Mechanical Properties of High-Strength Concrete reinforced with Basalt and Polypropylene Fibers

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ABSTRACT

The hybridization of Basalt Fibers (BF) and Polypropylene Fibers (PF) in High-Strength Concrete (HSC) has immense potential to improve its mechanical properties. This paper investigates the compressive strength, tensile splitting strength, and flexural strength of HSC reinforced with single BF, single PF, and hybrid fibers. Samples from thirteen mixes (i.e., one control, four BF, four PF, and four hybrid mixes) were prepared and tested at 7, 14, and 28 days. The BF content ranged from 0.1 to 0.7%, while that of PF ranged from 0.05 to 0.3%. The results indicate that at 0.3% BF dosage, the compressive strength increased from 60.66 MPa in the control mix to 62.70 MPa (a 3.36% increase). Similarly, at a 0.1% PF dosage, it increased to 61.42 MPa (a 1.25% increase). The tensile splitting strength increased from 3.97 MPa in the control mix to 4.61 MPa (a 16.12% increase) with optimal BF, and to 4.22 MPa (a 6.30% increase) with optimal PF. Similarly, the flexural strength increased from 6.22 MPa to 7.40 MPa (an 18.97% increase) with optimal BF, and to 6.70 MPa (a 7.72% increase) with optimal PF. The optimal hybrid combination consisted of 0.3% BF and 0.1% PF, which increased the compressive strength to 64.62 MPa (a 6.53% increase) at 28 days. The tensile splitting strength and flexural strength increased by 44.33% and 29.58%, respectively. It was therefore concluded that combining both fiber types in concrete produced a positive synergistic effect. Thus, using fibers in a hybrid form is more beneficial for producing high-strength fiber-reinforced concrete.

Keywords-basalt fiber; high-strength concrete; mechanical properties; optimum fiber content; polypropylene fiber

I. INTRODUCTION

The American Concrete Institute (ACI) defines HSC as concrete with a specified compressive strength of 55 MPa or higher [1]. The use of HSC as a construction material has significantly increased over the decades due to its numerous advantages and wide applications, involving offshore structures, tunnels, bridges, and high-rise apartments, among others. Some advantages associated with this material include higher compressive strength, higher durability, and higher corrosion resistance [2]. HSC use also allows for a reduction in the cross-sectional areas for load bearing elements [3]. However, HSC has certain shortcomings, including susceptibility to brittle failure, and poor post-crack behavior [4]. It also behaves poorly under thermal loads and is susceptible to spalling [5]. The addition of short, discrete fibers during concrete mixing has been shown to mitigate one or more of these deficiencies. The ACI defines Fiber Reinforced Concrete (FRC) as a concrete type which contains dispersed, randomly oriented fibers [1]. FRC exhibits higher tensile and flexural strength than non-FRC [4]. It also demonstrates better crack control, deformation characteristics, and more desirable ductile behavior [6].

Traditionally, fibers have been added to concrete in their singular forms. Various types of fibers are commercially available for the production of FRC, including steel, glass, carbon, synthetic, and organic fibers [7]. Each of the different categories has distinct advantages and disadvantages. For instance, Steel Fibers (SF) have high tensile strength and elastic modulus, which are beneficial but susceptible to corrosion [4]. They are also of relatively higher density, which negatively impacts the overall weight of a structure [8]. Synthetic fibers, including polypropylene and Polyvinyl Alcohol (PVA) fibers, improve the ductility of structures but are costly to manufacture and consume significant amounts of energy in production; hence, they are unsustainable [5]. Organic fibers are excellent sustainability choices, since they are often obtained from naturally occurring sources [9]. They are, however, susceptible to long-term degradation and difficult to standardize in the production of FRC [4]. The use of fibers from recycled plastics supports sustainable construction practices, but is subject to significant degradation from Ultraviolet (UV) exposure and fire [10]. Consequently, while some benefits can be realized in the use of singular fibers, there is significantly greater potential in blending fibers to form a hybrid matrix with enhanced properties.

Hybrid FRC (HFRC) is obtained either by adding fibers of different size/shapes to the concrete or by blending fibers of different elastic moduli [11]. In HFRC, each type of fiber offers unique chemical or mechanical contributions to the overall performance of the matrix, and through positive synergistic effects, a superior material can be achieved [12]. When fibers of varying elastic moduli are used, the stiffer fiber improves the ultimate strength of the concrete, while the more ductile fiber with a lower elastic modulus improves the ductility and strain capacity of the matrix. The resultant HFRC, if properly blended, is stronger with improved energy dissipation ability compared to the FRC of singular fibers. This study investigates the hybridization of BF as a stiff fiber and PF as a ductile fiber.

BF is a relatively new fiber type obtained by the extrusion of basalt rock [13]. Its production consumes less energy than that of other fibers, such as steel or synthetic fibers, making it more sustainable [5]. It is also more resistant to corrosion than SF and is about three times lighter than steel, hence is a desirable alternative to the traditionally used SF. Furthermore, BF has high tensile strength and a high modulus of elasticity, which can significantly improve the mechanical properties of hardened concrete [14]. PF, on the other hand, is useful in preventing the early age cracking of concrete and in bridging micro-cracks in hardened concrete. This study investigates the effect of the two fibers on the compressive, tensile splitting, and flexural strengths of concrete in both their singular and hybrid forms. The properties of the FRC are investigated to identify any positive synergistic effects from the hybridization. Research has been carried out to investigate the effect of the Individual fiber types on concrete properties. Authors in [5] investigated the effect of fiber length and dosage rates of BF on the compressive, tensile, and flexural concrete properties. A study compared the effects of 12 mm and 22 mm long BF and found that the longer fiber length led to a greater increase in the mechanical properties of concrete than the shorter fiber length. Authors in [15] investigated the effect of BF volume on the basic mechanical properties of normal-strength concrete (NSC). The study found that BF significantly improved the tensile and flexural properties of concrete, while the compressive strength improved marginally. They also reported that BF changed the failure mode of the NSC from brittle to non-brittle forms [15]. Additionally, authors in [16] explored the effect of varying PF content on the properties of NSC. By varying the fiber dosage rates from 0% to 2%, the study found that the compressive strength of concrete increased at lower dosage rates, whereas beyond certain dosage rates the strength decreased. The study also reported that PF is responsible for reducing early age shrinkage in concrete. Several studies have also been carried out to investigate the hybrid effect of different fiber combinations. Authors in [2] examined the effectiveness of mixing SF and BF in fly-ash concrete and reported the great potential of this hybrid combination in improving concrete compressive strength. Authors in [6] sought to optimize the combination of SF and PF in concrete exposed to thermal loads. The properties investigated included compressive strength, tensile splitting strength, flexural strength, and the static modulus of elasticity. The study found that the hybrid combination improved both the mechanical and thermal behavior of concrete. Similarly, authors in [17] investigated the effect of SF and PF on the mechanical and durability properties of concrete. The study concluded that for 60 mm long, hooked-end SF, the optimum combinations of SF and PF were 0.85% and 0.15%, respectively. Authors in [18] examined the rheological and mechanical properties of concrete reinforced with hybrid SF and coconut (coir) fibers. From the study, it was established that while the hybrid fibers reduced the workability of the concrete, the tensile splitting and flexural properties improved by 18.36% and 24.87%, respectively. Additionally, authors in [19] explored the effect of hybrid BF and bamboo fibers on the compressive, tensile splitting, and flexural strength of concrete. The study found the optimum combination being at 0.75% BF and 1% bamboo fibers, but reported that bamboo fibers have a negative impact on the compressive and tensile splitting properties of concrete. Finally, authors in [20] investigated the hybrid effect of BF and PVA fibers and found a positive hybrid effect when the proportion of BF was equal to or greater than that of PVA fibers. The study also reported that PVA fibers had a greater attenuation range than BF and an increased dosage of PVA fibers even led to a reduction in the mechanical properties of concrete. All these studies point to the great potential benefits that may be realized from the hybridization of fibers.

Many of the previous studies on HFRC have focused on SF as the stiffer fiber in the concrete, while few studies have explored the use of BF in hybrid form. The aforementioned benefits of BF over SF indicate significant advantages in substituting BF for SF in HFRC. This study, therefore, aims to expand the existing body of knowledge by providing valuable information on HFRC based on BF. This study examines the compressive, tensile splitting, and flexural properties of HSC dosed with single BF, single PF, and hybrid fibers. It will help determine any potential gains from combining the two fibers, rather than using them individually, as traditionally done.

II. MATERIALS AND METHODS

A. Materials

The materials used in this study included cement, fine and Coarse Aggregates (CAs), polycarboxylate ether (PCE)-based superplasticizer (SP), BF, and PF. The cement type was Portland-pozzolana cement designated CEM II/B-P 42.5N and conforming to BS EN 197-1:2011. Its physical, chemical, and mechanical properties are listed in Table I. The Fine Aggregate (FA) was natural river sand, with maximum aggregate size of 5 mm and a fineness modulus of 2.55, while the CA was derived from crushed stone from Ndarugo quarry, with a maximum aggregate size of 12.5 mm. The particle size distribution curves for the FA and CA are given in Figure 1 (a) and 1 (b), respectively, while their physical properties are listed in Table II. All aggregates conformed to ASTM C33/C33M standards [21]. The PCE-based SP was obtained from Sika Kenya Ltd. and conforms to ASTM C494/C494M standards [22]. Its properties are outlined in Table III. Clean, potable water tapped from the mains, as supplied to the university premises, was used for all mixes and curing purposes, in accordance with ASTM C1602 standards [23]. The BF, as depicted in Figure 2a, was sourced from Sichuan Jumeisheng New Material Technology Co., Ltd. while the PF, as illustrated in Figure 2b, was sourced from a local reseller. The properties of both fiber types are presented in Table IV.

TABLE I. CHEMICAL, PHYSICAL, AND MECHANICAL PROPERTIES OF CEMENT

Chemical properties			
SiO_2 (%)	24.88	CaO (%)	54.42
Al_2O_3 (%)	5.30	MgO (%)	1.44
Fe_2O_3 (%)	2.83	SO_3 (%)	2.23
Na_2O (%)	0.78	K_2O (%)	0.86
Loss on Ignition (%)	4.83		
Physical properties			
Density (g/cm^3)	2.94	Specific surface (cm^2/g)	4284
Initial setting time (min)	206	Final setting time (nin)	357
Mechanical properties			
Mortar compressive strength (MPa)			
At 2 days	23.2	At 28 days	48.9

TABLE II. FA AND CA PROPERTIES

Property	CA	FA
Specific gravity (Oven-dry basis)	2.4677	2.5244
Specific gravity (SSD basis)	2.5497	2.5777
Apparent specific gravity	2.6882	2.6665
Water absorption (%)	3.3240	2.1164
Natural moisture content (%)	1.3229	0.2006
Bulk density uncompacted (kg/m^3)	1343.7448	1437.6136
Bulk density compacted (kg/m^3)	1505.7015	1630.1438
Voids (uncompacted)	45.5463	43.0508
Voids (compacted)	38.9832	35.4240
Silt content		3.3333
Fineness modulus		2.55145

TABLE III. SP PROPERTIES

Composition	Modified polycarboxylates in aqueous solution
Specific gravity and water absorption	1.09 kg/l at 20 °C
pH value	4.5
Conventional dry material content	40.0 M. %
Viscosity	145 mPa.s (at 23 °C)

TABLE IV. BS AND PF PROPERTIES

	BF	PF
Tensile strength (MPa)	≥ 1200	189 – 325
Fiber length (mm)	18	18
Aspect ratio	1058	720
Density (g/cm^3)	2.6 – 2.8	0.91
Elastic modulus (GPa)	≥ 75	2.6

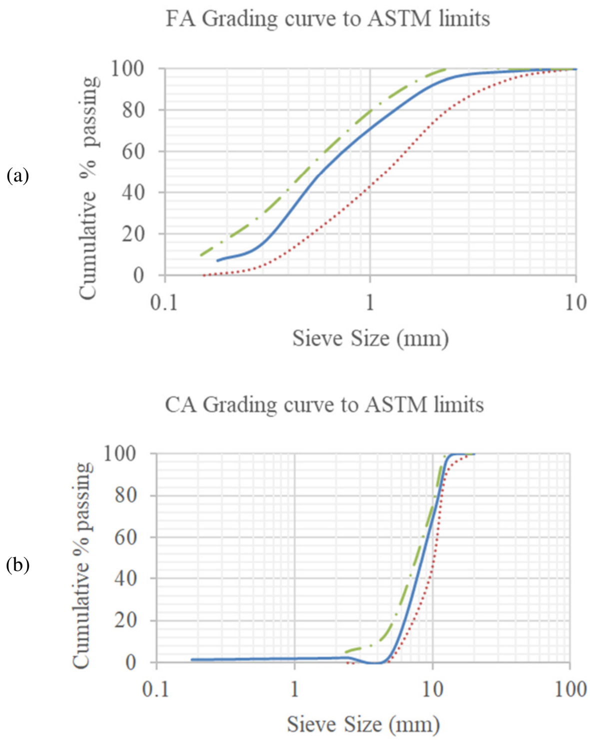

Fig. 1. Particle size distribution curves for (a) FA, (b) CA.

(a) (b)

Fig. 2. (a) BF, (b) PF.

B. Mix Proportions

Thirteen concrete mixes were prepared for this study, as shown in Table V. All mixes were designed to achieve a target compressive strength of 60MPa at 28 days. The water-cement (w/c) ratio for all mixes was 0.35 and the SP was dosed at 0.4% by cement weight. One of the mixes was the control mix, with no fibers added. Eight of the mixes were dosed with single fibers: four with single BF and four with single PF. The dosage rates for the single BF were 0.1%, 0.3%, 0.5%, and 0.7% by volume of concrete, while the volumetric dosages for the PF were 0.05%, 0.1%, 0.2%, and 0.3%.

Finally, four mixes were prepared using a hybrid of the two fibers, with the dosage rate of PF held constant at 0.1%, while that of BF was varied as before. BF has a higher elastic modulus than PF; hence, it is expected to influence the mechanical properties of the matrix to a greater extent than PF. This informed the decision to hold the PF constant and investigate the variation of BF in this study.

C. Casting and Curing

In preparing the concrete mixes, the cement and FA were first mixed in the rotary drum mixer to homogeneity before adding the water mixed with the SP to form a cement slurry. This slurry was then mixed to homogeneity before adding in the fibers. The mixing was allowed to continue for three to five minutes before the addition of the CA. Figure 3 shows the flowchart of concrete production employed. The slump test was then carried out to determine the workability of the fresh concrete, in accordance with BS EN 12350-2: 2019. After casting, all specimens were demolded after 24 hours and immediately transferred to curing tanks, where the water temperature was maintained at 23 ± 2°C throughout the curing period.

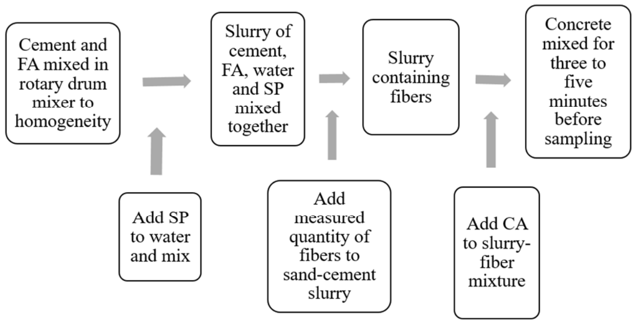

Fig. 3. Flowchart of concrete mixing.

D. Mechanical Properties

1) Compressive Strength

The cube specimens used for this test were of nominal dimensions 100 mm × 100 mm × 100 mm in accordance with BS EN 12390-1:2021. For each concrete mix indicated in Table V, nine cubes were prepared for testing at 7, 14, and 28 days, with 3 cubes at each age. A total of 117 concrete cubes were prepared. At the respective testing dates, each specimen was placed in a Universal Testing Machine (UTM) with a maximum capacity of 1,500 kN, as prescribed and loaded to failure. The test was carried out in accordance with BS EN 12390-3:2019, with a loading rate of 0.5 MPa/s. The compressive strength of the specimen (f_c) was reported as the maximum load at failure (F) divided by the cross-sectional area (A_c), as shown in:

$$f_c = \frac{F}{A_c} \tag{1}$$

The average of three readings was taken and reported as the compressive strength of the respective concrete mix at the reported testing age.

2) Tensile Splitting Strength

Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were used for the tensile splitting test of concrete, in accordance with BS EN 12390-6:2009. For each concrete mix, 6 cylinders were prepared for testing - 3 at 7 days and 3 at 28 days. A total of 78 cylinders were prepared. At the respective testing date, the specimen was placed in the UTM as prescribed and loaded at a rate of 1.5 kN/s until failure. The tensile splitting strength (f_{ct}) for a specimen of length L and diameter d was calculated from:

$$f_{ct} = \frac{2\, x\, F}{\pi\, x\, L\, x\, d} \tag{2}$$

The average of three readings was taken and reported as the tensile splitting strength of the respective concrete mix at the reported testing age.

3) Flexural Strength

Prisms measuring 100 mm × 100 mm × 350 mm were used to measure the flexural strength of the concrete mixes, deploying the three-point method, in accordance with BS EN 12390-5:2009.

The lateral dimensions d_1 and d_2 were 100 mm, while the distance between the lower supporting rollers (L) was 300 mm. The specimens were loaded at a rate 0.1 kN/s until failure. For a maximum load of F, the flexural strength of the specimen (f_{cf}) was calculated from:

$$f_{cf} = \frac{3\, x\, F\, x\, L}{2\, x\, d_1\, x\, d_2^2} \tag{3}$$

The average of three readings was taken and reported as the flexural strength of the respective concrete mix at the reported testing age.

III. RESULTS AND DISCUSSION

A. Slump Loss

Figure 4 shows the reduction of slump with the variation of the single BF, PF, and hybrid fiber contents. The slump of the control mix (without any fibers) was 124 mm. The addition of fibers in the concrete mix significantly reduced its workability, with the slump falling to 38 mm, 17 mm, 10 mm, and 8 mm for BF0.1, BF03, BF0.5, and BF0.7, respectively. Similarly, for the PF, the slump value fell to 45 mm, 20 mm, 13 mm, and 6 mm for PP0.05, PP0.1, PP0.2, and PP0.3, respectively. When the fibers were combined, the slump fell to 30 mm, 18 mm, 12 mm, and 4 mm for Hy0.1, Hy0.3, Hy0.5, and Hy0.7, respectively.

TABLE V. MIX PROPORTIONS

Mix No.	Mix ID	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	SP (%, by weight of cement)	BF (%, by volume of concrete)	PF (%, by volume of concrete)
1	Cont.	500	755	920	175	0.4	-	-
2	BF0.1	500	755	920	175	0.4	0.1	-
3	BF0.3	500	755	920	175	0.4	0.3	-
4	BF0.5	500	755	920	175	0.4	0.5	-
5	BF0.7	500	755	920	175	0.4	0.7	-
6	PF0.05	500	755	920	175	0.4	-	0.05
7	PF0.1	500	755	920	175	0.4	-	0.1
8	PF0.2	500	755	920	175	0.4	-	0.2
9	PF0.3	500	755	920	175	0.4	-	0.3
10	Hy0.1	500	755	920	175	0.4	0.1	0.1
11	Hy0.3	500	755	920	175	0.4	0.3	0.1
12	Hy0.5	500	755	920	175	0.4	0.5	0.1
13	Hy0.7	500	755	920	175	0.4	0.7	0.1

The loss of slump in the FRC is due to the increase in total surface area of the material within the concrete mix when the fiber is added. As the fiber content increases, the surface area to be coated by the cement paste increases, thus reducing the viscosity of the mix [4]. The addition of fibers also increases the internal friction to be overcome within the concrete mix, thereby contributing to the slump loss [10]. A significant loss in slump may limit the applicability of FRC in contexts where a high slump is desirable, for example in Self-Compacting Concrete (SCC). However, this can be addressed by selecting chemical admixtures that retain the workability of the concrete and optimizing the gradation of the concrete mix design for these particular scenarios [24]. Fiber dispersion techniques that improve the hydrophilicity of the fibers in the mix may also be further studied and developed for these specific contexts.

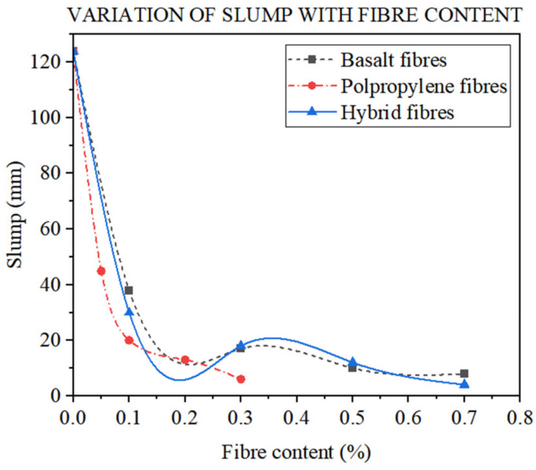

Fig. 4. Variation of slump with fiber content.

B. *Compressive Strength*

Figure 5 shows the variation of concrete compressive strength with fiber dosage for (a) single BF, (b) single PF, and (c) hybrid combination of fibers. The plotted results are the average of the three readings taken for each fiber volume and concrete age. At 28 days, the compressive strength of the control mix was 60.66 MPa. For the BF samples, the compressive strengths were established as 61.55 MPa, 62.70 MPa, 59.02MPa, and 58.02 MPa, for the respective fiber dosages. Similarly, for the PF, the compressive strengths were found to be 60.77 MPa, 61.42 MPa, 59.04 MPa, and 58.91 MPa, respectively. Finally, for the hybrid fiber combinations, the compressive strengths were 60.50 MPa, 64.62 MPa, 63.74 MPa, and 59.61 MPa, for the respective dosages.

From the results obtained, it was established that incorporating single BF in the concrete led to an increase in compressive strength by 3.98% , 2.34%, and 3.36% at 7, 14, and 28 days, respectively. It was also noted that increasing the fiber content increased the compressive strength of concrete marginally up to the optimum point beyond which it began reducing. When fibers are added into concrete, they serve as secondary reinforcement and bridge the cracks that develop within the matrix [17]. This improves the load bearing capacity of the concrete, as the fibers prevent stress concentration and redistribute the stresses within the matrix. However, beyond the optimal fiber content, the fiber begins to agglomerate together during mixing and forms weak zones within the concrete [25]. The load bearing capacity of this non-uniform matrix is compromised and reduces with a further increase in fiber content. For BF, this optimal fiber percentage is 0.3% by volume of concrete. Beyond this, the concrete loses its compressive strength by 2.70% and 4.35% for fiber dosages of 0.5% and 0.7%, respectively, at 28 days.

Similarly, for the concrete mixes dosed with single PF, an increase in the fiber content past the optimal dosage point leads to a decrease in the compression strength of the concrete. This optimal point for PF is at a dosage of 0.1% by volume of concrete, where the compressive strength increases by 3.45 %, 0.26%, and 1.25% at 7, 14 and 28 days, respectively. Beyond this point, the compressive strength of the concrete reduces by 3.37%, 2.30%, and 2.88% at 7, 14 and 28 days, respectively, for a fiber dosage of 0.03%. The reduction in the compressive strength is due to the increased non-uniformity of the concrete mix, which compromises the load transfer within the matrix and the eventual capacity of the mix [26]. The improvement of compressive strength is also noted to be greater for BF than for PF at all concrete ages. This is because BF has a higher elastic modulus than PF, hence, influences the mechanical properties of the concrete more significantly [5].

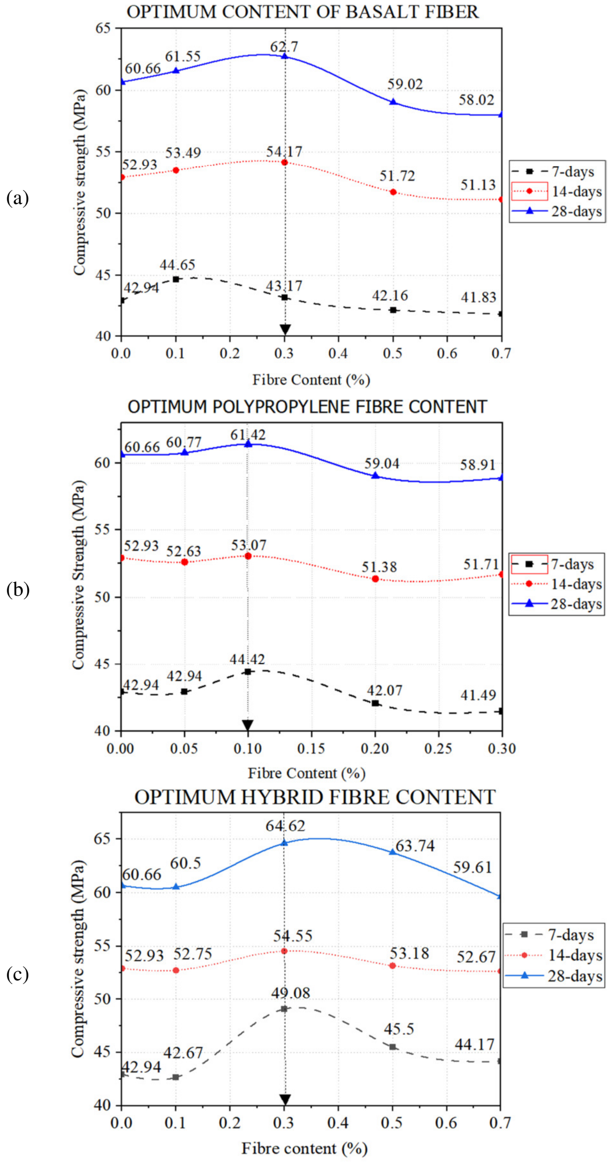

Fig. 5. Compressive strength of concrete with: (a) BF, (b) PF, and (c) hybrid fibers.

For the HFRC, a positive synergistic effect was noted for the combined BF and PF fibers. The increase in compressive strength for the hybrid fibers was higher than that of the individual, single fibers. The optimal dosage of the hybrid combination was noted at Hy0.3 for all ages beyond which the compressive strength decreased significantly. At this optimal dosage, the compressive strength increased by 14.30%, 3.06%, and 6.53% at 7, 14, and 28 days, respectively. This represents a 3.06% and 5.21% increase in strength over the individual BF and PF, respectively, at 28 days. The synergetic effect arises from the different roles played by the individual fibers in the concrete matrix. The PF, which has a low modulus of elasticity, is able to bridge micro-cracks, while the BF prevents the expansion of larger cracks. The positive hybrid effect further increases the compressive strength of concrete beyond that observed for the single fibers.

C. Tensile Splitting Strength

Figure 6 shows the variation of the tensile splitting strength of concrete with fiber content for (a) BF, (b) PF, and (c) hybrid fibers.

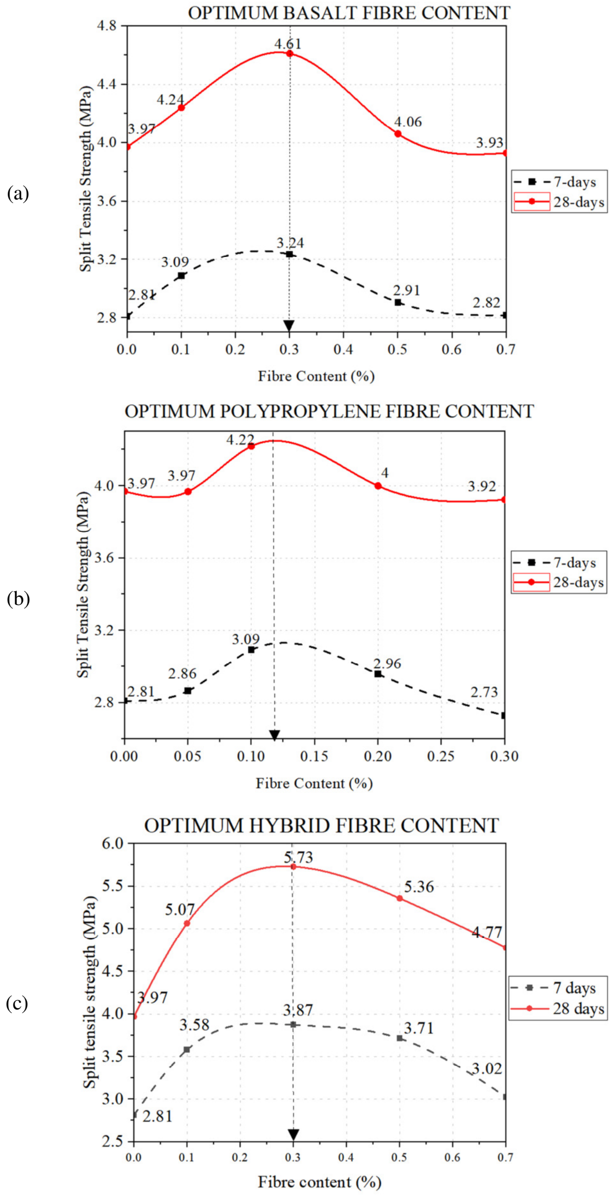

Fig. 6. Tensile splitting strength of concrete with: (a) BF, (b) PF, and (c) hybrid fibers.

The results plotted are the average of the three readings taken for each fiber volume and concrete age. While it was noted that the change in compressive strength for FRC was only marginal, it is apparent that the effect of fibers on the tensile splitting strength property are more significant. At 28 days, the tensile splitting strength for the control mix was 3.97 MPa. For BF, the tensile splitting strength was established as 4.24 MPa, 4.61 MPa, 4.06 MPa, and 3.93 MPa, for the respective dosage rates. For the concrete dosed with PF, the tensile splitting strength was 3.97 MPa, 4.22 MPa, 4.00 MPa, and 3.92 MPa, for the respective fiber dosage rates. Finally, for the hybrid combination of the fibers, the tensile splitting strength was 5.07 MPa, 5.73 MPa, 5.36 MPa, and 4.77 MPa, for the respective dosage rates at 28 days. When load is applied to FRC, the fibers within the matrix arrest the development and propagation of cracks within the concrete [26]. The fibers bridge any cracks within the matrix and dissipate the energy applied to it. This leads to the observed increase in FRC load bearing capacity. The optimum fiber content for the BF is 0.3% as it corresponds to the highest strength gain for the samples. The inclusion of BF creates a network within the matrix that absorbs energy and ultimately increases the ultimate capacity of the mix [27]. For the single PF, the gain in tensile splitting strength is 1.77%, 9.96%, 5.34%, and -2.85% at 7 days and 0%, 6.30%, 0.76%, and -1.25% at 28 days for the respective fiber dosages. The optimal fiber content for the PF is 0.1% by volume of the concrete. Beyond the optimal fiber content, there is a decrease in the tensile splitting strength. This is attributed to the interference with the concrete matrix, which consequently reduces the load-bearing capacity of the specimens at higher fiber dosages [25].

When the two fibers are combined, a significant positive hybrid effect is noted, with the total increase in tensile splitting strength being 27.40%, 37.72%, 32.03%, and 7.47% for Hy0.1, Hy0.3, Hy0.5, and Hy0.7, respectively, at 7 days. The same trend remains true for the concrete at 28 days, with the increase being 27.71%, 44.33%, 33.75%, and 20.15% for the respective hybrid fiber percentages. When the two fibers are combined, the ultimate capacity is increased, and the onset and propagation of cracks is controlled, resulting in a mix superior to the individually dosed mixes [27].

It was also noted that the addition of fibers changed the failure pattern of the specimens. The control specimens that had no fibers failed in a brittle manner and split evenly into two after the application of the maximum load, whereas in the FRC, the fibers bridged the cracks along the failure planes and allowed the samples to maintain their integrity even after the maximum load had been reached. Figure 7 displays the failure modes observed for (a) control samples and (b) FRC samples.

(a) (b)

Fig. 7. Tensile splitting failure patterns for: (a) control samples, (b) FRC samples.

D. *Flexural Strength*

Similarly to tensile splitting strength, the flexural strength of concrete is also significantly affected by the addition of fibers. Figure 8 depicts the variation of the flexural strength of concrete with fiber dosages of (a) BF, (b) PF, and (c) hybrid fibers. The plotted results are the average of the three readings taken for each fiber volume and concrete age. The control mix attained a flexural strength of 6.22 MPa. After the addition of BF, the concrete attained a flexural strength of 6.62 MPa, 7.40 MPa, 6.47 MPa, and 6.27 MPa, for the respective fiber dosages at 28 days. Similarly, at 28 days, the concrete dosed with PF attained a flexural strength of 6.02 MP, 6.70 MPa, 6.69 MPa, and 6.56 MPa, for the respective fiber dosage rates. Finally, for the hybrid combination, the flexural strength was reported as 7.37 MPa, 8.03 MPa, 7.45 MPa, and 7.46 MPa, respectively.

According to the results, concrete reinforced with BF exhibited an increase in flexural strength of 22.15 %, 32.46 %, 28.07 %, and 22.81 % at 7 days and 6.43 %, 18.97 %, 1.61 %, and 5.62 % at 28 days for the respective fiber dosage rates. On the other hand, the flexural strength of concrete reinforced with PF increased by 16.67 %, 22.37 %, 22.15 %, and 5.48 % at 7 days and -3.22%, 7.72%, 7.56%, and 5.47% at 28 days. The optimal fiber dosage for the BF remained at 0.3%, while that for PF was reported as 0.13% by volume of concrete for the flexural strength. The slight change observed for the reported optimum of PF is due to the relatively small fiber dosage rates associated with PF compared to the BF.

Furthermore, the hybrid combination of fibers outperformed the single fiber dosages as in the aforementioned case with compressive and tensile strength before. The optimum hybrid dosage rate was reported at Hy0.3, where the content of BF is 0.3% while that of PF is 0.1%. At this optimum, the flexural strength of the concrete increased by 31.69% and 29.10% at 7 and 28 days, respectively. In the HFRC, both fibers work in tandem to increase the ultimate capacity and ductility of the prismatic samples [27]. Thus, the hybrid mix outperforms the mixes with mono fibers, and is established as the superior matrix.

IV. CONCLUSION

The present study investigated the effect of Basalt Fiber (BF) and Polypropylene Fiber (PF) in single and hybrid form on the mechanical properties of High-Strength Concrete (HSC) by testing the compressive, tensile splitting, and flexural strength of HSC. The study showed that there are significant benefits that can be achieved by blending BF and PF in the production of Fiber Reinforced Concrete (FRC), rather than using them in their singular form, as has been the typical case. BF improves the ultimate capacity of HSC, while PF improves the ductility and crack control properties, thereby resulting in a net positive synergetic effect.

The study also determined the optimal dosage rates of the BF and PF in the singular and hybrid states. It was established that while the fibers slightly improve the compressive strength of HSC, their effect is more pronounced in the tensile splitting and flexural strength properties. The optimal dosage of single BF was found to be 0.3% by volume of concrete, which increased the compressive strength from 60.66 MPa to 62.7

MPa at 28days, an increase of 3.36%. The tensile and flexural strength also increased from 3.97 MPa to 4.61 MPa, and from 6.22 MPa to 7.40 MPa, respectively. The optimum content for the PF was 0.1%, where the compressive, tensile splitting, and flexural strengths increased to 61.42 MPa, 4.22 MPa, and 6.7 MPa, respectively. It was also noted that, when dosed in their single forms, BF affected the mechanical properties of FRC more than PF, due to its higher elastic modulus. In the Hybrid FRC (HFRC), the maximum compressive, tensile splitting and flexural strengths were 64.62 MPa, 5.73 MPa, and 8.03 MPa, respectively, translating to respective increases of 6.53%, 44.33%, and 29.10%. The study, therefore, concludes that the use of BF and PF in a hybrid manner is more beneficial than dosing the fibers in their single states, as it significantly improves the mechanical properties of HSC.

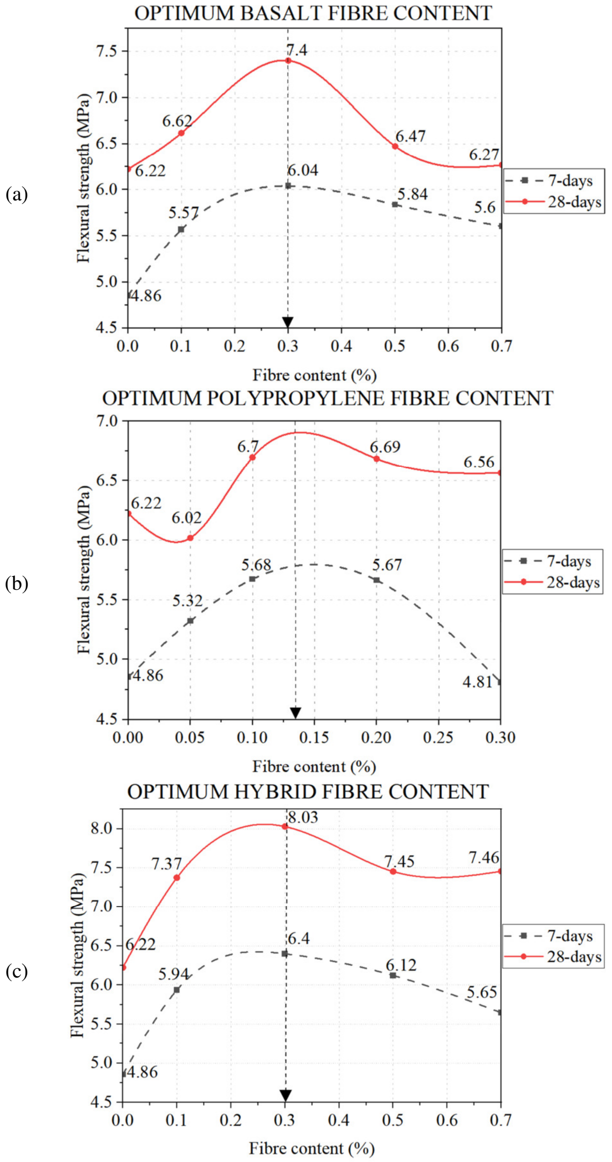

Fig. 8. Flexural strength of concrete with: (a) BF, (b) PF, and (c) hybrid fiber.

The study further reported the loss of workability as a drawback of FRC, which reduces the ease of handling the concrete. The slump of the control mix was 124 mm, while those of BF, PF, and hybrid mixes at their optimal dosages were 17 mm, 20 mm, and 18 mm, respectively. The study proposes that where high workability is desired, additional combinations of admixtures may be investigated to fulfil this need. This also forms a basis for further research that future studies can review.

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