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Banana agriculture waste as eco-friendly material in fibre-reinforced concrete: An experimental study

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Abstract. This paper investigates the impact of length and volume fractions (VFs) of banana fibres (BFs) on the mechanical and physical properties of concrete. The mechanical properties were compressive strength, splitting tensile, flexural strength, and bond stress, while the physical properties were unit weight and absorption. The slump test was used to determine workability. The concrete's behaviour with BFs was studied using scanning electron microscopy. Experimental work of concrete mixtures with BFs of various lengths (12 mm, 25 mm, and 35 mm) and VFs (0%, 0.5%, 1.0%, and 1.5%) were carried out. The samples did not indicate any agglomeration of fibres or heterogeneity during mixing. The addition of BFs to concrete with VFs of up to 1.50% for all fibre lengths have a significant impact on mechanical properties, also the longer fibres performed better than shorter ones at all volume fractions of BFs. The mix10, which contain BFs with VFs 1.5% and length 35 mm, demonstrated the highest mechanical properties. The compressive strength, splitting tensile, flexural strength, and bond stress of the mix10 were 37.71 MPa, 4.27 Mpa, 6.12 MPa, and 6.75 MPa, an increase of 7.37%, 20.96%, 24.13%, and 11.2% over the reference concrete, which was 35.12 MPa, 3.53 MPa, 4.93 MPa, and 6.07 MP, respectively. The absorption is increased for all lengths by increasing the VFs up to 1.5%. Longer fibres have lower absorption, while shorter fibres have higher absorption. The mix8 had the highest absorption of 4.52%, compared to 3.12% for the control mix. Furthermore, the microstructure of concrete was improved through improved bonding between the fibres and the matrix, which resulted in improved mechanical properties of the composite.

Keywords: banana fiber; bond stress; compressive strength; fiber-reinforced concrete; scanning electron microscopy; split tensile strength

1. Introduction

Concrete's widespread use as a construction material with various applications and suitable characteristics, such as durability, high strength, and low cost, is well established (Najaf and Abbasi 2022a, Kiruthigasri and Sathishkumar 2020, El-Sayed *et al*. 2013). Traditional concrete has poor tensile strength and cracks easily in service, which allows deleterious agents easy access to it and results in freeze-thaw damage, steel corrosion and discoloration (Saranya and Vijay Vikram 2018, Okeola *et al*. 2018). Furthermore, Rebar corrosion and structural deterioration in reinforced concrete Structures are popular, so many researchers have been looking for alternative materials for rehabilitation technologies (Bishett 2019, Geremew *et al*. 2021).

Fibre-reinforced concrete (FRC) is a type of concrete that contains water, hydraulic cement, aggregate and discontinuous discrete fibres (Ganesan *et al*. 2017, Mukhopadhyay and Bhattacharjee 2015). In the concrete matrix, fibres operate as multi-directional uniformly disseminated micro reinforcement (Sharma and Bansal 2019, Raja Rajeshwari and Sivakumar 2020). By exerting strain across the break, fibres bridge across the break and prevent it from developing (Fediuk *et al*. 2020, Haido *et al*. 2021).

Fibres added to concrete help increase its toughness in addition to its strength (Najaf and Abbasi 2022b). The presence of fibres in concrete controls thermal cracking and shrinkage during the plastic stage as well as micro-cracking in the concrete matrix during the loading stage (Rehman and Sudheer 2019, Dadmand *et al*. 2020, Maia Pederneiras *et al*. 2021). Fibres improve the tensile and shear strength, ductility, durability, fatigue resistance and shrinkage resistance of concrete (Anowai and Job 2017, Raj *et al*. 2021, Majeed *et al*. 2021, Nurwidayati and Fardheny 2021). There are numerous uses for fibre reinforced concrete, including in ground slabs, precast members, and shotcrete tunnel linings (Orouji *et al*. 2021, Attia *et al*. 2022a). Fibre form, type, length, cross-section, fibre strength, binding features, fibre content, matrix strength, concrete mix design and mixing all influence the efficiency of fibres in concrete (Attia *et al*. 2022b, Al-Oraimi and Seibi 1995, Asteris *et al*. 2021, Khalil *et al*. 2018).

According to their size, fibres are separated into two groups: microfibers and microfibers. Microfibers typically

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have a diameter of a few microns and a length of 6 to 20 mm. Due to their small size, they have little structural strength, even when the structure is in the large-deformation zone, but they are effective at reducing plastic shrinkage. On the other hand, microfibers with lengths of 30-60 mm and a diameter of greater than 0.3 mm can support heavier loads and stop the spread of large cracks after a cement matrix break, much like steel rebars can. As a result, they increase the concrete's performance after cracking and toughness (Xiaochun *et al*. 2017, Shi *et al*. 2020). Man-made and natural fibres (NFs) are the two types of fibres (Attia *et al*. 2022b, Jaradat *et al*. 2021, Thomas and Jose 2022, Kesavraman 2017). The ACI committee divides fibres into four categories: glass, steel, synthetic fibres, and natural fibres (Orouji *et al*. 2021). (Khan *et al*. 2022) studied the effect of steel fibre on mechanical Properties of Concrete. It founded that a 3 cm length and a 2% dosage of steel fibre, showed compression and flexure were excellent. Despite the fact that steel fibre is widely used in practise due to their high efficiency, they have some drawbacks, including poor workability, susceptibility to rusting, and also the ability to break (Balouch *et al*. 2010). (Ahmad *et al*. 2022) showed that the strength of concrete was increased by the addition of glass fibres, but the flowability was decreased. Glass fibres also have some drawbacks, such as poor mechanical properties, a weak alkaline resistance, and unpredictability in long-term use (Xiaochun *et al*. 2017).

Due to their excessive use, construction materials are now more expensive, which has a negative impact on the economy (Najaf *et al*. 2022a). NFs come from vegetable, animal, and mineral sources, whereas man-made fibres are manufactured from synthetic resources like steel and polymers (Indira *et al*. 2013, Ahamed *et al*. 2021, Peponi *et al*. 2008). The growing desire to develop environmentally friendly materials and minimise or eliminate the use of synthetic fibres is driving interest in NFs for a variety of technical applications (Bharathi *et al*. 2021, Alhijazi *et al*. 2020). Owing to its advantages over other conventional fibres and environmental concerns and increased environmental awareness, NF materials have drawn the attention of many researchers and scientists (de Azevedo *et al*. 2021, Campilho 2015).

Bananas are a popular fruit in many parts of the world, with almost 60% of banana biomass wasted after harvest (Kuyu and Tola 2018). Around 114.08 million metric tons of banana trash are produced worldwide, causing environmental issues such as excessive gas emissions (Alzate Acevedo *et al*. 2021). These wastes are high in important industrial materials, like cellulose, hemicellulose and NFs (García *et al*. 2020). Banana fibres (BFs) are a promising candidate because they can be removed readily from banana stalks, which are otherwise left to rot in plantations as agricultural waste (Jordan and Chester 2017).

Some studies used NFs in the cement mix, but only a few studies included BFs (Camargo *et al*. 2020, Majid 2012). BFs have been found to have good performance capabilities, high specific strength and fire resistance and are environmentally friendly and relatively expensive (Attia *et al*. 2021, Elbhiery *et al*. 2020). They are also readily available, suggesting that they can be used to improve the mechanical properties of concrete (Chandramouli *et al*. 2019, Savastano *et al*. 2000). However, most research examining fibre content has focused on a single fibre length (Mukhopadhyay and Bhattacharjee 2016, Danso 2020). Furthermore, only a limited number of studies have been conducted on the impact of BFs on concrete microstructure (Bentur and Mindess 2007).

2. Significance

The lands allocated to banana production globally amount to approximately 5.6 million hectares, with a production of 138.2 million tons, and Egypt recorded 1.35 million tons. Traditionally, the pseudo-stem is discarded after harvesting the fruit. This biomass, which amounts to 3.4 million MT per year, is discarded on farm boundaries and incinerated after natural drying. It was useful to recycle this natural resource (the banana pseudo-stem), transform it into a fibre, and stop this trend because it was not commercially nor environmentally viable. On the other hand, most studies looking at fibre composition have only looked at one fibre length. Therefore, the aim of this study is to investigate the effect of BFs with different lengths and volume fractions on the mechanical properties and microstructure of concrete.

3. Experimental programme

3.1 Materials

3.1.1 Cement

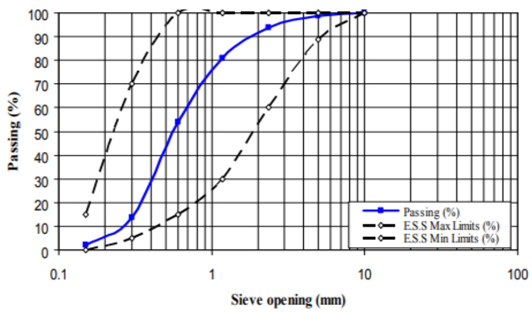
Ordinary Portland cement (OPC) CEM I 42.5 N by Egypt's Tourah factory was utilised. Table 1 shows the physical properties and chemical compositions of cement, which complies with (ASTM C150/C150M-19a 2019).

3.1.2 Aggregate

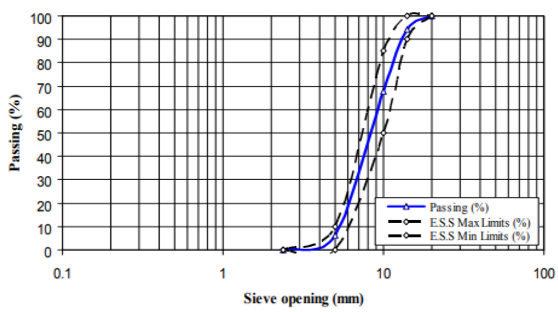
Natural fine and coarse aggregates were used. Siliceous sand with a specific gravity of 2.54 gm/cm^3 and water absorption of 1.7% was utilised as fine aggregate. Crushed stone free of impurities with a maximum nominal size of12 mm, water absorption of 1.1% and specific gravity of 2.67 gm/cm^3 was classified as coarse aggregate. Fig. 1

Table 1 Physical properties of cement

Physical properties	CEM I
Specific gravity	3.15
Blaine surface area (cm^2/g)	3300
Color	Gray
Chemical composition	
SiO_2	20.89
Al_2O_3	4.78
Fe_2O_3	3.94
CaO	63.01
MgO	2.01
SO_3	2.0
Na_2O	0.1
K_2O	1.99
L.O.I	



(a) Fine aggregate



(b) Coarse aggregate

Fig. 1 Sieve analysis of fine and coarse aggregates

illustrates a sieve analysis test of fine and coarse aggregates in accordance with the standard (ASTM C33/C33M-18 2018).

3.1.3 Admixture

To improve the workability of concrete, Sika ViscoCrete 3425 with a specific gravity of 1.08 and 2% of cement content was utilised. It conforms with the ASTM-C-494 Types G and F (ASTM C494/C494M-19 2019). Sika ViscoCrete 3425 is a dual-action liquid super-plasticiser that can be employed to make free-flowing concrete or as a significant water-reducing agent for ultimate strength and high early.

3.1.4 Banana fibres

The banana pseudo-stem was used in this study; it is a portion of the banana plant that resembles a trunk made up of a soft central core and tightly wrapped by up to 25 leaf sheaths. The wastes from banana plantations in Egypt's Nubaria Region were collected. A decorticator machine was used to remove fibres from banana pseudo-stem leaves. As soon as the pseudo-leaves' stems were cut, the extraction procedure began. Separating the fibre bundles from the remaining pieces is the first stage, known as tuxing. After the tuxing process, the non-fibrous parts and any remaining components in the fibres were removed in the second phase. Afterwards, the fibres were properly cleaned and dried in sunlight. Finally, as shown in Fig. 2, the fibres were sliced to the desired length. Table 2 shows the characteristics of BFs. Fig. 3 exhibits scanning electron microscopy (SEM) scans, and Fig. 4 illustrates the key elements determined by EDX spectrum analysis utilising the spot scan EDX of BFs.

Table 2 Characteristics of banana fibres

Properties	BFs
Mechanical properties	
Tensile strength (MPa)	754
Young's modulus (GPa)	27
Elongation at break (%)	10.35
L/D ratio	150
Physical properties	
Density (kg/m^3)	1350
Moisture content	10
Water absorption (%)	61.2
Width or diameter (μm)	80-250
Chemical composition (%)	
Cellulose	63.2
Hemicellulose	18.6
Lignin	5.10

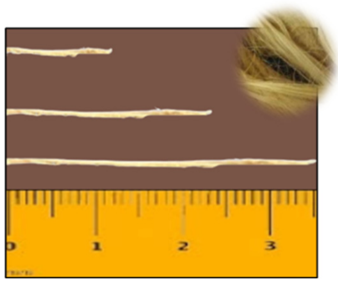


Fig. 2 Length of banana fibers

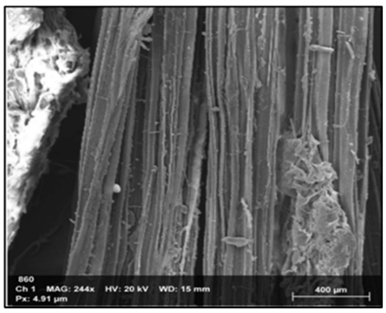


Fig. 3 SEM image of banana fibers

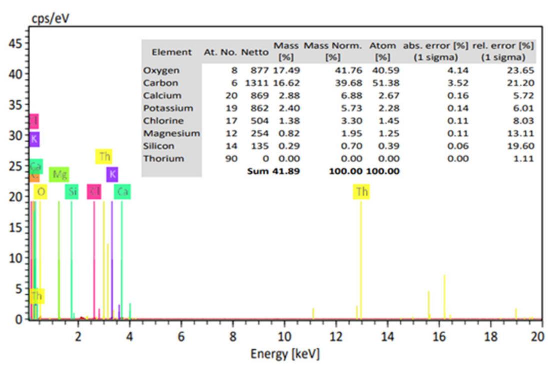


Fig. 4 EDX of banana fibers

Table 3 Proportions of concrete mixtures

No.	BFs (%)	BFs Length (mm)			Cement (kg)	Water (Liter)	Fine Agg. (Kg)	Coarse Agg. (Kg)	Admixture (liter)
		35	25	12					
1	0				400	175	925	1387	7
2		■			400	175	923	1384	7
3	0.5		■		400	175	921	1381	7
4				■	400	175	919	932	7
5		■			400	175	923	1384	7
6	1		■		400	175	921	1381	7
7				■	400	175	919	1378	7
8		■			400	175	923	1384	7
9	1.5		■		400	175	921	1381	7
10				■	400	175	919	1378	7

3.2 Mixing procedure

The ACI standard (ACI 211.1-91 2002, ACI 544.1R-96 2002) was used to establish the mix design for the OPC with and without fibres (OPC-Concrete). Table 3 shows the design proportions for the various mixes. The addition of BFs of various lengths and VFs was the main difference between the mixes. In this work, three fibre lengths of 35, 25 and 12 mm were utilised at different VFs of cement weight of 0.5%, 1% and 1.5%.

Concrete was mixed according to ACI guidelines (ACI 211.1-91 2002, ACI 544.1R-96 2002) which included introducing aggregates, sand and cement into the mixer and then dry mixing for 1.5 minutes. The mixing water, which contained a superplasticiser admixture, was added to the ingredients, and blended for another 2 minutes. Finally, the BFs were manually dispersed throughout the mixture and mixing was continued to ensure total homogeneity. In fibrous concrete, the prior technique was important to provide good fibre dispersion, thereby resulting in a homogeneous composite and avoiding the balling effect, which would have otherwise resulted in the development of fibre balls during concrete mixing.

3.3 Testing procedure

The properties of mixes were measured in both fresh and hardened stages. The slump test was performed according to the method in ASTM (ASTM C143/C143M-15a 2015). The compressive, tensile, bond stress and flexural strengths of the mixes were determined. Compression test was carried out on cubic samples with a size of 150 × 150 × 150 mm on 3, 7 and 28d in conformity with BS 1881–116 (1983). A Testing Machine with a maximum capacity of 1500 KN and a loading rate of 0.6 MPa/s was used to compressive test as shown in Fig. 5(a). An indirect splitting tensile test was performed on cylinder specimens with a diameter of 150 mm and a length of 300 mm on day 28 according to ASTM (ASTM C496/C496M-17 2017), as shown Fig. 5(b). The splitting tensile strength (f_t) of concrete was calculated using the following formula

$$ft = \frac{2 \cdot p}{\pi \cdot d \cdot L}\, MPa \tag{1}$$

Where P = Maximum applied load indicated by testing machine, (N). d = Diameter of the specimen, (mm). L = Length of the specimen, (mm).

A flexural test was done on prism samples with dimensions of 100 × 100 × 500 mm on day 28 in accordance with the method in ASTM (ASTM C78/C78M-18 2018), as shown Fig. 5(c). The specimens were tested under one point loading at the middle of the beam till failure. The modulus of rupture (f_r) was calculated using the following formula

$$fr = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot d^2}\, MPa \tag{2}$$

Where P = Maximum applied load indicated by testing machine, (N). b, d = Width and depth of beam, (mm). L = Span Length of the specimen, (mm).

(a) (b) (c)

Fig. 5 (a) Compression test; (b) Splitting test; (c) Flexural test

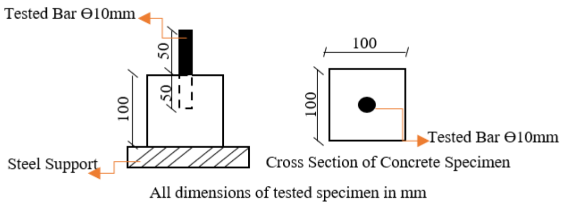


Fig. 6 Bond test of all specimens

Three 70 × 70 × 70 mm cubical specimens were used in the absorption test, which was performed according to ASTM C642-97 (2002). The bond stress process was performed on reinforcement steel bar-embedded in cubic specimens with a 100 × 100 × 100 edge as shown Fig. 6, according to Yazici and Arel (2013). A deformed steel bar with a diameter of 10 mm was employed as reinforcement in the bond tests. The reinforcement used has a yield strength of 482 MPa, tensile strength of 560 MPa and elongation ratio of 9.98%. The reinforcement inserted in the concrete has a bond length of 50 mm, resulting in a bond length that was five times the diameter of each specimen. The specimens wase cured in water for 28 days until test date. The bond strength was computed using the following equation

$$\tau = \frac{P}{\pi \cdot l_m \cdot d_P} \text{ MPa} \qquad (3)$$

Where τ is the bond strength, P is the ultimate load, L_m is the embedded length, and dp is the bar diameter.

Microscopic morphology was performed on samples using a Variable Pressure Scanning Electron Microscope (SEM) in accordance with ASTM standards (ASTM C856-95 1998, ASTM C1723-16 2016).

4. Results and discussions

4.1 Workability

As illustrated in Fig. 7, the slump test was conducted to determine the workability of concrete with and without BFs. It illustrates that, independent of fibre length, workability decreased as the VFs of fibres increased. This is because the BFs absorb water (Benaimeche *et al*. 2020). Regardless of the VFs or lengths of the fibres, the samples did not indicate any agglomeration of fibres or heterogeneity during mixing. The experimental data showed that increasing the BFs in samples with a length of 12 mm from 0% to 0.5%, 1% and 1.5% decreases workability by 20.69%, 26.64% and 32.02%, respectively, in 28 curing days. A similar conclusion was reached in laboratory research conducted by Kesavraman (2017). Meanwhile, for the samples that were 25 and 35 mm in length, they decreased by 30.46% and 22.7%, respectively, by increasing the BFs from 0% to 1.5%. (George *et al*. 2019) summarized that the workability decreases as the fiber does increase, and the lowest slump value showed at 1.5 percent fiber.

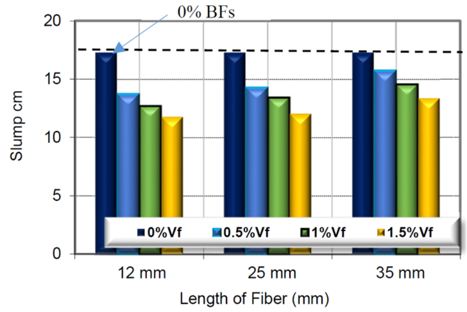


Fig. 7 Effect of fibre length and VFs of BFs on workability

Generally, when fibres were added, the slump value decreased, and when long fibres were used compared to short ones with the same amount of fibre, the slump value increased. The results exhibited a significant influence of fibre length on workability, which improved as fibre length increased. At 0.5% BFs, increasing the fibre length from 12 mm to 35 mm increased the slump value by up to 14.65%. The slump values for fibre with lengths of 12 mm, 25 mm, and 35 mm, wase 11.76 mm, 12.03 mm, and 13.37 mm respectively when using BFs by 1.5 percent. This due to, the long fibres may be uniformly distributed throughout the concrete matrix, and as their length increases, fewer of them are present in the matrix, which allows the concrete matrix material to flow (Behera *et al*. 2020). Furthermore, Limited-length fibres have a larger surface area, which improves the binding of fibre cement paste (Yew *et al*. 2015). Song *et al*. (2005) discovered that short length fibres had lower flowability than longer length fibres.

4.2 Unit weight properties

The influence of fibre length and VFs of BFs on the unit weight of concrete is shown in Fig. 8. It was observed that increasing BFs reduces the unit weight of concrete in general regardless of fibre length. The reason for this is that BFs have a lower specific gravity than other concrete constituents. The control mix, which without BFs, recorded unite weight 2489 kg/m^3. Compared to control mix, the unit weight of samples with a fibre length of 12 mm wase decreased by 1.5 to 2.9% when the VFs of BFs increased from 0%, to 1.5%, while the unit weight of samples with a fibre length of 25 mm recorded increased by 2.17% when the VFs of BFs increased up to 1.5%. The unit weight of samples with a fibre length of 35 mm decreased by 0.7%,

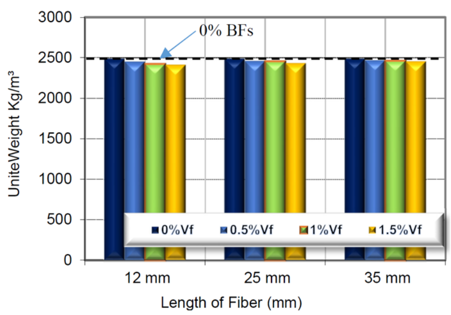


Fig. 8 Effect of fibre length and VFs of BFs on unit weight

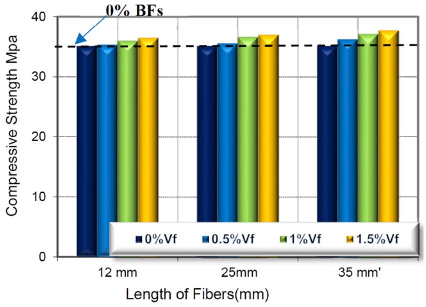


Fig. 9 Effect of fibre length and VFs of BFs on compressive strength

1.05%, and 1.3% when the VFs of BFs were 0%, 1%, and 1.5%, respectively. In comparison to samples with 12 mm, 25 mm and 35 mm fibres, those with 35 mm fibres length and volume fraction of 1.5% had the minimum density with 2415 kg/m^3.

4.3 Compressive strength

Among the features of concrete, compressive strength is the most important. The compressive strength of BFs is influenced by their VFs and fibre length, as shown in Fig. 9. By arresting fracture propagation based on the bond of BFs and cement paste, the incorporation of BFs into a matrix serves to insignificantly enhance ultimate compressive strength., The compressive strength of control sample, which without BFs, was 35.12 MPa. The compressive strength of samples BFs with 12 mm length and dosage 0.5%, 1%, and 1.5% were 35.32 MPa, 35.98 MPa, and 36.47 MPa, respectively, by increase up to 3.8%, compared to control mix. The compressive strength of sample BFs with 25 mm and 35 mm length and dosage 0.5% to 1.5% increased gradually to 5.27% and 7.37%. It can be seen the highest compressive strength of sample contained BFs with length 35 mm and dosage 1.5% which recorded 37.71 MPa.

Athiappan and Vijaychandrakanth (2014), determined the compressive strength of concrete by varying the fibre content by volume of cement from 0.1% to 0.2%, 0.3% to 0.4%, and 0.5%. The optimal fibre dosage was determined to be 0.3%, up to which the compressive strength increased. (Najaf and Abbasi 2022a), concluded that the compressive strength increases as the amount of fibres increases in the fibre types from 0 to 1.5%, with 1.5% fibres being the maximum dosage. This effect was achieved because of the high degree of compaction between the fibres and the matrix, which resulted in a homogeneous mix (Andiç-Çakir *et al*. 2014, Chandramouli *et al*. 2019, Ozerkan *et al*. 2013), It can be seen in samples with 1.5% and 12 mm length of BFs, which recorded the lowest slump test value of 11.76 mm compared to all samples and produces high-quality concrete have satisfy workability. Furthermore, the increase in compressive strength with increasing fibre content is most likely related to the effect of fibres on Interfacial Transition Zones (ITZs) and voids in concrete. It is expected that the greater the amount of fibres until 1.5%, the little the ITZs in concrete will be, which will have a positive effect on the compressive strength (Xiong *et al*. 2020). Furthermore, it has been proposed that the addition of fibres to concrete can limit the lateral dilation caused by the Poisson effect when subjected to axial compression (Han and Xiang 2017). Furthermore, the addition of BFs to concrete changes its failure mode from brittle to plastic, reducing the formation and propagation of cracks (Xiong *et al*. 2020). Other researchers reported that fibres control microcrack formation and delay failure, increasing ultimate strength, and significantly enhancing the post-peak phase's load-carrying capacity, and observed similar results (Plagué *et al*. 2017).

For all samples containing BFs, longer fibres displayed higher compressive strength values in comparison to shorter fibres. The sample with 12 mm, 25 mm, and 35 mm and VFs 0.5% demonstrated compressive strength 35.32 Mpa, 35.54 MPa, and 36.24 Mpa, respectively. The samples of contained 1% BFs and length 12 mm, 25 mm, and 35 mm showed compressive strength 35.98 MPa, 36.61 MPa and 37.12 MPa, respectively. The samples which contain 1.5% BFs and length 12mm, 25mm, and 35 mm illustrated compressive strength 36.47 MPa, 36.97 MPa, and 37.71 MPa, respectively. However, BFs samples, the effect of fibre length was unclear on compressive strength. The preceding shows that when lower fibre contents are used, the amount of fibres used is more important than the fibre dimension/length, whereas when higher fibre contents are used, the fibre dimension/length is more important than the amount of fibres.

Figs. 10-12 show the effect of curing age on samples with fibre lengths of 12, 25 and 35 mm, respectively. For example, for samples with 12 mm and 0.5% BFs the

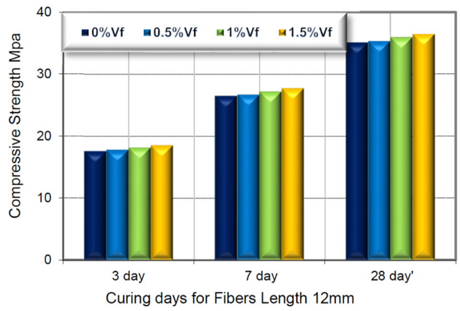


Fig. 10 Effect of curing age on the compressive strength of 12 mm fibers

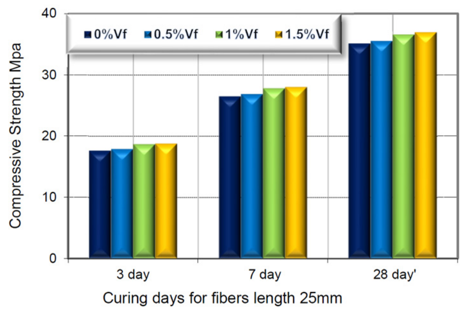


Fig. 11 Effect of curing age on the compressive strength of 25 mm fibers

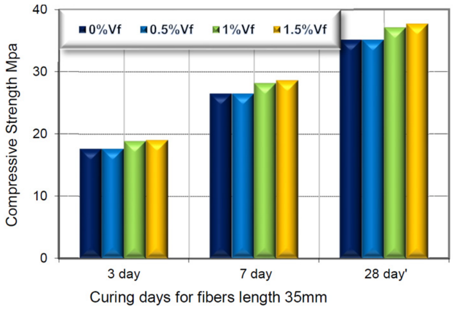


Fig. 12 Effect of curing age on the compressive strength of 35 mm fibers

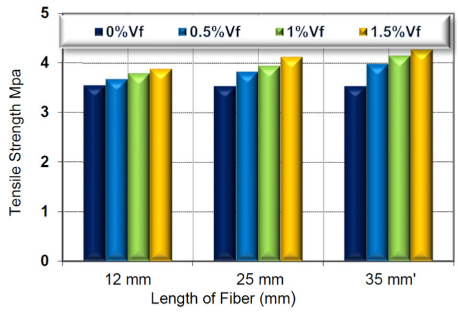


Fig. 13 Effect of fibre length and VFs of BFs on tensile strength

compressive strength was 17.77 MPa, 26.68 MPa, and 35.32 MPa at 3 d, 7 d, 28 d, respectively, which increased gradually to 98.7% from 3 d to 28 d. The results illustrate that the concrete gained increased strength for every additional day of curing regardless of VFs or BF length. After the first six days of curing, the concrete gains significant compressive strength. Meanwhile, it continued to harden through cement hydration to achieve the highest resistance at 28 d.

4.4 Tensile strength

Fig. 13 illustrates the 28-day splitting tensile strength of all the concrete mixtures. In comparison to the control mix (without fibres) which recorded tensile strength 3.55 MPa, adding BFs to the concrete mix increased the splitting tensile strength. The tensile strength of samples with a fibre length of 12 mm improved by 3.38% when the BFs were increased from 0% to 0.5%, 6.76% when the BFs were increased from 0% to 1% and 9.29% when the BFs were increased from 0% to 1.5%. The tensile strength of samples with a fibre length of 25 mm improved by roughly 8.20%, 11.64% and 16.71% when the BFs were increased from 0% to 0.5%, 1% and 1.5%, respectively. The samples with fibre length of 35 mm had increased tensile strength up to 12.74%, 17.56% and 20.96% for samples with 0.5%, 1% and 1.5% BFs, respectively. This refers to a fibre's ability to bridge across a crack and prevent it from growing due to load sharing, resulting in an increase in tensile strength of up to 1.5% (Chacko *et al*. 2016, Haido *et al*. 2021). Similar to (Najaf *et al*. 2022), it found that 1.5% of the fibres achieved the best tensile strength. (Najaf and Abbasi 2022b) reported the fibres have a significant impact on the increase in tensile strength and stiffness. (Wu *et al*. 2020) discovered that for all fibres used (basalt, glass, and polypropylene fibres), the tensile strength of concrete increased noticeably. Furthermore, as previously discussed, the incorporation of BFs in concrete changes its failure mode from brittle to plastic, particularly as the fibre content increases, because fibres adequately inhibit the formation and propagation of cracks while also limiting the confluence of cracks and adsorbing more destructive energy in the end (Khan and Cao 2019). On the other hand, the influence of fibre length on splitting tensile strength can likewise be seen, which improved as the fibre length was increased. The splitting tensile strength of samples of BFs with 35 mm length and

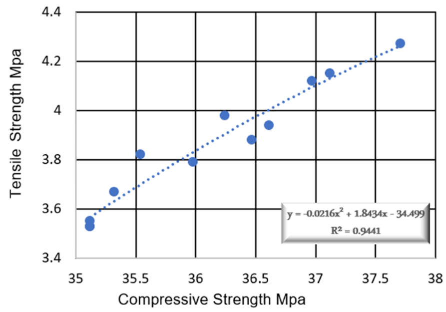


Fig. 14 Splitting tensile strength versus compressive strength

1.5% was the highest value by 4.27 MPa compared to all samples. Longer fibres outperformed shorter fibres up to 1.5% dosage. This increase could be attributed to the superior mechanical anchoring of BFs at their surfaces, which results in high bond strength between the fibres and the matrix. The splitting tensile strength versus compressive strength is shown in Fig. 14. The sample with fibres 35 mm in length and VFs 1.5% of BFs had the highest tensile strength with an improvement of 21% over the control sample without fibres. A second-order polynomial association with an R-squared value of 0.944 was found for splitting tensile strength of cylindrical specimens (150 × 300 mm). Eq. (4) illustrates the correlation between compressive and splitting tensile strength

$$F_t = -0.216 f_c^2 + 1.843 f_c - 34.499 \quad (4)$$

Where F_t denotes the splitting tensile strength of the cylindrical sample, and fc denotes the compressive strength of the cube sample.

4.5 Flexural strength

Fig. 15 shows the 28-day flexural strength of all the concrete mixes. The study indicates that with increasing BFs, the specimens showed a continuing increase in flexural strength. The flexural strengths of all BFs mixes were greater than those of plain concrete. This outcome is due to the good bond between BFs and concrete and not the agglomeration of BFs in the concrete mix (Ali *et al*. 2020). The control sample, which without BFs, the flexural strength was 4.93 Mpa. The addition of fibres with lengths

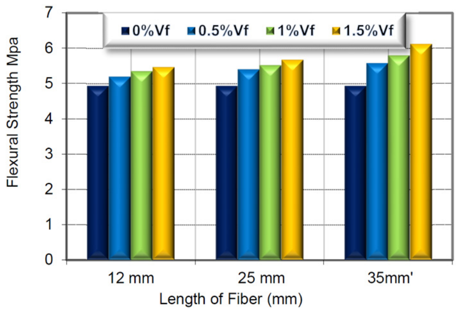


Fig. 15 Effect of fibre length and VFs of BFs on flexural strength

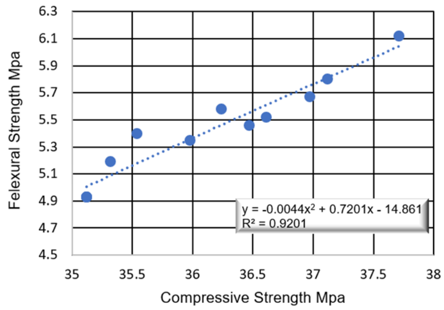


Fig. 16 Flexural strength versus compressive strength

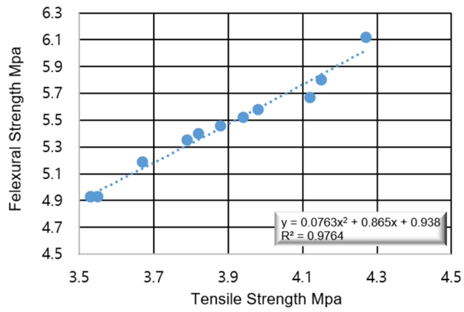


Fig. 17 Flexural strength versus tensile strength

of 12 mm and ratios of 0.5%, 1%, and 1.5% increases the flexural strength by 5.27%, 8.52%, and 10.75%, respectively, compared to the reference concrete. The samples which content BFs with 25 mm length, the volume fraction increase by 0.5%, 1%, and 1.5%, the flexural strength increase by 9.53%, 11.97%, and 15.01%, respectively. Furthermore, the addition of BFs with 35 mm length to concrete mixtures by 0.5%, 1%, and 1.5% the flexural strength increases by 13.18%, 17.65%, and 24.14%, respectively. Th samples which content BFs with 35 mm length and volume fraction 1.5%, demonstrated the highest flexural strength by 6.12 Mpa. Like the compressive strength test, adding fibre up to 1.5% increases the flexural strength. The flexural strength of banana fibre concrete was good, the flexural strength increased with the use of banana fibre by 0.5%, 1%, and 1.5%, and then decreased with the use of fibre by 2% (Makebo and Basa 2020). On the other hand, the effect of fibre length on flexural strength improved with the significant increase of fibre length. The samples which contain dose 0.5% of BFs and lengths 12 mm, 25 mm, and 35 mm showed flexural strength 3.67 MPa, 3.82 MPa, and 3.98 MPa, which increased by 4% and 8.45%, compared to the sample with 12 mm length of BFs. The flexural strength of the samples with BFs that were 25 mm and 35 mm on length gradually increased up to 5 percent and 9.68. According to the results, the presence of BFs contributed to the peak flexural strength of the specimens before failure, unlike the samples without BFs that failed immediately after reaching their peak flexural strength, breaking into two pieces. This result indicates that the fibres are acting to prevent the spread of microcracks and breaking the sample into two parts. Furthermore, this is consistent with the findings for splitting strength of BFs containing longer fibres at high fibre dosage, and it is related to the spread of longer fibres during the mixing process.

Fig. 16 illustrates the relationship between the flexural strength and compressive strength of FRC. The flexural strength of FRC increased monotonically with the increase in its compressive strength. The sample with fibres 35 mm in length and 1.5% BF had the highest tensile strength with an improvement of 24.13% over the control sample without fibres. A second-order polynomial association with an R-squared value of 0.920 was found, which indicated that the fitting results agreed very well with the experimental results. Eq. (5) illustrates the correlation between compressive and flexural strength

$$F_b = -0.0044 f_c^2 + 0.7201 f_c - 14.861 \quad (5)$$

Where F_b denotes the flexural strength of the prismatic sample, and f_c denotes the compressive strength of the cube sample.

On the other hand, Fig. 17 exhibits the flexural strength versus tensile strength relationship. A second-order polynomial association with an R-squared value of 0.976 was found for the flexural strength of prismatic samples (100 × 100 × 500 mm) and the splitting tensile strength of cylindrical specimens (150 × 300 mm). Eq. (6) illustrates the correlation between flexural strength and splitting tensile strength

$$F_b = 0.0763 f_t^2 + 0.8651 f_t + 0.938 \quad (6)$$

where F_b denotes the flexural strength of the prismatic sample, and f_t denotes the splitting tensile strength of the cylindrical sample.

4.6 Bond stress

All specimens failed due to vertical crack formation, as shown in Fig. 18. It can be noted that fibre helps arrest cracks, which limits their development. The addition of fibres to concrete can increase the tensile characteristics of the concrete in all directions. The bond stress of BFs because of VFs and fibre length is shown in Fig. 19. Compared with control concrete, the bond stress of the concrete produced with BFs that had 0%, 0.5%, 1% and 1.5% VFs increased. The control sample without BFs showed bond stress by 6.07 MPa. The BFs samples of a 12 mm length recorded bond stress by 6.12 MPa, 6.24 MPa, and 6.37 MPa, with dosages of BFs 0.5%, 1%, and 1.5%, respectively. Bond stresses of 6.32 MPa, 6.48 MPa, and 6.58 MPa were measured in samples of 25 mm BFs at 0.5%, 1%, and 1.5%, respectively. The BFs samples of a 35 mm length recorded bond stress 6.37 MPa, 6.61 MPa and 6.75 MPa with ratio of BFs 0.5%, 1%, and 1.5%, respectively. Depending on the length and VFs of fibres, the increase was observed to be between 4.9% and 11.2% with different length from 12 mm to 35 mm. The BFs sample with 35 mm length and 1.5% VFs showed the highest value by 6.75 MPa. On the other hand, the influence of fibre length on bond stress can be seen, which is improved by increasing the fibre length. This increase can be attributed to the increase in bond strength of the FRC (Bharathi *et al*. 2021, Batu and Lemu 2020). Furthermore, according to (Plizzari 1999), fibres strengthened the bond by reducing radial cracking close to the reinforcement bar and thereby enhancing confinement action around the bar.

4.7 Absorption characteristic

The water absorption test determines how quickly the concrete's outer and inner surfaces absorb water. The test involves measuring the increase in density of samples caused by water absorption over time after the sample has been exposed to water. More water absorption leads to lower durability because water contains numerous harmful substances that soak into concrete, causing concrete disintegration and resulting in decreased durability (Ahmad *et al*. 2022). Fig. 20 illustrates the influence BF ratio on the water absorption of all specimens. It was found that adding BFs to concrete mixes had a direct effect on water absorption by increasing the water absorption of all specimens. As the BFs of samples with fibre lengths of 12, 25 and 35 mm were added to concrete mixes, water absorption increased gradually up to 44.8%, 39.42% and 32.05%, respectively, compared to the reference concrete. Similarly, (Anowai and Job 2017) found that water absorption of concrete reinforced with 0.5% VFs of BFs increased by 21%. This is due to BFs absorbing more water because of its surface morphology. On the other hand, the fibre length has an influence on absorption, which decreases as the length of the fibre increases. This effect is related to the fact that the length of the fibres relates to a decrease in their number.

4.8 Microstructure analysis

The morphology of concrete was investigated using SEM. The purpose of concrete morphology was to figure out how fibres affected interfacial transition zones (ITZs), micro-cracks and their propagation in the matrix between fibre-cement paste and aggregate-cement paste. The specimens that were used have a diameter of 5-10 mm and were extracted from cubes in a compressive test.

SEM images of the mixture without fibre (control) are shown in Fig. 21(a). The control mixture had a porous morphology with various diameters and a normal setting, and the ITZ was specified between the bulk paste and aggregate composite of around 45 μm (Abdul-Rahman *et al*. 2020). The observed porosity was due to the initial water absorption, which influenced the rate of hydration. The findings in this investigation are comparable to those in a previous study (Amin and Tayeh 2020). On the other hand, as seen in Figs. 21(b) to 21(d), the mixture with BFs had bigger pores within the matrix. A definite ITZ was noted between BFs and paste, and the BFs were easily recognisable. In addition, micro-cracks were seen in the control composite, though no evident micro-cracks were found in the mixtures with BFs. This could be due to the fibres' inclusion, which reduced the production of micro-cracks and prevented them from growth. This finding agrees with the mechanical features of the concrete mixtures, such as compressive, splitting tensile and flexural strengths, all of which have already been mentioned. The fibres were likewise shown to be embedded in cement paste, which has an impact on improving matrix strength because of a stress transfer mechanism between the matrix and the fibres. This effect, combined with its resistance to tensile stresses caused by applied loads, contributed to the microstructure's preservation by preventing crack growth.

Fig. 18 Failure mode of the sample after bond test

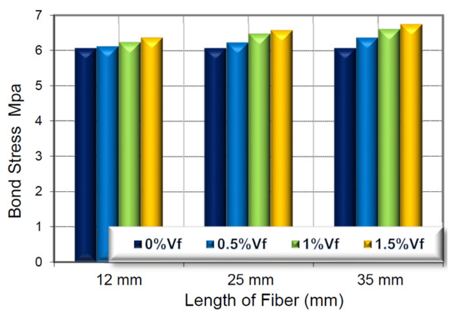


Fig. 19 Effect of fibre length and VFs of BFs on bond stress

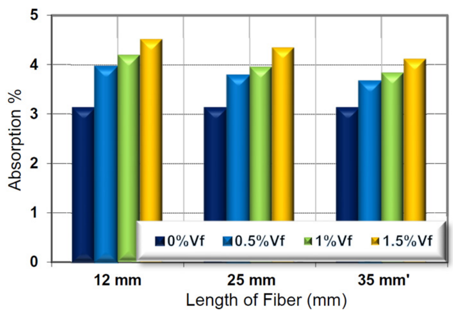
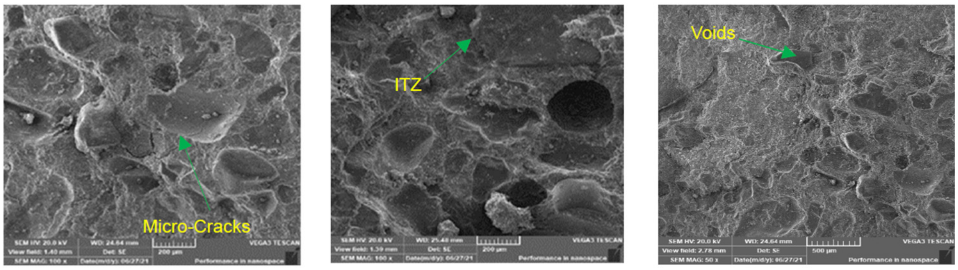
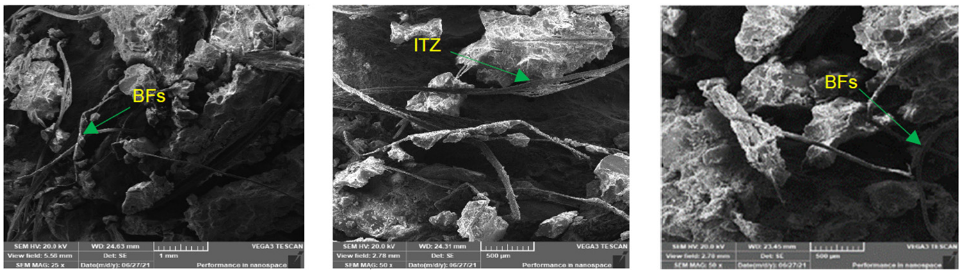


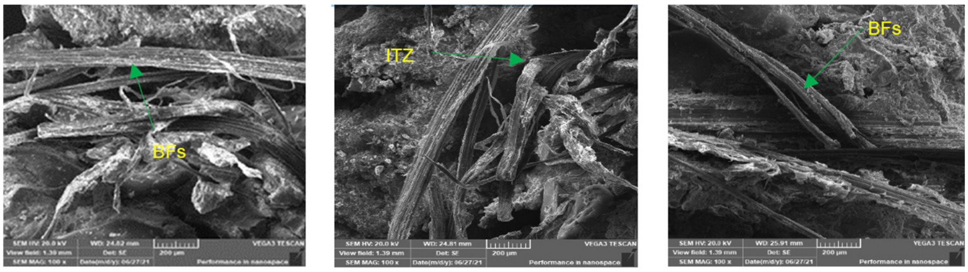
Fig. 20 Effect of fibre length and VFs of BFs on absorption



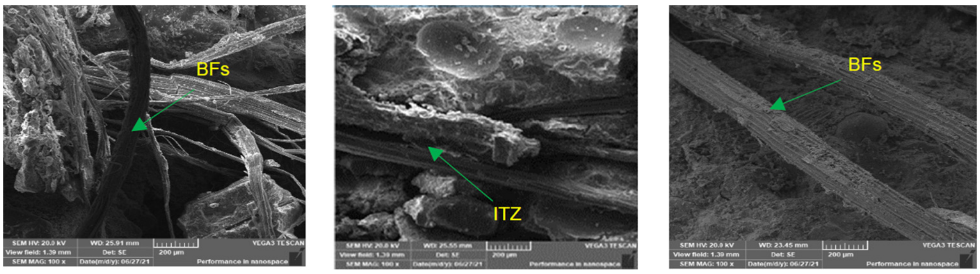
(a) Sample without banana fibres (control)



(b) Sample with 0.5% banana fibres



(c) Sample with 1% banana fibres



(d) Sample with 1.5% banana fibres

Fig. 21 SEM morphology of all samples with and without fibres

5. Conclusions

The results of experimental investigations into the strength characteristics of BF-reinforced concrete are presented. From the results, the following conclusions can be drawn:

- The slump values for fibre with lengths of 12 mm, 25 mm, and 35 mm, wase 11.76 mm, 12.03 mm, and 13.37 mm respectively when using BFs by 1.5 percent. The experimental data showed that increasing the BFs in samples with a length of 12 mm from 0% to 0.5%, 1% and 1.5% decreases workability by 20.69%, 26.64% and 32.02%, respectively, Meanwhile, for the samples that were 25 and 35 mm in length, they decreased by 30.46% and 22.7%, respectively, by increasing the BFs from 0% to 1.5%. The workability of fibrous concrete decreased with the increasing VFs of fibres. Although, the mixes showed good workability and no agglomeration of fibres or heterogeneity during mixing was shown.
- The unit weight of concrete decreased by increasing BFs, regardless of the fibre length. Compared to control mix, the unit weight of samples with a fibre length of 12 mm wase decreased by 1.5 to 2.9% when the VFs of BFs increased from 0%, to 1.5%, while the unit weight of samples with a fibre length of 25 mm recorded increased by 2.17% when the VFs of BFs increased up to 1.5%. The unit weight of samples with a fibre length of 35 mm decreased by 0.7%, 1.05%, and 1.3% when the VFs of BFs were

0%, 1%, and 1.5%, respectively. In comparison to samples with 12 mm, 25 mm and 35 mm fibres, those with 35 mm fibres length and volume fraction of 1.5% had the minimum density with 2415 kg/m^3.

- The compressive strength of control sample, which without BFs, was 35.12 MPa. The compressive strength of samples BFs with 12 mm length and dosage 0.5%, 1%, and 1.5% were 35.32 MPa, 35.98 MPa, and 36.47 MPa, respectively, by increase up to 3.8%, compared to control mix. The compressive strength of sample BFs with 25 mm and 35 mm length and dosage 0.5% to 1.5% increased gradually to 5.27% and 7.37%. It can be seen the highest compressive strength of sample contained BFs with length 35 mm and dosage 1.5% which recorded 37.71 MPa. On the other hand, the addition of fibres had a non-mentioned effect on compressive strength.
- The tensile strength of samples with a fibre length of 12 mm improved by 3.38% when the BFs were increased from 0% to 0.5%, 6.76% when the BFs were increased from 0% to 1% and 9.29% when the BFs were increased from 0% to 1.5%. The tensile strength of samples with a fibre length of 25 mm improved by roughly 8.20%, 11.64% and 16.71% when the BFs were increased from 0% to 0.5%, 1% and 1.5%, respectively. The samples with fibre length of 35 mm had increased tensile strength up to 12.74%, 17.56% and 20.96% for samples with 0.5%, 1% and 1.5% BFs, respectively. The splitting tensile strength of samples of BFs with 35 mm length and 1.5% was the highest value by 4.27 MPa compared to all samples. Longer fibres outperformed shorter fibres up to 1.5% dosage. Despite its many advantages, BFs as a concrete enhancer are unlikely to replace steel in the vast majority of constructions.
- The control sample, which without BFs, the flexural strength was 4.93 Mpa. The addition of fibres with lengths of 12 mm and ratios of 0.5%, 1%, and 1.5% increases the flexural strength by 5.27%, 8.52%, and 10.75%, respectively, compared to the reference concrete. The samples which content BFs with 25 mm length, the volume fraction increase by 0.5%, 1%, and 1.5%, the flexural strength increase by 9.53%, 11.97%, and 15.01%, respectively. Furthermore, the addition of BFs with 35 mm length to concrete mixtures by 0.5%, 1%, and 1.5% the flexural strength increases by 13.18%, 17.65%, and 24.14%, respectively. Th samples which content BFs with 35 mm length and volume fraction 1.5%, demonstrated the highest flexural strength by 6.12 Mpa. Like the compressive strength test, adding fibre up to 1.5% increases the flexural strength.
- The control sample without BFs showed bond stress by 6.07 MPa. The BFs samples of a 12 mm length recorded bond stress by 6.12 MPa, 6.24 MPa, and 6.37 MPa, with dosages of BFs 0.5%, 1%, and 1.5%, respectively. Bond stresses of 6.32 MPa, 6.48 MPa, and 6.58 MPa were measured in samples of 25 mm BFs at 0.5%, 1%, and 1.5%, respectively. The BFs samples of a 35 mm length recorded bond stress 6.37 MPa, 6.61 MPa and 6.75 MPa with ratio of BFs 0.5%, 1%, and 1.5%, respectively. The BFs sample with 35 mm length and 1.5% VFs showed the highest value by 6.75 MPa.
- The control sample without BFs showed bond stress by 6.07 MPa. The BFs samples of a 12 mm length recorded bond stress by 6.12 MPa, 6.24 MPa, and 6.37 MPa, with dosages of BFs 0.5%, 1%, and 1.5%, respectively. Bond stresses of 6.32 MPa, 6.48 MPa, and 6.58 MPa were measured in samples of 25 mm BFs at 0.5%, 1%, and 1.5%, respectively. The BFs samples of a 35 mm length recorded bond stress 6.37 MPa, 6.61 MPa and 6.75 MPa with ratio of BFs 0.5%, 1%, and 1.5%, respectively. The BFs sample with 35 mm length and 1.5% VFs showed the highest value by 6.75 MPa.
- Introducing the fibre developed the microstructure of concrete by developing cohesiveness between the BFs and the matrix as well reducing the size of ITZ. As a result, the porosity of the matrix was also reduced by filling its pores, resulting in developed mechanical properties of the composite as observed from the results.
- Agriculture waste can be used as a building material, which solves the problem of a limited amount of space for dumped agricultural waste. Furthermore, if agricultural waste is burned, it can help minimise air pollution.

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