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EFFECT OF ADHESIVE QUANTITY ON SELECTED PHYSICO-MECHANICAL PROPERTIES OF BAMBOO GLULAM

Olukayode Yekin Ogunsanwo[1], Adewunmi Omobolaji Adenaiya[1,*], Christianah Aderonke Adedeji[1]

ABSTRACT

This study was aimed at determining the optimal glue quantity for bamboo lamination. Bamboo laminated boards were produced using glue applied at three different rates: 150 g/m^2, 200 g/m^2 and 250 g/m^2. The boards produced were evaluated for their physical (density, longitudinal, tangential, radial and volumetric shrinkage) and mechanical (impact bending strength, modulus of elasticity, modulus of rupture and maximum compressive strength parallel to grain properties. It was discovered that the boards were uniform in their investigated physical properties but the glue quantity significantly influenced both the impact bending strength and modulus of rupture of the boards. Based on the results, it was observed that the boards produced with glue applied at the rate of 200 g/m^2 met all the technical specifications on the basis of the investigated physical and mechanical properties, hence, concluded to be the optimal glue quantity for bamboo lamination.

Keywords: *Bambusa vulgaris*, compressive strength, density, glue application rate, optimal glue quantity.

INTRODUCTION

The increasing world population has been met with a proportional increase in demand for timber, culminating in the depletion of both the natural forests and plantations (Chaowana 2013). The problem of deforestation is a long standing one confronting the forestry sector, coupled with the increasing scarcity of the commonly used species in tropical forests. This therefore necessitates the need to conduct intensive researches into the potentials of lesser used wood species or alternative woody materials in order to address the problems of wood shortages and relieve the pressure on the economic timber species (Ogunsanwo *et al*. 2015). One of such important woody species currently gaining attention worldwide is bamboo. Bamboo is a naturally occurring composite material, as it consists of cellulose fibres imbedded within a lignin matrix (Li 2004). It is a fast-growing woody plant, which takes up to 5-6 months to attain its maximum height and ready for harvesting after 3-5 years (Abd Rasak 1992). It also has the added advantage of being able to replenish itself after harvesting (Anwar *et al*. 2009, Anwar *et al*. 2011). In bamboo, there are no rays or knots, which gives bamboo a far more evenly distributed stress along its length (Li 2004). Bamboo is a hollow tube, sometimes with thin walls, and consequently, it poses some difficulty in joining bamboo pieces than wood. This has been a major challenge confronting bamboo utilisation globally. Hence, bamboo is mostly utilized in the wood industry as a panel product. However, bamboo does not contain the same chemical extractives as wood, and therefore can be glued very well (Jassen 1995). In addition, laminated bamboo boards exhibits higher specific strength when compared to some highly preferred tropical wood species such as *Mansonia altissima*, *Khaya senegalensis*, and *Milicia excelsa* (Ogunsanwo and Terziev 2010), thus, making bamboo panel products good alternatives to wood.

Structural Glued Laminated Timber (Glulam) is a structural composite composed of several layers

[1]Department of Forest Resources Management, University of Ibadan, Ibadan, Nigeria
[*]Corresponding author: wumexrulz@gmail.com
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of lumber or lamellae which are placed such that the grains of the layers lie parallel to the longitudinal axis of the member and are bonded together with durable, moisture-resistant adhesives (Chaowana *et al*. 2015). Bamboo Glulam, on the other hand, is a composite lumber made from bamboo, where the bamboo strips constitute the lamellae being glued together. Due to the tubular shape of bamboo, it is virtually impossible to use them in applications where flat surfaces are required. Thus, Laminated bamboo lumber (LBL) overcomes these drawbacks in the natural shape of bamboo because it is processed into rectangular sections which are more suitable for use in traditional structural applications (Mahdavi *et al*. 2011).

While bamboo has gained wide recognition in the Asian countries, serving as a major raw material in the Asian wood industry, its importance still remains marginal in Africa. It is mainly used for scaffolding in Africa, with only a small volume of it being used for this purpose (Ogunsanwo *et al*. 2015). With the abundance of bamboo in countries such as Nigeria, the manufacture of glued products in the country remains insignificant (Ogunsanwo *et al*. 2015). This should not be, due to the potential contributions such products can have on the economy as well as how important they can help in alleviating the problem of deforestation. However, in the manufacture of wood composite material, adhesive is essential to bond wood members together. Not only is the adhesive a significant cost factor, it also influences some of the product properties (Chaowana 2013). Thus, consideration has to be given to the cost of production of bamboo Glulam in order for producers to maximize profit while also ensuring its affordability and competitiveness in the wood industry. It therefore becomes necessary to determine the optimal glue quantity needed for the production of bamboo Glulam in order to reduce its production cost. However, the quantity of glue used may have an influence on the bonding strength of the bamboo Glulam which, invariably, may have a long-ranging effect on the technical properties of the Glulam produced. With paucity of information on the effect of adhesive quantity on bamboo Glulam physical and mechanical properties, this study is therefore designed to fill this lacuna in knowledge.

MATERIALS AND METHODS

Sourcing of bamboo and processing of bamboo culms

Three to five years old culms of *Bambusa vulgaris* were obtained from the roadside bamboo merchants at Bodija market, Ibadan. These merchants source for the bamboo culms from Lalupon in Lagelu Local Government Area of Oyo State. The choice was made after a preliminary investigation of the stock maturity, species type and culm thickness. The culms were transported to the Department of Forest Resources Management wood workshop, University of Ibadan, where the culms were cut from the base into 1,4m length using a circular saw and air-dried for 2 weeks. Only the first three cuts from the base of the culms were used so as to ensure that the laminate members were relatively of equal thickness. The culms were further splitted into strips. The bamboo strips were edged, after which the outer and inner surfaces of the bamboo strips were planed to uniform thickness in order to smoothen them as well as to completely remove the impermeable cuticle on the outer surface.

Bonding process and laminate production

The planed strips were glued together using a synthetic glue with the trade name «Top bond» (a polyvinyl acetate glue). Three types of bamboo Glulam boards were produced, measuring 1000 mm x 420 mm x 15 mm (length x width x thickness) as shown in Figure 1, with the laminate boards produced consisting of glue applied at three different rates: 150 g/m^2, 200 g/m^2 and 250 g/m^2. Each of the laminate board so produced were clamped together and cold-pressed to ensure proper penetration of the adhesive into the laminate members as well as the formation of a strong bond line. For all the laminated bamboo boards produced, a total of forty seven (47) laminates were joined together. Boards were allowed to cure for 14 days, after which they were planed and edged to the aforementioned Glulam dimension. The boards were then subsequently converted to the required test dimensions of 20 x 20 x 300 mm and 20 x 20 x 60 mm. The specimens were conditioned in the oven at 103°C and 65 % RH until constant weight was observed before property testing.

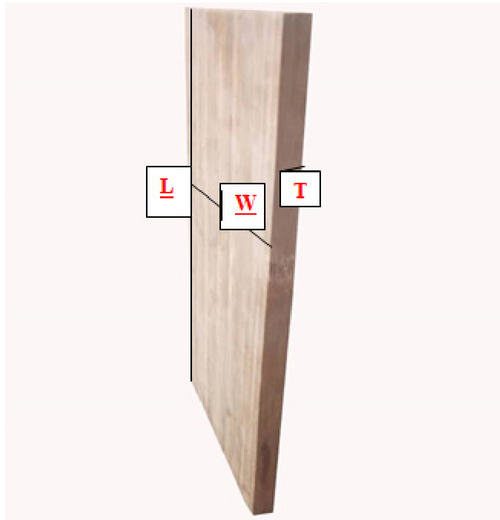

Figure 1: The three planes of the laminated bamboo.

Physical properties of bamboo glulam boards

Physical properties evaluated include density and shrinkage (longitudinal, radial, tangential and volumetric). For density determination, samples of dimensions 20 x 20 x 60 mm were prepared from each of the Glulam boards produced, dried at 103±2°C to constant weight in the oven, after which the oven-dried mass and volume were measured. Density was determined using the formula below Equation 1.

$$Density = \frac{mass}{volume} \quad (1)$$

For shrinkage, similar sample dimension used for density estimation was also used. Shrinkage was determined using standard procedures as described by Ogunsanwo and Omole (2010). The specimens were properly aligned and coded 'T', 'R' and 'L' denoting tangential, radial and longitudinal respectively. The samples were immersed in water for 24 hours in order to get them conditioned to moisture above FSP. Saturated dimensions along the three planes were measured using a digital vernier calliper. Dimensions below Fibre Saturation Point (FSP) along these planes were measured subsequently after oven-drying the samples at 103±2°C to constant weight. Percentage shrinkage along each of the planes was determined using the relationship below Equation 2:

$$S(\%) = \frac{D_s - D_o}{D_s} x100 \quad (2)$$

Where: S(%) = Shrinkage; D_s = Dimension at saturated condition; D_o = Dimension after oven-drying. Volumetric shrinkage (Vs) was estimated in accordance with the procedure adopted by Dinwoodie (1989) as given below Equation 3:

$$VS = S_R + S_T \quad (3)$$

Where V_S= volumetric shrinkage; S_R = radial shrinkage and S_T = tangential shrinkage

Mechanical properties of bamboo glulam boards

The boards were tested for their Impact bending strength, Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and Maximum Compressive Strength parallel to grain (MCS//). Sample dimensions of 20 x 20 x 300 mm were used for the determination of impact bending strength, MOE and MOR, while 20 x 20 x 60 mm sample dimensions were used in estimating MCS//. The mechanical properties of the boards were determined using the Universal Testing Machine (UTM) in accordance with the ASTM D-1037-06 (2006).

Experimental design and statistical analysis

The data was analysed using one-way ANOVA in completely randomised design. Each treatment was replicated ten times thus, giving a total of 30 specimens for each of the parameter evaluated. Follow-up test (Duncan multiple range test) was also carried out at 0,05 level of significance where significant differences were observed.

RESULTS AND DISCUSSION

Physical properties

Density

The mean values of the *B. vulgaris* Glulam samples tested for density ranged from 643,59 kg/m^3 to 682,26 kg/m^3 as shown in Table 1. Samples with glue quantity rate 150 g/m^2 had the lowest density while those with glue quantity rate 250 g/m^2 had the highest density. A consistent increase in density was observed as glue quantity increased from 150 g/m^2 to 250 g/m^2. This can be attributed to the weight gain due to increase in glue quantity, thus resulting into an increase in density in the produced Glulam. The average density recorded was 663,54 kg/m^3 and this is in conformity with various studies carried out on the density of bamboo Glulam. Anokye *et al*. (2016) reported the basic density of bamboo material to be in the range of 0,4 to 0,9 g/cm^3. Ogunsanwo *et al*. (2015) also reported an average density value of 666,8 kg/m^3 for *Bambusa vulgaris* samples taken from the moist forest zone of Nigeria. The value obtained in this study is similar to the study of Ogunsanwo *et al.* (2015), but less by 0,49 %. Despite the change in the density of the samples, statistical analysis showed no significant difference in the mean density of the samples as shown in Table 1. This implies that bamboo glu-lam density was uniform over the three glue quantity rate.

Longitudinal shrinkage

The mean values of the *B. vulgaris* Glulam samples tested for longitudinal shrinkage ranged from 0,28 % to 0,95 % with an average of 0,58 % as shown in Table 1. An inconsistent pattern of variation was observed for longitudinal shrinkage with increasing glue quantity application. This study showed an increasing trend in longitudinal shrinkage as glue quantity increased from 150 g/m^2 to 200 g/m^2 followed by a decline in the quantity rate 250 g/m^2. This variation may be due to the variations in the anatomical characteristics of the individual laminate member making up the Glulam samples. According to Yu *et al*. (2008), earlywoods of bamboo longitudinally swell or shrink more, based on the assumption that fibre bundles and latewood of woods are functionally similar, while parenchyma cells and earlywood are functionally alike. On this premise, it is suggested that the microfibrillar angle in the cell walls of earlywoods of some of the laminate members of the Glulam are higher since earlywoods show similar characteristics with juvenile woods, thus resulting into higher longitudinal shrinkage. However, the abnormally high longitudinal shrinkage observed for the Glulam with the 200 g/m^2 adhesive quantity shows that wide anatomical variations exist in the Glulam samples which is evident from the high standard error observed when compared with those of the 150 g/m^2 and 250 g/m^2 Glulam samples. The analysis of variance however shows that there was no significant difference in the means of the samples tested (p>0,05) despite the inconsistent variation observed as shown in Table 1. This observation indicated that bamboo Glulam longitudinal shrinkage was uniform over the three glue quantity rate.

Tangential shrinkage

The mean values of the *B. vulgaris* Glulam samples tested for tangential shrinkage ranged from 4,45 % to 4,71 % with an average of 4,56 % as shown in Table 1. An inconsistent pattern of variation was observed in the values for tangential shrinkage with increasing glue quantity application. An initial increase in tangential shrinkage was observed when glue quantity was increased from 150 g/m^2 to 200 g/m^2, followed by a decline in the quantity rate 250 g/m^2. This reduction in tangential shrinkage observed in the Glulam with glue quantity 250 g/m^2 may be as a result of deeper penetration of the adhesive into the bamboo cells due to the increased glue quantity, thereby reducing moisture loss by the Glulam due to a reduction in the cell proportion available for moisture loss. The implication is that more of the bamboo cells have become enveloped by the adhesive and thus, resulting in a lesser tangential shrinkage due to minimal loss of moisture from the Glulam, as shrinkage occurs in the wood cell walls (Desch and Dinwoodie 1981). The result of analysis of variance however shows that there was no significant difference in the means of the samples tested (p>0,05) despite the variation observed as shown in Table 1. This observation indicates that bamboo Glulam tangential shrinkage was uniform over the three glue quantity rate.

Radial shrinkage

The mean values of the *B. vulgaris* Glulam samples tested for radial shrinkage ranged from 3,65 % to 4,33 % with an average of 3,98 % as shown in Table 1. An inconsistent pattern of variation was equally observed in the radial shrinkage as glue quantity was increased from 150 g/m^2 to 250 g/m^2. An initial decrease in radial shrinkage was observed as glue quantity increased from 150 g/m^2 to 200 g/m^2 followed by an increase in the glue quantity rate 250 g/m^2. The slight increase noticed in radial shrinkage for the Glulam with 250 g/m^2 adhesive quantity may be due to wide anatomical variations in the individual laminate members making up the Glulam produced as evidenced by the higher standard error of its mean (Table 1). However, the overall trend of radial shrinkage can be said to decrease with increasing adhesive quantity and this can also be explained by the fact that more adhesives penetrated into the individual laminate cells as the glue quantity increased, thus reducing excessive moisture loss from the walls of the bamboo laminate cells due to the reduction in cell proportion exposed for moisture exchange with the environment. Despite the change in the radial shrinkage of the samples, the result of analysis of variance showed no significant difference in the means of the samples tested as shown in Table 1. This observation indicated that *B. vulgaris* Glulam radial shrinkage was uniform over the three glue quantity rate.

Volumetric shrinkage

The mean values of the *B. vulgaris* Glulam samples tested for volumetric shrinkage ranged from 8,36 % to 8,87 % with an average of 8,54 % as shown in Table 1. An inconsistent trend of variation was observed as glue quantity was increased from 150 g/m^2 to 250 g/m^2. An initial decrease in volumetric shrinkage was observed as glue quantity increased from 150 g/m^2 to 200 g/m^2, followed by an increase in the glue quantity rate 250 g/m^2. This inconsistency can be attributed to the combined effects of the variation patterns observed for both the tangential and radial shrinkages in the Glulam. As shown in the table, shrinkage along the tangential dimension is more than that along the radial dimension which is also much more than the longitudinal shrinkage. This observation is similar to that reported by Erakhrumen and Ogunsanwo (2009) and Gutu (2013). They noted that shrinkage is highest in the tangential direction. Liese (1985) and Malanit *et al*. (2008) also submitted that tangential shrinkage is about one-half as much in radial and much less along the longitudinal direction. From this study, it is also clear that radial shrinkage is lower than tangential shrinkage. This is in contrast with the conclusions made by Anokye *et al*. (2014) who submitted that shrinkage pattern along the radial direction was slightly more compared to the tangential directions with a ratio of 1,15: 1. There was no significant difference among the mean volumetric shrinkages of the Glulam boards as shown in the Table 1.

Table 1: Mean values of physical properties of laminated boards produced with *Bambusa vulgaris.*

Parameters	150 g/m^2	200 g/m^2	250 g/m^2
Density (kg/m^3)	643,59±3,37^a	664.66±17,79^a	682,37±14,42^a
Longitudinal Shrinkage (%)	0,52±0,17^a	0,96±0,35^a	0,28±0,05^a
Tangential Shrinkage (%)	4,54±0,24^a	4,71±0,23^a	4,46±0,45^a
Radial Shrinkage (%)	4,34±0,37^a	3,65±0,29^a	3,95±0,54^a
Volumetric Shrinkage (%)	8,87±0,50^a	8,36±0,42^a	8,41±0,48^a

Means ± Standard error values with the same superscript along the same row are not significantly different at p< 0,05.

MECHANICAL PROPERTIES

Impact bending strength

The mean values of the impact strength ranged from 0,75 MPa to 1,98 MPa with an average of 1,39 MPa as shown in the Table 2. Samples with glue quantity rate 150 g/m^2 had the lowest impact strength values while those with glue quantity rate 200 g/m^2 had the highest values. An inconsistent pattern of variation was observed in the impact bending strength of the Glulam, with an initial increase observed from quantity rate 150 g/m^2 to quantity rate 200 g/m^2, followed by a decline in the quantity rate 250 g/m^2. The initial increase in this strength property can be attributed to better bonding of the laminate members as a result of the addition of more glue. However, the decrease in the impact strength as glue quantity increased to 250 g/m^2 in this study may be due to the variations in the porosity of some of the laminate members, consequently affecting the bonding strength of the resulting Glulam. This view was echoed by Malanit *et al.* (2009) where they reported that less dense species are less difficult for adhesive to penetrate due to the large size of the fibre lumen, thin cell wall and wide pit openings between fibres. The individual laminate members constituting this sample may have more vessels and fewer fibres, thereby absorbing much of the adhesive and starving the glue joint line. This will in turn prevent the laminate members from binding well and as such, they can be easily disengaged after applying a sudden load to them (Ogunsanwo *et al.* 2015). Alternatively, it could also be that deep penetration of glue into the cells at the interface created more adhesion between the bamboo laminate and the forces needed to produce failure along the interface was so high that failure occurred within the bamboo cells rather than occurring along the glue line (Ogunsanwo *et al.* 2015). Statistical analysis revealed that glue quantity had a significant effect on the impact strength of the Glulam as shown in Table 2. Samples with glue quantity 150 g/m^2 were significantly different from those with 200 g/m^2 and those with 250 g/m^2. However, there was no significant difference between the means of samples with 200 g/m^2 and those with 250 g/m^2.

Modulus of elasticity

The mean values of the *B. vulgaris* Glulam samples tested for modulus of elasticity ranged from 19,32 GPa to 25,41 GPa with an average of 22,29 GPa as shown in Table 2. Samples with glue quantity 150 g/m^2 had the lowest MOE value while those with 250 g/m^2 had the highest MOE value. A consistent increase was observed in the MOE as glue quantity was increased from 150 g/m^2 to 250 g/m^2. This

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increase in strength property can be simply attributed to the increase in the bonding strength within the Glulam due to deeper penetration of the adhesive into the laminate members. However, despite the increase in the MOE value as glue quantity increased, statistical analysis showed that there was no significant difference in the means of the samples tested as shown in Table 2.

Modulus of rupture

The mean values of the *B. vulgaris* Glulam samples tested for modulus of rupture ranged from 90,46 MPa to 142,80 MPa as shown in Table 2. Samples with glue quantity 150 g/m^2 had the lowest MOR value while those with 250 g/m^2 had the highest MOR value. A consistent increase in the MOR value was observed as glue quantity increased from 150 g/m^2 to 250 g/m^2. This can be attributed to the increase in the bonding strength consequent of the increasing glue quantity as earlier observed. The average MOR recorded for this study was 118,31 MPa. This is different from the values recorded by Ogunsanwo *et al.* (2015) for bamboo Glulam boards produced from Nigerian-grown bamboo with a range of 151 MPa to 166 MPa. It is however similar to the value reported by Anokye *et al.* (2016) which was 86,0 MPa for *B. vulgaris* in Indonesia. This value compares well with timber species such as *Tectona grandis* with 95,9 MPa and 100,8 MPa in India and Bangladesh respectively, *Shorea robusta* with 131,8 MPa and 103,7 MPa also in India and Bangladesh respectively (Anokye *et al.* 2016). The result of analysis of variance shows significant difference in the means of the samples as shown in Table 2 The mean of samples of glue quantity rate 150 g/m^2 was significantly different from the means of the other two samples. However, there was no significant difference in the means of samples with glue quantity rate 200 g/m^2 and 250 g/m^2.

Maximum compressive strength //

The mean values of the *B. vulgaris* Glulam samples tested for maximum compression strength ranged from 47,70 MPa to 48,70 MPa with an average of 48,10 MPa (Table 2). Samples with glue quantity rate 150 g/m^2 had the lowest compression strength values while those with glue quantity rate 250 g/m^2 had the highest values. An increasing trend was observed with increasing glue quantity. This may be as a result of the increase in glue quantity which resulted into a higher bonding strength within the Glulam boards. Analysis of variance however showed that there was no significant difference in the means MCS// of the samples (Table 2). Thus, the MCS// was uniform over the three glue quantity.

Table 2: Mean values of mechanical properties of laminated boards produced with *Bambusa vulgaris.*

Parameter	150 g/m^2	200 g/m^2	250 g/m^2
Impact Bending (MPa)	0,75±0,14^a	1,98±0,17^b	1,47±0,27^b
Modulus of Elasticity (GPa)	19,32±1,81^a	22,45±2,83^a	25,41±3,35^a
Modulus of Rupture (MPa)	90,47±8,78^a	124,12±12,17^b	142,81±13,27^b
Compression Strength (MPa)	47,70±0,47^a	47,90±0,43^a	48,70±0,15^a

Means ± Standard error values with the same superscript along the same row are not significantly different at p< 0,05.

CONCLUSIONS

Bamboo is a fast growing, readily available, cheap alternative raw material to wood. Investigating the optimum quantity of adhesive required to produce bamboo laminate boards with good technical properties became imperative in order to minimize the cost of production, maximize profit and ensure its affordability by end users. At the end of this study, the following conclusions were made:

Glue quantity had no significant effect on the physical properties of bamboo Glulam. Significant differences were observed for some of the mechanical properties investigated such as for impact bending strength and the modulus of rupture. The impact bending strength and Modulus of rupture for Glulam with glue quantity 150 g/m^2 were significantly different (p<0,05) from those of glue quantities 200 g/m^2 and 250 g/m^2, but insignificant difference (p>0,05) was observed between those of glue quantities 200 g/m^2 and 250 g/m^2.

Based on these results, glue quantity 150 g/m^2 is therefore recommended when the selected physical properties are the major determinants of the bamboo Glulam end use.

However, with consideration for the mechanical properties, the 150 g/m^2 is also recommended when only MCS// and MOE are major determinants of the end uses such as for chair legs, book shelves, columns. For uses such as flooring, hammer handles, table tops, etc where impact bending strength and MOR are determinants of end use, the 200 g/m^2 glue quantity is recommended.

It can be concluded that adhesives should be applied at the rate of 200 g/m^2 for *B. vulgaris* Glulam production as this is the optimum rate at which all the produced bamboo glu-lam meets all technical specifications.

B. vulgaris compares well with some timber species such as *T. Grandis* and *S. robusta* in terms of mechanical properties as seen earlier. This reaffirms the fact that bamboo is a good alternative wood material.

Based on the findings from this study, the following recommendations are essential: Variation along and across bamboo culms is inevitable; all of which affects the gluability of bamboos in laminate production. It is therefore recommended that further research be conducted to investigate the effect of adhesive quantity, axial and radial sampling positions on the physico-mechanical properties of bamboo. Further studies should be carried out on the effect of other types of adhesive such as the natural adhesives on bamboo Glulam technical properties as the natural adhesives are more environmental friendly and will be cheaper than their synthetic counterparts.

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