Determination of some Anatomical Properties of Acetylated Bamboo (*Bambusa vulgaris* Schrad.) for Construction Applications

Ajayi, J. A.[1]*, Riki, J. T. B.*[2] *and Ogunsanwo, O. Y.*[1]

[1]*Department of Forest Production and Products, Faculty of Renewable Natural Resources, University of Ibadan, Ibadan, Nigeria*
[2]*Department of Forestry and Wildlife Management, Faculty of Agriculture and Life Sciences, Federal University Wukari, Taraba State, Nigeria*

KEYWORDS

Bambusa Vulgaris,
Fibre length,
Fibre diameter,
Lumen width,
Cell wall Thickness

*CORRESPONDING AUTHOR

rikijosiah @gmail.com

ABSTRACT

Due to its high specific strength and renewability, bamboo fiber has generated a lot of interest. At the University of Ibadan, Nigeria, five matured bamboo plants (Bambusa vulgaris) with comparable heights and internode counts were cut down at a height of 30 cm above the ground. Modified bamboo test samples with dimensions 20mm (tangentially) x 60mm (longitudinally) x 5mm (radially) as well as the unmodified test samples with the same dimensions from each individual culm were used for this study. Test samples were sliced into match stick size splints with one side blade and placed into test tubes. Splints were macerated with an equal volume (1:1) of 10% glacial acetic acid and 30% Hydrogen Peroxide (H_2O_2) at 100±2˚C, the macerated slivers were boiled in a water bath at a temperature of 100°C for 10minutes. Results show that rate of reaction mean range between 0.95 to 1.41% with a marked effect along culm height. Fibre length shows no significant differences between the treated and the untreated samples with a mean of 1.78 to 2.44mm. The fibre diameter, lumen width and cell wall thickness of bamboo showed positive correlation between the treated and the untreated bamboo samples with mean of 9.65 to 13.24µm, 2.35 to 4.62µm and 7.32 to 9.1µm respectively, along the sampling height. The strength of the bamboo fiber is relatively greater among the plant fibers and its superior mechanical properties originate from the intricate lamellar structure of its cell wall is excellent for construction purposes.

INTRODUCTION

As a fibre, bamboo is a natural cellulosic regenerated biodegradable environment friendly textile material. Not only a green fibre but it has also inherent property of anti-bacterial and ultraviolet protective property, which makes it a unique ecofriendly textile material in 21st century (Jia *et al.,* 2022). Bamboo is considered a fast-growing plant that is widely used for the manufacture of handicrafts, baskets, furniture, and general merchandise (Rathour *et al.,* 2022). The use of bamboo has evolved from traditional to more value-added products. According to Xing *et al.,* (2015), bamboo can be regarded as the best alternative for replacing timber because bamboo has high strength and is fast-growing. As stated by Krause and Ghavami (2009) and Cui *et al.,* (2020), bamboo in its round form demonstrates excellent mechanical properties that make it useful for the construction industry and can reduce the need for steel. Bamboo is a cylindrical, usually hollow, light-weight, and functionally-graded material that demonstrates optimal characteristics for building truss elements that are frequently used in civil construction. It is crucial to comprehend the fundamental anatomical, physical, and mechanical characteristics of bamboo in order to determine whether it is suitable for the planned uses given the wide range of uses for which it is now used.

According to Razak *et al.,* (2010), Wang *et al.,* (2016), and Siam *et al.,* (2023), the anatomical properties of Bamboo are significant because of how they affect mechanical characteristics, preservative absorption, and characteristics of finished goods, particularly pulp and paper. Anatomical properties can also influence the bamboo's durability, toughness, workability, and strength (Razak *et al.,* 2010; Akinlabi *et al.,* 2017). These findings were further supported with a study by Xin *et al.,* (2015), where it was concluded that the anatomical structure of bamboo is basic knowledge for understanding the physical and mechanical properties as well as the utilizations of the bamboo.

Bambusa vulgaris is an erect, evergreen, clump-forming bamboo growing 15 - 20 metres tall. The thin-walled, hollow canes are 40 - 120mm in diameter with internodes 20 - 45cm long. The plant has a very wide range of uses and is a very important component of the local economy in many areas of the tropics. It is widely cultivated in the tropics and subtropics both as an ornamental plant and for its many uses. It adds a particularly tropical forest appearance where it is planted, though it needs a lot of space to spread. They are secured by sheaths at the underlying phases of development that tumble off as the plantling develops. The distance between two nodes between nodal length changes extensively crosswise over bamboo species, going from five to more than sixty centimetres. Generally, the nodal length between two nodes increments upwards along the culm from the lower part to the centre, and after that reduces. For the most part cross segment of bamboo have filaments from which the mechanical properties of bamboo shift. The properties may shift in light of the idea of development, climatic conditions and soil dampness condition (Kaur *et al.,* 2017).

Since bamboo is susceptible to environmental degradation and there is need for modification to enhance its workability. To protect the lignocellulosic material from degradation and enhance its service life for structural uses, various treatment methods have been employed during last few decades such as treating with mineral oil, coal tar; heating in hydrocarbon oil, smoking, treating with various etherifying and esterifying agents, acetals, alkylene oxide and alkoxysilane-coupling agents and have been documented by several researchers (Amin *et al.,* 2021). Acetylation is a reaction that introduces an acetyl functional group (acetoxy group, CH_3CO) into an organic chemical compound namely the substitution of the acetyl group for a hydrogen atom (Danouche *et al.,* 2021). The reaction occurs between the hydroxyl groups of the polymers and the reagent molecules and leads to a change in the chemical and physical properties of the woody products.

Finding more environmentally friendly construction methods for development is our obligation because the building sector indirectly contributes significantly to environmental damage (Riki *et al.,* 2020). One of the solutions is to search for a new material that can be recycled and reused. Therefore, it is necessary to go for a new material that is naturally available such as bamboo (Rajesh *et al.,* 2019). Bamboo is one of the renewable natural resources known to us. But sufficient care has not been given to investigation and change in bamboo (Awoyera *et al.,* 2019). Due to the beneficial physical characteristics of bamboo, research has been made of bamboo as fiber material in concrete (Banu *et al.,* 2019; Ayande *et al.,* 2020 and Momoh *et al.,* 2022). Siam *et al.,* (2019) studies the anatomical, physical, and mechanical properties of thirteen Malaysian bamboo species while Ajayi *et al.,* (2022), earlier studied suitability of selected physical properties of acetylated Bamboo (*Bambusa vulgaris*) for structural uses in Nigeria and they have both proven that the species is durable for construction purposes. With the development of science and technology, new techniques are implemented for treating of bamboo to make it durable and more working in terms of construction materials. Therefore, for bamboo to be able to serve as a substitute for wood, its properties need to be improved. This study investigates fibre characteristics of bamboo for construction purpose.

MATERIALS AND METHODS

Description of the Study Area

The study was carried out at University of Ibadan, Ibadan, Oyo State. Nigeria, which is sited 3km to the North of the city of Ibadan. The University of Ibadan is located between latitude 7°23' and 28°19′N, and longitude 3°54' and 59°99'E. The topography of the area is flat and undulating, in terms of climate classifications, the altitude of the area ranges from 150 m to 275 m. The mean total rainfall for Ibadan is 1420.06 mm, falling in approximately 109 days. There are two peaks for rainfall, June and September. The mean maximum temperature is 34.4°C, minimum 18.07°C and the relative humidity is 74.55% (Riki *et al.,* 2021).

Collection of Samples

Five mature Bamboo (Bambusa vulgaris) with equal height and internodes numbers were harvested at a height of 30cm above the ground level from a bamboo grove naturally growing but managed by the Biodiversity Management Committee, University of Ibadan, Ibadan, Nigeria (Ajayi *et al.,* 2022).

Specimen Preparation

Bamboo culms were marked at each internode using permanent marker from the base to the top to allow for easy identification and re-arrangement of the culm. The culms were thereafter cut across the nodes with the aid of a hacksaw for accessibility and easy transportation. Each internode was placed in a separate jute bag to avoid contamination from soil. The culms were then transported to and stored for 5 days in the wood workshop of the Department of Forest Production and Products, University of Ibadan, Ibadan, Nigeria for conversion to test specimens.

The culms were carefully sawn with circular sawing machine longitudinally into strips. Each strip was planed on both the inner and outer surface, using a planning machine, in order to obtain the bamboo timber devoid of the outer protective skin with mean culm thickness of 5±0.5mm for the tests. The bamboo strips obtained were further converted to test samples according to EN 113 (1996) test standard. From each internode, 5 test samples were obtained, the total number of test samples converted was 625 samples. The test samples with dimensions 20mm (tangentially) x 60mm (longitudinally) x 5mm (radially) were oven dried at 105± 2°C until constant weight is achieved to determine the dry weight before acetylation (Ajayi *et al*., 2022).

Acetylation of Bamboo Samples

The oven dried bamboo specimens were weighed (Wo) and recorded with the use of digital weighing balance of 0.01 precision, the dimensions of the test samples were measured using digital venier calliper and used to estimate the volume of the test samples. Substantial volume of acetic anhydride was poured into the reaction vessel and the oven dried specimens of known weight were subjected to non-pressure hot treatment for 10 hours using a constant heat of 100°C as the only catalyst (the treatment took place in a closed reaction vessel which was tightly wrapped with aluminium foil to prevent evaporation and contamination). After 10 hours, the specimen was brought out of the reaction vessel, rinsed with distilled water to arrest the reaction and dried with the aid of filter paper. The dried modified specimens were then oven dried at 105°C for 24 hours and allowed to cool in a desiccator. The weight of the treated specimens were determined (Wt) using digital weighing balance, the volume was also estimated by measuring the dimensions using digital veneer calliper (Ajayi *et al.,* 2022).

Determination of modifiability of Bamboo

Determination of Percent Weight Gain (WPG)

The weight percent gain (WPG) of the treated bamboo samples was calculated on an oven-dried weight basis by measuring the extractive-free untreated specimens and the treated specimens using the following formula:

$$\text{WPG} = \frac{W_t - W_o}{W_0} x \frac{100}{1} \qquad (1)$$

Where: *WPG* is the weight percent gain, W_o is the weight of oven-dried sample before acetylation (g), W_t is the weight of oven-dried sample after acetylation (g).

Determination of Bulking Coefficient

The bulking coefficient (B) was also determined for all prepared specimens using the following formula.

$$\text{B} = \frac{V_t - V_o}{V_0} x \frac{100}{1} \qquad (2)$$

Where: *B* is the bulking coefficient, *Vt* is the volume of oven-dried wood after being acetylated, V_o is the volume of oven-dried wood before acetylation

Determination of Rate of Reaction

The rate of reaction was calculated using the following formula.

$$R = \frac{WPG}{t} \qquad (3)$$

Where: R is the rate of reaction ($\% \cdot h^{-1}$), WPG is the weight percent gain (%), t is the reaction time (h).

Determination of Anatomical Properties of Acetylated Bamboo

Anatomical Characteristics test

Studies on anatomical characteristics were carried out in accordance with the ASTM D 1030-95 (2007) and ASTM D1413-61 (2007). Modified bamboo test samples with dimensions 20mm (tangentially) x 60mm (longitudinally) x 5mm (radially) as well as the unmodified test samples with the same dimension from each individual culm were used for this study. Test samples were sliced into match stick size splints with one side blade and placed into test tubes. Splints were macerated with an equal volume (1:1) of 10% glacial acetic acid and 30% Hydrogen Peroxide (H_2O_2) at 100±2˚C, the macerated slivers was boiled in a water bath at a temperature of 100°C for 10minutes following the procedure adopted by Ogbonnaya *et al.,* (1997) and bleached white with 10% domestic bleach. The slivers were washed on a sieve, placed in 30ml-test tubes with 20ml-distiled water and shaken vigorously to separate the fibre bundles into individual fibre. The macerated fibre suspension was then carefully aligned on a slide and air dried.

The resulting images were viewed on Rheichert visopan microscope screen and measured using a stage micrometer and an eyepiece micrometer for fibre length, diameter, lumen width and cell wall thickness.

Statistical Analysis

A one-way analysis of variance (ANOVA) was used. Data were subjected to statistical analysis of 2 × 25 factorial experiment in a completely randomized design (CRD) and Mean±SEM. However, a follow-up test was carried out using the least significant difference test (LSD) at 5% level of probability.

RESULTS AND DISCUSSION

Rate of reaction for Acetylated Bamboo

There was a remarkable effect in the rate of reactions across the culm heights. The mean range between 0.95 to 1.41% as presented in Table 1. Also, the mean weight percent gain (WPG) for all the acetylated bamboo samples ranged from 11.41% to 16.88% across the culm heights with positive difference among the samples across the culm height**.** The results obtained for the bulking coefficient of the sampled wood species show that significant differences were observed among the twenty-five-culm height at 5% probability level. The mean values were ranged 3.21% to 4.75% for the culm height as previously reported by Ajayi *et al.* (2022)**.**

Table 1: Analysis of variance for Rate of reaction of Acetylated Bamboo

Properties	Source of variation	Df	SS	MS	F	Sig,
Rate of reaction (%h^{-1})	Culm position	24	15.771	0.657	4.700	0.001*
	Error	50	6.991	0.140		
	Total	74	22.762			

Note: "*" Significant at $p<0.05$.

Determination of Anatomical Properties of Acetylated Bamboo

Fibre Length

The result of the Fibre length of the study samples are presented in figure 1. The mean value obtained were ranged 1.78 to 2.44mm for both the treated and the untreated samples. The result of the analysis of variance of fibre length for the acetylated bamboo sampled are presented in the Table 2. There were no significant differences observed within the treated and the untreated. A significant difference was shown in the fibre length along the culm height at 5% probability level.

The bamboo fibres play an important role in the supporting of bamboo self-weight. The fibres are ground in fibre strands as reported by Wang *et al.,* (2011). It was observed that the fibre length had a gradual but steady increase from the base to a point at the middle before it then decreases progressively towards the top. These observations is in accordance with the findings and documentation of Abd-Latif *et al.,* (1994) who also observed similar variation in Malaysian bamboo (*Gigantochloa scortechinii*). Liese (1998), gives an insight into why these is so, he reported that this variation pattern of fibre length along the culm height could be attributed to the correlation between fibre length and internode length as there are longer internode at the middle compare to the top and the base. Wang *et al*., (2011) reported that the longest fibre length located at the middle segment and the longer at the base with the top segment having the shortest fibre length. However, Pu and Du (2003) reported that the longest fibre length was located in the bottom culms while the shortest fibre length was recorded at the top of the culm. Abd-Latif and Mohd-Tamizi (1992), concluded that the variation trends which were found among various bamboo species across the globe might have resulted from the difference in growth rates among different bamboo species. The bamboo has longitudinal alignment of fibre due ro its inherited property. Compared to any other natural fibre material bamboo fibre having higher modulus of elasticity. The lengthier the fibre advanced it gives the tensile strength. Adding of Bamboo fibres to the concrete increases the tensile and mechanical strength (Kumarasamy *et al.,* 2020).

The strength of the bamboo fiber is relatively greater among the plant fibers (Li and Shen, 2011). Its superior mechanical properties originate from the intricate lamellar structure of its cell wall. The tensile strength of bamboo is generally more than 2 times that of wood, and the specific tensile strength of bamboo is about 3–4 times that of steel (Yu *et al.,* 2011).

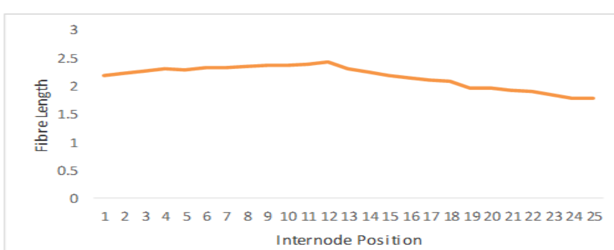

Figure 1. Trend of fibre length variation in acetylated bamboo along the culm

Table 2: Significance (p-values) of Anatomical Morphology along bamboo culm sampling heights

SOURCE	Df	FL	FD	FLW	CLT
Treatment	1	1.000^{ns}	0.000*	0.000*	0.000*
Culm Position	24	0.000*	0.000*	0.000*	0.000*
Treatment * Culm Position	49	0.000*	0.000*	0.000*	0.000*
Error	100				
Total	150				

Notes: *p-values > 0.05 are not significant. DF = Degree of freedom, FL = Fibre length, FD = Fibre diameter, FLW = Fibre Lumen width, CLT = Cell wall thickness.

Fibre Diameter

The mean value obtained of the sampled treated bamboo for fibre diameter after observed on Rheichert visopan microscope screen and measured using a stage micrometer and an eyepiece micrometer were ranged 9.65 to 13.24μm. The mean value observed for the untreated ranged 13.81 to 15.24μm (Figure 2).

The result of the analysis of variance for fibre diameter showed a significant difference between the treated and the untreated bamboo samples. Significant differences were also observed within the height along the culm. There is a significant difference in the interaction of the treatment and the culm height at 5% probability level as presented in Table 2.

The fibre diameter is an indicator of the relationship between the cell-wall thickness and the lumen width (Riki and Oluwadare, 2020). Fibre diameter decreased from base to top along the longitudinal position. The observed trend could be due to the fact that minimal net photosynthate for cell development at the top caused by competition for leaf and branch development lead to better cells production at the base (Ogunleye *et al*., 2017).

Monteiro *et al*., (2017), investigated the effect of diameter on the mechanical resistance of bamboo fibers extracted from the stem of the giant bamboo (dendrocalmus giganteus) as possible composite reinforcement due to their relatively high tensile strength. They found that the thinnest fibers of the giant bamboo exhibit a maximum tensile strength of about 300 MPa. As mentioned above, the superior mechanical performance highly depends on its arranged orderly thick-wall structure. Specifically, the bamboo cellulose content gradually increases from the inner yellow portion to the outer bamboo green portion, providing excellent fracture resistance. The vascular bundles on the outer side are stronger and stiffer than those on the inner side along the cross-section. In addition, for vascular bundles of varying heights, the strength and modulus of the top part are nearly equal to that of the middle part but higher than that of the base part (Gao *et al*., 2022).

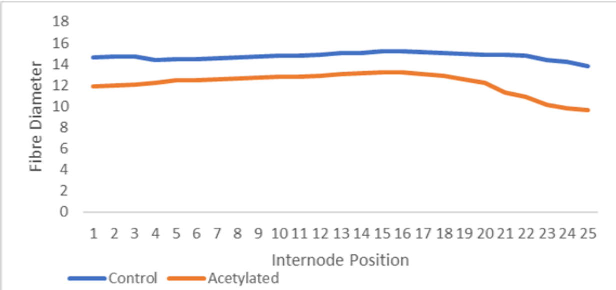

Figure 2: Trend of fibre diameter variation in treated and untreated bamboo samples along the culm

Fibre Lumen Width

The mean value obtained of the sampled treated bamboo for fibre lumen diameter after observed on Rheichert visopan microscope screen and measured using a stage micrometer and an eyepiece micrometer were ranged 2.35 to 4.62μm. The mean value observed for the untreated ranged 8.36 to 10.63μm (Figure 3).

The result of the analysis of variance for fibre lumen diameter showed a significant difference between the treated and the untreated bamboo samples. Significant differences were also observed within the height along the culm. There is a significant difference in the interaction of the treatment and the culm height at 5% probability level as presented in Table 2.

Lumen size is important for fibre dimensions because of its effect on the rigidity and strength in construction materials (Akpakpan *et al*., 2012). The cell-lumen obtained in the stalk decreased along the sampling height which is in agreement with pattern observed for T. daniellii reported by Sotannde, (2015). The smallest lumen diameter was observed at the top and the base segment of the culm height. The results in this study is in consonance with the work of Su *et al*., (2005).

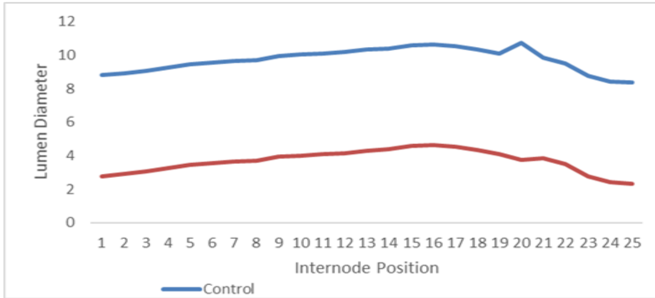

Figure 3. Trend of fibre lumen width variation in treated and untreated bamboo samples along the culm

Cell wall Thickness

The mean value obtained of the sampled treated bamboo for cell wall thickness after observed on Rheichert visopan microscope screen and measured using a stage micrometer and an eyepiece micrometer were ranged 7.32 to 9.1µm. The mean value observed for the untreated ranged4.61 to 5.87µm (Figure 4)

The result of the analysis of variance for cell wall thickness showed a marked effect between the treated and the untreated bamboo samples. Significant differences were also observed within the height along the culm. There is a significant difference in the interaction of the treatment and the culm height at 5% probability level as presented in Table 2.

The cell wall of bamboo fiber highly affects its mechanical performance. The bamboo cell wall structure is more complex than that of wood (Huang *et al*., 2016). Fei *et al*., (2016), examined the bamboo cell wall using a light microscope and found more cell layers near parenchyma cells across the bamboo vascular bundle and at the inner edge of the vascular bundle. Cellulose is the structural skeleton of a bamboo cell wall, and its molecular bundles aggregate to form microfibrils. The micro-fibril angle (MFA), which may be determined using XRD or wide-angle X-ray scattering (WAXS), is the angle between the arrangement direction of microfibrils and the main axis of the cell (Li and Shen, 2011).

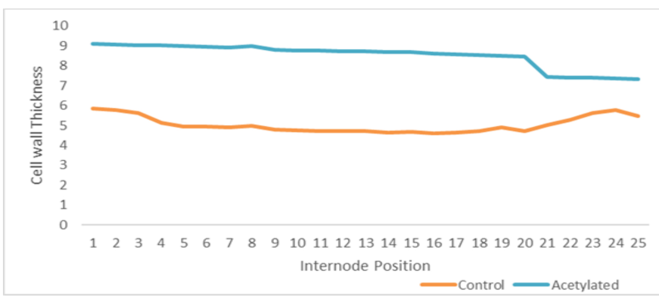

Figure 4. Trend of fibre cell wall thickness variation in treated and untreated bamboo samples along the culm

CONCLUSION

This study therefore establishes the fact that bamboo could be chemically modified using acetic anhydride to improve its anatomical properties and as a result of the modification in the bamboo fibre cell wall, there is a significant improvement in its dimensional stability and hydrophobicity hence, enhances the utilization of bamboo for structural application which may be due to its long fibre length. Bamboo with its high fibre length can be treated and use as alternative to wood as a construction material in order to reduce the pressure on wood and combat global warming.

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