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Investigating the Effect of Age on Some Mechanical Properties of Coconut Fibre Reinforced Concrete (CFRC)

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Abstract. This study explores the long-term effects of aging on the mechanical properties of Coconut Fibre Reinforced Concrete (CFRC) compared to plain concrete (PC). An experimental analysis was conducted on structural-grade concrete mixes, ranging from 20 to 50 N/mm^2, over curing periods of 28, 60, 120, and 180 days to evaluate compressive strength, split tensile strength, and density. The results indicate that CFRC exhibited a 10–18% reduction in compressive strength compared to PC, depending on the grade and curing duration. In contrast, CFRC's split tensile strength showed a notable 22–35% increase, demonstrating enhanced ductility and crack resistance over time. Additionally, density measurements revealed a 4–9% reduction due to the incorporation of coconut fibres. While CFRC improves sustainability and tensile performance, addressing long-term degradation challenges is crucial for optimal structural applications. These findings provide valuable insights into the viability of CFRC in sustainable construction, informing engineers and policymakers about its long-term performance in tropical environments.

Key words: Coconut fibre, reinforced concrete, CFRC aging, compressive strength of CFRC and split tensile strength of CFRC.

1. Introduction

Concrete is a fundamental material in the construction industry, known for its exceptional compressive strength, durability, fire resistance, and low permeability (Amran *et al.*, 2022). However, its limitations, including low tensile strength, brittleness, susceptibility to cracking, and poor impact resistance, necessitate improvements (Makul, 2020). To address these shortcomings, researchers have explored Fibre-Reinforced Concrete (FRC), incorporating natural or synthetic fibres to enhance concrete performance (Ahmad & Zhou, 2022). Coconut fibre (coir) has emerged as a promising natural fibre reinforcement due to its eco-friendly properties, economic viability, and unique characteristics. Its high lignin content, cellulose structure, and resistance to microbial degradation make it an effective material for improving concrete's structural integrity (Martinelli *et al.,* 2023).

Coconut fibre's unique characteristics enhanced concrete's mechanical performance, particularly in tensile strength, ductility, and impact resistance. A previous study by Ahmed *et al.,* (2022) optimized fibre dosage and length, demonstrating significant improvements in mechanical properties. However, concrete's aging process influenced its mechanical properties, impacting structural integrity (Malik *et al.,* 2021). The selection of concrete grades ranging from 20 to 50 N/mm^2 is well-suited for structural applications in tropical regions, offering a balanced combination of durability, strength, and cost-efficiency (Cai *et al.,* 2023; Ahmed *et al.,* 2024). This range ensures optimal performance while adapting to environmental stresses, justifying its widespread use in tropical regions.

Coconut fibre is prone to degradation due to its composition and environmental exposure (Mishra & Basu, 2020). With a moisture content of 7.01%, the fibre weakens over time. Its organic nature characterized by an ash content of 0.19% and fixed carbon of 22.53% renders it susceptible to alkaline hydrolysis, leading to the breakdown of its lignocellulosic structure. A high volatile matter content (70.27%) further presents a thermal decomposition risk (De-Araújo *et al.,* 2024). Exposure to alkaline environments and moisture accelerates fibre degradation, diminishing its strength and elasticity while making it brittle (Lv & Liu, 2023). Repeated wet-dry cycles intensify this deterioration, causing fibre swelling and the breakdown of its microstructure, ultimately affecting durability and mechanical performance (Addis *et al.,* 2022).

This study addresses the existing knowledge gap regarding the long-term performance of Coconut Fibre Reinforced Concrete (CFRC), contributing to the development of sustainable and resilient construction materials (Wang *et al.*, 2022). By advancing the understanding of CFRC's properties, benefits, and limitations, researchers and practitioners can harness its potential for sustainable infrastructure development. The findings will provide essential data for engineers, architects, and policymakers, promoting sustainable construction practices and guiding the formulation of eco-friendly construction materials (Abdulrazaq *et al.,* 2024). The use of 2.5% fibre content is supported by previous literature, which found that a fibre dosage ranging from 2% to 3% significantly enhances tensile strength while maintaining workability (Ahmad *et al.,* 2022). This fibre content improves durability and mechanical performance, reinforcing coconut fibre as a viable alternative to synthetic fibres.

2. Materials and Methods

This study utilized ordinary Portland cement (OPC), fine aggregate (river sand), coarse aggregate (crushed granite), water, and coconut fibre. These materials were evaluated against established standards:

i. **Cement:** OPC grade 42.5, conforming to BS EN 197-5:2011 and NIS 444-1:2014, with a specific gravity of 3.15 g/ml.
ii. **Fine Aggregate:** River sharp sand, free of clay and silt, passing through a 4.75 mm sieve and predominantly retained on a 75 µm sieve, conforming to BS EN 12620-3:2013.
iii. **Coarse Aggregate:** Crushed granite stone passing through a 20 mm sieve and retained on a 10 mm sieve, conforming to BS EN 12620-3:2013.
iv. **Water:** Clean, potable water meeting the standards of the material laboratory at Kaduna Polytechnic.
v. **Coconut Fibre:** Locally sourced coconut fibre, washed, air-dried, and cut to a 50 mm length. Tensile strength, bulk density, and moisture content were measured using ASTM D638-10 and ASTM D1895-20 respectively.

2.1. Aggregate Testing Procedures

This study employed various tests to evaluate the properties of fine and coarse aggregates, adhering to international standards.

i. Sieve Analysis (BS EN 933-2:2020)

Sieve analysis determined the particle size distribution of aggregates. A representative sample was dried, weighed, and sieved using standard sieves. The material retained on each sieve was weighed, and the percentage retained was calculated using equation 1.

$$\text{Percentage Retained} = \frac{Weight\ of\ material\ on\ sieve\ (Wx)}{Total\ sample\ weight\ (W1)} \times 100 \qquad \textbf{Eqn.1}$$

ii. Specific Gravity (BS 812: Part 109:1990)

Specific gravity testing measured the density of aggregates. A pycnometer was used to determine the mass of oven-dried aggregate, water, and the combination. The specific gravity (G) was calculated using equation 2 as follows:

$$G = \frac{(M2-M1)}{(M2-M1)-(M3-M4)} \quad \textbf{\textit{Eqn.2}}$$

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.

The results of these investigations are presented in appendix A-1 and A-2.

i. Relative Density and Water Absorption (BS 812: Part 2:1975)

Relative density and water absorption tests evaluated the aggregate's ability to absorb water. A sample was washed, saturated, and weighed. The relative density (ρ_d) and water absorption (ω_{abs}) were calculated using equation 3 and 4 respectively.

$$\rho_d = \frac{Md}{Ma-(Mb-Mc)} \quad \textbf{\textit{Eqn.3}}$$

$$\omega_{abs} = \frac{100[Ma-Md]}{Md} \quad \textbf{\textit{Eqn.4}}$$

Where;

ρ_d = Relative Density of an oven dried basis

ω_{abs} = Water absorption

2.2. Coconut Fibre Preparation and some of its Mechanical and Physical Tests

Coconut fibres were manually extracted, washed, air-dried, and cut to 50mm lengths. The mechanical properties, including tensile strength, bulk density, and water absorption, were determined using standard methods as enlisted below. Tensile strength was tested using an INSTRON 3369 universal testing machine according to ASTM D3822-07 as illustrated in plate 1, while bulk density was determined using ASTM D1895-20.

A. Some tests on Mechanical and Physical Properties of Coconut Fibre

This study examines the mechanical and physical properties of coconut fibres through tensile strength, bulk density, and water absorption tests, adhering to relevant ASTM standards.

Table 1. Proximate Analysis of Coconut fibre (coir) Sample.

S/N	Parameter	Unit	Result
1	Moisture Content	%	7.01
2	Ash Content	%	0.19
3	Volatile Matter	%	70.27
4	Fixed Carbon	%	22.53
5	Hemicellulose	%	28.58
6	Lignin	%	32.23
7	Cellulose	%	39.19
8	Holocellulose	%	67.77

i. Tensile Strength Test (ASTM D638-10)

The tensile strength of coconut fibres was tested using an Instron mechanical testing machine as illustrated in figure 1. Single fibre specimen was prepared and tested under a crosshead speed of 1 mm/min. Tensile strength (F_t) was calculated from the breaking load and cross-sectional area and the stress-strain curve is shown in figure 1.

$$Ft = \frac{2P}{\pi l d} \qquad \textbf{Eqn.5}$$

Where:

P is the applied load at failure (in Newtons),

l is the length of the specimen (in mm),

d is the diameter of the specimen (in mm).

Plate 1. Fibre is ready for test in the machine

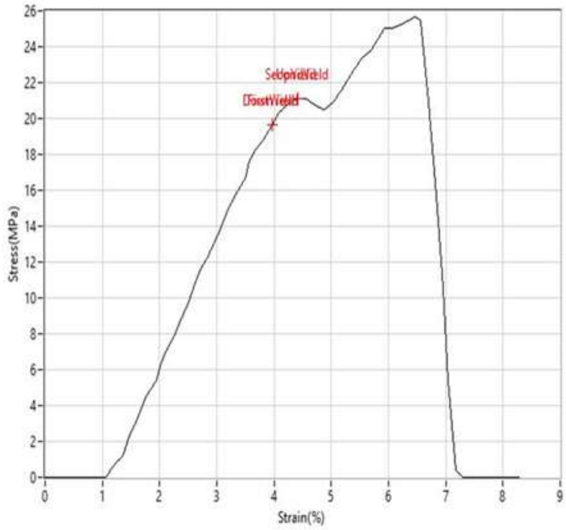

Fig. 1. Fibre is ready for test in the machine fibre

ii. Bulk Density Test (ASTM D1895-96)

The bulk density of coconut fibres was measured by filling a cylinder with fibres and recording the weight before and after filling. Bulk density was calculated and reported in grams per cubic centimeter (g/cm^3) using equation 6.

$$Bulk\ density = \frac{(W1-W2)}{V} \qquad \textbf{Eqn.6}$$

Where:

W1 = Weight of the empty cylinder (g)

W2 = Weight of the cylinder with the coconut fibre (g)

V = Volume of the cylinder (cm^3)

iii. Water Absorption Test (BS 1881, Part 122 (1983))

The water absorption test involved oven-drying the fibres at 105 ± 3°C until constant weight. Moisture content was calculated as a percentage of the initial wet weight using:

$$Moisture\ content\ (\%) = \frac{(W1-W2)}{W2}\ x\ 100 \qquad \textbf{Eqn.7}$$

Where:

W_1 was the initial wet weight and W_2 was the final dry weight.

B. Mix Design

Concrete mixes were designed using the absolute volume method to ensure accurate material quantities for the target concrete grades. Four grades were designed: 20, 30, 40, and 50 N/mm^2. The specific gravities of cement, fine aggregate, and coarse aggregate were assumed to be 3.10, 2.65, and 2.43, respectively. Equation 8 was used to calculate the Absolute volume of fully compacted fresh concrete as follows:

$$V_c = \frac{w}{1000} + \frac{C}{1000SGc} + \frac{F.A}{1000SGf} + \frac{C.A}{1000SGca} \qquad \textbf{\textit{Eqn.8}}$$

Where, Vc = Absolute volume of fully compacted fresh concrete

W = Mass of water

C = Mass of cement

Ca = Mass of coarse aggregates

For fibre-reinforced mixes, 2.5% of the cement mass was replaced with coconut fibre. Concrete specimens were cast in cube molds (150 mm x 150 mm x 150 mm) for compressive strength tests and cylinder molds (150 mm diameter and 300 mm height) for split tensile strength tests.

C. Testing Procedures

Concrete Testing Procedures

This study evaluated the properties of fresh and hardened concrete using various tests.

1. Workability Test (BS EN 12350-2:2019 and BS EN 12350-4:2019)

The slump test and compacting factor tests assessed the workability of fresh concrete. The slump test measured the vertical drop in concrete height after removing a frustum cone mold. The compacting factor test calculated the ratio of compacted to loose concrete weight.

i. Slump Test (BS EN 12350-2:2019)

The slump test is a widely used method to assess the workability and consistency of fresh concrete. It involves filling a frustum-shaped mold in four layers, compacting each layer, and then lifting the mold vertically. The slump is measured as the distance between the mold's top and the slumped concrete's highest point. There are three types of slump: true slump, indicating good cohesion and workability; shear slump, indicating lack of cohesion and potential segregation; and collapse slump, suggesting a too-wet mix with poor workability.

The addition of fibers to concrete, such as coconut fibers, reduces workability and slump due to internal friction, water absorption, and fiber entanglement. The fibers create a reinforcement network that resists movement and acts as a bridge between cement particles, influencing workability and compaction characteristics. In Coconut Fibre Reinforced Concrete (CFRC), the slump reduction is attributed to the fibre's characteristics, including longer fibre length (50 mm), rough surface texture, and high lignin content, which enhance mechanical interlocking and restrict flowability. Furthermore, the hydrophilic nature of coconut fibres absorbs water, reducing free water and increasing viscosity, ultimately lowering slump values compared to plain concrete. As a result, CFRC requires more effort for compaction, and improper compaction can lead to air voids, affecting density and durability.

ii. Compacting Factor Test (BS EN 12350-4:2019)

The compacting factor test measured the degree of compaction for low-workability mixes. The test procedure involved setting up an apparatus consisting of two hoppers and a cylindrical mold. The freshly mixed concrete was then placed into the upper hopper without compaction, filling it to the brim. The trapdoor of the upper hopper was opened, allowing the concrete to fall into the lower hopper, which had a smaller opening to restrict free flow. The concrete then filled the lower hopper, and its trapdoor was opened, allowing the concrete to fall freely into the cylindrical mold. The compacted weight (Wc) of the concrete in the mold was measured, and then the mold was refilled with the same mix without compaction to determine the loose weight (Wl). The compacting factor (CF) was calculated using the formula :

$$C_f = \frac{Wc}{W1} \qquad \textbf{Eqn.9}$$

Where;

Wc is the weight after compaction and

W_l is the weight in the loose state.

Plate 2: Slump test on fresh concrete.

Plate 3: Compacting factor test

2. Compressive Strength Test (BS EN 12390-3:2019)

Cube specimens (150 mm × 150 mm × 150 mm) were tested for compressive strength using a Universal Testing Machine. The compressive strength (f) was calculated using equation 10.

$$f = \frac{F}{Ac} \qquad \textbf{Eqn.10}$$

Where;

f = Compressive strength, in MPa (N/mm^2)

F = Maximum load at failure, in newton

Ac = Cross-sectional area of the specimen on which the compression test is carried out, calculated from the designated size of the specimen or from measurements on the specimen in mm^2 See plate 7 for the cube samples.

3. Split Tensile Strength Test (ASTM C496-71)

Cylindrical specimens (150 mm diameter and 300 mm height) were subjected to diametral compression. The tensile strength was calculated using equation 11 as follows:

$$\Delta_t = \frac{2p}{\pi ld} \qquad \textbf{Eqn.11}$$

Where P = load, l= clear span length, d=diameter of the specimen.

4. Density Test (BS EN 12390-7:2019)

The density (D) of hardened concrete was calculated using equation 12 as follows:

$$\boldsymbol{D} = \frac{\boldsymbol{m}}{\boldsymbol{v}} \qquad \textit{Eqn.11}$$

Where;

D is the density related to the condition of the specimen and method of determining the volume in kg/m^3;

m is the mass of the specimen as determined by mass as received specimen, mass of water saturated specimen and mass of oven dried specimen

V volume determined by the particular method in m^3.

D. Curing Procedure

The concrete specimens underwent a standardized curing process, adhering to BS EN 12390-2:2019. Initially, the specimens were left in their molds for 24 hours, followed by immersion in a water tank for curing at ambient temperature. Optimal curing conditions for Coconut Fibre Reinforced Concrete (CFRC) specimens exposed to varied weather conditions, including rain and dry seasons with different temperatures, involve exposing them from moderate environmental conditions.

Plate 2. Slump test on fresh concrete.

Plate 3. Compacting factor test

1. Testing Schedule

A comprehensive testing schedule was devised to evaluate the specimens' compressive and tensile strengths at various curing ages. A total of 192 specimens were prepared and tested, comprising 96 cubic specimens for compressive strength and 96 cylindrical specimens for split tensile strength.

2. Specimen Distribution and Testing

The specimens represented four concrete grades, with 48 specimens allocated to each grade. These were evenly distributed across four curing ages: 28, 60, 120, and 180 days. For each curing age and grade, three specimens were tested, and their average value was recorded for both compressive strength and split tensile strength. This rigorous testing regimen ensured reliable and accurate results, providing valuable insights into the specimens' mechanical properties over time.

3. Results and Discussion

Physical and Engineering Properties

The laboratory result for the constituent material and coconut fibre are presented in Table 2 and the summary of the mix ratios and water – cement ratios is presented in Table 3.

Table 2. Test results on Aggregate and Coconut fibre.

Material	Property	Measured Value	Typical Ranges (from Journals)	Reference/Citation
Fine Aggregate	Specific Gravity	2.65	2.5 - 2.8 (normal sand)	Mamo *et al*., (2019)
	Relative Density	2.65	2.5 - 2.9	Ajagbe *et al*., (2018)
	Water Absorption	1.20%	0.5% - 2.0%	Chinzorigt *et al*., (2020)
	Sieve Analysis	90% passing through 4.75 mm sieve	75% - 95% passing for fine grading	Li *et al*., (2021)
Coarse Aggregate	Specific Gravity	2.7	2.6 - 2.7	Chinnu et al*.,* (2021)
	Relative Density	2.7	2.6 - 2.9	
	Water Absorption	0.50%	0.1% - 2.0%	Cantero *et al.,* (2022)
	Sieve Analysis	85% retained on 4.75 mm sieve	80% - 90% retained for coarse aggregate	Pradhan *et al.,* (2020)
Coconut Fibre	Tensile Strength	200 MPa	150 - 250 MPa (natural coconut fibre)	Tawasil *et al*., (2021)
	Bulk Density	0.6 g/cm^3	0.019 - 2.68 g/cm^3 (common for natural fibres)	Tapia-Blácido *et al.,* (2022); Graupner *et al.,* (2020)
	Water Absorption	150%	15% - 61%	Mishra & Basu, (2020)

Table 3. Achieved Mix Ratios and Water-Cement Ratios (Summary)

Concrete Type	Grade (Strength)	Mix Ratio (Cement: Sand: Gravel)	Water-Cement Ratio (w/c)	Coconut Fibre Content
Plain Concrete	G20	1:2.35:3.2	0.6	None
Coconut Fibre-Reinforced		1:2.35:3.2 + 2.5% Coconut Fibre	0.6	2.5% of Cement
Plain Concrete	G30	1:1.88:2.48	0.48	None
Coconut Fibre-Reinforced		1:1.88:2.48 + 2.5% Coconut Fibre	0.48	2.5% of Cement
Plain Concrete	G40	1:1.12:2.03	0.38	None
Coconut Fibre-Reinforced		1:1.12:2.03 + 2.5% Coconut Fibre	0.38	2.5% of Cement
Plain Concrete	G50	1:0.51:1.44	0.27	None
Coconut Fibre-Reinforced		1:0.51:1.44 + 2.5% Coconut Fibre	0.27	2.5% of Cement

1. Workability

    i. Compacting Factor Test:

The compacting factor tests showed that four out of eight specimens demonstrated medium workability (0.88 to 0.92), three specimens had low workability (0.82 to 0.84), and one specimen had very low workability (0.78)1. GFRC specimens generally exhibited lower workability across all grades as illustrated in figure 2.

ii. Slump Test:

The slump test results indicated in figure 3 shows that five samples had very low workability (below 25 mm), three samples had low workability (25 to 50 mm), and none achieved medium or high workability ranges3. The addition of coconut fibres reduced the slump flow due to their hydrophilic nature and increased internal friction within the concrete mix.

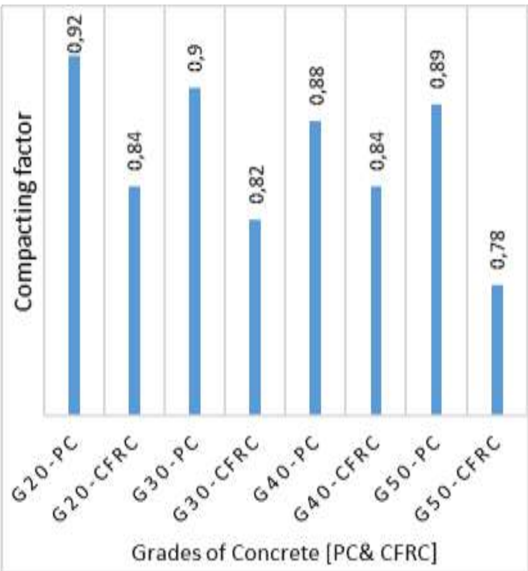

Fig. 2. Compacting Factor Test Results

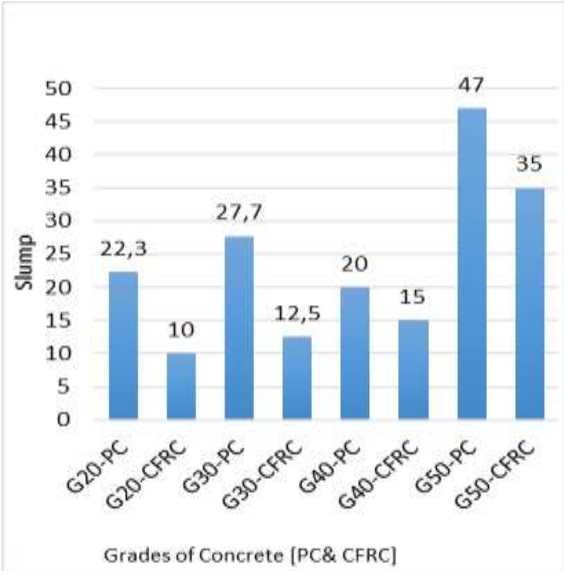

Fig. 3. Slump Test Results

2. Compressive Strength

Generally, CFRC exhibited lower compressive strength compared to PC across all grades and ages as illustrated in figure 4. For instance, G50 CFRC showed a compressive strength of 40.03 N/mm^2 at 0 days, which increased to 45.82 N/mm^2 at 180 days5. This represents a 21% reduction in strength compared to PC.

In relation to ages, both CFRC and PC showed improvements in compressive strength over time. The percentage reduction in strength from PC to CFRC varied across grades, with G20 showing a 1.77% reduction at 0 days and 19.2% at 180 days, while G50 showed a 20.13% reduction at 0 days and 21% at 180 days.

3. Split Tensile Strength

CFRC demonstrated higher tensile strength compared to PC across all grades and ages as illustrated in figure 5. For example, G50 CFRC had a split tensile strength of 4.61 N/mm^2 at 0 days, increasing to 5.20 N/mm^2 at 180 days, showing a 16.1% improvement over PC10.

Both CFRC and PC showed increases in tensile strength with age. The percentage increment in tensile strength for CFRC compared to PC was consistent across grades, with G20 showing a 15.7% increase at 0 days and 16.13% at 180 days, and G50 showing a 16.1% increase at both 0 and 180 days.

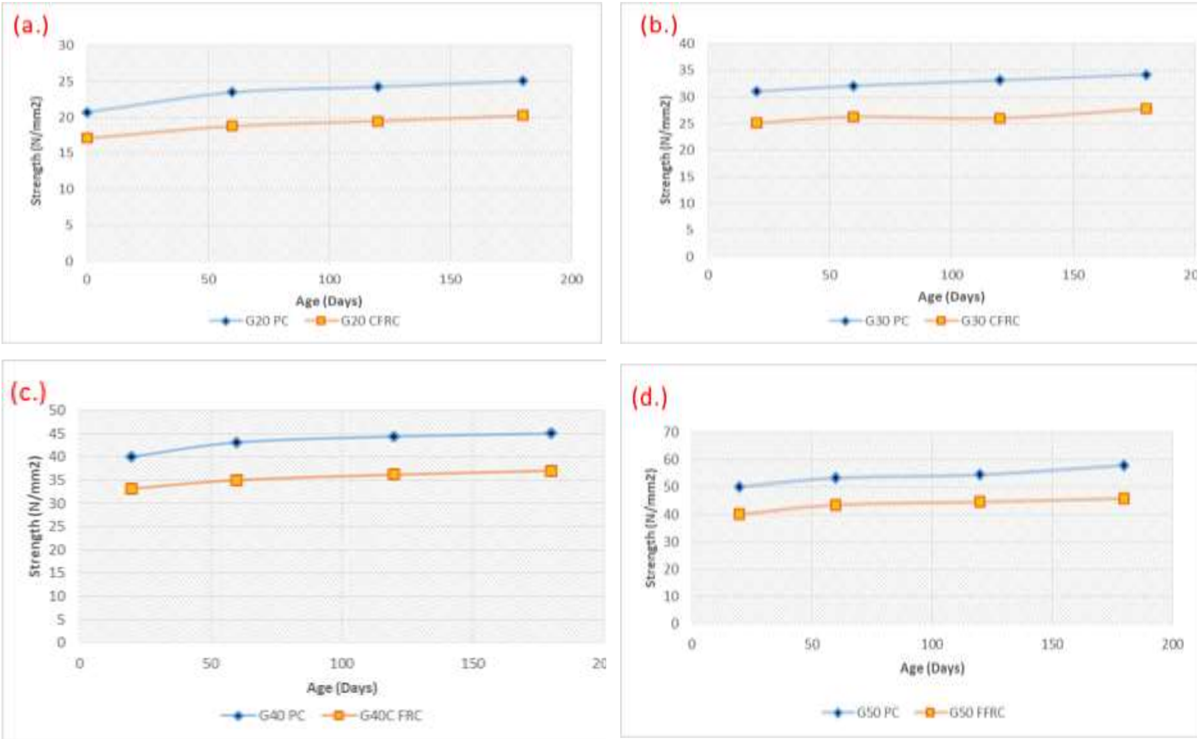

Fig. 4. Curve showing Compressive Strengths against curing ages of G20, G30, G40 & G50 respectively CFRC and PC

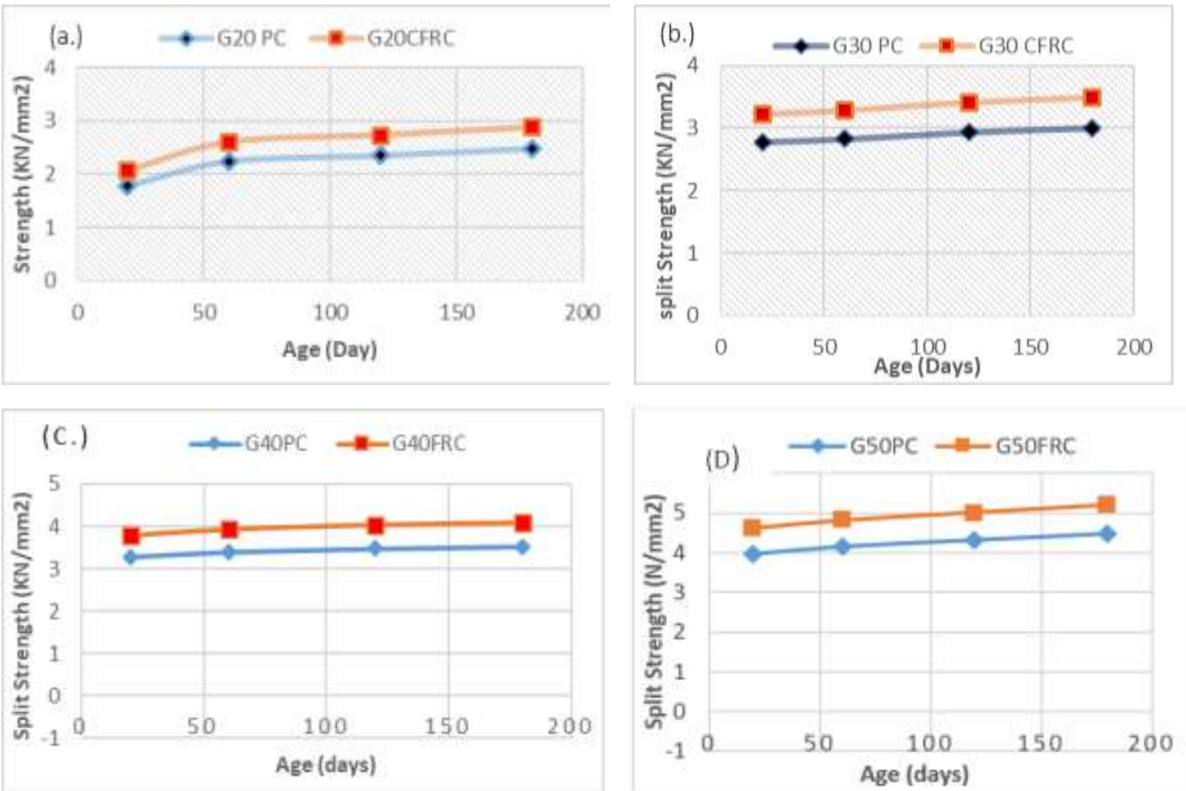

Figure 5: Curve showing Split Tensile Strengths against curing ages of G20, G30, D40 and G50 for both CFRC & PC.

4. Density

The use of coconut fibre slightly decreased the concrete's density compared to PC due to the lightweight nature of the fibre as shown in figure 6. For instance, G50 CFRC had a density of 2200 kg/m^3 at 0 days, increasing to 2290 kg/m^3 at 180 days, representing a 7.7% decrease compared to PC.

Both CFRC and PC showed slight increases in density with age117. The percentage decrement in density for CFRC compared to PC varied across grades, with G20 showing a 9.5% lower density at 0 days and 3.5% lower at 180 days, while G50 showed a 6.0% lower density at 0 days and 7.7% lower at 180 days.

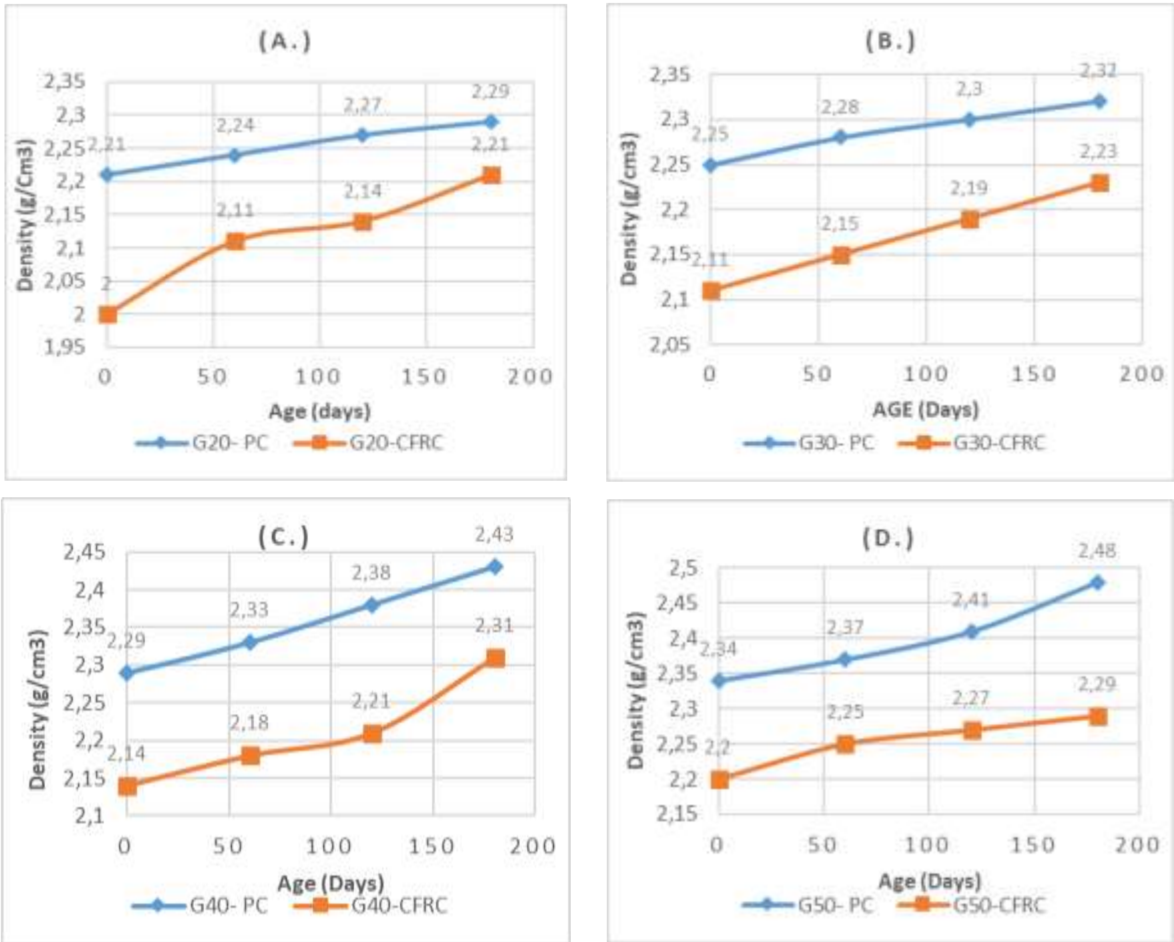

Figure 6: Curve showing Density against curing ages of G20, G30, D40 and G50 for both CFRC & PC.

4. Conclusion

This study investigated the age-related effects on Coconut Fibre Reinforced Concrete (CFRC) mechanical properties. CFRC exhibited lower compressive strength but higher tensile strength than plain concrete across all grades and ages. Both CFRC and plain concrete improved over time, with CFRC's tensile strength increasing significantly. However, fibre degradation may compromise long-term structural integrity due to environmental exposure. Regular maintenance is essential to mitigate deterioration. Further research on fibre treatment techniques is necessary to enhance sustainability and resilience of CFRC structures. CFRC's unique properties make it a promising material, but careful consideration of its limitations is crucial for practical applications.

5. Implications for Sustainable Construction

The use of coconut fibre in concrete aligns with sustainable construction practices by utilizing a renewable and biodegradable material. CFRC offers enhanced tensile strength and ductility, making it suitable for applications where these properties are critical. Furthermore, CFRC has shown the potential to contribute to the development of more sustainable and resilient infrastructure, particularly in tropical regions where coconut fibre is readily available.

6. Recommendations for Future Research

To further develop CFRC's potential, future research should focus on investigating the long-term performance of CFRC, particularly the effects of environmental exposure on its mechanical properties. Other areas of study include exploring hybrid fibre combinations and optimizing fibre dosage and length. Assessing the economic and environmental benefits of using CFRC in large-scale construction projects would also provide valuable insights for its widespread adoption. By addressing these areas, the knowledge gap can be bridged, and the use of sustainable construction materials can be promoted.

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