Malaysian
Journal Of Civil
Engineering

Full Paper

EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF OIL-PALM EMPTY FRUIT BUNCH (OPEFB) FIBRE ON STRENGTHS AND STRENGTH RELATIONS OF CONCRETE

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Article history
Received
25 October 2025
Received in revised form
19 February 2026
Accepted
16 March 2026
Published online
30 July 2026

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Graphical abstract

Abstract

Though concrete remains the leading preferred construction material to date, its vulnerability to tensile forces, even when reinforcement is embedded, remains a credible concern. This is because of the tendency for the formation of tensile cracks, thereby weakening the overall structural response of concrete to external forces and thus undermining the achievement of UN-SDG 9-1 as it relates to the development of quality, reliable, sustainable, and resilient infrastructure in the long run. The effects of reinforcing concrete specimens with fiber derived from Oil Palm Empty Fruit Bunches (OPEFBF) were assessed in this study. The evaluation encompassed measurements of its properties, specifically compressive strength, modulus of rupture, and splitting tensile strength. For this research, concrete mixtures were formulated incorporating OPEFBF at varying percentages (0.0%, 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, and 1.2%) relative to the weight of cement. From these mixes, a total complement of specimens was produced, including 105 cubes (150 mm x 150 mm x 150 mm), 105 cylinders (150 mm x 300 mm), and 105 beams (100 mm x 100 mm x 500 mm) for compressive strength, splitting tensile strength, and modulus of rupture tests, respectively. All specimens underwent curing periods of 7, 14, 21, 28, and 90 days. The investigations were governed by relevant standards. The findings demonstrated that (i) adding fiber up to 0.4% increased compressive strength (ii) up to 0.6% of fiber addition increased both the modulus of rupture and the splitting tensile strength when compared to the control mix, and (iii) the power equation perfectly represents how the tensile strength and compressive strength are related. For practical applications, a fiber content not greater than 0.4% is suggested to obtain an optimal balance between compressive and tensile strength.

Keywords: Compressive strength; Concrete; Modulus of rupture; Oil Palm Empty Fruit Bunch Fiber (OPEFBF) Splitting tensile strength; Modulus of Rupture

1.0 INTRODUCTION

Concrete remains the most globally used building material because of its superior compressive strength, durability, and adaptability (Fapohunda & Shittu, 2017). However, its inherent brittleness and poor tensile capacity render it prone to cracking and structural failure under tensile stresses (Omoniyi, 2019). While steel reinforcement has traditionally been employed to address these limitations, issues related to cost, corrosion, and environmental impact have spurred the search for more sustainable alternatives (Alani & Aboutalebi, 2013). These scenarios weaken the overall structural response of concrete to external forces and thus undermine the achievement of UN-SDG 9-1 as it relates to the development of quality, reliable, sustainable and resilient infrastructure in the long run. Fiber-reinforced concrete (FRC) has shown to be a feasible alternative since it provides better tensile strength and crack resistance. Although man-made reinforcing fibres, including polypropylene and steel filaments, have demonstrated structural efficacy, their non-biodegradable nature and high embodied energy conflict with sustainability goals (Musa et al., 2018). Natural fibers have gained attention as a sustainable option because of their renewability, accessibility, and lower carbon emissions. Of all the materials considered, fibers obtained from Oil Palm Empty Fruit Bunch (OPEFBF), which is a byproduct of palm oil processing, exhibit considerable potential. These fibers are abundant in tropical regions such as Malaysia, Indonesia, and Nigeria, where their disposal poses environmental challenges (Rao & Ramakrishna, 2022). Repurposing OPEFBF fibers in concrete both aids in waste management and enhances sustainability in construction. With a high cellulose content (48–65%) and an average tensile strength of ~71–82 N/mm^2, OPEFBF fibers demonstrate compatibility with cementitious matrices (Fapohunda & Kilani, 2021; Yusoff et al., 2009). Surface treatments like alkali modification improve fiber-matrix bonding by removing surface impurities and increasing roughness (Arifin et al., 2022). Concrete reinforced with OPEFB fibers exhibits improved tensile behavior, crack resistance, and energy absorption, especially under flexural loading (Somkeattikul et al., 2021). Unlike conventional concrete, which fails suddenly under tensile stress, fiber-reinforced composites delay tensile failure by spanning cracks and dispersing internal stresses (Fapohunda et al., 2023). However, issues persist, including fiber clumping, diminished workability, and deterioration when exposed to alkaline conditions, remain critical concerns (Nguyen et al., 2017; Siregar et al., 2021). Standardized treatments and optimized mix designs including the use of retarders and advanced dispersants are necessary to ensure durability and uniform performance (Abu Bakar et al., 2024). Studies have also explored hybrid reinforcement systems, combining OPEFB with synthetic or metallic fibers to enhance post-crack resistance and energy dissipation (Ling et al., 2022). Furthermore, life cycle assessments (LCAs) affirm that OPEFB-reinforced concrete has lower embodied energy and greenhouse gas emissions compared to conventional fiber-reinforced systems (Omoniyi, 2019; Tutu et al., 2025). While existing research highlights the mechanical and environmental advantages of OPEFB fiber-reinforced concrete, key gaps remain particularly in its ability mitigate tensile forces in concrete and thus improve its overall structural quality. Therefore, the aim of this study is to investigate the effects of Oil-Palm Empty Fruit Bunch (OPEFB) Fibre on Strengths and Strength relations of Concrete. The specific objectives are: (i) to evaluate the effects of OPEFB fiber on the compressive, flexural, and splitting tensile strengths of concrete; (ii) to develop empirical correlations among these strength parameters; and (iii) to identify the optimum fiber dosage for sustainable structural performance.

2.0 METHODOLOGY

2.1 Materials

The mechanical characteristics for concrete reinforced with Oil Palm Empty Fruit Bunch Fiber (OPEFBF) were examined in this study using an experimental methodology. To ensure the results are accurate and reproducible, standardized practices were used for material characterization, mix proportioning, specimen preparation, and mechanical property evaluation. The primary materials utilized in this investigation were Ordinary Portland Cement (OPC), both fine and coarse aggregates, water, and the fiber. The cement was 42.5 grade Dangote brand. The cement met the requirements of BS EN 197-1:2000 (British Standards Institution, 2000) and NIS 444-2014 (Nigerian Industrial Standards, 2014). The fine aggregate, specifically Ureje River sand, was sourced from a nearby river adjacent to the university. BS EN 12620:2002 + A1 (Nigerian Industrial Standards, 2014) was followed in the preparation of the fine aggregate. A quarry provided the coarse aggregate. Regarding the maximum sizes of 4.75mm and 20mm, it was treated to conform with BS 8110 (British Standards Institution, 2008). For this investigation, drinkable water that complied with ASTM C1602 (ASTM International, 2012a) was utilized.

A local palm oil mill located in Ikole-Ekiti, Nigeria, provided the Oil Palm Empty Fruit Bunch (OPEFBF) fibres utilized for this research. To enhance fiber extraction, the bunches were soaked in water for 48–72 hours, sun-dried for 7–10 days, and subsequently cut to a uniform length of 20 mm as in Figure 1.

Figure 1 Extraction of OPEFB fibers: (a) Raw bunches, (b) Processing stage, (c) Cleaned fibers ready for use.

This ensured an aspect ratio between 60 and 75. The mechanical interlocking, crack-bridging, and overall reinforcing efficiency of fibers in cementitious composites are all greatly impacted by the fiber's aspect ratio (i.e., the ratio of fiber length to its diameter).

2.2 Concrete Mix Proportion and Production

The mix design utilized a cement-to-sand-to-coarse aggregate proportion of 1:2:4, which is typical in Nigerian construction. To achieve adequate workability, a fixed water-cement ratio of 0.50 was employed, following COREN's recommendations (Council for the Regulation of Engineering in Nigeria, 2017) for a 28-day compressive strength of 20 N/mm². As per Fapohunda and Kilani's (Fapohunda & Kilani, 2021) recommendations, OPEFBF was added to the concrete mix at different dosages, ranging from 0.2% to 1.2% by cement weight, with increments of 0.2%. The mix proportions are shown in Table 1.

Table 1 Concrete Material Mix Proportion utilized for the Investigation

% Composition of Fibre in the mix	Mix ID	Cement Kg/m³	Sand Kg/m³	Gravel Kg/m³	Fibre Kg/m³	Water Kg/m³	Water-Cement ratio
0	$M_{0.0}$	343	686	1372	0.00	173	0.5
0.2	$M_{0.2}$	343	686	1372	0.69	173	0.5
0.4	$M_{0.4}$	343	686	1372	1.37	173	0.5
0.6	$M_{0.6}$	343	686	1372	2.06	173	0.5
0.8	$M_{0.8}$	343	686	1372	2.74	173	0.5
1.0	$M_{1.0}$	343	686	1372	3.43	173	0.5
1.2	$M_{1.2}$	343	686	1372	4.12	173	0.5

Cubes with dimensions of 150 mm × 150 mm × 150 mm, beams measuring 100 mm × 100 mm × 500 mm, and cylinders of 150 mm × 300 mm were prepared in triplicate for each mix. All specimens were demolded after 24 hours and subsequently cured in a water tank until the specified testing ages for compressive strength, modulus of rupture, and splitting tensile strength were reached.

2.3 Experimental Investigations

2.3.1 Characterization of Materials

To ascertain whether the materials were appropriate for concrete production, material characterization was performed. Using standard test procedures, physical tests were performed on both fine and coarse aggregates to ascertain their density, specific gravity, moisture content, water absorption capacity, and particle size distribution profile. The OPEFB fibers' mechanical, chemical, and physical characteristics were thoroughly investigated. Fiber density and aspect ratio were calculated using ASTM D3800 (ASTM International, 2016), while the tensile characteristics of single fibers were assessed using ASTM D3822/D3822M (ASTM International, 2016). The fibers' Young's modulus and tensile strength were evaluated using BS EN ISO 11566 (ASTM International, 2016) and ASTM D3379 (ASTM International, 2012), respectively. Additionally, water absorption and moisture content were analyzed following (ASTM International, 2010) and BS EN ISO 12570 (ASTM International, 2010). The carbohydrate composition of the fibers, including pentosan, lignin, cellulose, and hemicellulose content, was determined using ASTM E1758 (ASTM International, 2015) for carbohydrate analysis in biomass, ASTM D1106 (ASTM International, 2015) for acid-insoluble lignin, and ASTM D1102 (ASTM International, 2013) for ash content in wood.

2.3.2 Density and Compressive Strength Test:

In accordance with BS EN 12390-3:2019 (British Standards Institution, 2019a), the compressive strength of the OPEFBF-reinforced concrete was assessed at curing periods of 7, 14, 21, 28, and 90 days. The testing was performed with a Universal Testing Machine (UTM)(Figure 2), and the compressive strength (f_c) was computed using Equation 1. Each cube specimen was weighed before testing to obtain its mass (in kg). The density (γ) of hardened concrete specimens was determined by Equation 2, adhering to BS EN 12390-7:2019 (British Standards Institution, 2019c).

$$f_c = \frac{P\ (N)}{A\ (mm^2))} \quad (1)$$

Figure 2 Compression testing machine with cube specimen

$$\gamma = \frac{M\ (kg)}{V\ (mm^3)} \quad (2)$$

2.4 Evaluation of Tensile Strength

The tensile strength for the concrete specimens containing OPEFBF fibers was assessed using two approaches, namely the flexural strength and splitting tensile capacity

2.4.1 Modulus of Rupture (Flexural Strength):

In alignment with ASTM C78 and BS EN 12390-5 (British Standards Institution, 2019b), beam specimens measuring 100 mm by 100 mm by 500 mm were employed to evaluate the concrete's resistance to bending, as shown in Figure 3 Equation 3 was employed to determine the modulus of rupture (MOR) from a three-point bending test:

$$MOR = \frac{PL}{bd^2} \quad (3)$$

where P is the maximum load at failure in N, L is the span length in mm, b is the width of the beam in mm and d is the depth of the beam in mm.

Figure 3 Testing of specimens for modulus of rupture

2.4.2 Splitting Tensile Strength

In adherence to BS EN 12390-6:2023 (British Standards Institution, 2019b), cylindrical concrete specimens, 150 mm in diameter and 300 mm tall, underwent indirect tensile strength testing as in Figure 4.

Figure 4 Testing of specimens for splitting tensile strength.

Equation 4 was then used to calculate the splitting tensile strength:

$$Ts = \frac{2P}{\pi LD} \tag{4}$$

Where: Ts is Splitting tensile strength (N/mm²), P denotes the peak applied load (in Newtons), L represents the cylinder's length (in mm), and D is the cylinder's diameter (in mm).

3.0 RESULTS AND DISCUSSION

3.1 Materials Characterization

3.1.1 Properties of Aggregates

Investigations conducted to characterize the aggregates yielded the results shown in Table 2. The findings shed light on whether the fine and coarse aggregates were appropriate for use in concrete production.

Table 2: Some Physical Properties of Fine and Coarse Aggregate

Property	Fine Aggregate	Coarse Aggregate
Specific gravity	2.64	2.67
Bulk density	1667.90	1642.67
Water absorption	2.00	2.04
Moisture content	0.0	0.0
Curvature coefficient	0.88	1.00
Coefficient of uniformity	3.00	2.43
Fineness modulus	2.70	-

As recommended by ASTM C127 (ASTM International, 2018a) and ASTM C128 (ASTM International, 2018b) for natural aggregates, the specific gravity values (2.64 for fine aggregate and 2.67 for coarse aggregate) fall within the allowable range. These numbers show that the aggregates have a sufficient density, which is a prerequisite for achieving the requisite concrete strength and durability that are desired. BS EN 1097-3 (British Standards Institution, 2019c) classifies normal weight aggregates; accordingly, the bulk densities for the fine and coarse aggregates were measured as 1667.90 kg/m3 and 1642.67 kg/m3, respectively. water absorption rates of 2.00% for fine aggregate and 2.04% for coarse aggregate fall between the acceptable range of 0.5% and 3.0% that ASTM C127 (British Standards Institution, 2019b) and ASTM C128 (British Standards Institution, 2019c) specify. This implies that the aggregates' low permeability will help keep the water-to-cement ratio within the intended ranges. According to BS EN 1097-5 (British Standards Institution, 2019c), both aggregates had an oven-dry condition at the time of testing, as evidenced by their recorded moisture content of 0%. According to BS EN 933-1 (British Standards Institution, 2019c), the aggregates' proper grading and particle size distribution were confirmed by the curvature coefficient (0.88 for fine aggregate and 1.00 for coarse aggregate) and coefficient of uniformity (3.00 for fine aggregate and 2.43 for coarse aggregate). These characteristics contribute to improved concrete strength, less segregation, and appropriate compaction. Furthermore, the test results verify that the fine and coarse aggregates meet the standard requirements and are suitable for concrete production. The fine aggregate's fineness modulus was 2.70, which is within the recommended range of 2.3–3.1 (ASTM C33) (British Standards Institution, 2019c). This suggests that the fine aggregate is well-graded and should positively contribute to workability and density in the concrete mix.

3.1.2 Properties of Oil Palm Empty Fruit Bunch Fiber (OPEFBF)

The characterization for Oil Palm Empty Fruit Bunch Fiber (OPEFBF), encompassing physical and elemental properties, is provided in Tables 3 and 4.

Table 3 Physical Parameters of OPEFBF Fiber

Physical Properties	Values
Colour	Brown
Average length (mm)	20mm
Diameter of a single fibre (mm)	0.25-0.50
Density (g/cm^3)	1.18
Aspect ratio	70
Tensile strength (N/mm2)	82
Young modulus (Gpa)	6.30

Table 4 Elemental Properties of OPEFB Fibre

Elemental Properties	Values
Water absorption (%)	5.50
Moisture content (%)	0.02
Hemicellulose (%)	15.20
Extraction (%)	3.20
Lignin (%)	22.0
Ashes (%)	4.57
Pentosan (%)	26.0

The fibers are brown in color, with an approximate length of 20 mm and a diameter ranging from 0.25 to 0.50 mm. These dimensions fall within the recommended range for natural fibers used in cementitious composites (ASTM standards). The density of the fiber was found to be 1.18 g/cm³, which is suitable for lightweight concrete applications. The aspect ratio of 70 meets the recommended values in ACI 544.1R (American Concrete Institute, 2013, 2014), ensuring sufficient crack resistance and tensile reinforcement in concrete. The water absorption capacity of OPEFBF was 5.50%, while its moisture content was 0.02%, aligning with the acceptable limits stipulated in ASTM C1658 (ASTM International, 2021). Chemical composition analysis showed that hemicellulose content was 15.20%, lignin content was 22.00%, and pentosan was 26.00%. These values suggest that the fibers have adequate stiffness and strength, supporting their use in reinforcing concrete (BS EN 13432) (British Standards Institution, 2018). The low ash content of 4.57% ensures minimal chemical interference with cement hydration. These findings demonstrate that OPEFB fibers possess desirable physical and chemical characteristics for their application in concrete reinforcement.

3.2 Density of Hardened Concrete

Figure 5 shows the density of the concrete specimens based on their curing duration. As stated in ACI 318 (British Standards Institution, 2018) and BS EN 12390-7 (British Standards Institution, 2018), the control mix's relatively stable density of 2440–2489 kg/m³ is within the normal weight concrete range of 2200–2500 kg/m³. At 0.2% and 0.4% fiber content, density values were slightly higher at early curing ages due to fiber compaction within the matrix. However, for fiber contents above 0.6%, a decrease in density was observed at later curing ages. For instance, at 1.2% fiber content, density dropped to 2410–2430 kg/m³ at 28 and 90 days.

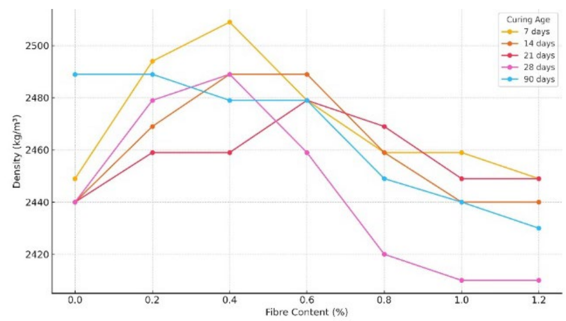

Figure 5 Density of concrete specimens with OPEFBF at different curing ages

This reduction is a result of the fibres having a lower specific gravity (1.18 g/cm3) than the cementitious materials, as well as the potential for micro-voids to form from fiber clustering (ASTM C642) (British Standards Institution, 2018). While all mixes remained within the normal weight concrete range, careful mix design considerations, such as the addition of superplasticizers (ASTM C494) (British Standards Institution, 2018), may be necessary to maintain density and ensure structural performance.

3.3 Compressive Strength of Concrete with OPEFB Fiber

As shown in Figure 6, the results for compressive strength emphasize the impact of OPEFB fiber content on the development of concrete strength.

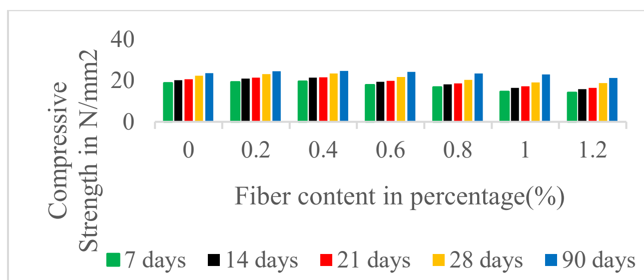

Figure 6 Compressive Strength of Concrete with oil palm Empty Fruit Bunch Fibre

As per ASTM C39 (American Concrete Institute, 2020) and BS EN 12390-3 (American Concrete Institute, 2020), the control mix's maximum compressive strength was 18.84 N/mm2 at 7 days and 23.63 N/mm2 at 90 days, consistent with expected strength gain patterns for normal concrete. All curing ages showed a slight increase in compressive strength for fiber contents of 0.2% and 0.4%. For instance, at 28 days, the 0.2% and 0.4% fiber mixes' respective compressive strengths were 23.17 and 23.53 N/mm², while the control mix's was 22.33 N/mm². This rise is explained by the low fiber content's capacity to improve stress distribution and bridge micro-cracks. On the other hand, compressive strength started to decrease at fiber contents higher than 0.6%. The 28-day compressive strength dropped to 18.80 N/mm² at 1.2% fiber content.

Based on findings published in ACI 544.1R (American Concrete Institute, 2014), the decrease is ascribed to void formation, potential fiber clustering, and the fibers' decreased density. Fiber content should be kept below 0.6% to ensure the best structural performance of the OPEFB fiber-reinforced concrete. Adjustments like better fiber dispersion and the use of superplasticizers should be made in compliance with ACI 211.1 (American Concrete Institute, 2014) and BS EN 206 (American Concrete Institute, 2014) if a higher fiber content is needed.

3.4 Effects of Oil Palm Empty Fruit Bunch Fiber (OPEFBF) on Modulus of Rupture

The relationship between Modulus of Rupture and Curing Age for different amounts of OPEFB fiber is presented in Figure 7.

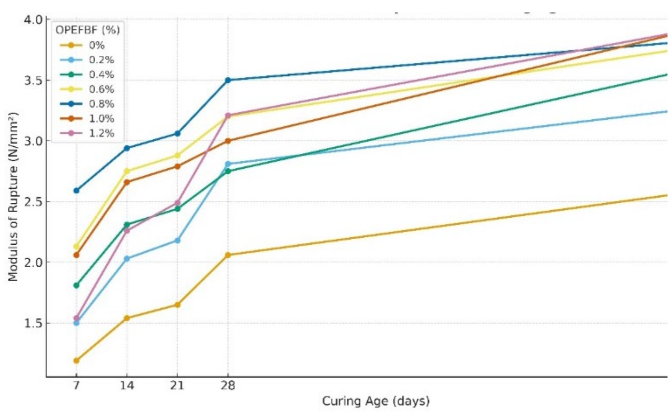

Figure 7 Modulus of Rupture versus curing age for Various OPEFB Fibre Contents

Modulus of rupture (MOR) tests were performed at 7, 14, 21, 28, and 90-day intervals to evaluate the effect of Oil Palm Empty Fruit Bunch Fiber (OPEFBF) on the concrete's flexural behaviour. Figure 7 above illustrates the results, which showed that MOR generally increased with curing age and fiber content up to an ideal range. At 90 days, the control mix (0.0% fiber) demonstrated a flexural strength of 2.56 N/mm², whereas mixes with 0.2–0.8% OPEFBF showed notable gains. At 28 days, the MOR for the 0.6% and 0.8% fiber content was 3.20 N/mm² and 3.50 N/mm², respectively, compared to 2.06 N/mm² for the control. As indicated by ACI 544.1R (American Concrete Institute, 2014) guidelines, this improvement is credited to the fibres' enhanced crack-bridging ability and better stress redistribution. It is worth noting that prolonged curing counteracted the detrimental effects of higher fiber dosages (1.0% and 1.2%), which at 28 days showed lower MOR due to likely fiber clumping and poor dispersion.

3.5 Effect of fibre on the Splitting Tensile strength of the Specimens

Table 5 presents the splitting tensile strength data obtained from concrete reinforced with OPEFB fibre.

According to ASTM C496 (American Concrete Institute, 2014) and BS EN 12390-6 (American Concrete Institute, 2014), the control mix (0.0% fiber) showed a steady increase in splitting tensile strength from 1.34 N/mm² at 7 days to 2.46 N/mm² at 90 days, reflecting the anticipated trend of strength gain through continuous hydration. This is due to the strengthening effect of Oil Palm Empty Fruit Bunch Fiber (OPEFBF) on the splitting tensile strength of concrete, as shown in Table 5. Incorporation of OPEFBF at 0.2% and 0.4% consistently enhanced the tensile performance of the material throughout all curing periods. At 28 days, the splitting tensile strengths for these mixes were 2.96 N/mm2 and 2.73 N/mm2, respectively, significantly exceeding the control mix. This improvement is attributed to the crack-bridging capability and tensile load-sharing behavior of the fibers, as highlighted in ACI 544.1R (American Concrete Institute, 2014). The highest tensile strength was recorded at 0.4% fibre content on day 90 (3.59 N/mm²), confirming that moderate fiber incorporation effectively improves crack resistance.

However, at higher fiber volumes (0.8%, 1.0%, and 1.2%), a downward trend in performance was observed. At 28 days, splitting tensile strengths declined to 2.31 N/mm2, 1.99 N/mm2 and 1.95 N/mm2, respectively, with only marginal improvements by day 90. The reductions are linked to fiber agglomeration, decreased workability, and weaker fiber-matrix bonding, in agreement with ASTM C1116 (American Concrete Institute, 2014). In addition, the result establishes that enhances the tensile splitting strength of concrete most effectively when the fiber content is in the range of 0.2% to 0.6%. Beyond this threshold, the benefits are offset by dispersion challenges.

3.6 Relationship between the Compressive strength and splitting tensile strength

3.6.1 Strength Ratios Between Splitting Tensile And Compressive Strengths

The ratio of splitting tensile strength (obtained from the cylinder tests) to the compressive strength (obtained from the cubes) was evaluated using the provided experimental data. To determine the strength ratios, the mean splitting tensile strength was divided by the mean compressive strength for each curing age. These results are presented in Table 6. From Table 6, the tensile-to-compressive strength ratio varied from 0.0711 to 0.145 across curing periods. This shows a fairly consistent proportional increase in tensile strength relative to compressive strength. The slightly higher ratios at 0.4%–0.6% fibre content indicate that moderate fibre inclusion enhances tensile capacity relative to compressive gain, due to effective micro-crack bridging. It is also to be noted that the ratio grew as the fibre content and curing age increased. For example, at 1.2% fibre content, the ratio increased progressively 0.0777, 0.0866, 0.0927, 0.1041, and 0.1269 at 7, 14, 21, 28 and 90 days of curing respectively. Such behaviour, according to (Arioglu et al., 2006; C. Fapohunda et al., 2018), is an indication that the compressive strengths increased more slowly than the splitting tensile strength.

Table 5 Splitting Tensile Strength of Concrete with OPEFB Fibre

Curing Age(days)	Splitting tensile strength						
	0.0	0.2	0.4	0.6	0.8	1.0	1.2
7	1.34	1.54	1.59	1.45	1.28	1.23	1.10
14	1.66	1.83	1.85	1.87	1.61	1.53	1.38
21	1.73	1.97	2.07	1.99	1.75	1.66	1.53
28	2.11	2.96	2.73	2.45	2.31	1.99	1.95
90	2.46	3.50	3.59	3.25	2.95	2.91	2.71

Table 6 Ratio of Splitting Tensile Strength to Compressive Strength

Curing Age (Days)	Fibre Content (%)	Compressive Strength (N/mm²) f_c	Splitting Tensile (N/mm²) f_t	Ratio $\alpha = \frac{f_t}{f_c}$
	0.0	18.84	1.34	0.0711
	0.2	19.29	1.54	0.0798
	0.4	19.64	1.59	0.0810
7	0.6	17.88	1.45	0.0811
	0.8	16.84	1.28	0.0760
	1.0	14.68	1.23	0.0838
	1.2	14.15	1.10	0.0777
	0.0	20.25	1.66	0.0820
	0.2	20.98	1.83	0.0872
	0.4	21.44	1.85	0.0863
14	0.6	19.45	1.87	0.0961
	0.8	18.22	1.61	0.0884
	1.0	16.43	1.53	0.0931
	1.2	15.93	1.38	0.0866
	0.0	20.65	1.73	0.0838
	0.2	21.48	1.97	0.0917
	0.4	21.60	2.07	0.0958
21	0.6	19.97	1.99	0.0996
	0.8	18.73	1.75	0.0934
	1.0	17.32	1.66	0.0959
	1.2	16.50	1.53	0.0927
	0.0	22.33	2.11	0.0945
	0.2	23.17	2.96	0.1277
	0.4	23.53	2.73	0.1160
28	0.6	21.78	2.45	0.1125
	0.8	20.37	2.31	0.1134
	1.0	19.07	1.99	0.1044
	1.2	18.80	1.95	0.1037
	0.0	23.63	2.46	0.1041
	0.2	24.56	3.50	0.1425
	0.4	24.77	3.59	0.1450
90	0.6	24.28	3.25	0.1339
	0.8	23.44	2.95	0.1258
	1.0	23.04	2.91	0.1263
	1.2	21.35	2.71	0.1269

3.6.2 Strength Ratios Between Modulus Of Rupture And Compressive Strength

The modulus-of-rupture-to-compressive strength ratio provides an indication of the concrete's ductility and its post-crack behaviour (Prusty & Patro, 2015; Yusuf et al., 2016). This is shown in Table 7. This was determined by calculating the ratio (β) of the average modulus of rupture to the corresponding average compressive strength at each curing age. The results are presented in the following Table 7. Based on Table 7, the flexural-to-compressive strength ratio increases with both fiber content and curing age. At lower fibre dosages, this ratio remains moderate (typically between 0.06 and 0.09), but a notable rise is observed as fibre content increases, reaching a peak of approximately 0.15 at 0.8% fibre on day 7. This trend aligns with established literature (Fapohunda et al., 2018; Yusuf et al., 2016), which suggests that the modulus of rupture is generally about 15% of the compressive strength. The improvement at higher fibre contents indicates that, although compressive strength may slightly decline, the flexural performance is significantly enhanced due to the fibers' capacity to bridge cracks and redistribute stress more effectively over time.

Table 7 Modulus of Rupture to Compressive Strength Ratio

Curing Age (Days)	Fibre Content (%)	Compressive Strength (N/mm²) f_c	Modulus of rupture (N/mm²) f_m	Ratio $\delta = \frac{f_m}{f_c}$
7	0.0	18.84	1.19	0.0632
	0.2	19.29	1.50	0.0778
	0.4	19.64	1.81	0.0922
	0.6	17.88	2.13	0.1191
	0.8	16.84	2.59	0.1538
	1.0	14.68	2.06	0.1403
	1.2	14.15	1.54	0.1088
14	0.0	20.25	1.54	0.0760
	0.2	20.98	2.03	0.0968
	0.4	21.44	2.31	0.1077
	0.6	19.45	2.75	0.1414
	0.8	18.22	2.94	0.1614
	1.0	16.43	2.66	0.1620
	1.2	15.93	2.26	0.1418
21	0.0	20.65	1.65	0.0799
	0.2	21.48	2.18	0.1015
	0.4	21.60	2.44	0.1130
	0.6	19.97	2.88	0.1442
	0.8	18.73	3.06	0.1634
	1.0	17.32	2.79	0.1611
	1.2	16.50	2.49	0.1510
28	0.0	22.33	2.06	0.0922
	0.2	23.17	2.81	0.1212
	0.4	23.53	2.75	0.1169
	0.6	21.78	3.20	0.1469
	0.8	20.37	3.50	0.1718
	1.0	19.07	3.00	0.1573
	1.2	18.80	3.21	0.1707
90	0.0	23.63	2.56	0.1083
	0.2	24.56	3.25	0.1323
	0.4	24.77	3.56	0.1437
	0.6	24.28	3.75	0.1545
	0.8	23.44	3.81	0.1625
	1.0	23.04	3.88	0.1684
	1.2	21.35	3.89	0.1823

3.6.3 Development Of Strength Relations

To develop the strength relations between the strengths, a statistical model, in the form of a power function, as seen in Equation 4, was utilized to define the correlation between the splitting tensile strength and the compressive strength.

$$f_t = \beta f_c^{\kappa} \quad \textbf{(4)}$$

In equation 4; f_t denotes the tensile strength, f_c is the compressive strength, while β and κ are dimensionless coefficients. This expression was chosen because most established formulas linking tensile strength to compressive strength share this structure, thus enabling straightforward comparison of results (Arioglu et al., 2006; Fapohunda et al., 2018, 2020)).

3.6.3.1 Strength Relations Between Splitting Tensile Strength And The Compressive Strength

By representing the data for the splitting tensile and compressive strength values in Tables 6 in a scattered plot, Figure 8, which illustrates the correlation between the splitting tensile and compressive strengths to facilitate regression analysis, was obtained. It can be seen that the coefficient of determinations (R^2) resulting from the regression are quite large for all the replacement levels of the fibre. All the values are in excess of 0.90. Thus, it can be deducted that the power expression adequately represents the relationship between splitting tensile strength and compressive strength for concrete specimens with OPEFB fiber. İn order to confirm this deduction (Arioglu et al., 2006), recommended reliability test to evaluate the errors associated with regression equations through integral absolute errors (IAE). The values of IAE between 0 and 10%, according to (Arioglu et al., 2006) represents the limit of acceptable regression equation. The works of (Arioglu et al., 2006; C. Fapohunda et al., 2020) showed that all values of R^2 in excess of 0.76, will produce IAE values of less than 10%. Since the R^2 of equations 5 – 10 are in excess of 0.76, it can be concluded that their respective IAE are less than 10%. İt can thus be concluded that the relationship between splitting tensile strength and compressive strength of OPEFBF fiber at all the replacement levels considered, can be perfectly represented the power model equation.

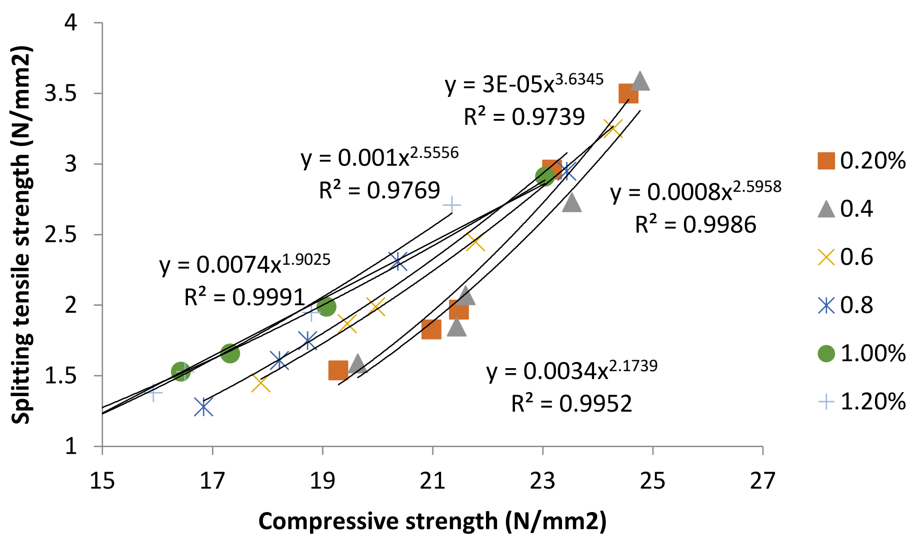

Figure 8 Relationship between Splitting tensile and compressive strength

The equations of the regression analysis from the plot are shown in equations 5 – 10

$f_t = 0.000f_c^{2.645}$	$R^2 = 0.998$	0.2%	(5)
$f_t = 4E\text{-}5f_c^{3.535}$	$R^2 = 0.958$	0.4%	(6)
$f_t = 0.000f_c^{2.595}$	$R^2 = 0.997$	0.6%	(7)
$f_t = 0.001f_c^{2.555}$	$R^2 = 0.980$	0.8%	(8)
$f_t = 0.007f_c^{1.902}$	$R^2 = 0.999$	1.0%	(9)
$f_t = 0.003f_c^{2.173}$	$R^2 = 0.995$	1.2%	(10)

3.6.3.2 Strength Relations Modulus Of Rupture And Compressive Strength

To determine the relationship between the modulus of rupture (mor) and compressive strengths, the data in Table 7 were used to obtain the scattered plots shown in Figure 8. The regression equations from the plots are as presented in equations 11 - 16. The coefficient of determination R^2 followed the same pattern as the relationship between splitting tensile strength and compressive strength, since the values were also in excess of 0.90. The R^2 of equations 11−16, being in excess of 0.76, their respective IAE are also less than 10% (Arioglu et al., 2006; Fapohunda et al., 2020).

$f_{mor} = 0.000f_c^{3.220}$	$R^2 = 0.995$	0.2%	(11)
$f_{mor} = 0.000f_c^{2.992}$	$R^2 = 0.994$	0.4%	(12)
$f_{mor} = 0.015f_c^{1.739}$	$R^2 = 0.947$	0.6%	(13)
$f_{mor} = 0.098f_c^{1.170}$	$R^2 = 0.952$	0.8%	(14)
$f_{mor} = 0.070f_c^{1.277}$	$R^2 = 0.959$	1.0%	(15)
$f_{mor} = 0.007f_c^{2.075}$	$R^2 = 0.895$	1.2%	(16)

İt can thus be concluded that the relationship between modulus of rupture and compressive strength of OPEFBF fibre at all the levels of replacement considered, can be perfectly represented by the power model equation.

4.0 CONCLUSIONS

From the analysis of the results as presented above, the following were concluded:

i. The density of hardened concrete remains within the normal weight concrete range according to ACI 318 (American Concrete Institute, 2011) and BS EN 12390-7 (British Standards Institution, 2019c) but declines slightly at fiber contents exceeding 0.6% due to void formation and fiber clustering.
ii. Compressive strength improves at fiber contents between 0.2% and 0.4%, with the highest strength recorded at 24.77 N/mm² after 90 days. Beyond 0.6% fiber content, strength reductions occur due to clustering effects.
iii. The flexural strength (modulus of rupture) improves at fiber contents of 0.2%–0.8%, with peak performance at 0.6%–0.8%.
iv. The splitting tensile strength increases between 0.2% and 0.6%, with optimal performance at 0.4% –0.6%. Higher fiber contents (≥0.8%) lead to strength deterioration due to fiber agglomeration and inadequate stress transfer.
v. Power model equation can be considered to represent the relationship between splitting tensile strength and compressive strength; as well as the relationship between modulus of rupture and compressive strength.

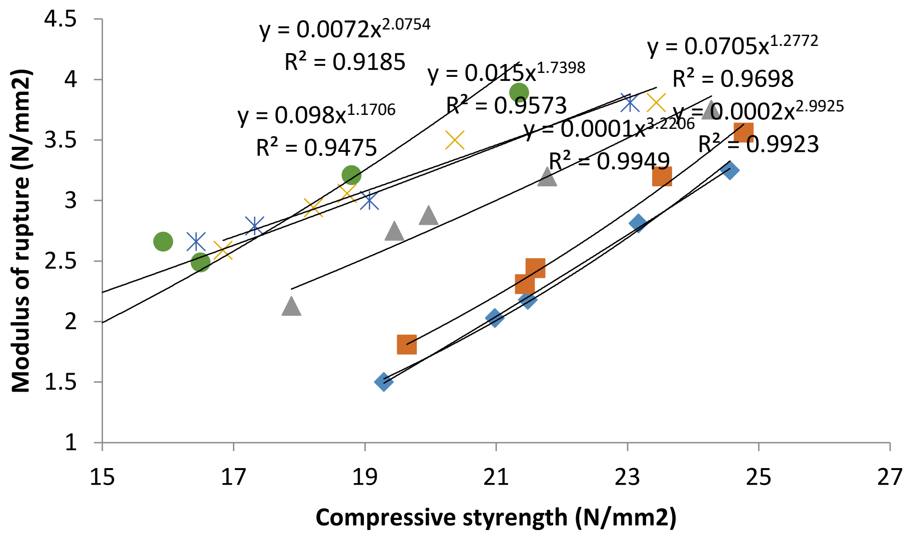

Figure 8 Relationship between modulus of rupture and compressive strength

Acknowledgements

The technical assistance of the technologist in the Concrete Laboratory of Civil Engineering Department, Federal Polytechnic Ado-Ekiti, Nigeria, is acknowledged.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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