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Research Article

Impact of Addition of Banana Fibres at Varying Fibre Length and Content on Mechanical and Microstructural Properties of Concrete

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This experimental study aimed at investigating the impact of addition of banana fibres on the mechanical (compression, splitting tension, and flexure) and microstructural (microscopic morphology and Energy Dispersive X-ray Spectroscopy) properties of concrete. Concrete mixes comprising of banana fibres of varying fibre lengths (40, 50, and 60 mm) and fibre contents (0.1, 0.2, 1.0, 1.5, and 2.5%) were assessed. Addition of banana fibres to concrete was observed to significantly impact on compressive strength only at lower fibre contents of up to 0.25% for all fibre lengths. Fibre length had no significant impact on compressive strength at lower fibre contents of up to 0.25%, but shorter fibres were observed to perform better than longer ones at higher dosages more than 0.25%. Increase in fibre content positively impacted on tensile strength of concrete at relatively lower fibre dosages of up to 1%. Similarly, fibre length impacted on tensile strength of concrete at lower fibre contents of up to 1% and, longer fibres were observed to be more effective than shorter ones. Addition of banana fibres generally did not greatly contribute to flexural strength of concrete but had a marginal impact only when shorter fibres were used at lower fibre dosages. Also, microstructure of concrete was improved through better bonding between the fibres and the matrix and reduction in porosity of the matrix, which resulted in improved mechanical properties of the composite. Banana fibres further contributed to changes in phases of the composite structure of Banana fibre-reinforced concrete (BFRC) through a reduction in its interplanar spacing and lattice structure. For optimal purposes, addition of banana fibres should be limited to a maximum of 1% fibre content preferably using shorter fibre lengths. Further research to improve flexural strength of BFRC to meet minimum technical requirements is required before it can be considered for structural applications.

1. Introduction

Concrete is one of the most widely used material in the construction industry because it offers good strength and durability properties, and its primary constituents are readily available and cheap [1–3]. Despite its numerous advantages, concrete is also well known to have several weaknesses, such as a low tensile strength capacity that is significantly lower than its higher capacity to resist compressive loading, brittleness, low postcracking capability, and low fracture resistance [4–10]. This makes it highly susceptible to large tensile or flexural stress-induced damages that often lead to cracking in concrete, which in turn negatively impacts on its strength and durability [6, 11, 12].

Recently, natural fibres have been advanced as an alternative reinforcing material to conventional synthetic fibres owing to their environmental and economic benefits [13–20]. Natural fibres are readily available, biodegradable, cheaper, and recyclable, and they have been observed to have high tensile and flexural strengths as well as low elongation at break, hence rendering them widely accepted in construction industry [21–24]. Elbhiery et al. [20] compared and summarised the mechanical properties of various plant fibres and E-glass. However, studies conducted on the performance of natural fibres have pointed to durability-related problems, such as their inability to deal with external damage due to moisture absorption, biological microorganisms, sulphate, or chloride attack, as well as internal damage mainly because of compatibility issues between fibres (due to presence of organic substances such as waxes, lignin, and pectin) and alkaline-cement paste environment [13, 15, 25–29]. Nonetheless, the benefits associated with the utilization of natural fibres in reinforcing concrete outweigh the disadvantages; besides, corrective measures can be undertaken to mitigate the likely shortcomings through fibre surface modification and/or treatments [30, 31].

Also, limited studies have been conducted on utilization of some natural fibres, such as banana, sisal, hemp, coconut, and jute fibres, among others as reinforcing materials in concrete [19, 20]. Banana fibres are a good prospect because they can easily be extracted from banana pseudostems, which are otherwise often left to rot in plantations in form of an agricultural waste. Studies conducted on Banana fibres have indicated that they possess good performance properties, are environment friendly, are less expensive, and are readily available, and thus, it can be utilized to improve mechanical properties of concrete [9, 10, 14, 20, 32–35]. However, studies carried out have majorly been concentrated on a single fibre length while investigating the fibre content [7, 9, 10, 34–36]. Furthermore, limited research has been conducted on the impact of banana fibres on microstructure of concrete. Microstructure of fibre-reinforced concrete comprises aggregates, bulk cementitious matrix, and the interfacial transition zone as well and the fibre-matrix interfacial zone [37]. It is important to study the microstructure of concrete in order to develop a better understanding of the relationship between a specific microstructural feature and a distinct physical, chemical, or engineering property of the material [38, 39]. Scanning Electron Microscope (SEM) is mostly utilized to investigate and examine microstructural characteristics of concrete [40, 41]. Most studies on microstructure of concrete have mainly concentrated on sisal, eucalyptus, coconut, sugarcane, and basalt fibres but not banana fibres [8, 40, 42, 43]. A study on the effect of banana fibres on microstructure by Humphrey [7] focused on the application of the fibres in mortar but not concrete. Therefore, the purpose of this experimental study is to investigate the influence of different banana fibre lengths and fibre contents on the mechanical and microstructural properties of concrete. Findings of the study will provide a better understanding of the properties of banana fibres as well as the impact of varying fibre lengths and contents on the mechanical and microstructural properties of concrete.

2. Materials and Methods

2.1. Materials

2.1.1. Cement. Portland cement (CEM I 42.5 N) conforming to ASTM C150 [44] was used in all mixes. Chemical composition and the physical and mechanical properties of cement are given in Tables 1 and 2, respectively.

2.1.2. Aggregates. Coarse and fine aggregates used were crushed granite stone and river sand, respectively. The particle size distribution and physical properties of the aggregates complied with ASTM C33 [45] and are shown in Figure 1 and Table 3, respectively.

2.1.3. Banana Fibres. Banana fibres used were obtained by manually scrapping them from the banana sheath of the harvested pseudostems and then cut into different sizes. To deal with the durability shortcomings associated with organic substances that are found in natural fibres, such as waxes, lignin, and pectin, fibres were first treated by immersion in 5% sodium hydroxide solution for 60 minutes at room temperature. Thereafter, fibres were thoroughly washed with tap water for a minimum of 10 minutes to remove the hemicellulose, lignin, and wax surrounding the cellulose. This process is known to exposes cellulose and increase surface roughness of the fibres, as well as improving their interfacial bonding strength [46]. Cut banana fibres as well as their geometry and mechanical characteristics are shown in Figure 2 and Table 4, respectively. Also, the microscopic morphology of fibres observed by Scanning Electron Microscope (SEM) are shown in Figure 3.

2.2. Mix Proportions

2.2. Mix Proportions. Normal strength concrete mixes of C20/25 class were prepared using OPC (Ordinary Portland Cement) and crushed stone with the maximum nominal size of 19 mm. Some parameters of the mix proportion were kept constant for all mixes: W/C of 45%, water content of 192 kg/m^3, and sand to aggregate ratio (s/a) of 50%. Addition of banana fibres of different lengths and volume fractions was the main differentiation of the mixes. Three fibre lengths of 40 mm, 50 mm, and 60 mm were used in this experimental study and applied at varying volume fractions by weight of cement of 0.1%, 0.25%, 1.0%, 1.5%, and 2.5%. The mix design methods were used in conformity with the ACI standards [47, 48]. Mix proportions and banana fibre quantity of concrete per cubic meter are given in Tables 5 and 6, respectively.

2.3. Sample Preparation. Mixing process of concrete was in conformity with the ACI standards [47, 48] and involved pouring of aggregates, sand, and cement into an electrically operated mechanical mixer. Specifically, for only banana fibre-reinforced concrete, manual dispersion of the fibres into the mixer was done followed by dry mixing for 60 seconds. Thereafter, water was added into the mixer, and the ingredients were further mixed for 90 seconds. Dry mixing was necessitated in Banana Fibre-Reinforced Concrete (BFRC) to ensure good fibre dispersion, which resulted in a homogeneous composite and circumvented the balling effect, which would otherwise lead to the formation of fibre balls during mixing of concrete.

Concrete test specimens for compressive strength, split tensile strength, and flexural strength were all cast in triplicate as shown in Table 7, resulting in a total of 144 samples. After casting, the specimens were cured in air for 24 hours

Table 1: Chemical composition of cement.

Chemical composition	SiO_2	CaO	Fe_2O_3	MgO	Al_2O_3	SO_3	LOI	I.R
Percentage (%)	22.86	65.08	4.07	1.95	5.05	2.41	1.12	1.33

Table 2: Physical and mechanical properties of cement.

Type	Blaine fineness (0.08 mm) % (m^2/g)	Specific surface area (m^2/g)	Standard consistency	Soundness (mm)	Setting time (min)		Compressive strength (MPa)	
					Initial	Final	2 d	28 d
CEM I 42.5 N	2.2	349.9	27.8	0.5	154	293	20.9	48.1

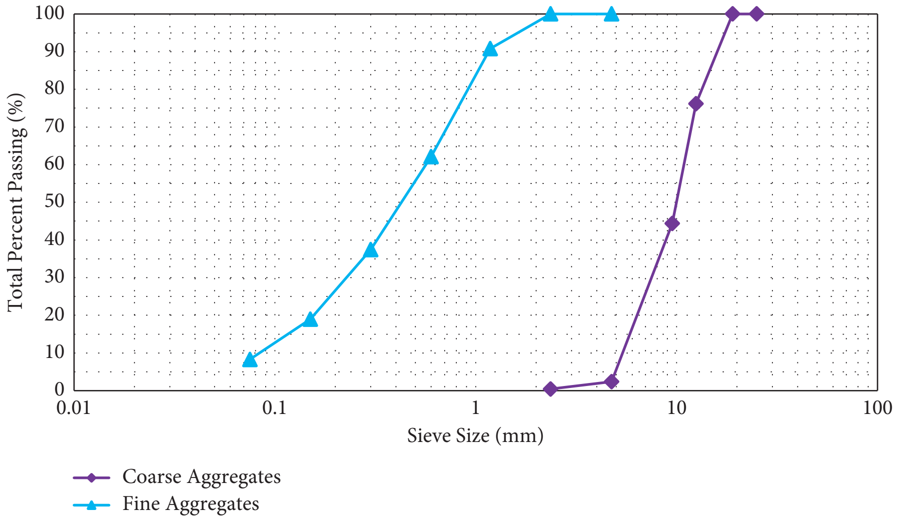


Figure 1: Particle size distribution of coarse and fine aggregates.

Table 3: Physical properties of aggregates.

Material properties	Coarse aggregate	Fine aggregate
Type	Crushed	River sand
Maximum size (mm)	19	4.75
Fineness modulus, FM	2.86	—
Water absorption (%)	0.61	0.37
Apparent density (g/m^3)	2800	2850
Mica content (%)	0.0	—
Fines < 0.075 mm (%)	2.74	—
Flakiness index (%)	—	9.5
Elongation index (%)	—	11.6

and thereafter demolded, immersed in a water tank, and cured at temperature of 20 ± 2°C for 28 days.

2.4. Test Method. Compressive and splitting tensile strength tests were performed in accordance with BS EN 12390-3 [49] and ASTM C496/C496M–17 [50], respectively. A Universal Testing Machine (UTM) with a 3000 kN maximum capacity was used at the loading rate of 0.6 MPa/s for compressive strength and 0.7 to 1.4 MPa/min for splitting tensile strength with the test setups as shown in Figures 4 and 5 , respectively. The maximum applied loads at failure were used to compute the compressive and tensile strengths using equation (1 and 2), respectively.

$$f_c = \left(\frac{P}{bd}\right), \tag{1}$$

where f_c is the compressive strength, MPa; P is the maximum applied load indicated by the testing machine, N; b and d are the average width and depth of specimen, mm.

$$f_t = \left(\frac{2P}{\pi l\, d}\right), \tag{2}$$

where f_t is the tensile strength, MPa; P is the maximum applied load indicated by the testing machine, N; l and d are the average length and diameter of specimen, mm.

Flexural tests under three-point loading were carried on a UTM with a capacity of 2500 kN at a loading rate of 0.1 mm/min in accordance with ASTM C293/C293M-16 [51] and the test setup is shown in Figure 6. The maximum applied load obtained at failure was used to calculate the flexural strength using equation (3).

$$f_f = \left(\frac{3Pl}{2bd^2}\right), \tag{3}$$

where f_f is the flexural strength, MPa; P is the maximum applied load indicated by the testing machine, N; b and d are the average width and depth of specimen, mm; and l is the span length of test specimen, mm.

Figure 2: Cut banana fibres.

Table 4: Geometry and mechanical characteristics of banana fibres.

Fibre parameter	Property
Stiffness (mm)	56.8
Weight (g)	56.8
Linear mass density (g/m)	1953
Diameter (μm)	102.82
Breaking strength (gf)	142.17
Breaking elongation (%)	3.22
Tensile strength (MPa)	167.89

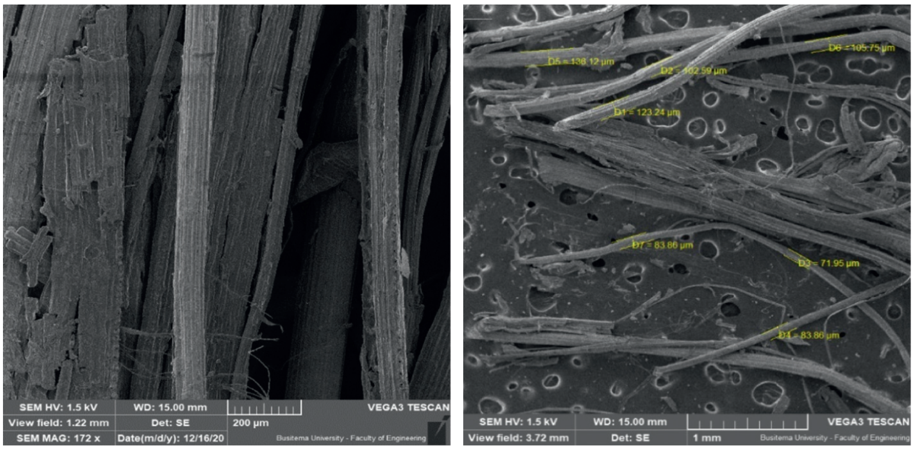


Figure 3: Images of banana fibre microstructure and diameter.

Microscopic morphology to determine general morphology was carried out on samples using a Variable Pressure Scanning Electron Microscope in accordance with ASTM standards [52, 53], and the test setup is shown in Figure 7. Also, Energy Dispersive X-ray Spectroscopy (EDS/XRD) to identify relative intensities at different diffraction angles within the composite was conducted on powdered samples in accordance with ASTM standards [53], and the test setup is shown in Figure 8.

3. Results and Discussion

3.1. Mechanical Properties. Mechanical properties of compressive, splitting tensile, and flexural strengths of Plain concrete (i.e. without fibres) and Banana Fibre-Reinforced Concrete (BFRC) mixes were determined, and the results are presented. For BFRC mixes, fibre lengths and contents were varied as follows: fibre lengths (40, 50, and 60 mm) and fibre contents (0.1, 0.2, 1.0, 1.5, and 2.5%).

Table 5: Mixture proportions.

Grade	Aggregates (mm)	W/C	Materials quantity (kg/m^3)			
			Water	Cement	Coarse aggregates	Fine aggregates
C20/25	19	0.45	192	444	1166	709

Table 6: Quantity of fibres for various mixes.

Fibre content (%)	0.0	0.1	0.25	1.0	1.5	2.5
Fibre quantity (kg/m^3)	0.0	0.44	1.11	4.44	6.66	11.1

Table 7: Concrete specimens prepared for testing.

Parameter	Plain concrete	BFRC	Dimension (mm)
Compressive strength	3	45*	150 × 150 × 150 mm cubes
Split tensile strength	3	45*	200Ø × 300 mm cylinders
Flexural strength	3	45*	100 × 100 × 350 mm beams

*5 (Fibre content) × 3 (Fibre length) × 3 (replicates) = 45 samples.

Figure 4: Compressive strength test setup.

3.1.1. Compressive Strength. Compressive strengths of Plain concrete ($f_{c(\text{Plain})}$) and BFRC ($f_{c(\text{BFRC})}$) as well as the compressive strength reinforced ratio ($f_{c(\text{BFRC})}/f_{c(\text{Plain})}$) at varying fibre lengths and contents are shown in Figure 9. It was clearly observed in Figure 9 that compressive strength values decreased with increasing fibre content at all fibre lengths. A similar behavior was observed in other previous studies conducted on fibre-reinforced concrete [54–56]. Xiong et al. [55] reported that compressive strength of concrete containing recycled carbon fibre-reinforced polymer (RCFRP) fibres decreased from 54.89 to 49.09 MPa when the fibre content was increased from 0.5 to 1.5%. A reduction in compressive strength is attributed to increase in porosity of the concrete matrix as a result of the addition of fibres, creating large contents of pores and microcracks at the matrix-fibre interface. Furthermore, reduction in compressive strength with increasing fibre content is likely to be associated with the effect of fibres on Interfacial Transition Zones (ITZs) and voids in concrete. It is expected that the more the amount of fibres, the more the ITZs will be created in concrete, which in turn negatively affects the compressive strength. Also, suggestions have been advanced that addition of fibres in concrete can restrict the lateral dilation instigated by Poisson effect when subjected to axial compression [57].

However, as shown in Figure 9(b), additional of fibres up to 0.25% resulted in higher compressive strength values in BFRC compared with Plain concrete, whereas an opposite trend was observed with fibre contents above 0.25%. Increase in compressive strength of BFRC in comparison with Plain concrete at increasing fibre content up to 0.25% was thought to result from the reinforcing action of fibres, which leads to the loads generated being shared between the fibres and concrete [2, 16]. Also, incorporation of banana fibres in concrete alters its failure mode from a brittle to plastic failure and hence mitigating the formation and propagation of cracks. Similar results were observed by other researchers who reported that fibres control microcrack formation and lead to the delay in failure and hence increasing the ultimate strength and strongly contribute in the load carrying capacity of the postpeak phase [58–60]. It has also been suggested that incorporating fibres in concrete enables it to resist extra compressive stress by blocking and redirecting the cracks [61]. Above 0.25% fibre content, the lower strength values of BFRC compared with Plain concrete can

(a) (b)

Figure 5: Splitting tensile strength testing. (a) Splitting tensile strength test setup. (b) Failure mode of concrete under splitting tension.

(a) (b)

Figure 6: Flexural strength testing. (a) Flexural strength test setup. (b) Failure mode of concrete under bending.

be attributed to the large quantity of fibres/excessive fibre content in the concrete having an adverse effect on compressive strength. Similar results were observed by other researchers [7, 9, 10, 34–36, 62–64] with Humphrey [7] noting that large quantity of fibres in the mortar produced voids and created nonuniform distribution within the composite, which led to reduced compressive strength.

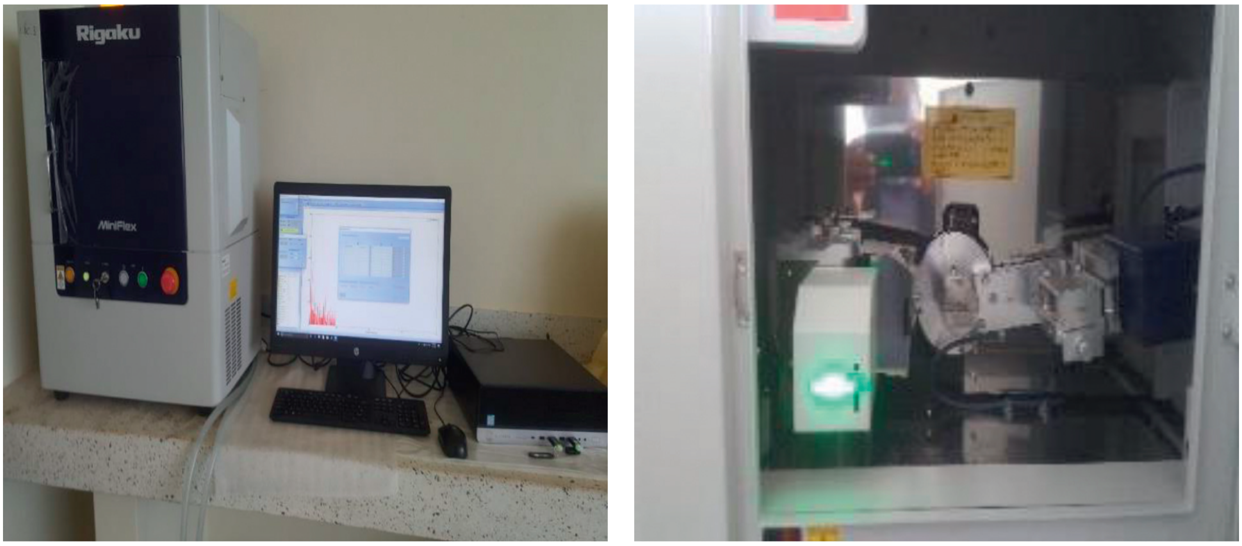
In relation to fibre length, shorter fibres exhibited higher compressive strength values compared with longer fibres for BFRC containing fibre content over 0.25%. However, it should be noted that for all BFRC mixes with fibre content above 0.25%, only concrete containing shorter 40 mm fibres at 1% fibre content had higher compressive strength values compared with Plain concrete. This finding indicated that for optimal purposes, the banana fibre content should be limited to a maximum of 1% preferably using shorter fibres instead of longer ones. However, the effect of fibre length was not clear for BFRC containing fibre content up to 0.25% because longer 60 mm fibres showed marginally lower compressive strength values than shorter 40 mm fibres but distinctly higher values compared with shorter 50 mm fibres. The above clearly shows that for compressive strength of BFRC, the amount of fibres used is predominant compared with the fibre dimension/length when lower fibre contents are applied while the fibre dimension/length is predominant to the amount of fibres when higher fibre contents are applied.

3.1.2. Splitting Tensile Strength. Splitting tensile strengths of Plain concrete ($f_{t(\mathrm{Plain})}$) and BFRC ($f_{t(\mathrm{BFRC})}$) as well as the splitting tensile strength reinforced ratio ($f_{t(\mathrm{BFRC})}/f_{t(\mathrm{Plain})}$) at varying fibre lengths and contents are shown in Figure 10. It was generally observed in Figure 10 that increase in fibre content up to 1% resulted in increase in splitting tensile strength values of BFRC with the exception of concrete with 60 mm length that experienced a drop in strength when fibre content was increased from 0.25% to 1%. However, it was observed that beyond 1% of fibre content, all BFRC mixes exhibited a drop in strength values with increasing fibre content. A similar behavior of an initial increase in tensile strength up to a certain amount of fibre content and thereafter experiencing a drop with further increase in fibre content has been observed in another study [58]. Wu et al. [58] observed that for all fibres used (i.e. polypropylene, glass, and basalt fibres), splitting tensile strength of apricot shell concrete (ASC) significantly increased when the fibre content was increased from 0.25 to 0.50% but then dropped when the fibre content was increased from 0.5 to 0.75%. Increase in strength of BFRC up to 1% can be attributed to the bridging action of the fibres across the cracks inside the concrete matrix, which in turn inhibits crack propagation due to load sharing. Also, as already discussed, incorporation of banana fibres in concrete alters its failure mode from a brittle to plastic failure especially as the fibre content

(a)

(b)

Figure 7: Microscopic morphology testing using a scanning electron microscope. (a) Variable SEM equipment. (b) Sample preparation for SEM.



(a)

(b)

Figure 8: Energy dispersive X-ray spectroscopy testing.

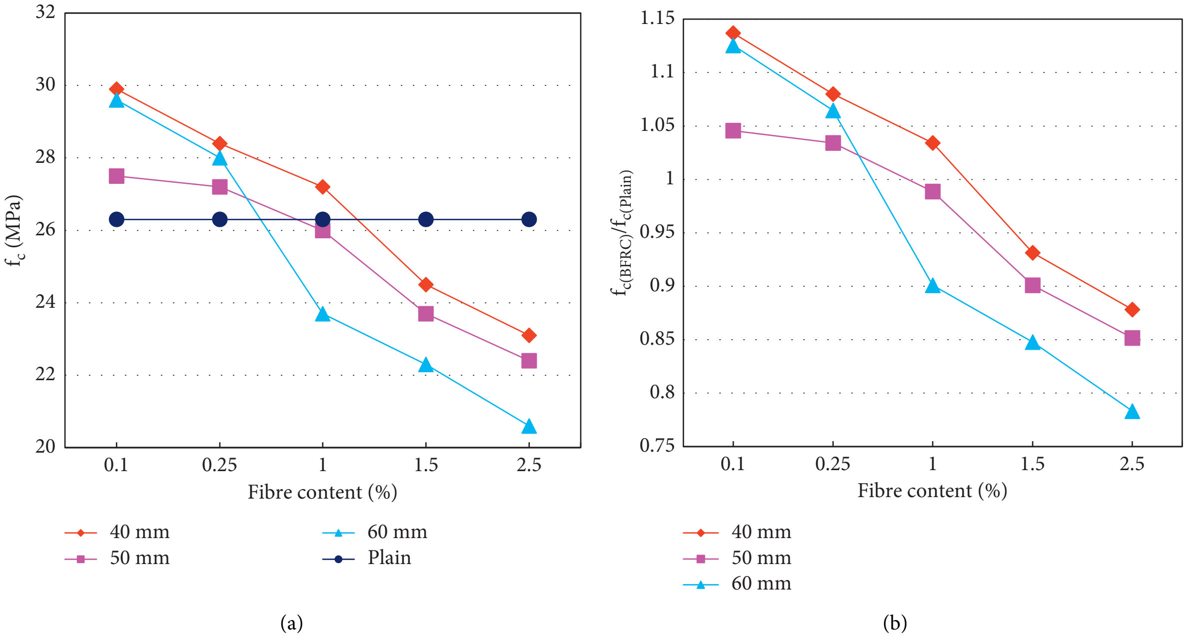


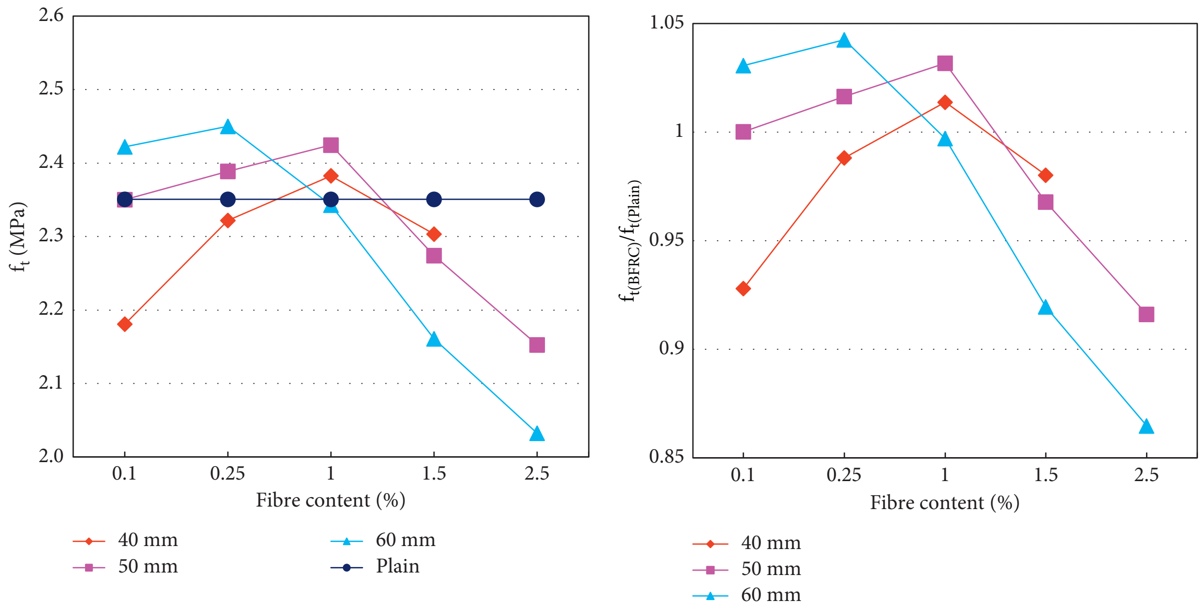
Figure 9: Effect of fibre length and fibre content on compressive strength of concrete. (a) Compressive strength. (b) Compressive strength reinforced ratio.

increases because fibres adequately inhibit the formation and propagation of cracks as well as limiting the confluence of cracks and adsorbing more destructive energy in the end [59]. Similar results were observed by other researchers who reported that addition of fibres had a significant improvement in tensile strength because they slowed down crack propagation, thereby enhancing mechanical strength of concrete [16, 58, 65, 66]. A drop in tensile strength of BFRC beyond 1% of fibre content can be attributed to excessive amount of fibre content in the concrete, which end up having an adverse effect on the strength of concrete as was similarly observed for compressive strength.

In relation to fibre length, BFRC having longer fibres exhibited higher tensile strength values compared with that having shorter fibres up to 1% of fibre content, except for BFRC having 60 mm length fibres at 1% fibre content. A similar effect of fibre length was observed when comparing plain and BFRC up to 1% fibre content. As shown in Figure 10(b), BFRC with longer fibre lengths of 60 and 50 mm exhibited better performance in comparison with Plain concrete, whereas strength values of BFRC with 40 mm length fibres were lower than those of Plain concrete. Longer fibres are expected to have contributed more in the mitigation of the pull-out effect of fibres compared with shorter fibres, thus preventing cracking and crack propagation [67]. The above phenomenon is therefore responsible for BFRC having longer fibres showing higher tensile strength values compared with that having shorter fibres up to 1% of fibre content.

However, although tensile strength was decreasing with increasing fibre content for all BFRC mixes containing fibre content above 1%, BFRC with shorter fibres exhibited higher tensile strength values compared with that containing longer fibres. This could be related to the cumulative amount of fibres in concrete, with longer fibres resulting in excessive amount of fibres at higher fibre dosage, which significantly diminish its performance due to the fibre curling and clustering. Furthermore, longer fibres are known to result in difficulty of dispersion of fibres during the mixing process [34]. Nonetheless, all BFRC mixes with fibre content above 1% exhibited lower strength values in comparison with Plain concrete. The above clearly shows that for tensile strength of BFRC, longer fibres performed better than shorter fibres up to 1% fibre content, with an opposite trend noticed above 1% fibre content. This phenomenon is more pronounced at the extreme ends of fibre dosage (i.e. 0.1% and 2.5%).

3.1.3. Flexural Strength. Flexural strengths of Plain concrete ($f_{f(\text{Plain})}$) and BFRC ($f_{f(\text{BFRC})}$) as well as the flexural strength reinforced ratio ($f_{f(\text{BFRC})}/f_{f(\text{Plain})}$) at varying fibre lengths and contents are shown in Figure 11. It was generally observed in Figure 11 that except for BFRC containing 40 mm length fibres at a dosage of 0.25%, flexural strengths of all BFRC mixes were lower in comparison to Plain concrete. The above observation indicated that addition of banana fibres generally does not greatly contribute to flexural strength of concrete but only has marginal impact when shorter fibres are used at lower fibre dosage. Similar results were observed by other researchers who reported that when compared with Plain concrete, addition of fibres had no significant impact on the flexural strength and stiffness of fibre-reinforced concrete [20, 68, 69]. This insignificant impact on flexural strength of BFRC could be attributed to banana fibres not providing the composite structure with a better capacity to resist high flexural deformations because of the loss of homogeneity and increased porosity caused by fibre addition. However, the general trend indicated that flexural



(a)

(b)

Figure 10: Effect of fibre length and fibre content on split tensile strength of concrete. (a) Splitting tensile strength. (b) Splitting tensile strength reinforced ratio.

strength of BFRC containing shorter fibres increased and peaked at a fibre content ranging between 0.25% and 1.0% before dropping with increasing fibre content. Contrastingly, the flexural strength of all BFRC mixes containing longer fibres decreased with increasing fibre content. This is similar to the results for splitting tensile strength of BFRC containing longer fibres at high-fibre dosage and is related to the difficulty of dispersion of longer fibres during the mixing process [34].

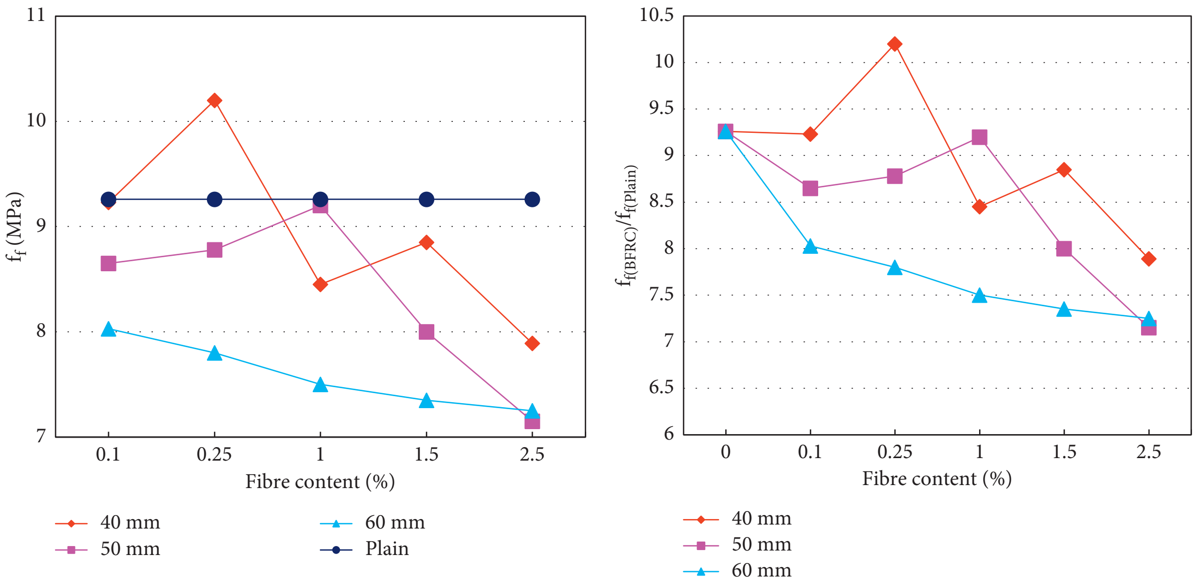
The above observed insignificant impact of banana fibres on flexural strength of BFRC is a critical disadvantage for their practical application in the construction industry in relation to the service deflection limits provided for in most technical specifications and codes of practice. Therefore, more research on how to improve the flexural strength of BFRC to meet the minimum technical requirements is paramount before banana fibres can be considered for structural applications in construction industry.

3.2. Microstructural Properties

3.2.1. Concrete Morphology under SEM. Concrete morphology was aimed at understanding the effect of the fibres on the interfacial transition zones (ITZs), microcracks, and their propagation in the matrix between fibre-cement paste and aggregate-cement paste. Microscopic morphology of Plain concrete and BFRC samples observed using SEM is shown in Figures 12 and 13, respectively. As shown in Figure 12, it was observed that Plain concrete exhibited a porous morphology with varying sizes, had normal setting, and the ITZ was identified between bulk paste-aggregate composite of approximately 50 μm [37], even though it was not clear. High porosity observed can be attributed to initial water absorption, which affected the rate of hydration. The above findings are similar to those from another study [43]. However, BFRC exhibited larger rectangular voids or pores within the matrix with clearly defined boundaries as shown in Figure 13. Furthermore, a clear ITZ was observed between fibres and paste ranging between 3.23 and 5.89 μm, and the fibres could be readily identified.

Furthermore, microcracks were observed within the composite of Plain concrete compared with BFRC, where no clear microcracks were observed. This could be attributed to the addition of the fibres, which alleviated bridged against the formation of the microcracks and prevented them from further propagation. This is consistent with results for the mechanical properties of compressive, splitting tensile, and flexural strengths of the concrete mixes already discussed. Furthermore, the fibres were observed to be surrounded by cement paste, which also has a bearing on improving the matrix strength resulting from a stress transfer mechanism between the matrix and reinforced fibres. This coupled with its resistance against tensile stresses generated by applied loads helped to maintain the microstructure intact by resisting crack propagation. Therefore, it can be concluded that the incorporation of fibres improved the microstructure of concrete through better bonding between the fibres and the matrix as well as a reduction in the size of ITZ and consequently the porosity of the matrix by filling its pores, which ultimately resulted in improved mechanical properties of the composite as observed from the test results.

3.2.2. Energy Dispersive X-Ray Spectroscopy (EDS/XRD). Energy Dispersive X-ray Spectroscopy (EDS/XRD) was used to characterize samples prepared from Plain concrete and BFRC. Data were collected in the 2θ range between 3° and 80°



(a)

(b)

Figure 11: Effect of fibre length and fibre content on flexural strength of concrete. (a) Flexural strength. (b) Flexural strength reinforced ratio.

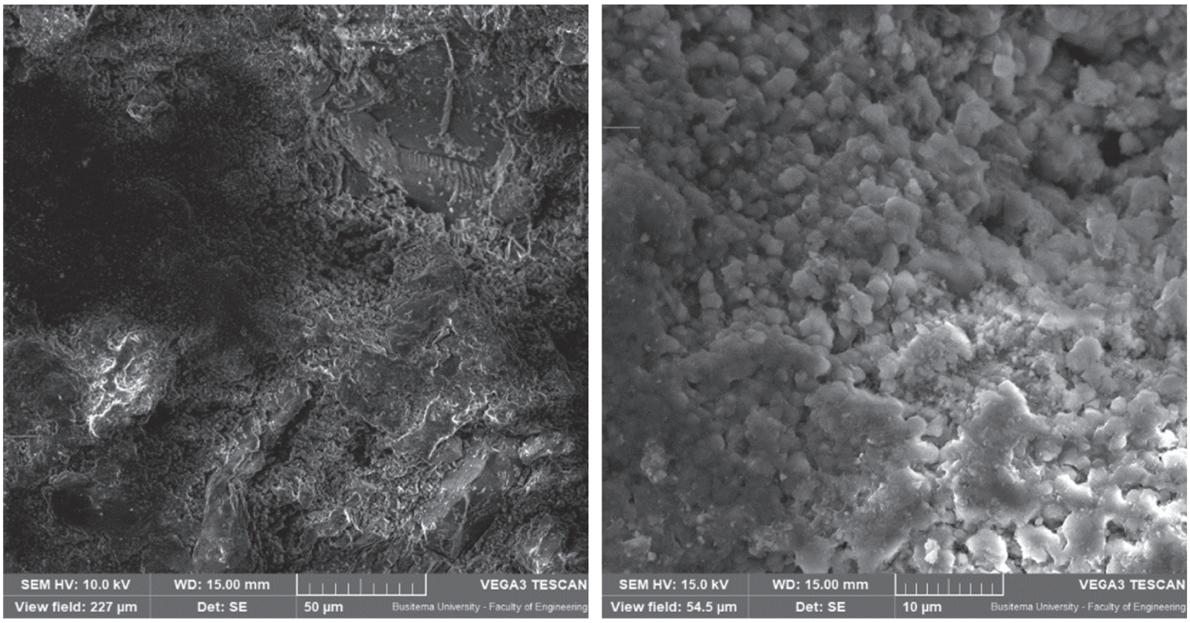


Figure 12: SEM morphology for plain concrete.

with a step size of 0.02° and a counting time of 0.06 sec./step. The XRD characteristic patterns of Plain concrete and BFRC samples at different diffraction angles and intensities that appear as peaks are shown in Figures 14 and 15 , respectively. It was observed that both Plain concrete and BFRC exhibited different peaks at different diffraction angles combined with sharp peaks, and higher characteristic peaks were achieved at 2θ range between 3° and 6° for both Plain concrete and BFRC as shown in Figures 14(b) and 15(b), respectively. As shown in Figure 14, the maximum characteristic peak intensity for Plain concrete was 13 counts occurring at a diffraction angle (2θ) of 4.28 with other similar corresponding peaks as follows: (3.04, 12.00), (3.14, 12.00), (3.28, 11.00), (3.68, 10.00), and (4.14, 9.00). For BFRC as shown in Figure 15, the maximum characteristic peak intensity observed was higher than that of Plain concrete at 25 counts occurring at an angle (2θ) of 3.04 with other similar corresponding peaks as follows: (3.00, 12.00), (3.06, 18.00), (3.16, 12.00), (3.28, 17.00), (3.82, 15.00), (3.94, 14.00), (4.26, 9.00), (4.42, 17.00), (5.72, 7.00), and (5.74, 10.00). Therefore, the patterns

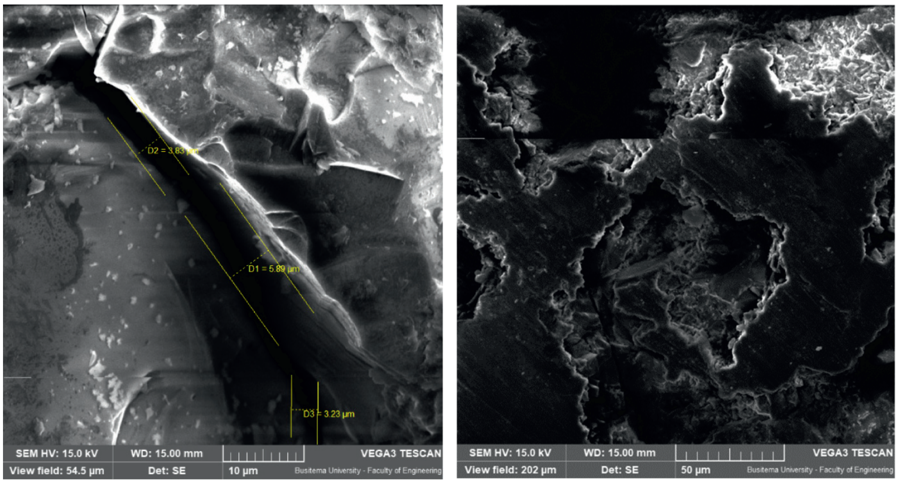
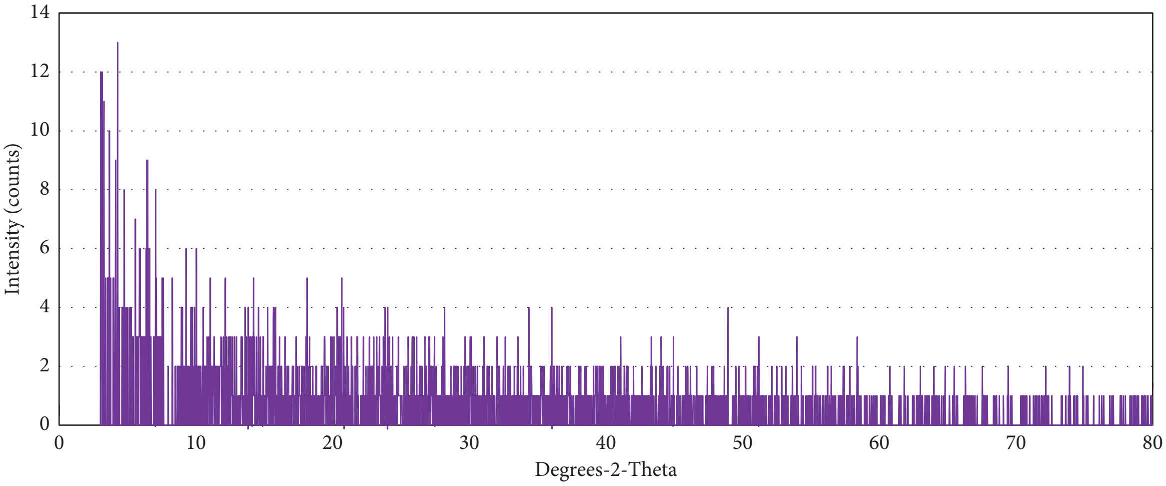
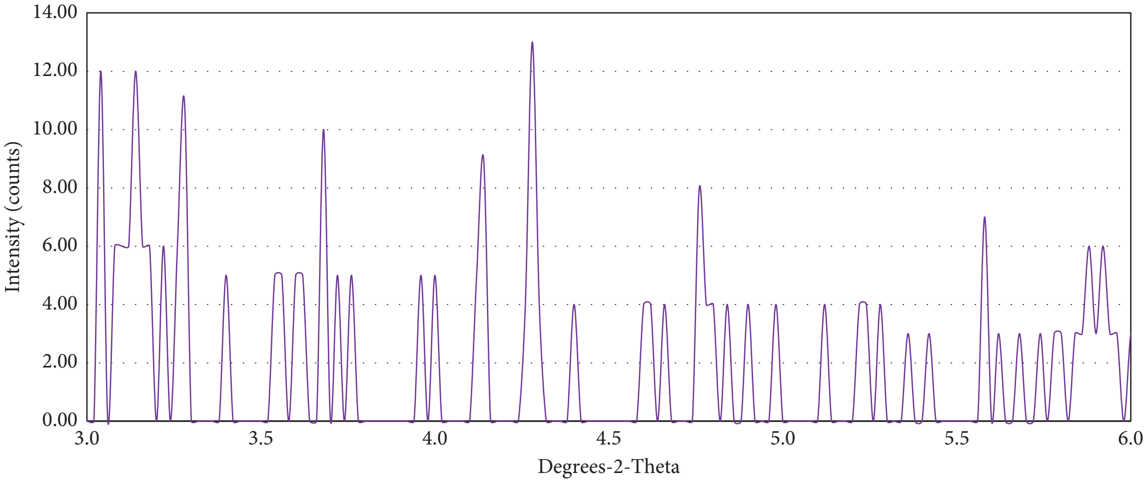


Figure 13: SEM morphology for banana fibre-reinforced concrete (BFRC).



(a)



(b)

Figure 14: XRD micrographs for plain concrete. (a) Characteristic patterns in the 2θ range between 3° and 80°. (b) Higher characteristic peaks in the 2θ range between 3° and 6°.

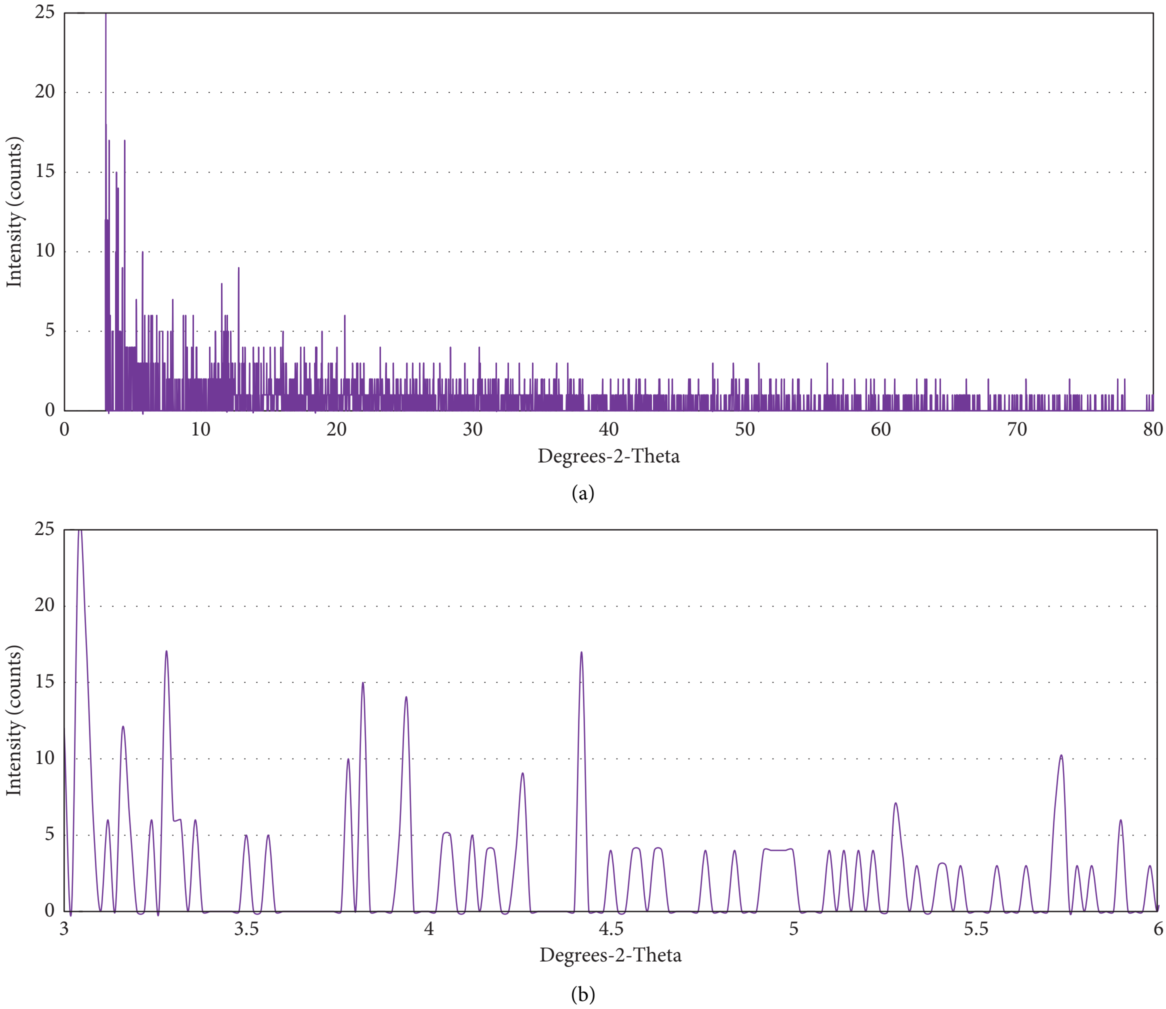


Figure 15: XRD micrographs for BFRC. (a) Characteristic patterns in the 2θ range between 3° and 80°. (b) Higher characteristic peaks in the 2θ range between 3° and 6°.

displayed for BFRC are greater in intensity than those for Plain concrete. It was further observed that there were variations in the shape of the peak intensities that were obtained. The higher peak intensities at a lower position (angle) indicated maximum interplanar spacing within the crystal structure, with the highest peaks for Plain concrete and BFRC having interplanar spacing (d) calculated as 206 Å and 29 Å, respectively, while the calculated lattice constant was 357 Å, and 50 Å meters, respectively. This indicated that the fibres contributed to changes in phases of the composite structure of the BFRC because the incorporation of fibres resulted in a reduction in the interplanar spacing and lattice structure of concrete.

4. Conclusions

This experimental study aimed at investigating the impact of addition of banana fibres on the mechanical and microstructural properties of concrete. Concrete mixes comprising banana fibres of varying fibre lengths (40, 50, and 60 mm) and fibre contents (0.1, 0.2, 1.0, 1.5, and 2.5%) were assessed against mechanical (compression, splitting tension, and flexure) and microstructural (microscopic morphology and Energy Dispersive X-ray Spectroscopy) properties. Based on the analysis carried out, the following conclusions can be drawn.

(1) Addition of banana fibres to concrete only significantly imparts on compressive strength at lower fibre contents of up to 0.25% for all fibre lengths because higher compressive strength was observed in BFRC compared with Plain concrete. However, there is no significant impact of fibre length on compressive strength at lower fibre contents of up to 0.25%. Impact of fibre length only becomes more pronounced at higher dosages above 0.25%, where BFRC with shorter fibre length perform better than that with longer ones.

(2) Increase fibre content only positively imparts on tensile strength of concrete at relatively lower fibre dosages of

up to 1%. Similarly, a significant impact of fibre length on tensile strength of concrete was observed at lower fibre contents of up to 1% with longer fibres noticed to be more effective compared with shorter ones, whereas an opposite trend was noticed above 1% fibre content. This phenomenon is more pronounced at the extreme ends of fibre dosages (i.e. 0.1% and 2.5%).

(3) Addition of banana fibres generally did not greatly contribute to flexural strength of concrete but had a marginal impact only when shorter fibres were used at lower fibre dosages. Contrastingly, the flexural strength of all BFRC mixes containing longer fibres decreased with increasing fibre content.

(4) Incorporation of banana fibres in concrete improved its microstructure through better bonding between the fibres and the matrix as well as a reduction in the size of ITZ and consequently the porosity of the matrix by filling its pores, which ultimately resulted in improved mechanical properties of the composite.

(5) Banana fibres contributed to changes in phases of the composite structure of the BFRC because their incorporation resulted in a reduction in the interplanar spacing and lattice structure of BFRC.

(6) For optimal purposes, addition of banana fibres should be limited to a maximum of 1% fibre content preferably using shorter fibres instead of longer ones. Further research on how to improve the flexural strength of BFRC to meet the minimum technical requirements is required before banana fibres can be considered for structural applications in construction industry.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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