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Evaluating Bamboo Against Steel for Enhanced Physical and Mechanical Performance for Sustainable Construction in Nigeria

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Abstract— ***Global climate change, characterized by increased flooding and extreme heat, is exacerbated by the construction industry's heavy reliance on high-carbon materials like steel and concrete. While bamboo (Bambusa Vulgaris Schrad) offers a low-carbon, thermally efficient alternative, its structural adoption in Nigeria remains limited. This study evaluates the potential of Bambusa vulgaris sourced from Abuja, Nigeria, as a resilient and sustainable building material to mitigate the environmental impact of the local construction sector. The research employed standardized laboratory testing to characterize the physical, mechanical, and durability properties of both fresh and dry bamboo specimens. Specific parameters investigated included water absorption capacity, moisture content, and ultimate strength under tensile and compressive loading. These tests were designed to simulate performance under diverse environmental conditions typical of the Nigerian climate. Laboratory analysis revealed that dry bamboo specimens exhibited superior mechanical performance, with an average tensile strength of 84.8 MPa and a compressive strength of 16.6 MPa (compared to 13.7 MPa for fresh samples). Physical testing showed average moisture contents of 17.7% for dry and 28.0% for fresh samples, with corresponding water absorption rates of 19.1% and 16.0%, respectively. The quantitative findings demonstrate that Bambusa vulgaris possesses the structural integrity and durability required for eco-friendly construction. Its favorable strength-to-weight ratio and low carbon footprint position it as a viable alternative to conventional materials. These results provide a technical foundation for the formulation of national building codes and standards, encouraging the integration of bamboo into sustainable architectural practices in Nigeria to combat climate-related vulnerabilities.***

I. INTRODUCTION

The global building and construction sector is a primary driver of environmental degradation, accounting for approximately 37% of energy-related CO_2 emissions and 34% of global energy demand (UNEP, 2023). In Nigeria, these environmental pressures are compounded by rapid urbanization and an increasing frequency of climate-induced events, such as extreme heatwaves, flooding, and hurricanes, which threaten the integrity of traditional infrastructure. Conventional building materials—including concrete, steel, and aluminium—are energy-intensive and often lack the thermal and ecological performance required for modern climate resilience. Consequently, there is an urgent need to transition toward sustainable construction practices that utilize eco-friendly, renewable resources (Windapo et al., 2021).

Bamboo, specifically Bambusa vulgaris Schrad., has emerged as a high-potential alternative due to its rapid renewability, significant sequestration capabilities, and superior strength-to-weight ratio. Unlike traditional materials that are susceptible to thermal expansion and failure under extreme weather, bamboo's natural flexibility and high tensile strength provide inherent resistance to seismic and wind loads (Bredenoord, 2024). While certain exotic species like Dendrocalamus brandisii may offer higher flexural strength, Bambusa vulgaris is widely available in Nigeria, making it a socio-economically viable tool for boosting local industries while reducing the construction sector's carbon footprint (Adedipe et al., 2013). However, the adoption of bamboo in Nigeria remains hindered by a lack of standardized technical data and specific building regulations.

This study aims to investigate the structural viability of Bambusa vulgaris sourced from Abuja, Nigeria, for use in climate-resilient housing. The primary objective is to establish a comprehensive profile of its physical, mechanical, and durability properties under varying environmental conditions to determine its suitability as a primary structural element.

The following sections detail the laboratory testing of fresh and dry bamboo specimens to evaluate moisture content, water absorption, and ultimate tensile and compressive strengths. By providing quantitative data on the performance of Bambusa vulgaris, this research serves as a technical foundation for the formulation of Nigerian building standards, ultimately promoting the integration of bamboo into the national framework for eco-friendly construction.

II. LITERATURE REVIEW

The transition from "global warming" to "climate change" in scientific discourse reflects the increasing complexity and severity of real-world weather patterns (Onoja et al., 2011). In the construction sector, this shift is manifested through increased "climate amplitude"—extreme temperature fluctuations—and extended durations of adverse conditions, such as prolonged heatwaves exceeding 38°C (Oruc et al., 2024). These shifts do not merely impact ecological balance; they jeopardize project budgets and labor safety, forcing a reactive and costly adaptation of traditional building methods.

Within the global movement toward resilient built environments, sustainable construction materials are defined by their low embodied energy, resource efficiency, and extended service life (Sun and Zheng, 2017). Bamboo has emerged as a premier "nature-based solution" due to its exceptional carbon sequestration capacity, which surpasses that of most terrestrial plants (Pan et al., 2023). This study locates Bambusa vulgaris within this green framework, positioning it as a strategic alternative for the Global South, where rapid urbanization intersects with high climate vulnerability.

Existing research characterizes bamboo by its high strength-to-weight ratio and anatomical versatility (Liese and Tang, 2015). Anatomically, bamboo's strength is derived from longitudinally oriented vascular bundles, providing tensile properties comparable to certain steel alloys and compressive strengths that can exceed conventional concrete (Gao et al., 2022; Xu et al., 2024). However, its performance is highly sensitive to species-specific density and moisture content; moisture management is critical to preventing decay and dimensional instability (Zhao et al., 2024).

Interpreting these physical traits through an engineering lens reveals that while bamboo is less rigid than steel or concrete, its inherent flexibility makes it superior for seismic-resistant and wind-resilient structures (Bin Azuwa, 2024). Despite these advantages, its integration into the mainstream infrastructure sector is hindered by a lack of formal building codes and a technical knowledge gap regarding architectural treatment and joints (Sharma et al., 2015). Current evidence suggests that these drawbacks are not inherent flaws of the material but rather "design challenges" that can be mitigated through innovative engineering and standardized treatment protocols (Obianyo et al., 2023).

The economic and environmental advantages of bamboo—ranging from rural job creation to the reduction of energy-intensive resource consumption—justify a rigorous re-evaluation of local species like Bambusa vulgaris (Isukuru et al., 2023). There is a clear motivation to move beyond the "reactive" stance of the current construction industry. By quantifying the mechanical and durability limits of Nigerian bamboo, this research seeks to fill the regulatory void identified by Janssen (2000), providing the empirical data necessary to transform bamboo from a "traditional" material into a standardized, climate-resilient structural component.

Furthermore, Nile University's research underscores a critical bottleneck in the adoption of these "nature-based solutions." Obianyo (2023) argues that the primary barrier to the mainstreaming of traditional and bio-based materials is not a lack of performance, but a lack of standardized building codes. Their work advocates for a formalized regulatory framework that translates empirical lab data into design protocols, mirroring the "design challenge" perspective required to transform bamboo into a standardized, climate-resilient structural component.

The push for standardization at Nile University is further exemplified by Obianyo and Mahamat (2024), who conducted a comprehensive assessment of the thermo-physical properties of local bio-aggregates. Their research identifies that the "technical knowledge gap" regarding moisture absorption and thermal conductivity is a major deterrent for local contractors. By providing a quantitative analysis of how local fibers respond to Nigeria's humid tropical climate, their work reinforces the argument that the transition to sustainable materials like Bambusa vulgaris is a matter of refining "design protocols" rather than overcoming material inferiority.

III. METHODOLOGY

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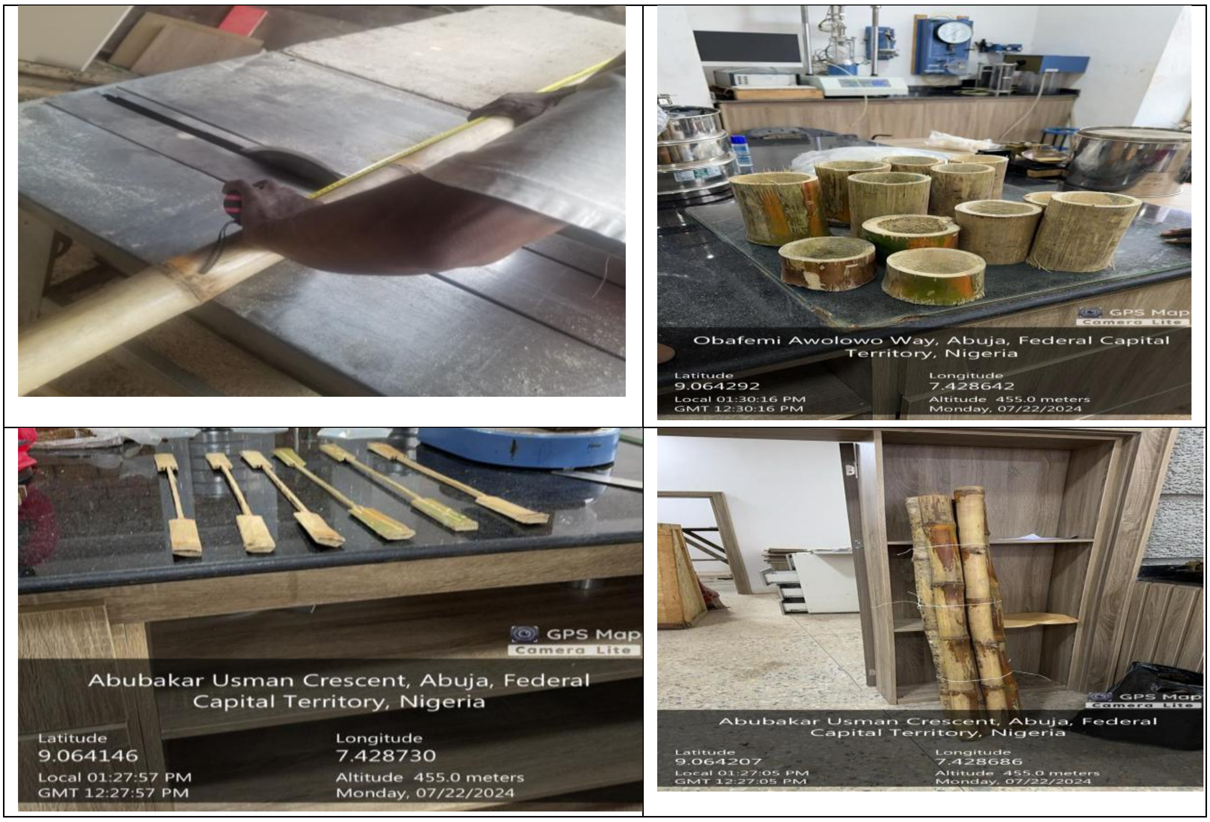
This study employed a Laboratory tests approach to determine the physical and mechanical properties of bamboo. Green and dry bamboo specimens were procured from the building materials market in Jabi, Abuja, Nigeria. The specimens were selected to ensure they represent common types of bamboo used in construction. Each bamboo specimen was classified into two categories:

- Green Bamboo: Freshly cut bamboo with high moisture content.
- Dry Bamboo: Bamboo that had been air-dried to reduce its moisture content.

Both green and dry bamboo were used to assess the impact of moisture content on various mechanical and physical properties.

- Cutting and Shaping: The bamboo was cut into the required dimensions and shapes. For tensile testing, dog-bone-shaped specimens were prepared. The dimensions for the dog-bone shape followed the ISO 22157-1 standard specifications. Specimens were also prepared for Bending, water absorption, moisture content, compressive strength and thermal cycling test.

Figure1: Preparation of bamboo test specimen



3.2 Methods

3.2.1 Tensile Test

The tensile test was performed to assess the tensile properties of bamboo specimens, including tensile strength, elongation at break, and Young's modulus, in accordance with ISO 22157-1 standards. Six bamboo specimens were prepared for the test: three green and three dry test specimens. Each specimen was shaped into a standardized dog-bone form with a gauge length of approximately 150 mm and a width of 20 mm at the narrow section, adhering to the dimensions specified by the standard. Preparation involved selecting defect-free bamboo, cutting it into the required shape, and ensuring uniformity through sanding or trimming.

After the test, the maximum tensile load and elongation at break were recorded. Tensile strength (σ) was calculated using the formula:

$$\sigma = \frac{F_{max}}{A} \qquad 3.1$$

Where,

F_{max} is the maximum load recorded during the test

A is the cross-sectional area of the specimen.

Elongation at break was measured as the difference between the initial and final gauge lengths of the specimen. Young's modulus (E) was determined by calculating the slope of the linear portion of the stress-strain curve, using the formula:

$$E = \frac{\Delta\sigma}{\Delta\epsilon} \quad 3.2$$

Where,

$\Delta\sigma$ is the change in stress

$\Delta\epsilon$ is the change in strain over the linear region of the curve.

Results, including stress-strain curves and tabulated data, were analyzed to compare the tensile properties of green versus dry bamboo specimens. Observations of any anomalies or deviations during testing were recorded. Throughout the testing process, safety precautions, such as wearing personal protective equipment and adhering to machine safety protocols, were strictly followed.

3.2.2 Bending Test

The bending test was conducted to determine the flexural properties of bamboo specimens, specifically bending strength and modulus of elasticity, in accordance with ISO 22157-1 standards. For this test, six bamboo specimens were prepared: three green and three dry test specimens. The preparation involved selecting defect-free bamboo, cutting it to the required dimensions, and ensuring uniformity in shape.After the test, the maximum load and the corresponding deflection at the midpoint were recorded. The bending strength (σ) was calculated using the formula:

$$\sigma = \frac{3FL}{2bd^2} \quad 3.3$$

Where,

F is the maximum load applied at failure,

L is the span length between the supports,

b is the width of the specimen,

d is the depth (height) of the specimen.

The deflection was determined from the load-time curve using the formula:

$$\delta = \frac{LR\ X\ T}{\sigma} \quad 3.4$$

Where,

LR is the load rate in N/mm,

T is the time in seconds

σ is the stress at maximum load.

Results, including bending strength and Deflection, were documented, and the data were analyzed to compare the bending properties of green and dry bamboo specimens. Stress-strain curves and tabulated data were presented to illustrate the flexural behavior.

3.2.3 Compressive Test

The compressive strength test was conducted to evaluate the compressive properties of bamboo specimens, specifically compressive strength and deformation characteristics, in accordance with ISO 22157-1 standards. Six bamboo specimens were prepared for the test: three green and three dry test specimens. Each specimen was cut into cylindrical or cuboidal shapes, with dimensions conforming to standard specifications—typically, cylinders with a length-to-diameter ratio of 2.

The compressive strength test was performed using a universal testing machine (UTM) equipped with a compression setup, including platens that apply uniform pressure to the specimen. The bamboo specimens were placed between the compression platens, ensuring that they were centered and aligned to avoid uneven loading.

Plate 3.5: Compressive strength test specimens and set up

After the test, the maximum compressive load and the corresponding deformation were recorded. Compressive strength was calculated using the formula:

$$\sigma = \frac{F_{max}}{A} \quad 3.5$$

Where,
F_{max} is the maximum load recorded during the test
A is the cross-sectional area of the specimen.
the cross-sectional area is calculated as:

$$A = \frac{\pi D^2}{4} \quad 3.6$$

Where, D is the diameter of the cylinder.

Results of the compressive strength were documented and analyzed to compare the properties of green and dry bamboo specimens.

3.2.4 Moisture Content Test
The water content test was conducted to determine the moisture content of bamboo specimens, which is crucial for evaluating the material's suitability and performance in different environmental conditions. This test followed standard procedures to ensure accurate and reliable results. Six bamboo specimens were prepared: three green and three dry test specimens. The specimens were cut into standardized cylindrical samples to facilitate uniform testing.
The moisture content of the bamboo specimens was calculated using the formula:

$$MC = \frac{W_{wet} - W_{dry}}{W_{dry}} X\ 100\ \% \quad 3.7$$

Where,
W_{wet} is the initial weight of the specimen,
W_{dry} is the weight after drying.
Results, including the moisture content for each specimen, were documented and analyzed. This analysis helped assess the effectiveness of the drying process and provided insights into the potential impact of moisture on the material properties of bamboo.

3.2.5 Water Absorption Test
The water absorption test was conducted to assess the capacity of bamboo specimens to absorb water, which is an important indicator of the material's behaviour in humid conditions. This test follows standard procedures to ensure accuracy and reliability. Six bamboo specimens were prepared for the test: three green and three dry test specimens. The specimens were cut into standardized cylindrical shapes, to ensure uniformity in testing.

The water absorption was calculated using the formula:

$$MC = \frac{W_{wet} - W_{dry}}{W_{dry}} X\ 100\ \% \quad 3.8$$

Where,
Wwet is the weight of the specimen after immersion and surface drying,
Wdry is the initial weight of the dry specimen.
Results, including the water absorption percentage for each specimen, were documented and analyzed to evaluate the performance of bamboo under wet conditions. This analysis provided insights into the material's susceptibility to moisture and potential implications for its use in construction.

3.2.6 Shrinkage Test
The shrinkage test was performed to measure the dimensional changes in bamboo specimens due to moisture variation, specifically to assess the shrinkage that occurs as the bamboo dries. This test follows standard procedures to ensure accurate and reliable results. Six bamboo specimens were prepared: three green and three dry test specimens. Each specimen was cut into standardized cylindrical shapes, to ensure uniform testing.

The procedure for the shrinkage test involved measuring the dimensions of the specimens before and after drying. Initially, the dimensions of each green bamboo specimen were measured using a Vernier calliper. These initial dimensions were recorded as the wet measurements (L_{wet}, W_{wet}, $H_{we}t$), where L, W, and H represent the length, width, and height of the specimen, respectively.
The specimens were then dried in an oven at a temperature of 105°C until they reached a constant weight, indicating that all moisture had been removed. This drying process typically took several hours. After drying, the specimens were cooled in a desiccator to prevent moisture absorption from the air. Once cooled, the dimensions of each dried specimen were measured again. These measurements were recorded as the dry dimensions (L_{dry}, W_{dry}, H_{dry}).
The shrinkage in each dimension was calculated using the formula:

$$Shrinkage = \frac{D_{wet} - D_{dry}}{D_{dry}} X\ 100\ \% \quad 3.9$$

Results, including the shrinkage percentages for each dimension, were documented and analyzed to assess the impact of drying on the bamboo specimens. This analysis provided insights into the material's dimensional stability and its suitability for use in environments with varying moisture conditions.

All testing procedures adhered strictly to ISO 22157:2019 protocols to ensure data reliability and structural safety. The bamboo was sourced legally from local commercial markets, supporting the regional economy and ensuring no protected forest areas were harvested for this research.

IV. RESULTS

4.1 Mechanical Properties

The results of the mechanical strength of the green and dry bamboo specimens are summarized in table 4.1 and figure 3. These include tensile strength, compressive strength, Bending strength, Elastic modulus in tension and deflection in bending.

Table 4. 1: Summary of Mechanical Properties of the Green and Dry bamboo specimens

Mechanical strength test parameter	Green Bamboo Specimen			Dry Bamboo Specimen		
	A	B	C	A	B	C
Tensile strength (Mpa)	48.568	66.896	47.652	78.351	84.765	84.307
Av. Tensile strength (Mpa)	54.372			82.474		
Compressive strength (Mpa)	12.112	14.210	14.899	15.837	17.412	16.614
Av. Compressive strength (Mpa)	13.741			16.621		
Bending strength (Mpa)	15.9	7.9	12.9	6.6	6.1	8.5
Av. Bending strength (N/mm^2)	12.23			7.07		
Elastic Modulus (Mpa)	6572	2087	6618	5006	2509	2219
Av. Elastic Modulus (Mpa)	5092			3245		
Deflection at maximum Force (mm)	0.642	2.72	0.792	0.808	1.008	0.718
Av. Deflection at maximum Force (mm)	1.385			0.845		

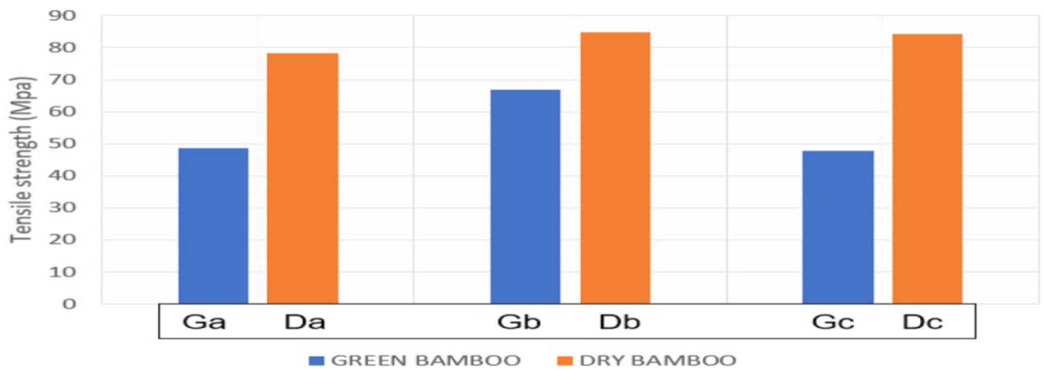


Figure 3: Mechanical Properties of Green and Dry Bamboo Specimen

4.2 Tensile Strength Test Parameters

The tensile strength analysis of bamboo specimens, as presented in Table 4.2 and Figures 4.4, demonstrates significant disparities between green and dry bamboo, underscoring the profound influence of moisture content on its mechanical behaviour. Green bamboo exhibited an average tensile strength of 54.372 MPa, whereas dry bamboo displayed a markedly higher tensile strength of 82.474 MPa. This substantial increase in tensile strength upon drying is consistent with findings from recent studies [17], which report tensile strength values for dry bamboo within a similar range.

Table 4.2: Tensile properties of the green and dry Bamboo specimens

Tensile strength test Parameter	Green Bamboo Specimen			Dry Bamboo Specimen		
	A	B	C	A	B	C
Max. Tensile Force (KN)	2.428	3.345	2.383	3.918	4.238	4.215
Tensile strength (Mpa)	48.568	66.896	47.652	78.351	84.765	84.307

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Yield stress (Mpa)	14.270	48.446	4.128	18.33	0.00	0.00
Elongation at Max. Force (%)	0.739	3.205	0.72	1.565	3.378	3.380
Elastic Modulus (Mpa)	6572	2087	6618	5006	2509	2219

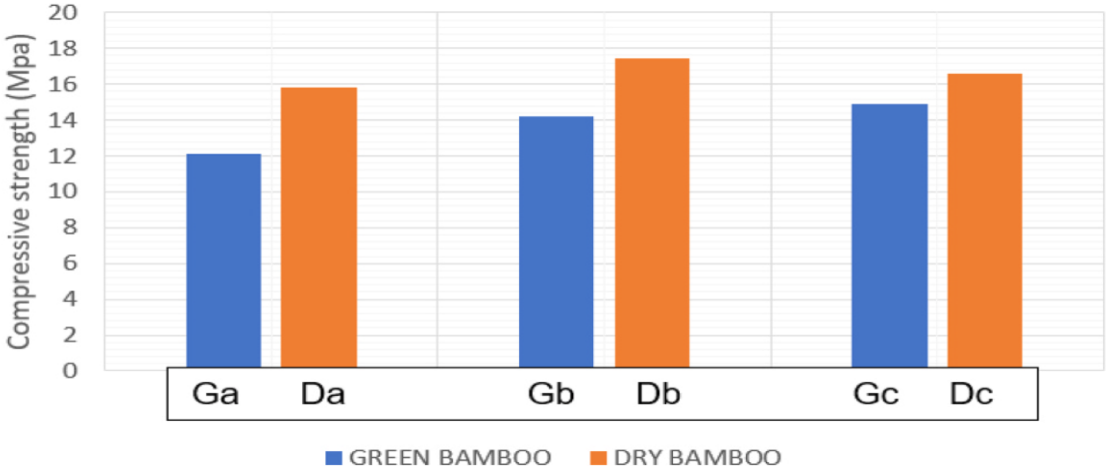

Figure 4. Compressive Strength of Green and Dry Bamboo

Regarding maximum tensile force, green bamboo specimens exhibited forces of 2.428 kN, 3.345 kN, and 2.383 kN, while dry bamboo specimens demonstrated significantly higher forces of 3.918 kN, 4.238 kN, and 4.215 kN. These results align with the findings of [18], who both reported that dry bamboo exhibits superior tensile force resistance compared to green bamboo, these results are presented in Table 4.2 and figure 4.

Table 4. 2: Bending Properties of the Green and Dry bamboo specimens

Bending strength test parameter	Green Bamboo Specimen			Dry Bamboo Specimen		
	A	B	C	A	B	C
Max. Bending Force (KN)	6.2	4.0	5.7	3.3	2.7	2.2
Bending strength (Mpa)	15.9	7.9	12.9	6.6	6.1	8.5
Time at Failure (s)	8.483	17.111	8.388	4.451	5.090	5.952
Deflection at Failure (mm)	0.642	2.72	0.792	0.808	1.008	0.718

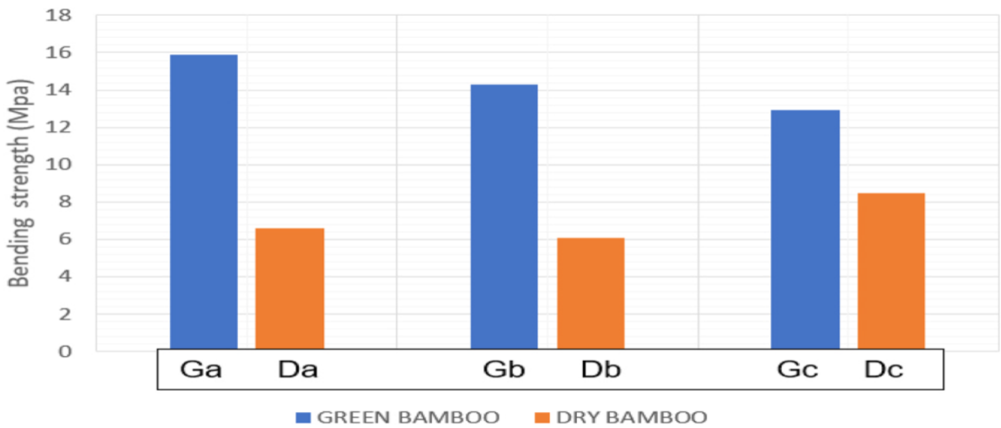

Figure 5: Bending Strength of Bamboo Specimen

The bending strength test results for the bamboo specimens reveal critical differences between green and dry bamboo, illustrating how moisture content influences its mechanical properties. Green bamboo exhibited a higher average bending strength of 12.23 MPa compared to 7.07 MPa for dry bamboo ans shown in figure 5 and Table 4.3

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4.3 Compressive strength test results

The compressive strength test results are presented in Table 4.4. The compressive strength for green bamboo was measured at 12.112 MPa, 14.210 MPa, and 14.899 MPa, averaging 13.741 MPa. In comparison, dry bamboo exhibited compressive strengths of 15.837 MPa, 17.412 MPa, and 16.614 MPa, with an average of 16.621 MPa. This indicates a clear increase in compressive strength when bamboo is dried.

Table 4. 3: Compressive strength properties of the Green and Dry bamboo specimens

Compressive strength test parameter	Green Bamboo Specimen			Dry Bamboo Specimen		
	A	B	C	A	B	C
Max. Compressive Force (KN)	69.574	77.850	81.623	69.998	74.919	72.456
Compressive strength (N/mm^2)	12.112	14.210	14.899	15.837	17.412	16.614

4.4: physical and durability test results

The results of the physical and durability properties of the green and dry bamboo specimens are summarized in Table 4.5. These include moisture content, Density, Water absorption, shrinkage and thermal cycling.

Table 4. 4: Summary of the physical and durability properties

	Green Bamboo Specimen			Dry Bamboo Specimen		
	A	B	C	A	B	C
Moisture content (%)	30.948	31.491	21.436	17.744	18.035	17.265
Av. Moisture content (%)	27.960			17.680		
Density (Kg/m^3)	388	356	298	354	352	353
Av. Density (Kg/m^3)	347			353		
Water Absorption (%)	14.907	18.417	14.764	19.504	20.799	16.877
Av. Water Absorption (%)	16.030			19.060		
Radial Shrinkage (%)	4.757	5.714	5.714	4.252	4.343	3.488
Av. Radial Shrinkage (%)	5.236			4.028		
Axial Shrinkage (%)	0.406	0.381	0.329	0.227	0.300	0.241
Av. Axial Shrinkage	0.372			0.256		

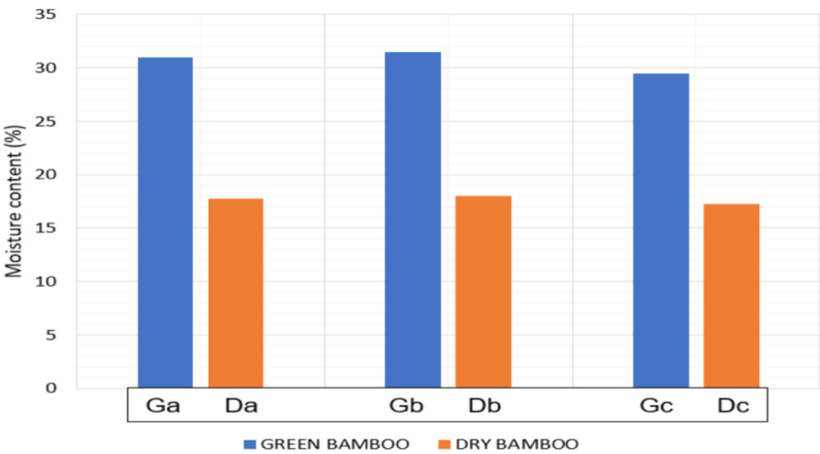

Figure 6: Moisture Content of the Green and Dry Bamboo Specimen

4.4.1 Moisture content test results

The moisture content data for bamboo specimens as shown in Table 4.5 reveal significant differences between green and dry bamboo. For green bamboo, moisture content values were 30.948%, 31.491%, and 21.436%, averaging 27.960%. In contrast, dry bamboo had moisture content levels of 17.744%, 18.035%, and 17.265%, with an average of 17.680% as in figure 6.

4.4.2 Water absorption test results
The water absorption test results for bamboo specimens reveal a distinct difference between green and dry bamboo as seen in table 4.4 and figure 7. Green bamboo had water absorption rates of 14.907%, 18.417%, and 14.764%, averaging 16.030%, while dry bamboo exhibited higher water absorption rates of 19.504%, 20.799%, and 16.877%, with an average of 19.060%. This indicates that green bamboo has lower water absorption compared to its dry counterpart.

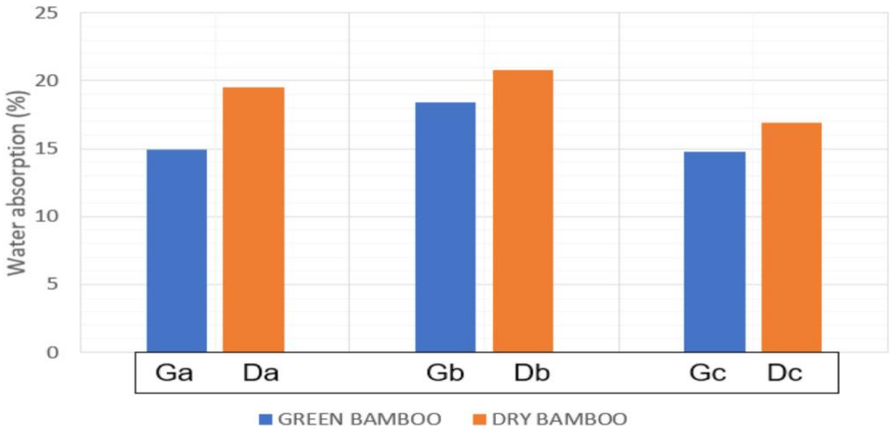

Figure 7: Water Absorption Properties of Green and Dry Bamboo Specimen

4.4.3 Shrinkage test results
The radial and axial shrinkage measurements of bamboo provide important insights into the material's dimensional stability. The radial shrinkage for green bamboo was measured at 4.757%, 5.714%, and 5.714%, in figure 8 with an average of 5.236%. In contrast, the radial shrinkage for dry bamboo was lower, with measurements of 4.252%, 4.343%, and 3.488%, averaging 4.028%. The axial shrinkage for green bamboo was 0.406%, 0.381%, and 0.329%, averaging 0.372%, whereas dry bamboo exhibited even lower axial shrinkage rates of 0.227%, 0.300%, and 0.241%, with an average of 0.256%. Tangential shrinkage measurements were not feasible due to the testing temperature affecting the specimens.

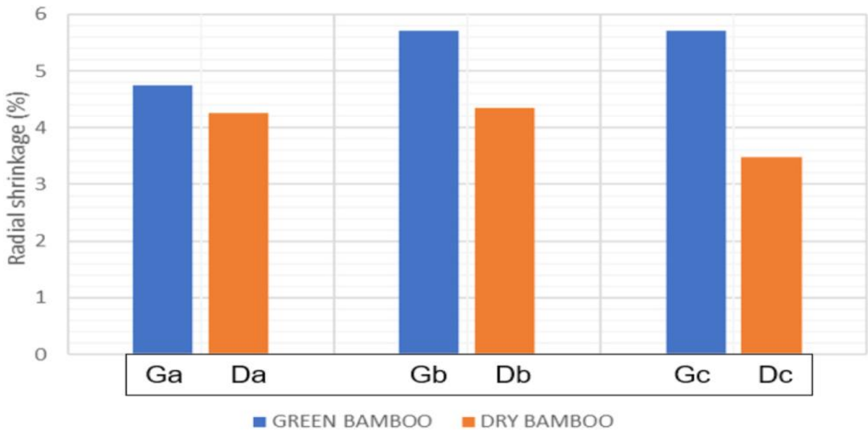

Figure 8: Shrinkage Properties of Green and Dry Bamboo Specimen

V. CONCLUSION

This study evaluated the structural and physical performance of *Bambusa vulgaris* to determine its viability as a sustainable, climate-resilient construction material in Nigeria. By analyzing both green and dry specimens, the research sought to establish a quantitative baseline for using bamboo as an eco-friendly alternative to energy-intensive materials like steel and concrete.

The investigation identified moisture content as the primary determinant of bamboo's mechanical behavior. Dry bamboo demonstrated superior performance in tensile strength (84.8 MPa) and compressive strength (16.6 MPa), offering higher stiffness suitable for load-bearing elements. Conversely, green bamboo exhibited greater ductility and flexibility, highlighting its potential for applications requiring significant shock absorption or specialized bending.

When compared to conventional materials, *Bambusa vulgaris* boasts a competitive tensile strength-to-weight ratio. However, unlike the predictable consistency of steel, bamboo's properties are highly variable and sensitive to environmental conditions. While dry bamboo provides the necessary rigidity for structural frames, its natural susceptibility to moisture and biological decay remains a critical constraint compared to the standardized performance of industrial alloys.

Bambusa vulgaris holds immense potential for low-cost, low-rise, and eco-friendly housing in Nigeria, provided the choice between green and dry bamboo is matched to the specific structural demand. To move from localized use to widespread industrial adoption, further research must focus on standardized treatment methods and composite technologies to enhance durability and moisture resistance. Establishing these protocols will be essential for integrating bamboo into national building codes and achieving long-term sustainability in the construction sector.

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