1%BF	Heated	45	Flexural
B4	1%BF	Unheated	42	Shear
B5	2%BF	Heated	40	Shear
B6	2%BF	Unheated	48	Flexural
B7	3.5%BF	Heated	45	Shear & Flexural
B8	3.5%BF	Unheated	56	Shear & Flexural
B9	1%BF 0.5%SF	Heated	50	Flexural
B10	2%BF 0.5%SF	Unheated	56	Flexural
B11	2%BF 0.5%SF	Heated	45	Flexural
B12	3.5%BF 0.5%SF	Heated	38	Flexural
B13	1%BF 1%SF	Heated	54	Flexural
B14	2%BF 1%SF	Unheated	40	Flexural
B15	2%BF 1%SF	Heated	50	Flexural
B16	3.5%BF 1%SF	Heated	70	Flexural
B17	1%BF 1.5%SF	Heated	43	Flexural
B18	2%BF 1.5%SF	Unheated	65	Flexural
B19	2%BF 1.5%SF	Heated	68	Flexural

Crack propagation for the beams began at mid-span and moved upwards towards the supports. The unheated control B2 suffered from a sudden shear failure, and exposure to high temperature caused the failure mode to change to a flexural-shear failure in the heated control B1 as can be seen in **Fig. 10**.

Adding BF alone did not change the failure mode at 1% and 2%, but at 3.5% BF, the failure mode moved towards the flexural part of the failure spectrum, while the addition of hybrid fibers (SF and BF) changed the failure mode to flexural failure for all beams heated or unheated.

The maximum mid-span displacement for the unheated control beam was 14 mm, and for the heated control was 9 mm, a decrease of about 36%. Most of the unheated beams utilizing any percentage of fiber had a higher displacement compared to control, up to 27 mm for B14 (1% BF – 2% SF), while B4 and B18 had lower displacement at failure of about 6% and 8% when compared to control, respectively. At elevated temperatures, usage of BF and SF increased the mid-span displacement for all specimens ranging from 14mm for B5 and 35mm for B15, compared to the control at 14mm. This increase in ultimate displacement can be attributed to the high tensile strength the fibers provide to the concrete, which can increase the likelihood of a flexural failure at higher ultimate mid-span displacements.

4 Conclusions

This study assess the l performance of RC beams with various percentages of basalt and steel fibers subjected to elevated and normal temperatures. The research outcomes led to these conclusions:

(1) The optimum fiber contents were found to be 1% for both basalt fibers (BF) and steel fibers (SF). Increasing the BF percentage beyond 1% while maintaining the same SF content led to reduced compressive strength.

(2) Incorporating SF and BF generally maintained or improved the compressive and tensile

strengths of concrete compared to the control, even at elevated temperatures. The tensile strength gains were more pronounced than the compressive strength gains, as the fibers helped mitigate the concrete's weakness in tension.

(3) At normal temperatures, the optimal fiber combination was 2% BF and 1% SF, enhancing the flexural capacity by 27% compared to the control. Excessive BF content (3.5%) reduced the flexural capacity.

(4) At high temperatures, increasing both BF and SF percentages led to further improvements in flexural capacity, with the best result achieved using 1% BF and 1.5% SF (27.2% increase over heated control).

(5) The inclusion of BF and SF delayed the appearance of first cracks, by up to 112% for the 3.5% BF - 1% SF mix.

(6) Fiber-reinforced beams generally exhibited higher mid-span displacements compared to the control, both at normal and elevated temperatures, indicating improved ductility.

(7) The failure mode of the control beams shifted from shear or flexure-shear to a more desirable flexural failure mode in the majority of the fiber-reinforced beams, both at normal and elevated temperatures.

In summary, the incorporation of basalt and steel fibers, at the optimal dosages, can effectively enhance the compressive and tensile strengths, flexural capacity, cracking resistance, and ductility of reinforced concrete beams, even under elevated temperature conditions. These findings demonstrate the feasibility and benefits of using these fiber reinforcements in concrete structures exposed to high temperatures.

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CRediT authorship contribution statement

Ashteyat: Investigation, funding, formal analysis, Writing original draft, Conceptualization, Supervision, Investigation, Formal analysis, Writing original draft. **Oaidat:** supervision, writing original draft, editing, investigation. **Kharabsheh:** investigation, writing original draft, writing review and editing, formal analysis. Supervision, Investigation. **Harahsheh:** formal analysis, writing original draft, Conceptualization, Supervision, Investigation.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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