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Synergistic effects of banana fibre and banana leaf ash on the strength and durability of eco-friendly concrete

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Abstract:
The quest for sustainable construction materials is driving the exploration of agricultural by-products as eco-friendly alternatives in concrete production. This study investigates the combined effect of banana fibre (BF) and banana leaf ash (BLA), derived from the Musa spp. plant, on the mechanical and durability performance of concrete. BFs at percentages of 0,25 %, 0,50 %, and 0,70 % were used as natural reinforcement to improve tensile characteristics. BLA, which is rich in silica and other pozzolanic compounds, was utilized as a partial cement replacement at varying percentages of 5 %, 10 %, 15 %, and 20 %. Experimental analysis included slump, compressive strength, split tensile strength, and flexural strength tests over different curing periods. An optimal combination of BF and BLA enhanced the tensile properties and improved resistance to environmental degradation without significantly compromising compressive strength. The findings suggest that incorporating banana waste derivatives enhances concrete performance and contributes to a more sustainable and circular construction economy.

Keywords:
supplementary cementitious material; banana fibre; banana leaf ash; compressive strength; sustainability

1 Introduction

The building and construction sector contributes significantly to environmental problems, particularly the considerable consumption of natural resources and generation of greenhouse gases during cement production. Plain concrete is the most widely used material in engineering and construction applications owing to its low cost, wide applicability, and ubiquitous availability. The strength of concrete increases with age, although it loses some of its strength as it ages [1]. However, concrete is significantly limited by low tensile strength and weak resistance to fracture propagation [2; 3]. Therefore, fibre-reinforced concrete (FRC), which is typically considered as a substitute, compensates for the brittleness of plain concrete [4; 5]. Fibres are typically categorised as steel, synthetic, glass, and natural in terms of how they have been combined to create the strength of concrete [6-8]. Steel fibres are used most frequently for reinforcing concrete [9-12] and its defining characteristics permit its exposure to corrosive environments. Consequently, natural fibres are being considered as potential substitutes for producing FRC. Jute, cotton, and coconut and banana trees are natural resources that can be used to acquire environmentally friendly recyclable, affordable, and manageable natural fibres [13; 14]. A connection exists between these natural fibres and the matrix of concrete, which is characterised by the random circulation of separate irregular threads across concrete composites with a smaller diameter [5]. For example, banana fibres (BFs) are derived from annual plants that are easily accessible and have the potential to be utilised as a component of cement matrices. Furthermore, these experiments demonstrate that BFs are potential substitutes for the conventional fibres used in concrete. The development of new concrete forms that exhibit improved characteristics and are more sustainable has led to the rise of the current civilisation, which has resulted in the generation of terrifying criteria. However, an excessive amount of cement elements in concrete negatively affects the environment because the cement industry contributes 7 % of the global carbon dioxide emissions [15; 16]. Managing industrial waste is another part of conservation. Paper waste, fly ash, and silica fume are examples of the waste components found in concrete and are suitable as extra cementitious materials [17; 18]. As a sustainable alternative, the inclusion of agricultural by-products in concrete has emerged as a potential solution for offsetting the effects of these externalities.

The cultivation of bananas, which is common in tropical countries, produces a significant amount of waste, including BF and leaves. Although these materials have traditionally been considered agricultural leftovers, they could be repurposed in the manufacturing of concrete. Because of the high silica and/or alumina contents of the minerals, they were selected as partial replacements for Portland cement (PC), which was obtained locally. In most cases, the performance of concrete is improved by the hydrated phases formed during the pozzolanic reaction [19; 20]. In addition, these materials could potentially reduce production costs and environmental impacts while maintaining a high level of mechanical performance and durability. Consequently, they are suitable as supplementary cementitious materials (SCMs) in concrete, which are technically viable, environmentally friendly, and effective [21]. The partial incorporation of SCM into cement could reduce both environmental impact [22].

Owing to its 48,7 % SiO_2 content, banana leaf ash (BLA) can partially replace cement [23; 24] and help mitigate global warming. BLA severely affects new, hardened, and durable concrete. Recent research has examined the impact of organic fibres in FRC on the fresh behaviour, mechanical responsiveness, and environmental impact resistance. Recently, natural fibres in concrete mixtures have provided sustainability research with a new perspective. Studies have examined the effects of BFs on fresh and cured concrete. BLA-based BF's fresh and hardened properties are unknown for sustainability. Previous studies, which utilized only a few data points, did not apply statistical analysis to explain their findings and compare them with existing standards. To fill the gaps in the existing research, NDT approaches must be investigated. This study evaluated the fresh (slump, density, ball penetration, and compaction factor) and mechanical properties (compressive, splitting, and flexural strengths) of BF with 0 %, 5 %, 10 %, 15 %, 20 %, and 25 % cement replacement by BLA at 7 and 28 days. NDT evaluated sustainability using embodied CO_2 and cost analyses. This study provides a foundation for studying normal-strength concrete made from eco-friendly plant fibres and suggests the use of BF and BLA in concrete to create sustainable construction materials. Further research is required to optimise their combined use and understand their effect on the mechanical and durability properties of concrete.

2 Identified research gap

Most studies have independently focused on BF or BLA, and few studies have explored the synergistic effects of both materials on concrete properties. The absence of a standardised method for fibre treatment (alkali, steam, or enzyme-based) leads to variability in the fibre-matrix bonding and the resulting concrete properties. Although mechanical properties such as compressive and flexural strengths are often studied, durability aspects such as chloride penetration, carbonation depth, sulphate resistance, and long-term shrinkage are underexplored. BF and BLA properties vary with geography and species, and no comparative studies have been conducted between varieties or regions of origin. The bond strength between BF and the cementitious matrix has not been extensively studied using pull out test.

3 Composition and materials utilised

In this study, ordinary Portland cement (OPC) of 53 grade conforming to IS 12269:2013 was used as the primary binder. The cement was grey in colour and had a specific gravity of approximately 3,15; ensuring good reactivity and consistent fineness. The fine aggregate used was well-graded river sand conforming to Zone II as per IS 383:2016, with a specific gravity and fineness modulus of 2,65; and 2,6; respectively. Coarse crushed granite aggregates with a size of 20 mm were used, which improved interlocking and load transfer. These aggregates had a specific gravity of 2,7 and water absorption of less than 1,5%; which ensured durability and strength compliance with IS 2386 standards. BF (Musa spp.), a natural lignocellulosic fibre extracted from banana pseudostems, was used as the reinforcing material. The fibres were manually extracted, sun-dried, and alkali-treated with a 5 % NaOH solution for 4 h to remove the hemicellulose and lignin, which enhanced the surface roughness and interfacial bonding with the cement matrix. The treatment process for BF is shown in Figure 1.

Figure 1. Processing of BF

BLA was produced by air-drying mature banana leaves and burning them in a muffle furnace at 550 °C for 5 h to ensure complete combustion. The resulting ash was ground to a fineness of 300-350 m²/kg (Blaine) and exhibited pozzolanic reactivity comparable to that of Class F fly ash. In this study, BLA was used to replace OPC at varying levels (5 %, 10 %, 15 %, 20 %, and 25 % by weight of cement) to evaluate its synergistic performance. Potable tap water free from organic and inorganic impurities was used for mixing and curing as per IS 456:2000. To enhance the workability of mixes incorporating fibres and ash, a polycarboxylate ether-based high-range water-reducing admixture (superplasticiser) conforming to IS 9103:1999 was used by weight of the cementitious materials. The compositions and particle size distributions the BLA and cement are shown in Figures 2 and 3, respectively.

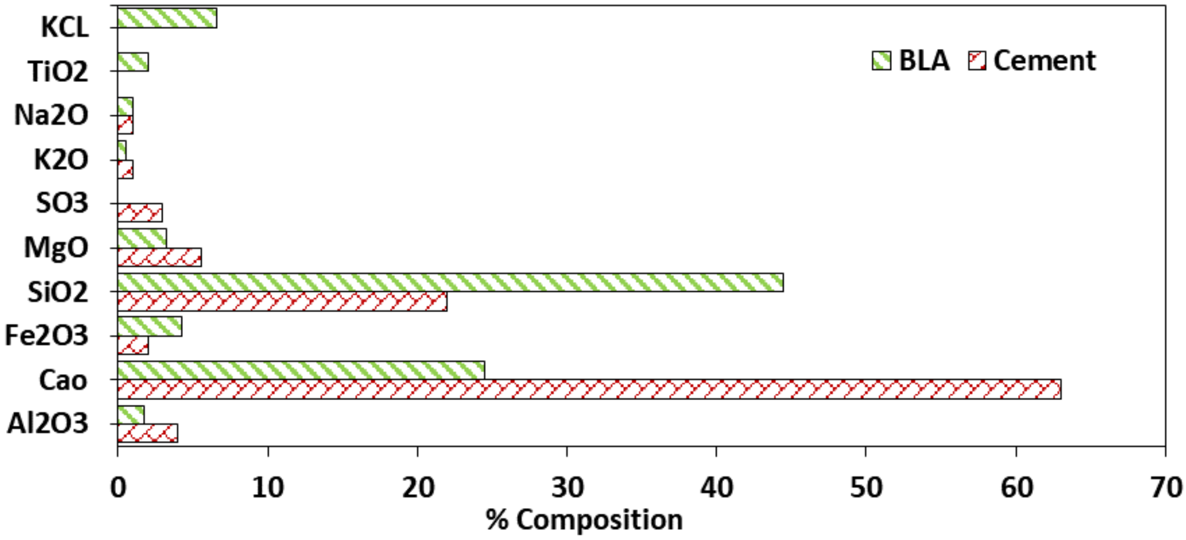

Figure 2. Chemical composition of cement and BLA

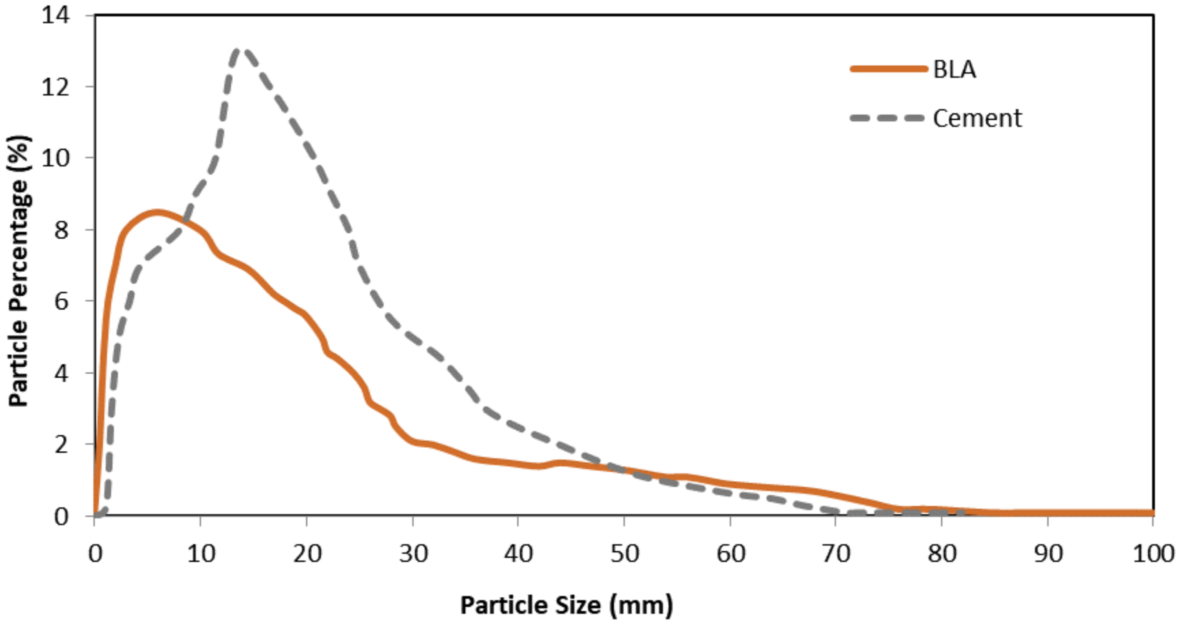

Figure 3. Particle size distributions of BLA and cement

4 Results and discussions

4.1 Slump flow

The slump values of all mixes are shown in Figure 4. The slump values of the control mix (CM) at the beginning and after 30 min were 110 and 10 mm, respectively. The graph shows that the addition of BLA and BF lowers the slump value compared to that of the CM. The initial slump values of the mixes BLA5B0,25; BLA10B0,25; BLA15B0,25; BLA20B0,25; BLA5B0,5; BLA10B0,5; BLA15B0,5; BLA20B0,5; BLA5B0,75; BLA10B0,75; BLA150,75; and BLA20B0,75 decrease by of −5,45 %; −12,73 %; −24,55 %; −25,45 %; −10,91 %; −15,45 %; −26,36 %; −30,91 %; −18,18 %; −24,55 %; −27,27 %; and −33,64 %; respectively. BLA20B0,75 exhibits the maximum slump reduction of 33,64 %.

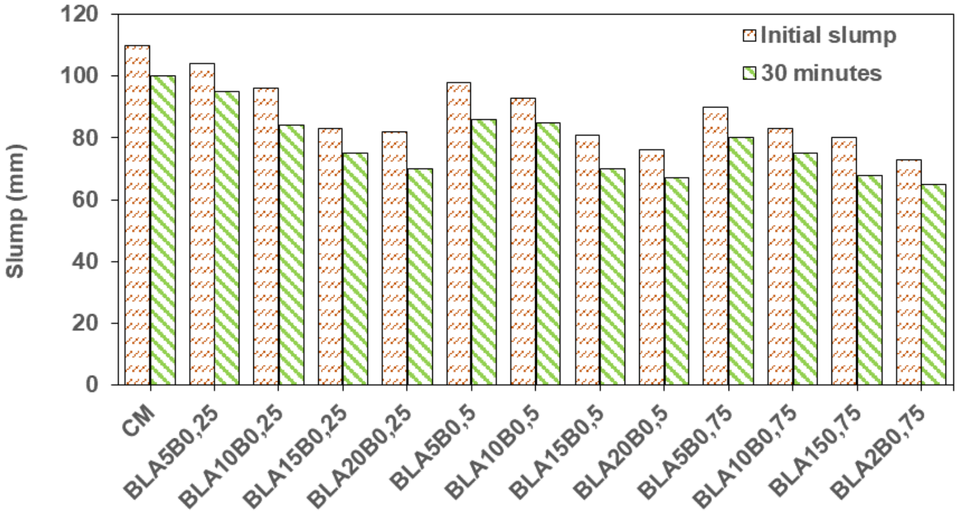

Figure 4. Slump results of all the mixes

The addition of a higher percentage of BLA and BF to the concrete reduced the slump value, which was primarily because of high water absorption and BFs restricting the flow of concrete. An increase in the percentage of BLA significantly reduced the initial slump. For instance, at a constant fibre dosage of 0,25 %; slump decreased from 105 mm (BLA5B0,25) to 82 mm (BLA20B0,25). BLA has a high surface area and contains fine porous particles, which increase the water demand and reduce the amount of free water available in the concrete mix. Additionally, the BLA accelerates the hydration reaction, leading to faster stiffening of the concrete, particularly within the first 30 min. This observation was consistent with the significant decrease in workability when cement was replaced with bagasse ash, owing to its higher surface area and water demand [25]. A comparison of the mixes at a constant BLA level shows that increasing the BF content decreases the slump. At 10 % BLA, the slump decreased from 96 mm (0,25 % BF) to 87 mm (0,75 % BF). The fibres absorbed water and formed a physical mesh within the mixture, thereby increasing the internal resistance. The interfibre friction increased with the fibre content, which restricted the free flow of the concrete matrix and reduced workability. Across all the mixes, the slump decreased between 5 % and 20 % after 30 min. The highest loss occurred in the mix with high BLA and high BF contents. The loss in slump was more pronounced owing to the accelerated hydration caused by BLA and the water absorption behaviour of BF. This synergistic effect causes rapid stiffening, necessitating the use of retarders or plasticisers in practical applications. Therefore, both BLA and BF independently and collectively reduce the slump of concrete. The effect intensifies over time, and a significant slump loss occurs within the first 30 min. Despite this, the mixture containing 10 % BLA and 0,50 % BF demonstrated balanced workability and stability, highlighting its suitability for practical and eco-friendly concrete applications.

4.2 Density of the concrete

Figure 5 illustrates the variation in the density of concrete mixes incorporating different proportions of BLA (5 %, 10 %, 15 %, and 20 %) and BF (0,25 %; 0,50 %; and 0,75 %) compared with the CM. CM exhibited a density of 2437 kg/m³, whereas the densities of the mixes gradually reduced with increasing BLA and BF content, reaching a minimum of approximately 2370 kg/m³ at higher replacement levels. Because BLA is a supplementary cementitious material (SCM), its specific gravity is typically lower than that of OPC often ranging between 1,9 and 2,3 compared to 3,14 for OPC [26]. When BLA replaces a portion of OPC, the overall density of the concrete decreases because of the reduced mass of binder per unit volume. Moreover, the porous, irregular microstructure of the BLA increases the air-void content within the concrete matrix, further reducing the density. The use of plant-based pozzolanic ash in concrete mixtures systematically reduces the density, which is correlated with the ash replacement levels [27]. BFs are lightweight organic materials with a density of around 1,35 g/cm³ significantly lower than both cement and aggregates. Their addition introduces microvoids and slightly disrupts the homogeneity and packing of the matrix, which further marginally reduces the density of concrete. The reduction is more pronounced at higher fibre dosages (0,75 %) because the increased fibre volume disrupts the particle packing efficiency [28]. When both BLA and BF were incorporated, their cumulative effect progressively reduced the density. As shown in the graph, mixes with higher BLA content (20 %) and higher BF content (0,75 %) recorded the lowest densities. The lower BLA and BF combinations exhibited densities closer to that of CM. This combined reduction is attributed to the low specific gravity of BLA, which lowers the binder density, low density of the fibre and its tendency to trap additional air voids, and potential for reduced compaction efficiency with higher fibre percentages [29].

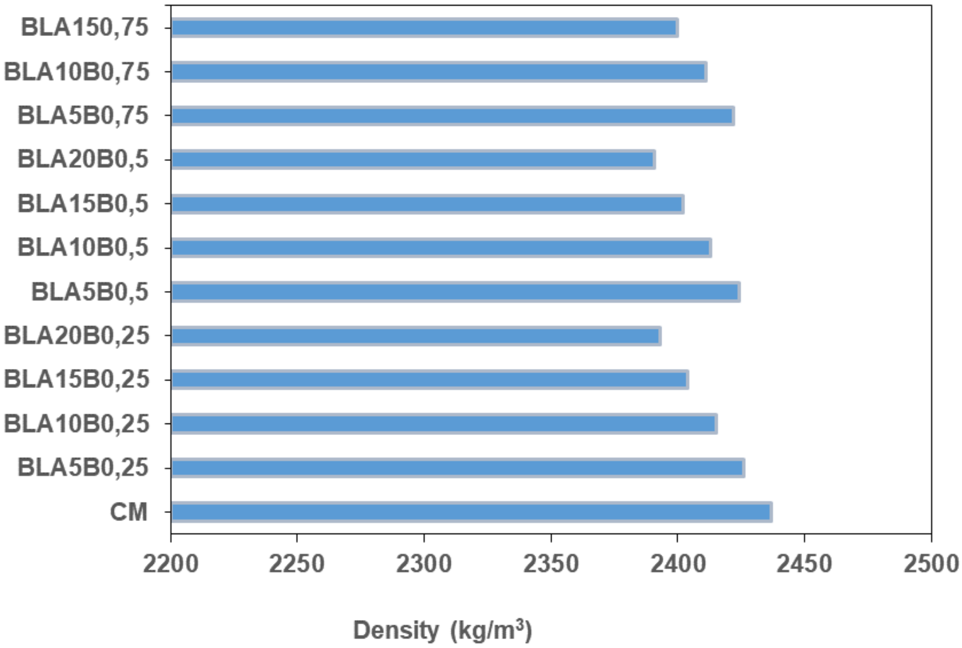

Figure 5. Densities of the mixes

4.3 Compressive strength of the concrete

Figure 6 illustrates the compressive strength development of various concrete mixes incorporating BLA and BF over 14, 28, 56, and 90 days. The CM was compared with multiple mixes containing varying percentages of BLA (5 %, 10 %, 15 %, and 20 %) and BF (0,25 %; 0,50 %; and 0,75%). The compressive strengths of CM at 28, 56, and 90days are 39,5; 44,8 and 46,3 MPa, respectively. Mixes BLA15B0,25; BLA20B0,25; BLA15B0,5 and BLA20B0,5 exhibit reduced compressive strengths of 3,54 %; 7,59 %; 1,77 % and 6,58 % respectively, compared with that of the CM concrete. The mix BLA5B0,5 displayed maximum increases in compressive strength 41,2; 46,4 and 48 MPa at 28, 56, and 90 d, respectively. The addition of BLA and BF to concrete increased the compressive strength, primarily because of pozzolanic activity and controlled microcracking behaviour. Across all the mixes, the compressive strength improved with the curing age, aligning with the hydration process and pozzolanic activity. This is consistent with the findings [28], where the pozzolanic reactivity in agricultural ash materials continued over long curing durations, enhancing the late-age strength. Mix BLA10B0,5 achieved the highest 90d compressive strength, surpassing that of the CM. This enhancement indicates the synergistic effects of the pozzolanic nature of BLA and the fibre-bridging effect of BF. Similar outcomes were reported by [30], in which 0,5 % BF increased the flexural and compressive strengths by 17,6 % owing to crack-bridging and energy absorption. Moderate increases in the compressive strength were observed at lower BLA and BF dosages. These levels were insufficient for maximising the benefits of pozzolanic or fibre reinforcement. Mixes with 20 % BLA and 0,75 % BF exhibited reduced compressive strength compared with that of the optimum mix. BLA10B0,25 achieved the highest compressive strength, representing an improvement of 5,4 % over that of the CM. This improvement is attributed to the pozzolanic activity of the BLA, which reacts with $Ca(OH)_2$ from hydration to form an additional calcium silicate hydrate (CSH) gel, enhancing its strength and durability. Incorporating 0,25-0,50 % BF promoted crack-bridging, arrested microcrack propagation, and improved post-peak load behaviour. Excessive fibre content (0,75 %) resulted in a slight decrease in strength owing to poor workability and fibre agglomeration. The reduction in strength was attributed to the excessive replacement of cement, leading to dilution effects and reduced calcium hydroxide availability for pozzolanic reactions. BLA contains reactive silica and alumina, which enhance the long-term strength development. Also confirmed that pozzolanic ashes such as SCBA and similar agricultural ashes improved the compressive strength to optimal levels (10 %) owing to their refined pore structure and secondary CSH formation. BF improved tensile and flexural strengths and delayed crack propagation. Previous investigations [29] showed that short BF improved the composite behaviour and increased the compressive strength by up to 18,62 % at a fibre content of 0,5 %. The standard deviation and coefficient of variation of the compressive strength of concrete for various mixes are listed in Table 1.

Table 1. Standard deviation and coefficient of variation for various mixes

Mix ID	14 days		28 d		56 days		90 days	
	SD	COV	SD	COV	SD	COV	SD	COV
CM	0,79	0,0250	1,01	0,0256	0,35	0,0078	0,89	0,0192
BLA5B0,25	0,67	0,0204	0,77	0,0189	0,46	0,0100	0,88	0,0185
BLA10B0,25	0,86	0,0269	0,56	0,0140	0,56	0,0124	0,75	0,0161
BLA15B0,25	0,90	0,0294	0,34	0,0089	0,55	0,0127	0,69	0,0154
BLA20B0,25	0,76	0,0259	0,56	0,0153	1,20	0,0289	0,85	0,0198
BLA5B0,5	0,94	0,0284	0,52	0,0126	1,40	0,0302	1,00	0,0208
BLA10B0,5	0,35	0,0108	0,89	0,0220	0,76	0,0166	0,67	0,0142
BLA15B0,5	0,46	0,0147	0,88	0,0227	1,01	0,0230	0,90	0,0198
BLA20B0,5	0,56	0,0190	0,84	0,0228	0,77	0,0183	0,55	0,0126
BLA5B0,75	0,55	0,0172	0,69	0,0177	0,56	0,0126	0,94	0,0204
BLA10B0,75	1,20	0,0385	0,85	0,0223	0,34	0,0078	0,66	0,0146
BLA15B0,75	1,40	0,0475	1,00	0,0274	0,56	0,0133	0,67	0,0154
BLA20B0,75	0,76	0,0269	0,67	0,0191	0,77	0,0190	0,86	0,0205

Where SD denotes standard deviation, and COV coefficient of variation.

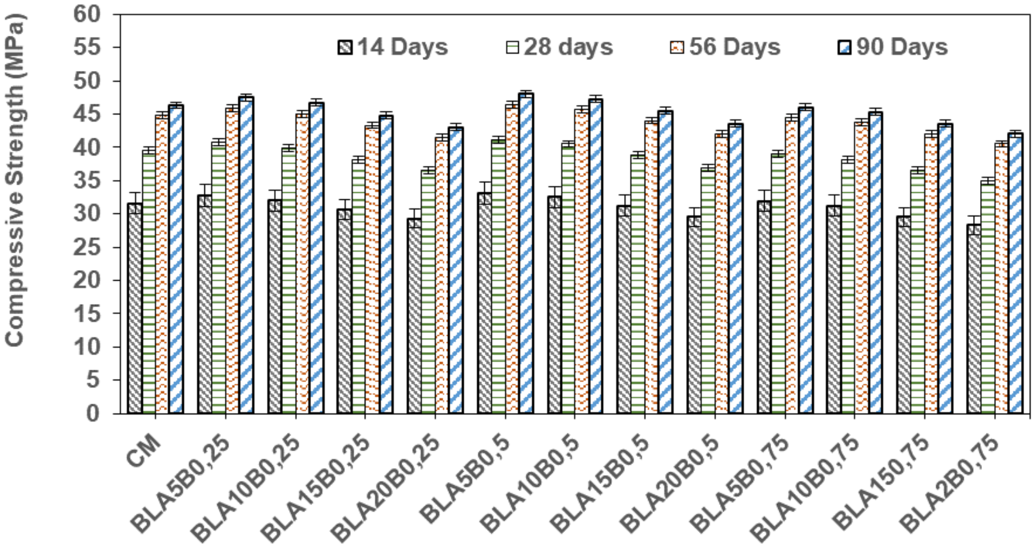

Figure 6. Compressive strengths of the mixes

4.4 Split tensile strength of the concrete mixes

The split tensile strengths of concrete mixes incorporating varying percentages of BLA and BF were evaluated at 14, 28, and 56 d, as shown in Figure 7. CM exhibited a tensile strength of 3,80 MPa at 28 d, whereas BLA5B0,5 achieved the highest tensile strength of 4,10 MPa at 28 d, representing an increase of 7,9 % over that of CM. At 28 d, the split tensile strength of BLA5B0,25 increases by 4,05 % compared to that of CM. Figure 7 demonstrates that among all the mixes, BLA5B0.5 attained the highest increase in split tensile strength of 9,46 % compared to that of CM. The split tensile strength of BLA20B0,75 decreased by 10,81 % compared to that of CM. Beyond 10 % BLA replacement, a marginal decline in tensile strength was observed across all fibre contents, which became more pronounced at the 15 % and 20 % BLA replacement levels.

The enhancement in tensile strength with 5 % and 10 % BLA was attributed to the pozzolanic reactivity of BLA, which contributed to CSH gel formation, matrix densification, and improvement of the fibre-matrix interfacial transition zone (ITZ). This was further supported by the incorporation of BF at 0,5 % which arrested microcrack propagation through a bridging mechanism, thereby enhancing the post-cracking tensile behaviour of the composite. At higher replacement levels of BLA (15-20 %), the dilution effect of excessive ash reduced the tensile strength, leading to reduced calcium hydroxide availability for secondary CSH formation and a possible increase in matrix porosity. Additionally, fibre balling and impaired workability at higher fibre contents (0,75 %) likely compromised compaction, resulting in weaker ITZs and reduced strength gains. These observations are consistent with prior findings.

The optimum tensile strength improvements with 5-10 % plant ash replacements in cement composites, citing improved matrix density and fibre-bridging effects. The vegetable fibres at a volume fraction of 0,5 % delivered the most balanced enhancement in the split tensile strength without adverse effects on workability and fibre dispersion [30]. The standard deviations and coefficients of variation of the split tensile strength of concrete for various mixes are listed in Table 2.

Table 2. Standard deviation and coefficient of variation for the various mixes

Mix ID	14 days		28 days		56 days	
	SD	COV	SD	COV	SD	COV
CM	0,0500	0,0172	0,032	0,0086	0,061	0,0153
BLA5B0,25	0,0340	0,0111	0,084	0,0218	0,043	0,0102
BLA10B0,25	0,0556	0,0188	0,036	0,0096	0,074	0,0185
BLA15B0,25	0,0490	0,0172	0,044	0,0122	0,059	0,0151
BLA20B0,25	0,0590	0,0219	0,083	0,0239	0,034	0,0089
BLA5B0,5	0,0340	0,0108	0,034	0,0084	0,061	0,0140
BLA10B0,5	0,0610	0,0198	0,061	0,0154	0,036	0,0085
BLA15B0,5	0,0530	0,0180	0,053	0,0141	0,074	0,0185
BLA20B0,5	0,0320	0,0119	0,074	0,0211	0,055	0,0143
BLA5B0,75	0,0740	0,0243	0,036	0,0092	0,034	0,0081
BLA10B0,75	0,0360	0,0122	0,085	0,0230	0,061	0,0153
BLA15B0,75	0,0440	0,0163	0,034	0,0097	0,053	0,0139
BLA20B0,75	0,0340	0,0135	0,056	0,0170	0,094	0,0254

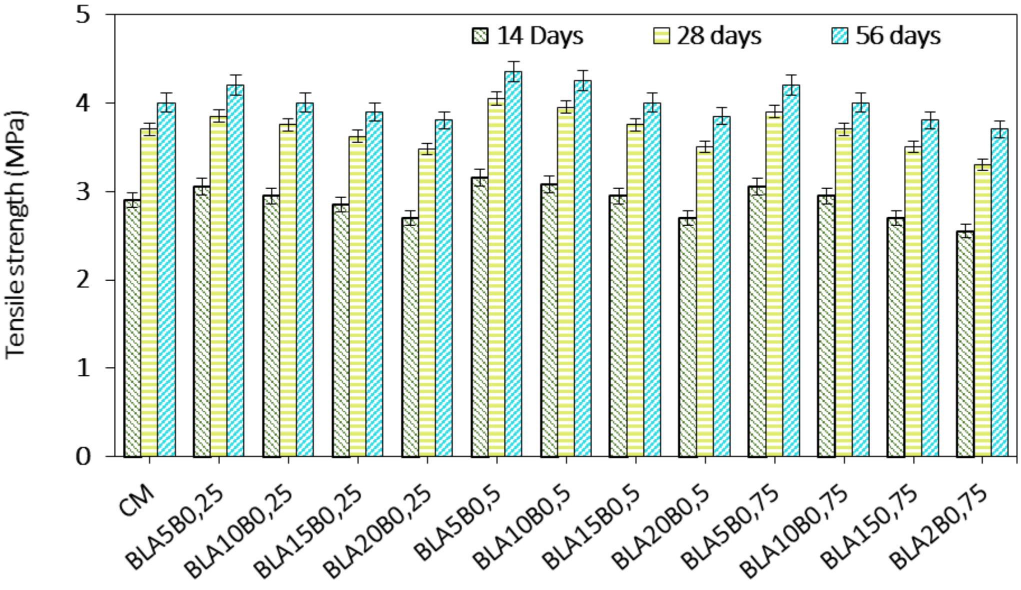

Figure 7. Split tensile strengths of all the mixes

4.5 Flexural strength of concrete

The flexural strengths for concrete mixes containing BLA and BF were determined at 14, 28, and 56 d, as shown in Figure 8. Among all the mixes, the flexural strength of BLA5B0,5 increases by 8,93 % compared with that of CM. BLA20B0,75 exhibits the maximum reduction of 12,50 %. CM achieves a flexural strength of 5,60 MPa at 28 d, whereas BLA5B0,5 exhibits a maximum value of 6,10 MPa, indicating an increase of 8,9 % over that of CM. The incorporation of up to 5-10 % of BLA enhanced the flexural strength across all fibre contents, particularly when the volume fraction of BF was 0,5%. The strength decreased progressively when either the BLA content exceeded 10% or the fibre content increased to 0,75 %. The improvement in flexural strength was attributed to two key factors: the pozzolanic activity of BLA, which produced additional CSH gel that improved the matrix density and bonding with fibres, and the bridging effect of BF under flexural loading, which effectively arrested crack propagation and enhanced post-cracking performance. The optimum mix (BLA5B0,5) exhibited superior flexural performance owing to the availability of sufficient calcium hydroxide for secondary CSH formation, improved ITZ quality and matrix densification, uniform fibre dispersion at 0,5 % and enhanced crack bridging without compromising workability. At higher BLA levels (15-20 %), the flexural strength decreased owing to the dilution effect, where excessive ash reduced the effective cement content and disrupted matrix continuity. Similarly, BF contents beyond 0,5% reduced the strength owing to fibre clumping and balling, increased matrix porosity, and impeded load transfer across cracks. The standard deviation and coefficient of variation of the flexural strength of concrete for various mixes are listed in Table 3.

Table 3. Standard deviation and coefficient of variation for the various mixes

Mix ID	14 days		28 days		56 days	
	SD	COV	SD	COV	SD	COV
CM	0,061	0,0136	0,059	0,0105	0,0970	0,0162
BLA5B0,25	0,043	0,0091	0,034	0,0059	0,0450	0,0073
BLA10B0,25	0,074	0,0161	0,061	0,0107	0,0860	0,0141
BLA15B0,25	0,059	0,0134	0,036	0,0067	0,0560	0,0096
BLA20B0,25	0,034	0,0081	0,054	0,0106	0,0360	0,0064
BLA5B0,5	0,061	0,0127	0,081	0,0133	0,0740	0,0114
BLA10B0,5	0,036	0,0077	0,073	0,0124	0,0810	0,0129
BLA15B0,5	0,074	0,0168	0,100	0,0182	0,0730	0,0124
BLA20B0,5	0,055	0,0134	0,097	0,0194	0,0610	0,0111
BLA5B0,75	0,054	0,0117	0,045	0,0075	0,0430	0,0067
BLA10B0,75	0,081	0,0180	0,086	0,0151	0,0740	0,0119
BLA15B0,75	0,073	0,0174	0,056	0,0109	0,0590	0,0104
BLA20B0,75	0,094	0,0235	0,076	0,0156	0,0768	0,0142

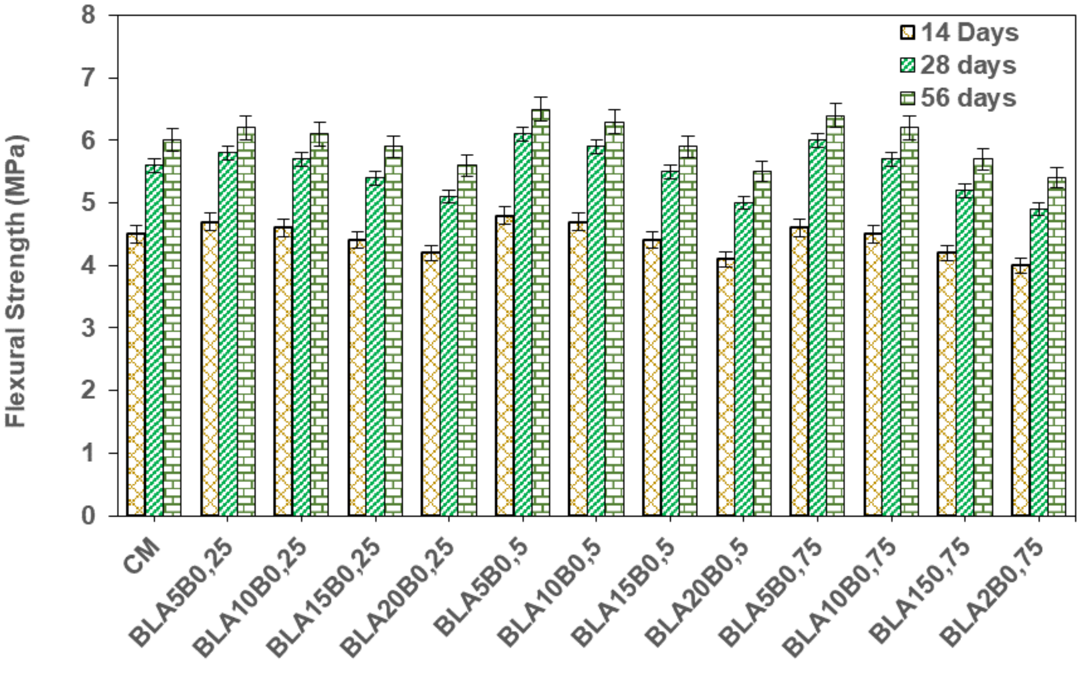

Figure 8. Flexural strengths of the mixes

4.6 Correlation between hardened properties

Figure 9 illustrates the correlation between the compressive and split tensile strengths of the various concrete mixes containing BLA and BF. Three distinct linear relationships are observed among the different groups of mixes. The high values of the coefficient of determination (R^2) for all three cases indicate a strong positive linear correlation between the compressive and split tensile strengths. The regression trends suggest that the split tensile strength increases linearly with the compressive strength, which is consistent with the classical mechanical behaviour of concrete. However, the different regression slopes and intercepts across the groups indicate the effect of the varying BLA replacement levels and BF content on the tensile behaviour relative to the compressive strength. Group 1, with the highest slope (0,1179), indicates a steeper rate of increase in split tensile strength relative to compressive strength, which may be attributed to optimal fibre bridging and improved matrix densification at lower BLA levels (5-10 %) combined with moderate fibre content (0,25-0,50 %). This observation matched the findings of [30], where natural fibres at a volume fraction of 0,5 % maximised the tensile efficiency per unit increase in compressive strength. Groups 2 and 3 exhibit lower slopes, which indicate lower gain in the tensile strength per unit compressive strength. This can be attributed to either higher BLA percentages (≥ 15 %) leading to excess ash-induced matrix dilution or excessive fibre content (0,75 %) causing poor fibre dispersion and increased porosity. This has been highlighted by studies on pozzolanic and fibre-reinforced eco-concretes.

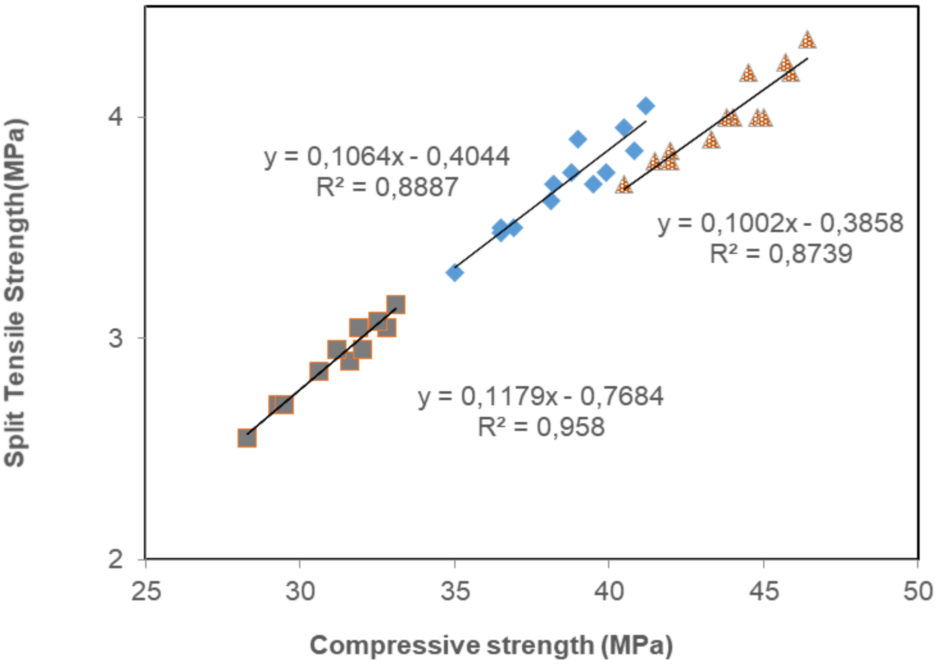

Figure 9. Correlation between the compressive and split tensile strengths

5 Conclusions

The combination of 5-10 % BLA and 0,5 % BF demonstrated optimal improvements in the split tensile strength, particularly at later curing ages (56 d), thereby validating the synergistic effect of pozzolanic activity and fibre reinforcement. Incorporating 5 % BLA and 0,5 % BF into the concrete significantly improved the flexural strength by up to 8,9 % at 28 d compared with the control concrete. Excessive ash and fibre content impaired the performance owing to matrix dilution and fibre entanglement. An optimum balance between the ash pozzolanic activity and fibre bridging effect is essential for maximising the flexural performance of eco-friendly concrete composites. The analysis confirmed that the relationship between the compressive and split tensile strengths in BLA and BF concrete follows a reliable linear trend, with optimum mix designs yielding superior strength synergy. Careful adjustment of the ash and fibre content is crucial for maximising the structural performance without compromising the balance between the compressive and tensile properties.

6 Suggestions for future research

Future studies on concrete containing coconut shell ash and coconut fibre can be conducted under extreme conditions, such as exposure to sulphate and chloride, carbonation, and freeze-thaw cycles. Research into innovative ways to treat fibres, mixing them with other cementitious materials such as fly ash or silica fume, and adding chemicals could further improve the workability and performance. In addition, microstructural studies using SEM and XRD, as well as predictive modelling using statistical and artificial intelligence techniques, can further aid in improving the mix design.

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