Bamboo (*Bambusa vulgaris* Schrad.) from Moist Forest and Derived Savanna Locations in South West Nigeria – Properties and Gluability

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Bamboo culms of *Bambusa vulgaris* Schrad. were collected from two locations in moist forests and two sites in derived Savanna zones in South West Nigeria. The study involved chemical analyses, density variability, bonding tests, gluability tests, and measurements of bending strength of the bamboo in addition to durability testing with decay fungi and treatability of glued boards with a copper-based wood preservative. Chemical analyses showed a uniform composition of the bamboo with a cellulose content of 45 to 47.5% and a lignin content of 23 to 25.6% as the predominant chemical constituents. An average wood density of 700 kg/m^3 was a prerequisite for high mechanical strength. The moduli of elasticity were high and exceeded 14 kN/mm^2 for bamboo boards and 13 kN/mm^2 for finger joints. Bamboo boards from all growth sites showed high moduli of rupture in the range of 150 to 166 N/mm^2 and 72.9 to 94.7 N/mm^2 for boards and finger joints, respectively. Bamboo from the four sites showed variable mass loss with the EN-113 (1996) test method, which classifies this biomass as a moderately to non-durable plant material. White rot fungus (*Trametes versicolor*) caused the highest mass losses (11.2 to 16.8%). The bamboo showed good treatability using a 500-kg/m^3 solution of a copper-based preservative.

Keywords: Density; Gluability; Mechanical properties; Treatability; Wood durability

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INTRODUCTION

Bamboo is a fast-growing woody plant, which takes 5 to 6 months to reach maximum height and reaches harvesting maturity after 3 to 5 years (Abd Razak 1992). The biomass productivity of bamboo can also be extremely high, since species such as *Guadua angustifolia* can produce *ca.* 500 cm^3 cell wall substances *per* day, resulting in a total of about 0.1 m^3 for the entire culms. These are major advantages for the production of bamboo-based panels and boards in that a high growth rate and hence higher rate of biomass accumulation provide opportunities for larger fiber volume *per* hectare. Bamboo panel products are ideal substitutes for wood considering the fact that bamboos are easier to propagate and mature faster (Virtucio 1999). Apart from the tremendous biomass production, there are no rays or knots, which gives bamboo a far more even distribution of stress along its length (Li 2004). The specific strength of laminated bamboo boards is also higher than some favored tropical wood species such as *Khaya senegalensis*, *Mansonia altissima*, and *Milicia excelsa* (Ogunsanwo and Terziev 2010). These attributes have stimulated the use of bamboo for different applications in many parts of the world, especially in Asia.

Effective bamboo lamination requires that there is proper bonding among laminated members such that shear forces acting to disengage individual members can be resisted. However, bonding between bamboo laminates is a function of several factors, among which is density, dictated by the anatomical structure at the bonding interface. According to Malanit *et al.* (2009), denser wood species are more difficult for adhesives to penetrate due to the small size of their fiber lumens, their thick cell walls, and their narrow pit openings between fibers. These factors restrict adhesive penetration, thereby creating poor bonding and weak products. Improving the penetration of adhesives may require that the waxy substances, as well as thick outer surfaces, are removed to allow for the better penetration of adhesives into the bamboo structure. However, this should be executed in such a way that there is balance between removal and strength properties of the resulting board, as the density is strongly linked with the strength performance of most materials. Therefore, it is important to study the density variation across bamboo culms.

While bamboo is traditionally widely used in Asian countries, it has only marginal importance in Africa. To date, only very small volumes of bamboo are used for scaffolding construction. Glued products are not manufactured in Nigeria, even though bamboo is abundant. The present study is therefore groundbreaking and intended to reveal some physical-mechanical properties of *Bambusa vulgaris* from selected locations in South West Nigeria. In addition, a technology for the production of glued- and finger-joined boards has been proposed, and some mechanical properties of the product are assessed. The study was initially constrained by the lack of any experience and tradition of bamboo utilization in the rural areas of Nigeria. Another limiting factor was the lack of any equipment and sometimes the absence of electricity. Thus, the aim of the work was to develop a very simple technology that can ensure some pre-manufacturing *in-situ* and final finishing of the product at specialized sites. It was expected that organized in this way, the manufacture of bamboo glued boards in rural areas rich in bamboo but lacking equipment will provide an income for the inhabitants.

In Nigeria and other West African countries, timber resources are dwindling and the necessary prerequisites for regeneration are not always readily available. The utilization of alternative raw materials such as bamboo with a great potential to address the problem of wood shortage with minimal negative impact on the environment can form part of the overall plan to secure future sustainable development. This study investigates some physical properties and gluability of *Bambusa vulgaris* from selected locations in South West Nigeria to identify the role of study site and the way of lamination on the properties of the composite product.

EXPERIMENTAL

Materials

Growth sites, sample selection, and preparation

Bamboo culms of *Bambusa vulgaris* were collected from locations in the moist forest and derived Savanna zones of Nigeria. Specific growth sites were at the following locations (Fig. 1), and samples were marked as follows: FR - Jericho Ibadan, 7^o 21' 36.82" N and 3^o 49' 11.89" E, moist forest; OL - Olodo 7^o 28' 41.10" N and 3^o 52' 24.54" E, moist forest; OK - Okuku, 7° 54' 34.80'' N and 4° 31' 3.47'' E, derived Savanna; and IB - Ijagbo 7° 8' 31.37'' N and 4° 42' 31.37'' E, derived Savanna.

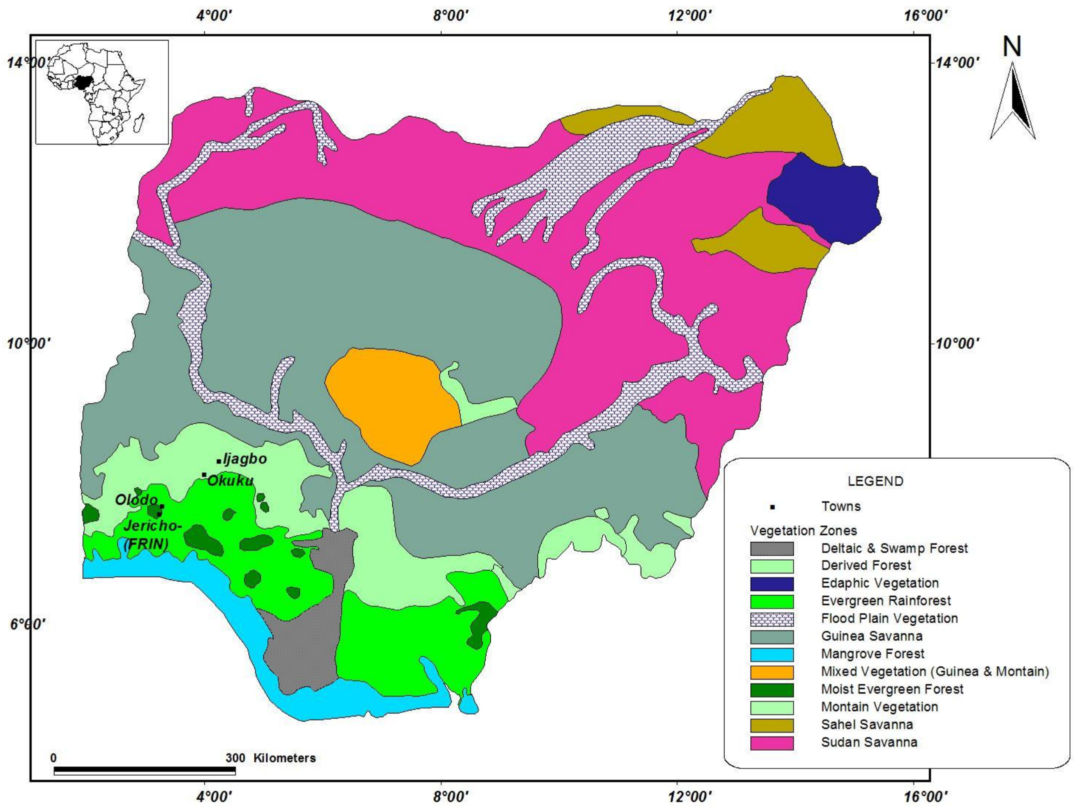

Fig. 1. Vegetation map of Nigeria showing the bamboo growth sites

Five to six year-old bamboo stands were selected. Twenty culms of 1.5 m in length (from the base) were harvested from each stand and air dried for 2 weeks. The culms were sawn through the nodes to form sections of 45 to 50 cm in length, which were further split into four equal strips using a circular saw. Specimens were cut from the middle of the strips for density and strength property testing.

For density studies, eight culms were selected from each site, and four samples from each culm were chosen, to give 32 strips in total. Each strip was partitioned into six layers from the inner to the back of the strip to give a total of 192 test specimens. The density of the layers was determined in accordance with the standard procedure in ISO 3131 (1975).

Methods

Chemical analyses

Samples were dried at 105 °C to constant mass prior to chemical analysis for monosaccharides and lignin. Dried samples were chipped and ground to pass through a 1-mm screen using a Tecator Cyclotec 1093 sample grinder (Sweden). Monosaccharide analyses were performed in accordance with TAPPI Standard T 249 cm-00 (2000), while Klason lignin analysis was in accordance with TAPPI Standard T 222 om-06 (2006) on an ash-free basis. By-products of acid hydrolysis, such as acetic acid, 4-*O*-methylglucuronic acid, HMF (5-hydroxymethyl-2-furfuraldehyde), furfural, acid-soluble lignin, and levulinic acid were not considered in this study.

Bonding process and gluability

The gluability of the bamboo strips (lamellae) was determined using shear resistance along the glue line. Samples were prepared in accordance with the standard procedure given in ISO 3347 (1976). Three types of specimens were prepared from two density classes: (1) the light inner portion of the stalk, part "I" and (2) the denser outer cutin, part "O". Samples were glued in three combinations: cutin outer-cutin outer (O-O), light inner-light inner (I-I), and cutin outer-light inner (O-I). Polyvinyl acetate glue (PVA) from Casco Adhesives AB (Sweden) was applied at 200 g/m^2 on both surfaces and pressed at 2 kg/cm^2 using a Shimadzu universal testing machine (UTM; AG-X 50 KN; Japan) for 60 min at room temperature. Test specimens were cured for 24 h and then tested for strength along the glue line using shear mode of the UTM.

Anatomical study

Small bamboo samples were carefully removed along the glue line and viewed using scanning electron microscopy (SEM) to observe the depth of glue penetration into the bamboo. Semi-thin radial-longitudinal sections (30 µm) were cut using a Leitz microtome (Germany), air-dried, mounted on stubs, coated with gold, and observed using a Philips XL30 ESEM (the Netherlands) operating at an accelerating voltage of 10 or 15 kV (Daniel *et al.* 2004). Features from the SEM observations were used to analyze the gluability of the bamboo lamellae.

Mechanical properties of the glued bamboo boards

Glu-lams for the production of finger-jointed boards were produced using the O-I combination. The bamboo lamellae from the studied stands were glued to form boards with a thickness equal to that of the width of the lamellae (*i.e.*, 70 mm). The material was placed in a conditioning room (20 °C and 65% relative humidity) to achieve equilibrium moisture content. The lamellae were further finger joined under industrial conditions. The finger joints had a length of 10 mm, 0.6 mm tip, 3.8 mm pitch, and angle of 22°. The lamellae and fingers were glued in accordance with the technical recommendations provided by the glue manufacturer. A melamine urea formaldehyde glue system MUF 1247/2526 (MUF adhesive 1247 and hardener 2526) from Casco Adhesives AB was selected to produce bamboo boards with length of 6 m. After gluing, the bamboo boards were re-conditioned and cut into 400-mm-long test specimens with and without finger joints. Ultimate strength in the three point static bending test (modulus of rupture, MOR) and modulus of elasticity (MOE) were measured in accordance with the standard ISO 3133 (1975) and ISO 3349 (1975), respectively. Finger joints were only tested vertically.

Natural durability against basidiomycetes fungi

Lamellae from the studied stands (cross-section dimensions shown in Table 2) were cut to 50 mm in length. Assessment of natural durability against fungal attack by basidiomycetes was carried out in accordance with the standard EN 113 (1996). Three brown rot fungi (*Coniophora puteana* BAM Ebw.15, *Gloeophyllum trabeum* BAM Ebw. 109, and *Postia placenta* FPRL 280; current name *Oligoporus placenta*) and one white rot fungus (*Trametes versicolor* CTB 863A) were used. The criteria used for classification of natural durability of wood are given in the standard EN 350-1 (1994). Evaluation of the laboratory decay test was based on the recorded mass loss (ML) after 16 weeks of exposure. The ratio of the ML of test specimens to the ML of the reference wood (beech (*Fagus sylvatica* L.)) was expressed as shown in Table 8.

Treatability of the glued boards with a wood preservative

The treatability of the glued boards with a wood preservative was studied by impregnation. A full cell impregnation schedule consisting of vacuum (90%, 30 min) and pressure (12 bars, 90 min) was used to infiltrate the bamboo with a copper-based water-soluble preservative (Celcure AC 800 by Koppers, UK). The bamboo was impregnated in accordance with the recommendations of the Nordic Wood Protection Council, *i.e.*, 36 kg/m^3 target retention of the concentrate (NWPC 2015). The weight of the samples was measured before and after impregnation; from this data, the retention of the solution was calculated.

RESULTS AND DISCUSSION

Chemical Analyses

The results of the chemical analyses of bamboo from the four growth sites are shown in Table 1. Overall, the content of all measured components show low variation among the growth sites. Glucan (*i.e.*, cellulose content) was highest in the OK site (47.46%) and lowest in the OL site (45.12%). Arabinan and mannan in all bamboo samples from various sites were less than 1.4%; galactan varied from *ca.* 0.70% in the IB site to 0.93% in the FR site. It can be concluded that the cellulose content of bamboo from all studied sites (Table 1) was similar to that of the majority of wood species.

Table 1. Monosaccharide and Lignin Content (wt.% oven-dried, extractive-free basis) of *Bambusa vulgaris* from the Four Growth Sites in Nigeria

	Growth site			
	FR	OL	OK	IB
Arabinan	1.43 (0.28)	1.26 (0.19)	1.26 (0.12)	1.35 (0.32)
Xylan	19.18 (0.97)	16.84 (0.95)	17.45 (1.77)	18.52 (1.02)
Mannan	1.13 (0.27)	0.92 (0.14)	0.72 (0.08)	1.01 (0.27)
Galactan	0.93 (0.20)	0.80 (0.12)	0.84 (0.09)	0.70 (0.11)
Cellulose (as glucan)	45.12 (0.71)	45.10 (1.24)	47.42 (1.56)	45.93 (1.32)
Lignin	24.3 (0.14)	25.6 (0.07)	25.0 (0.35)	22.9 (0.66)
Standard deviation in parentheses				

Schmidt *et al.* (2013) have studied two bamboo species and found 42.2% cellulose, 26.8% hemicellulose, and 26.2% lignin for *Phyllostachys pubescens* and 48.5% cellulose, 18.6% hemicellulose, and 29.5% lignin for *Gigantochloa atroviolacea*. According to Santana and Okino (2007), hemicelluloses are composed of xylan, galactan, mannan, arabinan, acetyl, and uronic anhydride. Hemicellulose in the studied bamboo was similar to that found in other hardwoods and are characterized by the high amount of xylan, which was the prevailing hemicellulose type. Bamboo from the OL site had the lowest (16.84%) and the FR site the highest (19.18%) amounts of xylan measured. Bamboo samples from the four sites showed negligible variations in lignin content (Table 1). Bamboo lignin is typical of monocotyledon lignin showing in its UV spectrum a guaiacyl peak at 280 nm and a shoulder between 310 and 320 nm (Koch and Kleist 2001; Schmidt *et al.* 2013). Based on average lignin content, the studied bamboo is comparable to some tropical hardwood species, such as icuria and metil (Lhate *et al.* 2010) with average lignin content below 27%. It can be concluded that the chemical compositions of the bamboos originating from the four studied sites were very similar. The high amount of hemicelluloses and low amount of lignin predetermine some of the bamboo's properties, *e.g.*, low durability.

Culm Characteristics

The characteristics of the culms from the studied sites, as well as the estimated and measured yield are shown in Table 2. The lamellae dimensions are also given.

Table 2. Characteristics of Culms from the Studied Sites, Estimated and Measured Yields, and Lamellae Dimensions

Growth site	Outer diameter (mm)	Wall thickness (mm)	Cutting to 4 sections		
			Estimated maximum yield (%)	Measured yield (%)	Lamellae dimensions (mm)
FR	78.0 (5.9)	11.2 (1.5)	44.2 (6.2)	33.0 (14.4)	8 × 32
OL	76.0 (3.8)	13.1 (3.4)	49.0 (10.2)	28.0 (11.0)	9 × 34
OK	68.2 (3.5)	14.1 (2.1)	55.0 (7.6)	43.1 (10.8)	10 × 34
IB	76.8 (4.4)	16.3 (3.0)	55.3 (5.5)	39.1 (14.1)	11 × 38
Standard deviation in parentheses					

Data for culm diameters show, with one exception (68.2 mm from OK), a uniform diameter size at all sites. The wall thickness varied from 11.2 to 16.3 mm. Splitting of the bamboo culms was improved by mathematically finding the optimal volume that can be sawn from a culm. The theoretical volume yield when a culm was split into four parts varied between 44.2 and 55.3%, while the measured yield after sawing and planing was 28.0 to 39.1%. The variation is explained by the culm wall thickness of the bamboo, *i.e.*, the growth site. Lamellae dimensions obtained for bamboo from the four sites were proportional to the diameter and wall thickness of the culm.

Bamboo Density Variation

The highest average bamboo density of 745 kg/m^3 was found at the IB site (derived Savanna zone), while the FR site (moist forest zone) had the lowest density of 666.8 kg/m^3 (Table 4). Apart from the FR site, which had a statistically significant different bamboo density, the values observed from the other sites were fairly similar, as shown by the post-mortem analysis (Table 4). This observation indicated that bamboo density was uniform over the study site areas. INBAR (2006) reported earlier that culm quality of locally grown bamboo in Ghana does not differ between sites within the same vegetation zone but does differ between vegetation zones; this implied that bamboo culms selected from plantations within the same vegetation zones may have the same quality when the planting stock and agricultural management are identical. Intra-culm analysis of the density showed that there were significant differences among bamboo layers (Table 3). Density ranged between 588.4 kg/m^3 in the lighter inner bamboo regions to 970.5 kg/m^3 in the cutin outer layer. This indicated that there was a density gradient from the inner to outer bamboo (Table 5 and Fig. 2). The trend was similar to that observed in moso bamboo (*Phyllostachys pubescens*) as reported by Yu *et al*. (2008). Lighter samples were found in the first 2 layers with increasing density towards the outer regions. Tukey's statistical tests (MATLAB, version 6.5, USA) compared the density among the growth sites (Table 5) and indicated that the density of bamboo within the first and second layers were not significantly different.

Table 3. Statistical Analysis of Variance of Between and Within Bamboo Sites

Source variation	DF	SS	MS	F-value	*P* > F
Site	3	188599.3	62866.4	26.55	< 0.0001*
Individual	7	225889.6	32269.9	13.63	< 0.0001*
Layer	5	3552850.3	710570.0	300.06	< 0.0001*
Layer – Site	15	63793.7	4252.9	1.80	0.0407*
Site – Individual	21	539471.9	25689.1	10.85	< 0.0001*
*Confidence level p < 0.05					

Table 4. Bamboo Density Variations among the Studied Sites in South West Nigeria

Growth site	Mean	Tukey grouping
FR	666.8 (98.3)	B
OL	737.8 (86.4)	A
OK	732.4 (98.0)	A
IB	745.1 (16.8)	A
Different letters indicate a significant difference (p < 0.05)		

Table 5. Post-Mortem Analysis of Density Variations in Bamboo Layers from the Lighter Inner to Cutin Outer Layers

Layer	Mean	Turkey group
Layer 6	970.5 (45.4)	A
Layer 5	814.3 (76.2)	B
Layer 4	715.5 (86.3)	C
Layer 3	639.0 (79.8)	D
Layer 2	595.5 (63.4)	E
Layer 1	588.4 (45.1)	E
Different letters indicate a significant difference (p < 0.05)		

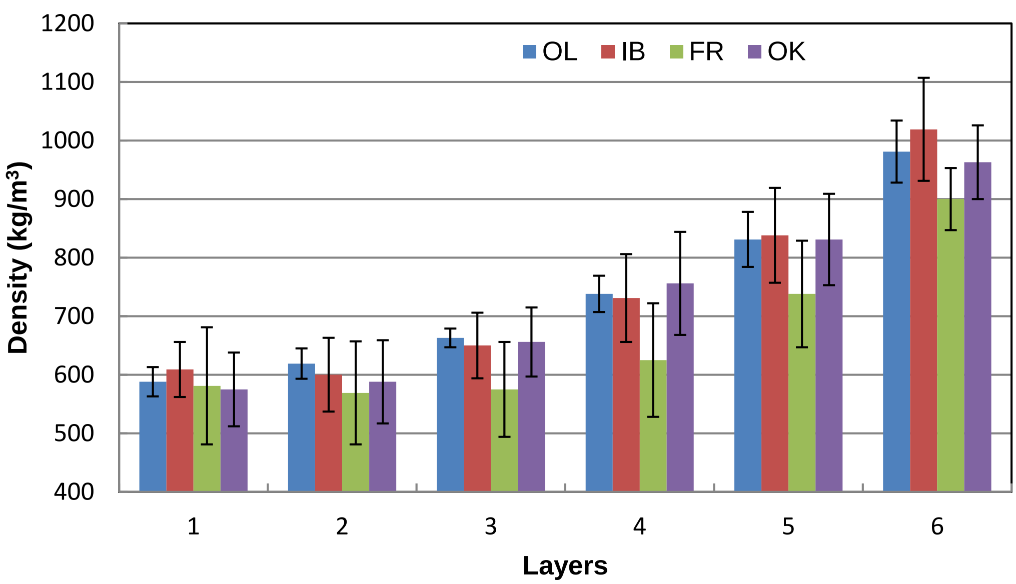

Fig. 2. Density variation in *Bambusa vulgaris* originating from Nigeria

Gluability of Bamboo

The shear strength ranged from 6.6 N/mm^2 for the bamboo from the FR site to 13.1 N/mm^2 for the IB site (Table 6). Two clear patterns of variation in shear strength were observed in this study. In the lighter FR bamboo, shear strength was highest for I-I (6.8 N/mm^2) and lowest for O-I (6.3 N/mm^2). On the other hand, denser bamboo samples from OL, IB, and OK had their highest values for O-O bonding, followed by O-I bonding; I-I bonding in these samples had the lowest shear strength along the glue line. It was expected that low glue permeability at the O-O interface would lead to low strength along the glue line, as reported by Malanit *et al.* (2009). However, the general trend shown in this study revealed a contrary pattern. This result provoked two lines of reasoning. The first was to assume that low gluability in the lighter bamboo may be due to more permeability of glue materials into immediate cells below the glue lines, which could have led to low availability of glue for adhesion at the interface (Fig. 3). Secondly, deep penetration of glue into the cells at the interface could have created more adhesion between the bamboo laminates and the shear forces needed to produce failure along the interface could have been high so that failure occurred within the bamboo cell rather than occurring along the glue line. If the shear strength of the bamboo is lower than that along the glue line, then the shear strength is expected to be lower at the interface where lighter and more permeable cells are bonded. In O-O bonding, where glue penetration into the immediate cells was not pronounced (Fig. 3), the shear strength was expected to be higher along the glue lines than in the other laminated boards.

Table 6. Shear Strength (N/mm^2) of *Bambusa vulgaris* along the Glue Line

Growth site	O-O	I-I	O-I	Mean
FR	6.7 (1.4)	6.8 (2.3)	6.3 (2.0)	6.6
OL	10.3 (1.9)	8.2 (2.5)	10.2 (1.4)	9.6
OK	10.8 (5.5)	8.8 (2.4)	9.3 (2.5)	9.6
IB	13.1 (2.2)	10.7 (2.4)	12.5 (3.2)	12.1
Mean	10.2	8.7	9.5	9.5
Standard deviation in parentheses				

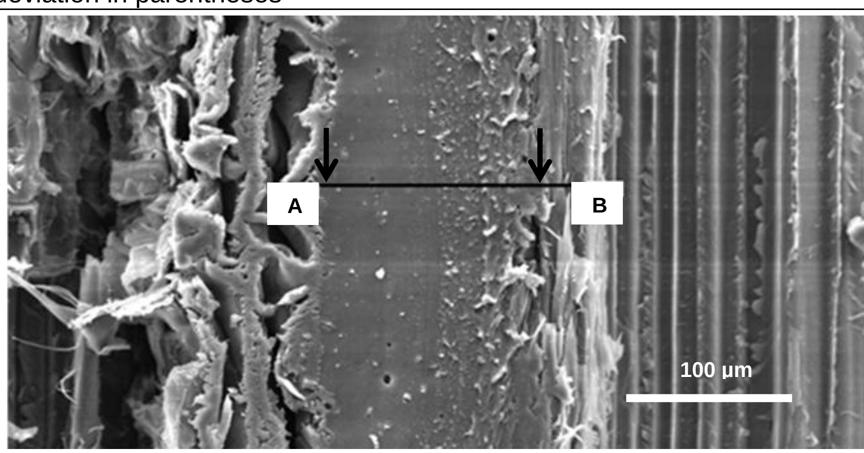

Fig. 3. Anatomical presentation of glue penetration along laminate interface for O-O. A-B (arrows) is the glue thickness at the interface

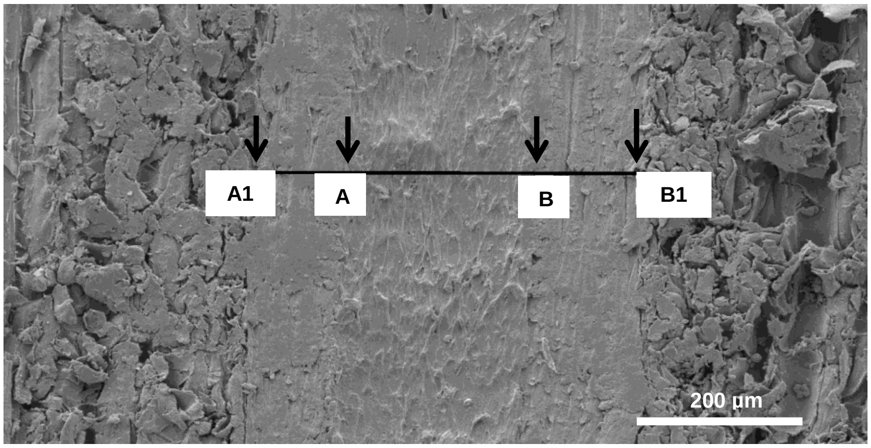

Fig. 4. Anatomical presentation of glue penetration along the laminate interface for I-I. A-B (arrows) is the glue thickness at the interface, while A1-A and B-B1 (arrowheads) show the extent of glue penetration beyond the interface into the immediate cells

Mechanical Properties of the Glued Bamboo Boards

Previously, Ogunsanwo and Terziev (2010) compared some mechanical properties of *Bambusa vulgaris* boards (without finger joints) to those of threatened wood species from Nigeria, with favorable results. The current study compared the strength of the boards formed with finger joints (Table 7). Results were similar to the previous study, and bamboo boards from all growth sites showed high MOR in the range of 151 to 166 N/mm^2. The modulus of rapture values of the finger joints were in the range of 72.9 to 94.7 N/mm^2, which was approximately half of the MOR in the adjacent area. This can be improved further by using larger finger joint lengths. The MOE of both boards and finger joints were high; the values exceeded 14 kN/mm^2 for the bamboo boards and 13 kN/mm^2 for the joints; *i.e.*, finger joints influenced the MOE significantly less than they did the MOR. The MOE decreased by approximately 10% in the finger joints when compared to the MOE of the boards. The measured bending characteristics are good prerequisites when bamboo boards are considered as a construction material. Furthermore, by gluing boards, large dimension glued construction elements can be manufactured.

Table 7. Bending Strength Properties of Finger-Jointed Boards Made from *Bambusa vulgaris*

Growth site	MOR boards (N/mm^2)	MOR finger joints (N/mm^2)	MOE boards (N/mm^2)	MOE finger joints (N/mm^2)
FR	166.1 (18.3)	73.4 (19.8)	17949.6 (588.4)	15314.9 (1906.4)
OL	151.3 (9.7)	72.9 (6.9)	14338.0 (1419.1)	13553.0 (1488.2)
OK	163.2 (17.3)	94.7 (5.9)	14178.7 (922.6)	13174.3 (864.6)
IB	162.5 (11.9)	79.0 (12.8)	16113.6 (1227.6)	15369.0 (471.5)
Standard deviation in parentheses				

A recent study (Aina *et al.* 2012) on the fiber morphology and bending strength of *Bambusa vulgaris* harvested from two sites in Nigeria also revealed the uniform anatomical structure of the studied species.

Durability and Treatability of Bamboo

The high amount of carbohydrates (*i.e.*, cellulose and xylan; Table 1) affects the durability of *Bambusa vulgaris* from the Nigerian sites (Table 8). It can be concluded that the studied bamboo species is slightly durable. Some variation between the sites was observed, *i.e.*, from moderately to non-durable, that might be explained by the prior location of the lamellae in the culm.

Table 8. Mass Loss of *Bambusa vulgaris* from the Four Nigerian Sites and Retention of Water-Soluble Preservative (Celcure AC 800) after Impregnation

Growth site	Fungi, average mass loss, and durability classes (%)				Durability class	Description	Retention (kg/m^3)
	Con. put.	*Gl. trab.*	*P. pl.*	*Tr. ver.*			
FR	4.7 (2)	5.5 (2)	13.4 (4)	16.8 (4)	4	Slightly durable	581.3 (10.9)
OL	2.8 (2)	2.2 (2)	7.7 (3)	15.0 (4)	4	Slightly durable	543.4 (41.7)
OK	5.2 (2)	1.3 (1)	6.0 (3)	16.4 (5)	5	Not durable	480.9 (29.3)
IB	1.2 (1)	2.2 (1)	5.4 (2)	11.2 (3)	3	Moderately durable	519.0 (19.6)
Durability class in parentheses							

Numerous studies on the decay and natural durability of bamboo species have been conducted (Liese 1985; Leithoff and Peek 2001; Schmidt *et al*. 2011) and the durability of *Bambusa vulgaris* grown in Indonesia reported (Suprapti 2010). Applying the standard EN 113, Wei *et al*. (2013) classified five bamboo species in durability class 2 by using four *C. puteana* and two *G. trabeum* strains; the white-rot fungus *T. versicolor* yielded durability classes 2 to 4 and two soft-rot fungi showed classes 2 to 3. Variations in bamboo durability are explained by the nature of the decay caused by organisms, growth stands, and bamboo species, as well as age and height from where the samples were taken. The majority of these authors agree, however, that bamboo possesses low natural durability when exposed to the outdoor elements. The species from the four Nigerian sites studied here showed variable mass loss, which classified the bamboo as a moderate to non-durable plant material. *T. versicolor* caused the highest mass loss (11.2 to 16.8%), similar to the results of Kim *et al.* (2011) but higher values relative to the results of Suprapti (2010), who found mass losses in the range 4 to 7.2% with the same fungus. Significant differences ($p<0.05$) in mass loss were found when the bamboo samples were exposed to *P. placenta* (*i.e.*, 5.4 to 13.4%), which was greater than the results of Suprapti (2010) (*i.e.*, 2.4 to 4.5%). The brown rot fungi *G. trabeum* and *C. puteana* were less aggressive and caused mass losses of less than 5%, which is in line with the findings of Schmidt *et al.* (2013). Bearing in mind the low durability of bamboo against termites and soft rot attack, some protective chemicals will need to be applied to protect the material if it is exposed to the outdoors.

The measured retention of the wood preservative (Celcure AC 800), was in the range of 480 to 580 kg/m^3 (Table 8). This result was acceptable when considering that the retention of the same preservative in Scots pine sapwood is approximately 650 kg/m^3. The retention was highest in the bamboo from the FR, which can be explained by its density being less when compared to the other stands. The results showed good treatability ensuring a proper retention to the studied bamboo and consequently reliable protection. An ongoing trial where the glued bamboo boards are exposed in a Nigerian in-ground contact field test will reveal the efficiency of the treatment.

Utilization of *Bambusa vulgaris* faces some practical difficulties. Workability and machining of the culms is difficult because of the nodes and their shape, hardness, and low flexibility. On the positive side, *Bambusa vulgaris* is thick-walled and mechanically strong (Louppe *et al.* 2008). Cutting the bamboo culms into short sections without nodes facilitates the production of the lamellae and ensures high yield (Table 2). Gluing lamellae is also easy and does not demand special equipment. The pre-manufactured boards can be further transported to small factories where planing and finger joining can be carried out.

CONCLUSIONS

1. Significant differences ($p < 0.05$) were found between the two geographical growth sites among bamboo density and other features, but the properties gluability, durability, bending strength, and treatability did not show any general difference trends.
2. An important feature of the bamboo from the four studied Nigerian sites was the low variability in the chemical composition.
3. Location of the sites in the moist forests or derived Savannas in Southwest Nigeria did not affect the properties of bamboo-glued boards.
4. The composite bamboo is suitable as a construction material. The bending characteristics of this material exceeded that of widely used softwood species from temperate regions (*e.g.*, Norway spruce), as well as that of some traditionally used hardwood species from tropical countries.
5. Being rich in carbohydrates with lignin similar to those of grasses and hardwoods, *Bambusa vulgaris* is slightly durable when exposed to decay fungi. The studied bamboo is porous enough to permit impregnation with preservatives; thus, its field performance can potentially be significantly improved.

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REFERENCES CITED

Abd. Razak, O. (1992). "Shoot production and cult growth of two commercial bamboo species in Peninisular Malaysia," *Bamboo Inform. Centre India Bulletin* 2(1), 5-7.

Aina, K. S., Areghan, S. E., Adeniyi, I. M., Alao, O. J., and Osuntuyi, E. O. (2012). "Variability studies on strength and fibre properties of *Bambusa vulgaris* Schrad. for panel products," *Pro Ligno* 8(1), 3-14.

Daniel, G., Duchesne, I., Tokoh, C., and Bardage, S. (2004). "The surface and intracellular nanostructure of wood fibres: Electron microscope methods and observations," in: *Proceedings of COST Action: Wood Fibre Cell Walls: Methods to Study Their Formation, Structure and Properties,* Swedish University of Agricultural Sciences, Uppsala, Sweden, pp. 87-104.

EN 350-1. (1994). "Durability of wood and wood-based products - Natural durability of solid wood, Part 1: Guide to the principles of testing and classification of the natural durability of wood," European Committee for Standardization, Brussels, Belgium.

EN 113. (1996). "Wood preservatives. Method of test for determining the protective effectiveness against wood destroying Basidiomycetes. Determination of toxic values," European Committee for Standardization, Brussels, Belgium.

INBAR. (2006). "Present status of research and development on bamboo and rattan in Africa and prospects for future co-operation with China," International Center for Bamboo and Rattan Open Fund Research Programme, International Network for Bamboo and Rattan (INBAR), Beijing, China.

ISO 3131. (1975). "Wood- Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

ISO 3133. (1975). "Wood-Determination of ultimate strength in static bending," International Organization for Standardization, Geneva, Switzerland.

ISO 3347. (1976). "Wood-Determination of ultimate shearing stress parallel to grain," International Organization for Standardization, Geneva, Switzerland.

ISO 3349. (1975). "Wood-Determination of modulus of elasticity in static bending," International Organization for Standardization, Geneva, Switzerland.

Kim, J.-J., Lee, S.-S., Ra, J.-B., Lee, H., Huh, N., and Kim, G.-H. (2011). "Fungi associated with bamboo and their decay capabilities," *Holzforschung* 65(2), 271-275.

Koch, G., and Kleist, G. (2001). "Application of scanning UV microspectrophotometry to localize lignins and phenolic extractives in plant cell walls," *Holzforschung* 55(6), 563-567.

Leithoff, H., and Peek, R. D. (2001). "Heat treatment of bamboo," International Research Group on Wood Preservation (IRG), Nara, Japan, May 20-25.

Lhate, I., Cuvilas, C. A., Terziev, N., and Jirjis, R. (2010). "Chemical composition of traditionally and lesser used wood species from Mozambique," *Wood Mater. Sci. Eng.* 5(3), 143-150.

Li, X. (2004). *Physical, Chemical, and Mechanical Properties of Bamboo and its Utilization Potential for Fibreboard Manufacturing,* M. S. thesis, School of Renewable Natural Resources, Louisiana State University, Baton Rouge, LA.

Liese, W. (1985). *Bamboos: Biology, Silvics, Properties, Utilization*, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany.

Louppe, D., Oteng-Amoako, A. A., and Brink, M. (2008). *Plant Resources of Tropical Africa: Timbers Vo1. 1,* PROTA Foundation, Backhuys Publishers, Wageningen, Netherlands.

Malanit, P., Barbu, M. C., and Fruhwald A. (2009). "The gluability and bonding quality of an Asian bamboo *Dendrocalamus asper* for the production of composite lumber," *J. Trop. Forest Sci.* 21(4), 361-368.

NWPC (2015). *Nordic Wood Protection Council,* http://www.ntr-nwpc.com/1.0.1.0/18/1/, (accessed on January 28, 2015).

Ogunsanwo, O. Y., and Terziev, N. (2010). "Mechanical properties of glue-laminated boards of bamboo *Bambusa vulgaris* from Nigeria," in: *Proceedings of 6th*

International Symposium on Wood Structure and Properties, Arbora, Zvolen, Slovakia, pp. 183-186.
Santana, M., and Okino, E. (2007). "Chemical composition of 36 Brazilian Amazon forest wood species," *Holzforschung* 61(1), 469-477.
Schmidt, O., Wei, D. S., Liese, W., and Wollenberg, E. (2011). "Fungal degradation of bamboo samples," *Holzforschung* 65(6), 883-888.
Schmidt, O., Wei, D. S., Tang, T. K. H., and Liese, W. (2013). "Bamboo and fungi," *J. Bamboo and Rattan* 12(1-4), 1-14.
Suprapti, S. (2010). "Decay resistance of five Indonesian bamboo species against fungi," *J. Trop. Forest Sci*. 22(3), 287-294.
TAPPI T 249 cm-00 (2000). "Carbohydrates composition of extractives-free wood and wood pulp by gas-liquid chromatography," TAPPI Press, Atlanta, GA.
TAPPI T 222 om-06 (2006). "Acid-insoluble lignin in wood and pulp," TAPPI Press, Atlanta, GA.
Virtucio, F. D. (1999). "Current status, problems and prospects of the bamboo industry in the Philippines," *Canopy Int.* 25(6), 6-7.
Yu, H. Q., Jiang, Z. H., Hse, C. Y., and Shupe, T. (2008). "Selected physical and mechanical properties of Moso bamboo (*Phyllostachys pubescens*)," *J. Trop. Forest Sci*. 20(4), 258-263.
Wei, D., Schmidt, O., and Liese, W. (2013). "Durability test of bamboo against fungi according to EN standards," *Eur. J. Wood Prod.* 71, 551-556.

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