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Comparative Analysis of Flexural Strength in Timber-Reinforced Concrete Beams Using African-Birch Timber and Steel Reinforcement

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Abstract. This study aimed to investigate the feasibility of African-Birch (AB) Timber-Reinforced Concrete (ABTRC) as an eco-friendly alternative to traditional steel-reinforced concrete. The objectives were to determine some material properties (e.g. specific gravity, moisture content, fineness modulus, sieve analysis etc.), develop mix designs, and evaluate the flexural strength of ABTRC beams. Four reinforcement configurations {Steel (hanger bar) + Steel (main bar), Steel (hanger bar) + AB (main bar), AB (hanger bar) + Steel (main bar), and AB (hanger bar) + AB (main bar)} were tested, with beams cured for 3, 7, 14, 21, and 28 days. Some physical properties were determined for African-Birch timber (specific gravity, moisture content and tensile strength), fine and coarse aggregates. A mix design was developed using the BS 196-3-2016 (1:2.39:3.24 and water-cement ratio of 0.6). The flexural strength was evaluated using a 3-point bending test on a Universal Testing Machine (UTM). The results/findings demonstrated a significant 127% increase in flexural strength for Steel (hanger bar) + Steel (main bar), while AB (hanger bar) + Steel (Main bar) improved by 19.32%. AB (hanger bar) + AB (main bar) exhibited the lowest strength values. While Steel-based and hybrid configurations showed minimal density changes, AB (hanger bar) + AB (main bar) experienced a 22.32% reduction. Additionally, ultimate loadingss increased by 19.4% for AB (hanger bar) + Steel (main bar) and 27.1% for Steel (hanger bar) + Steel (main bar), highlighting the potential of African-Birch timber for sustainable construction applications.

Key words: African-Birch Timber-Reinforced Concrete (ABTRC), sustainability, flexural strength, hybrid reinforcement, eco-friendly construction.

1. Introduction

Timber-reinforced concrete (TRC) has emerged as a promising construction material, combining the benefits of timbers and concrete to create a more environmentally friendly and energy-efficient built environment (Abera, 2024). By incorporating timber elements into the concrete mix, TRC reduces the carbon footprint associated with traditional concrete production (Immanuel & Baskar, 2023). The substitution of cement with renewable timber also mitigates climate change, as cement production is a significant contributor to greenhouse gas emissions (Elinwa & Abdulrazaq, 2020; Izumi *et al.,* 2021). Additionally, TRC enhances thermal insulation properties and improves structural performance.

This study aims to determine some of the physical and engineering properties of materials to develop an appropriate mix design while preparing steel and AB reinforcement into specific configurations for casting reinforced concrete beams. The flexural strength of African-Birch timber-reinforced concrete beams will be compared with traditional steel-reinforced concrete beams at different curing ages (3, 7, 14, 21, and 28 days).

The mechanical properties of timber, including density, moisture content, and strength, are critical to the performance of timber-reinforced concrete (TRC) beams (Yin *et al.,* 2021). African Birch timber, for instance, has been found to possess a tensile strength equivalent to approximately 16% of high-yield steel and 31% of mild steel at 18% moisture content (Bello &

Jimoh, 2017). In this present study, it had an average moisture content of 9.83% which is expected to influence the measured mechanical properties. However, the variability in timber's mechanical properties presents a significant challenge to the widespread adoption of TRC (Abdulraheem *et al.,* 2024).

Studies utilizing three-point bending tests have demonstrated that TRC beams can achieve flexural strength comparable to or even superior to that of traditional steel-reinforced concrete beams (Alrshoudi, 2021). Research also highlights the impact of curing duration, with longer curing ages significantly enhancing TRC beams' flexural performance (Yin *et al.,* 2021). Despite its promising potential, TRC still faces limitations, particularly due to the inconsistency in timber properties, which can affect structural reliability (Venigalla *et al.,* 2022).

The construction industry stands to benefit greatly from TRC, as it offers a more sustainable and energy-efficient alternative to conventional materials (Kirupakaran, 2024). To facilitate its broader adoption, further research is needed to establish standardized selection criteria for timber reinforcement, optimize curing processes, and address performance variability (Niemz & Dunky, 2023). Advancing TRC research will contribute to the development of sustainable construction materials, inform industry practices and policies, and support the creation of environmentally friendly and structurally sound buildings (Kirupakaran, 2024).

2. Materials and methods

2.1. Some Physical Property Test on the Materials

2.1.1. Fineness Modulus Test (on fine and coarse aggregate) BS 812: Part 103 1985

The fineness modulus of fine aggregate was determined to assess its particle size distribution. The test involved sieving approximately 1000g of fine aggregate through a series of sieves and recording the weight retained on each sieve. The fineness modulus (FM) was calculated using equation 2.1

Fineness Modulus (FM) = (Cumulative % Retained / 100) × 100 ***Equ. 2.1***

2.1.2. Sieve Analysis Test (on fine and coarse aggregate) BS: 1377- 1975, BS 1377; 1990 part 2

The sieve analysis test was conducted to determine the particle size distribution of fine and coarse aggregates. Approximately 1000g of aggregate was sieved through a series of sieves, and the weight retained on each sieve was recorded. The percentage retained and passing were calculated using the equations 2.2 and 2.3.

% Retained = (Weight Retained / Total Weight) × 100 ***Equ. 2.2***

% Passing = 100 - % Retained ***Equ. 2.3***

2.1.3. Moisture Content Test (on fine aggregate, coarse aggregate and African birch timber)

The moisture content of African-Birch timber was assessed using the oven drying method (Abdulrazaq *et al.*, 2024), as specified in BS812: Part 109:1990 (aggregates) and BS 373: 1957 (for African-birch). This method involves measuring the weight loss of timber samples after drying at a controlled temperature. Timber samples with dimensions 50mm x 50mm x 50mm were cut and weighed to record their initial weight (m1). The samples were then dried at 103°C ± 2°C for 24 hours and re-weighed to record their final weight (m2). The moisture content (%) was calculated as given in equations 2.4 and 2.5:

$$Mc\ (\%) = \frac{M2-M3}{M3-M1}\ X\ 100\% \qquad \text{(for aggregates)}$$ ***Equ. 2.4***

$$\boldsymbol{Mc}\ (\%) = \left(\frac{Initial\ Mc - Dry\ weight}{\text{Dry weight}}\right) * \mathbf{100} \qquad \text{(for African-birch)}$$ ***Equ. 2.5***

2.1.4. Specific Gravity Test (on fine aggregate, coarse aggregate and African birch timber) (According to BS812: Part 109:1990)

The specific gravity of African-Birch timber was determined according to BS EN 316:2009 (Putro *et al.,* 2020) & BS812: Part 109:1990. This method involves measuring the sample's dimensions (length, width, and height) and also weight (mass) of sample (aggregates). The volume (V) was calculated as V = L × W × H, and the specific gravity (G) was calculated with equations 2.6 and 2.7 given below.

$$G = \frac{(M)}{(V)\ X\ (\rho w)} \quad \text{(for timber)} \qquad \textit{Equ. 2.6}$$

Where;

ρw is the density of water (1000 kg/m^3). The specific gravity provides valuable information on the timber's density and potential durability.

$$G = \frac{(M2-M1)}{(M2-M1)-(M3-M4)} \quad \text{(for aggregates)} \qquad \textit{Equ. 2.7}$$

Where;

M1 = mass of empty pycnometer, M2 = mass of pycnometer and dry soil, M3 = mass of pycnometer, soil and water & M4 = mass of pycnometer filled with water only.

2.1.5. Tensile Strength Test(on African birch timber)

The tensile strength of African-Birch timber was evaluated using a universal testing machine with a 10mm/min crosshead speed, as specified in BS EN 310:1993. African-birch timber (ABT) samples with dimensions 20mm x 20mm x 300mm were cut, and the maximum load (F_{max}) at failure was recorded. The tensile strength (σt) was calculated using the formula as given in equation 2.8:

$$Tensilie\ Strength\ (\sigma t) = \frac{Maximum\ load\ (\text{Fmax})}{Cross\ sectional\ area\ (A)} \qquad \textit{Equ. 2.8}$$

2.2. Mix Design and Proportioning (BS EN 196-3-2016)

The absolute volume method of batching was adopted for the batching as against the BS EN 196-3-2016) method of design for the concrete mix. This method considers the absolute volume of cement, aggregates, water, and air in one cubic meter of concrete (Kirthika *et al.,* 2020). The batching method used is as given in equation 2.9:

$$V_c = \frac{W}{1000} + \frac{C}{1000SGc} + \frac{F.A}{1000SGf} + \frac{C.A}{1000SGca} \qquad \textit{Equ. 2.9}$$

Where:

Vc = Absolute volume of concrete, W = Mass of water, C = Mass of cement, FA = Fine Aggregates

CA = Coarse Aggregate, S*gc* = Specific gravity of cement, S*gfa* = Specific gravity of fine aggregate and S*gca* = Specific gravity of coarse aggregate.

Table 1: Summary of the mix proportion of constituent material.

Summary of Material Content		
Material	Content (Kg)	Ratio
Cement Content (Cc)	386	1
Fine Agg. Content	706	2.39
Coarse Agg. content	1040	3.24
Water-cement ratio	231.6	0.6
NOTE W/c ratio of 0.5 was to coarse, as the concrete mix have zero workability. Thus w/c ration of 0.6 was adopted		

The mix design yielded a mix ratio of approximately 1:2.39:3.24 (cement: fine aggregate: coarse aggregate) and a water-to-cement ratio (w/c) of 0.6. Initially, a w/c ratio of 0.5 was considered, but it resulted in zero workability.

2.2.1. Sample Preparation and Curing

Beam samples were cast in wooden molds and reinforced with 8mm diameter stirrups spaced at 200mm. Four different reinforcement configurations were used, including a control sample. A total of four (40) batches were cast, each with two (2) samples. The samples were cured for various durations (3, 7, 14, 21, and 28 days) and subjected to slump and compaction factor tests. After casting, the samples were tamped and allowed to set before demolding and curing.

2.3. Experimental Investigation

2.3.1. Workability of the Concrete Mix.

The workability of the fresh concrete mix was evaluated in accordance with BS EN 12350-2:2019 using the slump test. An initial water-cement ratio of 0.5 was used, resulting in a zero-slump mix, indicating poor workability. The water-cement ratio was subsequently increased to 0.6, yielding a true slump of 80 mm, indicating improved workability.

2.3.2. Flexural Strength Testing

Flexural strength, the maximum bending stress a material can withstand before yielding, was determined using a three-point bending method on a universal testing machine (Wilson *et al.*, 2022) as seen in plate 1. The beam samples were inspected for defects and then placed on the supports of a universal testing machine. A controlled load was applied at the center of each beam, inducing bending stresses (find attached the result on the appendix). The maximum load sustained by the beam was recorded and used to calculate flexural strength using the following formula of equation 2.10 (Bello & Jimoh, 2018).

$$Fs = \frac{3Pa}{bd^2} \qquad \textbf{Equ. 2.10}$$

Where;

P = Load, a = length of the sample, b = breath of the sample and d = depth of the sample.

Plate 1: Standard set up of specimen on a UTM machine.

3. Results and Discussion

3.1. Physical and Engineering Properties

The physical and engineering properties of materials influence their structural performance, durability, and suitability for reinforcement. This study examines key properties of African-birch timber-reinforced concrete (ABTRC) to optimize material selection, mix design, and curing processes for sustainable construction. Table 2 below summarizes the measured/obtained values of the materials obtained in the study, compares them with expected or range values from the literature, and provides the corresponding references for each property.

The concrete's workability was initially poor with a 0.5 water-cement ratio, showing a zero slump. Increasing the ratio to 0.6 improved workability of the mix, resulting in a measured slump value of 80mm. The African birch wood specimens had a relatively low moisture content of 9.83%, suggesting their strength values are likely comparable to or higher than those reported in other studies with higher moisture contents (Bello & Jimoh, 2018).

Table 2: Summary of the Physical test on all materials used.

Property	Material	Measured Value	Expected/Range Value	Reference
Specific Gravity	Fine Aggregate	2.65	2.30 – 2.90	Çelik *et al.,* (2021)
	Coarse Aggregate	2.43	2.30 – 2.90	Çelik *et al.,* (2021)
	African-Birch Timber	0.89	0.84 – 1.16	Jimoh *et al.*, (2018)
Moisture Content	African-Birch Timber	9.83%	6.01% – 12.39%	Jimoh *et al.,* (2018)
Fineness Modulus	Fine Aggregate	3.48	2.00 – 4.00	Liu *et al.,* (2024)
	Coarse Aggregate	3.84	3.0 – 6.0	Sharaky *et al., (2022)*; Kamara & Bure, (2020)
Tensile Strength	African-Birch Timber	99.86 N/mm^2	69.61 N/mm^2 – 115.9 N/mm^2	Bello & Jimoh (2018)

3.2. Flexural Strength against age

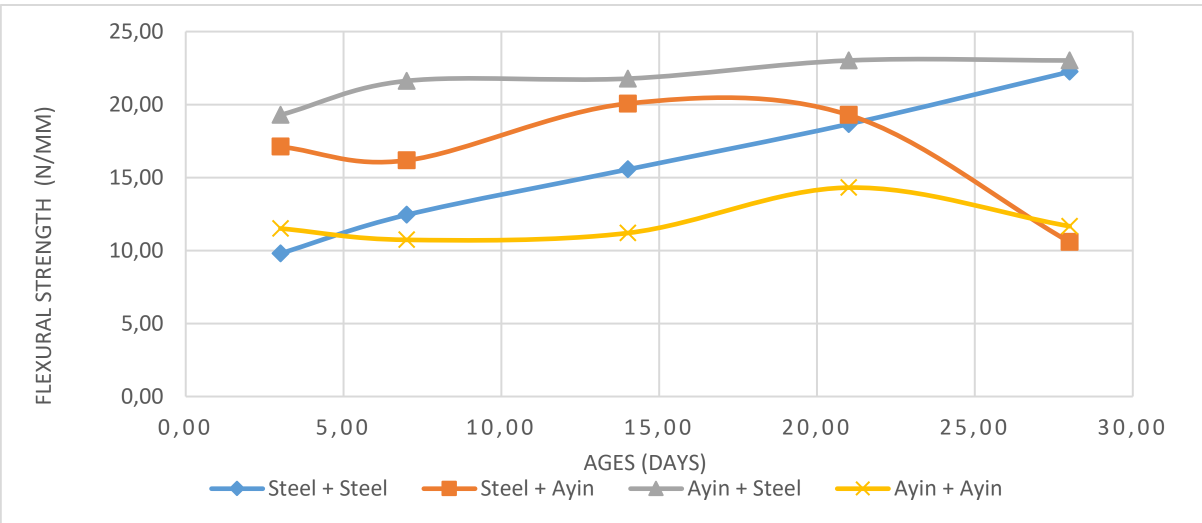

Figure 1: Curve showing Flexural Strength against curing ages.

From the figure 1 above, the flexural strength of African-birch timber-reinforced concrete (ABTRC) beams varies significantly with reinforcement configuration and curing age. The Steel (hanger bar) + Steel (main bar) configuration showed a 127% strength increase, from 9.80 N/mm^2 at 3 days to 22.24 N/mm^2 at 28 days, while Steel (hanger bar) + AB (main bar) declined by 38%. AB (hanger bar) + Steel (main bar) achieved the highest strength, rising 19.32% to 23.02 N/mm^2. AB (hanger bar) + AB (main bar) had the lowest values, peaking at 14.31 N/mm^2. These results support Sroka *et al.,* (2024) research on hybrid reinforcement effectiveness and contradict

Okeke *et al*., (2024) assertion of steel-only superiority. Additionally, the findings align with Wu *et al.*, (2023) conclusions on the significance of curing age in TRC beam performance, highlighting the potential of African-Birch timber for sustainable construction applications.

3.3. Density against Ages

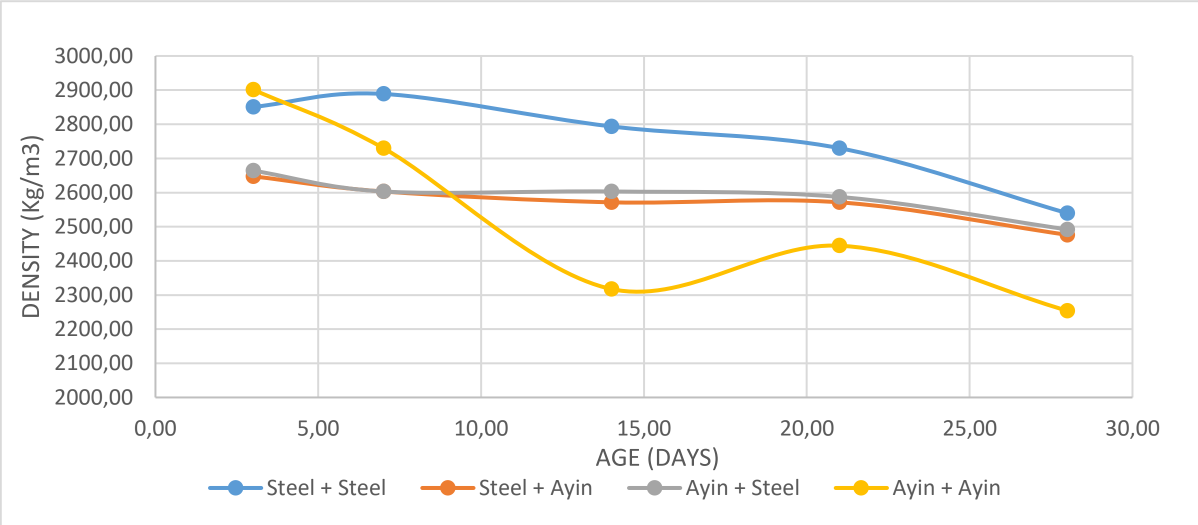

Figure 2: Curve showing Density against curing ages.

This section seeks to evaluated the density of timber-reinforced concrete (TRC) beams with Steel (hanger bar) + Steel (main bar), Steel (hanger bar) + AB (main bar), AB (hanger bar) + Steel (main bar), and AB (hanger bar) + AB (main bar) configurations at different curing ages. The AB (hanger bar) + AB (main bar) configuration showed a 22.32% decline, while Steel + Steel and hybrid configurations remained stable, with variations between -6.4% and +1.3%**.** These results align with studies on steel's early strength (Bhogone & Subramaniam, 2021) and timber's density loss moderation (Olowokere *et al.,* 2022), highlighting African-Birch timber's potential in TRC applications.

3.4. Load against Age

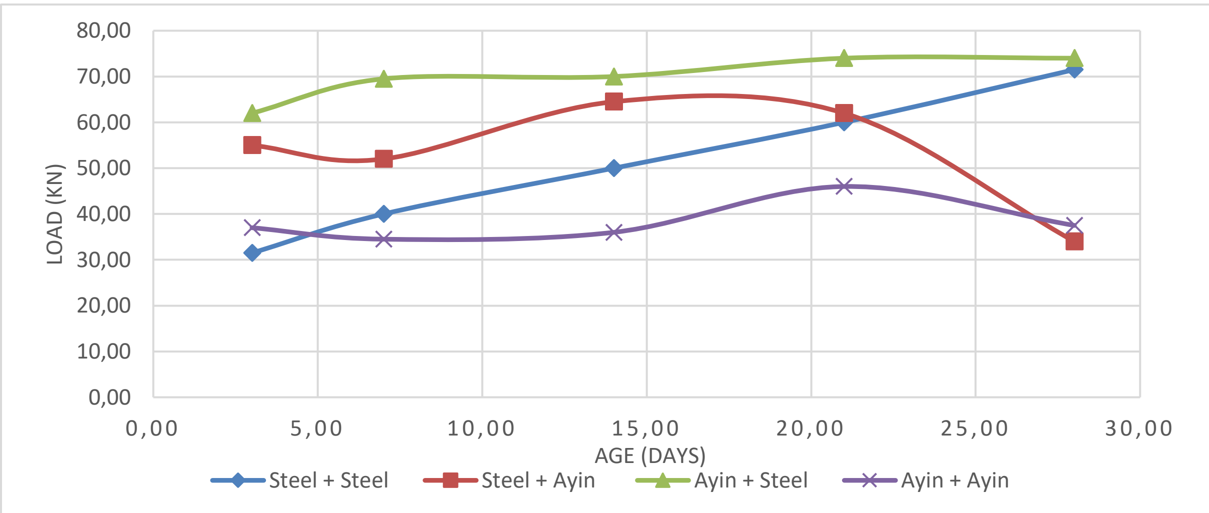

Figure 3: Curve showing Load (KN) against curing age (Days).

The load-bearing capacity of the African-birch timber-reinforced concrete (ABTRC) beams varied with reinforcement configuration and curing age. The AB (hanger bar) + Steel (main bar) configuration showed a 19.4% increase, from 62.00 kN at 3 days to 74.00 kN at 28 days, while Steel (hanger bar) + AB (main bar) declined by 38.2%**.** The Steel (hanger bar) + Steel (main bar) configuration increased by 27.1%**.** Findings support Alrshoudi (2021) hybrid reinforcement benefits and Wilson & Carter's (2021) emphasis on steel reliability, challenging Abed *et al.,* (2022).

4. Conclusions

The study examined timber-reinforced concrete (TRC) beams with various reinforcement configurations {Steel (hander bar) + Steel (main bar), Steel (hanger bar) + AB (main bar), AB (hanger bar) + Steel (main bar), and AB (hanger bar) + AB (main bar)} at different curing ages. The results showed Steel (hanger bar) + Steel (main bar) had a 127% increase in flexural strength, while AB (hanger bar) + Steel (main bar) improved by 19.32%. AB (hanger bar) + AB (main bar) had the lowest values. Density changes were minimal for Steel-based and hybrid configurations, but AB + AB showed a 22.32% decrease. Load resistance of the beam increased by 19.4% for AB (hanger bar) + Steel (main bar) and 27.1% for Steel (hanger bar) + Steel (main bar), supporting the potential of African-Birch timber for sustainable construction.

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