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Effects of some anatomical characteristics of Ethiopian lowland bamboo (*Oxytenanthera abyssinica)* on physical and mechanical properties

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Abstract: The aim of this study was to evaluate the effects of anatomical characteristics of *Oxytenanthera abyssinica* on selected physical and mechanical properties. A total of 45 solid culms from three different age groups (2, 3 and 4-year-old) were harvested from the natural bamboo forests in Ethiopia. The result indicates age and culm height have significant effects on fiber length, fiber diameter and fiber wall thickness and insignificant effects on vascular bundles concentration. Moreover, fiber length, fiber diameter and vascular bundles sizes have a significant effect on both properties of this solid culm bamboo. The density and moisture content were highly affected by age and culms height variations. Density increased with an increase of culm age and moisture content decreased with an increase in age. The higher values of modulus of rupture (MOR) and modulus of elasticity (MOE) were obtained in the middle portions of the culm. Both values show decreasing trend towards the top portion. Compression strength of culms decreases with increase in age and culm height. The results of correlation analyses revealed that fiber length, fiber diameter and fiber wall thickness positively correlated with density and negatively correlated with moisture content. All anatomical variables show insignificant correlation with shrinkage, except fiber wall thickness that shows negative correlation with radial shrinkage. The results further revealed strong positive correlation of density with MOR and negative correlation with MOE. The fiber length also shows strong positive correlation with MOE. Fiber diameter and vascular bundles size show positive correlation with compression strength. However, moisture content shows a negative correlation.

Keywords: *Oxytenanthera abyssinica,* vascular bundles, fiber length, physical properties, mechanical properties.

INTRODUCTION

The rapid decrease in Ethiopian natural forest resources and the development of residential and commercial buildings in the country has resulted in crucial shortage of sawn wood supply for wood processing factories. Over a million hectare of bamboo in the country can be used as an alternative raw material for wood factories. The

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country has two indigenous bamboo species: the highland bamboo (*Arundinaria alpina* K. Schumann Lin; synonym: *Yushania alpina*) and the monotypic genus lowland bamboo *Oxytenanthera abyssinica* (A. Richard) Munro.

Ethiopia is the only country in Africa which has over 850,000 ha of *O. abyssinica* natural bamboo forest. *O. abyssinica* is a clumping (sympodial) type bamboo with solid culm at maturing age. It has an average culm diameter of 5 cm, and is 7 m high. This species grows at an elevation of between 1000 to 1800 m a.s.l. and is widely distributed in lowland areas of the country (Anonymous, 1997). Due to lack of utilization knowledge, this bamboo forest is burning by fire every year. This solid culm bamboo may have many advantages and can be used for various types of products because of its high strength, straightness, workability, suitable fiber characteristics and rapid growth rate. It can be used for lodge and restaurant constructions in several cities and towns due to its solid culm structure. However, basic anatomical properties of this bamboo which affect its physical and mechanical properties have not been studied. There is a lack of information on processing methods of this bamboo for structural and industrial applications. As stated by Epsiloy (1992), anatomical, chemical and physical properties are the major species variables that determine the suitability of bamboo species for industrial applications.

Many researchers proved that the anatomical structure of bamboo culm is the basis for understanding the physical and mechanical properties and ultimately reflects its usability. For example, mechanical properties of the culm, important in building materials, wettability, gluing and finishing properties are determined by its basic density and anatomical properties (Abd. Latif, 1996; Lee, *et al.,* 1994; Liese, 1998). The length of the fibers is also an important feature for the paper industry (Latif and Liese, 2001).

The aim of this study was to describe the effects of anatomical characteristics of O. abyssinica on selected physical and mechanical properties from three age-groups and three different culm heights. Investigations concerning bamboo anatomical structure have focused mainly on vascular bundles distribution, bundles size as measurements of radial tangential ratios, fiber length, fiber diameter, and fiber wall thickness. The effects of these variables on physical and mechanical properties were evaluated to determine its use for various applications.

MATERIALS AND METHODS

Sample collection

O. abyssinica culms used in this study were harvested from Asosa, one of the major bamboo growing areas in Ethiopia. Asosa is located 695 km west of Addis Ababa, at 10^{o} 04íN latitude and 34^{o} 31 ëE longitude.

Two, three- and four-year-old culms were selected for this experiment. The age of culms was estimated based on visual inspection of colour and sheaths on culms by experienced field personnel familiar with this bamboo species. Fifteen representative culms for each age group and a total of fourty five culms were harvested in September, 2007. After harvesting, each culm was cut into three equal portions, namely the bottom (B), middle (M), and top (T) portions. The 2^{nd} internodes from the bottom side of each portion were chosen for anatomical and physical properties.

The experiment was conducted in International Center for Bamboo and Rattan Laboratory in Beijing in 2007. The density of this bamboo was determined by using one of the most commonly used method, which is defined as a ratio of ovenñdry weight to the weight of water displaced by green (undried) volume (Panshin and de Zeeuw, 1980). Samples used for density testing were also used for moisture contents evaluation.

Sample preparation for anatomical characteristics

Specimens of bamboo splits of 3 cm length were prepared from 3 age groups and 3 culm portions to evaluate basic anatomical parameters. Leica light microscope with the magnification of 5X was used for vascular bundles distribution and radial/ tangential ratio measurements (vascular bundles size) . Four fields with an area of 2174641 μm^2 were observed in each section. The number of vascular bundles were counted from each field and translated to an area of one square centimeter.

Specimens about 1-2 cm length were macerated in a solution of 50 per cent acetic acid and 50 per cent hydrogen peroxide in pipette glass and heated slightly in an oven (at 100 ± 3 ^{o}C) for 3 days to release individual fibers. A total of 35 randomly selected fibers were measured from each culm using Leica light microscope. For fiber length measurement a magnification of 5X was used, whereas magnification of 20X was used for fiber width and wall thickens measurements. A total of 945 fibers were measured from all age-groups to evaluate fiber dimension.

Sample preparation for mechanical properties

From each culm section, two 30 cm long pieces without node were cut. Every 30 cm long piece was split into halves and minimum planing was done on inner and outer perimeters to make the samples rectangular. All the samples where then dried by kiln drier to 12 per cent moisture content. From each culm portion and age, 12 samples and a total of 108 samples were prepared for MOR and MOE testing. Samples which have 300 mm length 25 mm width and 6 mm thickness were used for bending test.

A total of 108 samples (50 mm long, 13 mm wide and 6 mm thick) were prepared for compression parallel to the grain tests. Bending and compression tests were conducted following the ISO 3133 (1975) and ISO 3387(1976) standard procedures. After the bending test, specimens of 10 mm wide and 50 mm long were cut from each sample for measurement of the percent shrinkages in tangential and radial directions according to ISO 4469 (1981) standard procedures. Due to negligible differences of measurements along the length of the samples, the results of longitudinal shrinkages were not reported in this paper.

Experimental design and analyses

Completely randomized design (CRD) with factorial experiment was used to conduct this experiment. The analysis of variance (ANOVA) also used to evaluate the effects of anatomical characteristics on physical and mechanical properties of *O.abyssinica*. Further analysis of the means was carried out by mean separation using Duncan mean comparisons.

RESULTS AND DISCUSSION

Anatomical characteristics

The vascular bundles of *O. abyssinica* were examined and classified according to the classification of vascular bundles by Grosser and Liese (1971). *O. abyssinica* may be categorized under type III, consisting of two parts central vascular strand and one fiber strand. The vascular bundles of *O. abyssinica* are formed by two large metaxylem vessels two protoxylem elements, phloem, sclenrenchyma sheath and fiber sheath. The summary of the analyses of variances on anatomical characteristics of *O. abyssinica* from three age-groups and three culm heights are presented in Table1.

Table 1. Summary of analyses of variance on anatomical properties of *O. abyssinica*

Source of variation	DF	Mean square and statistical significances				
		Vascular bundles distribution	Radial/ Tangential ratio	Fiber length (μm)	Fiber diameter (μm)	Fiber wall thickness (μm)
Age	2	1644.60ns	0.056ns	7.32E-6**	307.01 E-6**	82.70 E-6**
Height	2	939.88ns	0.55*	7.28 E-6**	51.93 E-6**	9.38 E-6**
Age x height	4	23.49ns	0.098ns	1.90 E-6**	75.60 E-6**	14.25 E-6**

Note: ns- not significant at $P<0.05$, *Significant at $P<0.05$, **highly Significant at $P<0.01$

Bamboo culm age, height and their interaction had insignificant effects on vascular bundles distribution. However, culm height indicates significant ($P< 0.05$) effect on vascular bundles size. On the other hand, age, culm height and their interaction depict highly significant ($P<0.01$) effects on fiber length, fiber diameter and fiber wall thicknesses. The concentration and sizes of vascular bundles of *O. abyssinica* from three age-groups and three culm portions are presented in Table 2.

Table 2. Average concentration and sizes of vascular bundles

Measured variables	Culm height			Ages		
	bottom	middle	top	2	3	4
Vascular bundles distribution(no/cm^2)	291.24a	291.24a	306.57a	298.90a	283.57a	306.57a
Radial/Tangential ratio	1.85a	2.01a	1.59b	1.87a	1.74a	1.85a

Note: means having the same letter are not significantly different at P<0.05

The vascular bundles distribution did not show significant effects among the age-groups and culmís height. But the highest mean concentration of vascular bundles among the three age-groups of the culms was observed in 4-year-old culms (about 306.6 bundles/cm^2). The slight variation of vascular bundles concentration in 4-year-old culms may show the maturation of bamboo at this age level. Regarding culms height, the highest bundle concentration was found in top portion (about 306.6 bundles/ cm^2).

The size of vascular bundles as radial/tangential ratio differs significantly with culm height. The middle and bottom portions show (2 and 1.85 respectively) larger size than in the top portion (1.59). The reason for larger size of vascular bundles may be due to the tapering structure of the culms. The size of vascular bundles differs insignificantly with age of bamboo culms. The fiber length of *O. abyssinica* differs significantly with culm height and ages. The results revealed that the fiber length increases with increase of age (Table 3).

The longer fiber length was observed in the bottom portion of 4-year-old culms (3088.20 µm) and the shorter was found in top portion of 2-year-old culms (1817 µm). Fiber length shows decreasing trends towards the top portion in all age groups of the culm. As reported by earlier researches fiber length may vary within and between bamboo culms as the individual characteristics of bamboo itself (Liese and Winer, 1996; Murphy and Alvin, 1997; Li *et al.*, 2007). Regardless of bamboo age and culm portion, the fiber length of *O. abyssinica* obtained in this experiment falls within the range of 1817 µm 3088.10 µm.

The fiber diameter of *O. abyssinica* significantly differs with culm height and age (Table 3). The larger fiber diameter was observed in the middle portion of 3-year-old culms (18.67µm) and the thinner was found in middle portion of 2-year-old culms (13.10 µm). Fiber diameter shows slight increasing trend along the height in 4-year-old culms. However, fiber diameter was increasing from bottom towards middle and decreasing towards the top portion in 3-year-old culms. Fiber diameter in 2-year-old culms did not show significant variations. Regardless of bamboo age and culm portion the fiber diameter of *O. abyssinica* obtained in this experiment falls within the range of 13.10 µm to 18.67 µm.

Table 3. Average of fiber length, fiber diameter and fiber wall thickness of *O. abyssinica* culms

Measured variables	Age (yrs)	Culm portion		
		bottom	middle	top
Fiber length (µm)	2	2095.38	2050.39	1817.00
		[459.86]	[452.53]	[426.04]
	3	2500.59	2404.63	2139.72
		[829.59]	[336.44]	[444.37]
	4	3088.20	2254.95	2162.68
		[771.01]	[397.32]	[289.93]
Fiber diameter (µm)	2	13.33	13.10	13.22
		[1.89]	[3.19]	[2.86]
	3	16.49	18.67	14.11
		[3.14]	[2.70]	[1.94]
	4	15.00	16.08	16.17
		[3.12]	[2.83]	[2.39]
Fiber wall thickness ((µm)	2	4.25	4.02	4.18
		[0.90]	[1.12]	[0.69]
	3	4.85	5.47	4.26
		[0.88]	[0.91]	[0.65]
	4	5.73	6.36	6.44
		[1.14]	[1.33]	[0.96]

Note: Numbers in parentheses are standard deviations

The fiber wall thickness of this bamboo also significantly differs with culm height and age (Table 3). According to the results, the fiber wall underwent low thickening from 2- to 4-years growth rate. The thicker fiber wall was observed in the top portion of 4-year-old culms (6.44 µm) and the thinner was found in middle portion of 2-year-old culms (4.02 µm). Murphy and Alvin (1997), Liese and Winer (1996) reported that the fiber diameter and fiber wall thickness increase with increase in age. Regardless of bamboo age and culm portion, the fiber wall thickness of *O.abyssinica* obtained in this experiment falls within the range of 4.02 µm to 6.44 µm.

Physical properties

The statistical analyses of variances show the effects of age and culm height on physical properties of *O. abyssinica.* As depicted in Table 4, age, culm height and their

Table 4. Summary of analyses of variance on physical properties of *O. abyssinica*

Source of variation	DF	Mean square and statistical significances			
		Density	Moisture content	Tangential shrinkage	Radial shrinkage
Age2		0.082**	7908.99**	11.06ns	5.48ns
Height2		0.002**	119.82**	2.47ns	8.56*
Age x height 4		0.001**	207.04**	9.51ns	2.67ns

Note: ns- not significant at $P<0.05$, *Significant at $P<0.05$, **highly Significant at $P<0.01$

interaction had high significant effects on bamboo density and moisture content. Bamboo age and height had high significant effect ($P<0.01$) on density and moisture content. However, both show insignificant effect on shrinkage except culm height, that show significant ($P<0.05$) effect on radial shrinkage. The single best indicator of bamboo physical and mechanical characteristics is density, measured either green, oven-dry or air-dry (Panshin and de Zeeuw, 1980). The density of *O. abyssinica* (based on the oven-dry weight) increased with an increase in culm age (Table 5).

Table 5. Average density and moisture content

Measured variables	Age(yrs)	Culm portion		
		bottom	middle	top
Density (kg/m^3)	2	538.58	555.91	553.90
		[0.01]	[0.02]	[0.01]
	3	536.50	552.50	516.67
		[0.09]	[0.01]	[0.01]
	4	619.10	627.65	626.41
		[0.08]	[0.02]	[0.08]
Moisture content (%)	2	92.10	87.23	87.13
		[7.28]	[8.39]	[5.54]
	3	90.85	86.67	91.38
		[3.08]	[2.93]	[5.14]
	4	65.52	62.45	63.63
		[2.89]	[5.21]	[7.87]

Note Numbers in parentheses are standard deviations

Significantly, higher density (627.65 kg/m^3) was found in the middle portion of 4-year-old culms while the lowest density (516.67 kg/m^3) was found in the top portion of 3-year-old culms. The results indicate that the density of this solid bamboo was increasing from bottom to middle and further decreasing at the portion. The length of internodes in the middle portion of the culms and amount of cell wall substance per unit volume found in this portion might be responsible for increase in density in the middle portion. Findings reported by earlier researchers (Lee *et al*., 1994; Grosser and Liese, 1971; Seyoum *et al*., 2007) indicated that high density was found in the top portion. However, results in this experiment showed high density in the middle portion. This might be due to the solid structure of this bamboo species.

A comparison of mean density among culms of three age-groups and three culm heights has an important implication for determination of *O.abyssinica* for various applications. The mean density responds to fundamental change in culm height and age variations. Therefore, it is very important to distinguish that for this bamboo, age is a better predictor of variation in mean density than culm height.

Moisture content (MC) is the water contained in the cell wall and cell lumen of a culm section expressed as a percentage of its oven-dry weight. The initial moisture content was significantly different among three culm portions and three age groups

(Table 5). The moisture content showed a decreasing trend from basal portion towards the middle and an increasing trend towards the top portion.

Significantly, higher initial moisture content (92%) was observed at basal portion of 2- year-old culms, while the middle portion of 4-year-old culms had lower moisture content (62%). The initial moisture content shows a decreasing trend with increase in age. This might have happened due to differences of cell structure, distribution and concentration along the culm height. High moisture content variation among culms of different age groups might have happened due to differences and changes in anatomical feature of bamboo during its maturation period (Liese, 1985; Espiloy, 1992).

The magnitude of tangential shrinkage found differs insignificantly with culm height and age. However, radial shrinkage significantly differs with culm height but insignificantly with age (Table 6). As Liese (1985) reported bamboo begins to shrink from the very beginning of seasoning, unlike timber. Shrinkage affects both the wall thickness of the culm and the diameter, and it shows a tendency to decrease from the bottom to the top. However, results indicate the dimensional stability of the culm along the height. This might be due to the solid structure of *O. abyssinica.*

Table 6. Average radial and tangential shrinkages of *O. abyssinica*

Measured variables	Culm height			Ages		
	bottom	middle	top	2	3	4
Tangential shrinkage (%)	9.1a	8.65a	9.11a	9.41a	8.34a	9.11a
Radial shrinkage (%)	7.97a	7.01b	7.33a	7.88a	7.17a	7.26a

Note: means having the same letter are not significantly different at $P<0.05$

Mechanical properties

The summary of the analyses of variances (Table7) on bending stiffness and compression strength of *O. abyssinica* indicate that culm height, age and their interaction had significant ($P<0.01$) effects on MOR. Age shows insignificant effects on MOE. However, culm height and the interaction of age and height had significant *($P<0.05$)* effects on MOE. The analyses also indicate that bamboo age had insignificant effects on compression strength. Whereas, culm height depicts high significant

Table 7. Summary of the analyses of variance on mechanical properties of *O. abyssinica*

Source of variation	DF	Mean square and statistical significances		
		MOR	MOE	Compression
Age	2	5256.87**	3.15E-5ns	18.10ns
Height	2	5204.38**	9.72E-7	5207.14**
Age x height	4	1808.74**	1.07E-7*	384.54*

Note: ns- not significant at $P<0.05$, *Significant at $P<0.05$, **highly Significant at $P<0.01$

(P<0.01) effects on compression strength and the interaction of age and culm height also shows significant *(P<0.05)* effects on compression strength. The results of strength properties testing indicate that mean comparisons of bending, stiffness and compression strength vary among the age and height (Table 8). For bending strength, the highest value of MOR (191 N/mm^2) was found in the middle portion of 3-year-old culms. In general, higher MOR of rupture values of this bamboo were obtained in middle and bottom portions of the culm height. The MOR values indicate a decreasing trend towards the top portion.

Table 8. Average of bending, stiffness and compression strength

Measured variables	Age (yrs)	Culm portion bottom	middle	top
Modulus of rupture (N/mm^2)	2	183.33	186.66	140.77
		[20.23]	[19.67]	[12.39]
	3	190.55	190.94	187.83
		[11.40]	[29.87]	[12.60]
	4	172.86	172.66	157.60
		[22.0]	[23.71]	[15.93]
Modulus of elasticity (N/mm^2)	2	14999.56	14464.42	10154.91
		[2152.97]	[1899.08]	[1423.51]
	3	14039.92	13680.11	11437.06
		[1911.34]	[2157.38]	[1383.87]
	4	14534.95	13550.73	11664.94
		[2326.13]	[2025.41]	[1991.82]
Compression parallel to the grain (N/mm^2)	2	86.44	76.15	62.05
		[5.59]	[9.05]	[5.38]
	3	85.68	79.75	61.22
		[9.60]	[11.05]	[9.45]
	4	73.10	84.06	56.99
		[16.74]	[13.06]	[9.85]

Note: Numbers in parentheses are standard deviation

Regardless of bamboo age and culm portion the MOR falls within the range of 141 N/mm^2 to 191 N/mm^2. For MOE the highest value (15000 N/mm^2) was found in bottom portion of 2-year-old culms. The MOE also shows a decreasing trend towards the top portion. The top section has the lowest values for mechanical properties in most cases. It is well established that the mechanical properties of bamboo culm improve with anatomical characteristics (Liese, 1985; Liese and Weiner, 1996). The highest values for bending and stiffness strength in the bottom portion of this bamboo species may be due to large sizes of bamboo fibers in this portion.

Compression strength parallel to the grain is the capacity of bamboo fibers to resist longitudinal compression as in the case of bamboo used as column. Results indicated that the compression strength of *O. abyssinica* culms decreases with increase in of age and culms height (Table 7).

Table 9. Correlation coefficient of anatomical characteristics, of *O.abyssinica* with age and height

Variables	Age	Height
Vascular bundles distribution	0.43ns	0.43ns
Radial/tangential ratio	-0.04ns	-0.51ns
Fiber length	0.41**	-0.42**
Fiber diameter	0.30**	-0.10ns
Fiber wall thickness	0.67**	-0.10ns

Note: ns- not significant at $P<0.05$, *Significant at $P<0.05$, **highly Significant at $P<0.01$

Maximum compression strength (86 N/mm^2) was found in the bottom portion of 2-year-old culm, and minimum (57 N/mm^2) in top portion of 4-year-old culm. As mentioned earlier, fiber length, fiber wall thickness and fiber diameter are high in bottom portions of the culm.This condition may create strong influence for improvements of compression strength.

Earlier studies reported that bamboo fibers can retain their living protoplasts over several growing seasons as cell walls continue to thicken, acquiring multiple layers and lignification (Liese, 1998, Murphy and Alvin, 1997). Gritsch *et al.* (2004) reported bamboo fiber cell wall thickness increased during the first year of growth and from year one to year three. However, the results showed that at 2-year maturation, the solid bamboo appeared to achieve its maximum capacity that can improve bending stiffness and compression strength.

The effects of anatomical characteristics on physical and mechanical properties

Statistical analyses show that vascular bundles distribution and radial/tangential ratio had insignificant correlation with age and height of the culm. Fiber length, fiber diameter and fiber wall thickness showed significant positive (r = 0.41, r = 0.30 and r = 0.67 at $P<0.01$) correlation with age. Whereas, fiber length shows negative correlation (r = -0.42 at $P< 0.01$) with bamboo height.

As depicted in Table 10 bamboo age was positively correlated (r = 0.71 at $P<0.01$)

Table 10. Correlation coefficient of anatomical characteristics, bamboo height and age, with density moisture content and shrinkage

Variables	Density	Moisture content	Tangential shrinkage	Radial shrinkage
Age	0.71**	-0.71**	-0.08ns	-0.13ns
Height	0.00ns	0.00ns	-0.77ns	-0.14ns
Vascular bundles distribution	0.49ns	0.46ns	-0.16ns	-0.14ns
Radial/tangential ratio	0.30ns	0.39ns	-0.05ns	-0.23ns
Fiber length	0.24**	-0.27**	-0.07ns	0.07ns
Fiber diameter	0.18*	-0.19**	0.09ns	0.04ns
Fiber wall thickness	0.58**	-0.57**	-0.17ns	-0.71*

Note: ns- not significant at $P<0.05$, *Significant at $P<0.05$, **highly Significant at $P<0.01$

with density. The analysis shows that vascular bundles distribution and radial/tangential ratio had insignificant correlation with density, moisture content and shrinkage (Table 10). On the other hand, fiber length shows positive correlation ($r = 0.24$ at $P<0.01$) with density. The higher amount of cell wall substance formed in older age, fiber wall thickening and expansion might be responsible for the increase in bamboo density, as it gets older. Alvin and Murphy (1988), Abd. Latif *et al.* (1996) reported the cell wall of both fiber and ground tissue parenchyma could go on thickening up to the third year.

The fiber diameter of *O. abyssinica* shows a positive correlation ($r = 0.18$ at $P<0.05$) with density. This implies that with an increase of fiber diameter, the density of bamboo also increases. Whereas, the fiber diameter shows negative correlation ($r = -0.19$ at $P< 0.01$) with moisture content. This result proves that when the fiber diameter is big there is no place to hold water in bamboo cells. The fiber wall thickness of *O.abyssinica* indicates positive correlation ($r = 0.58$ at $P< 0.01$) with density. This indicates that thick fiber wall have higher density.

The results further revealed that fiber length and fiber diameter are negatively correlated ($r =-0.27$ and $r = -0.19$ at $P< 0.01$, respectively) with moisture content. This implies that the narrowing nature of the culm wall towards the top portion results in a reduction of its inner portion with less parenchyma cells, and high number of vascular bundles having small sizes. Further more, the fiber wall thicknesses also shows negative correlation ($r = -0.57$ at $P< 0.01$) with moisture content. This also indicates further increments of fiber wall that could be cause for reduction of lumen diameter. Therefore, there is only limited space in bamboo lumens to hold water. All anatomical properties did not show significant correlation with shrinkage except fiber wall thickness. The fiber wall shows negative correlation ($r = -0.71$ at $P<0.05$) with radial shrinkage. This implies that thick walled bamboo shrinks more than thin walled bamboos.

The result depicted in Table 11 indicates that bamboo age, vascular bundles distribution

Table 11. Correlation coefficient of anatomical characteristics, bamboo height and age, with strength properties, density and moisture content

Variables	MOR	MOE	Comp
Age	-0.10ns	0.59ns	-0.07ns
Height	-0.30**	-0.60**	-0.57**
Vascular bundles distribution	-0.40ns	-0.38ns	-0.56ns
Radial/tangential ratio	0.24ns	0.55ns	0.66*
Fiber length	0.10ns	0.31**	0.11ns
Fiber diameter	0.12ns	0.14ns	0.18*
Fiber wall thickness	-0.11ns	-0.02ns	-0.07ns
Density	0.71**	-0.71**	0.00ns
Moisture content	0.00ns	0.00ns	-0.26**

Note: ns- not significant at $P<0.05$,*Significant at $P<0.05$,** highly Significant at $P<0.01$

and size, fiber wall thickness and moisture content had insignificant correlation with MOR. Culm height shows negative correlation (r = -0.30 at *P*< 0.01) with MOR. This shows that the bending strength of the culms was decreasing from bottom towards the top portion. The result further revealed strong positive correlation (r = 0.71 at p <0.01) of density with MOR. This indicates the relationship of density and strength of bamboo. The higher amount of cell wall substances increases density and also improves the strength properties of bamboo.

Culm height shows negative correlation (r = -0.60 at *P*<0.01) with MOE which shows the stiffness of the culms decreases from bottom towards the top portion. The fiber length shows strong positive correlation (r = 0.31 at *P*<0.01) with MOE. This indicates that when the fiber length is long, the culms can resist external forces or load tending to change its size and shape. On the other hand, density shows negative correlation (r = -0.71 at *P*< 0.01) with MOE. This indicates that when the density of bamboo is low, its stiffness capacity decreases.

The culm height shows negative correlation (r = -0.57 at *P*< 0.01) with compression strength (Table 11). This indicates the compression strength of *O.abyssinica* is increasing from top towards the bottom portion. Fiber diameter shows positive correlation (r = 0.18 at *P*<0.05) with compression strength. Compression strength in the bottom portion shows higher values, where fiber dimensions are large.

The vascular bundles sizes show positive correlation (r = 0.66 at *P*<0.01) with compression strength. This indicates that when the sizes of vascular bundles are large, the compression strength increases. On the other hand, the moisture content shows negative correlation (r = -0.26 at *P*< 0.01) with compression strength. The result revealed that when there is less amount of water in bamboo cells, there is high compression strength.

To evaluate the suitability of *O. abyssinica* for structural and industrial applications the density and mechanical properties of 3-year-old culms were compared with some commercially important tree species in Ethiopia (Anonymous 1995) (Table 12).

O. abyssinica has high bending, stffness and compression strength than commercially important tree species in Ethiopia. The MOR of *O.abyssinica* was high by 51 per cent and 35 per cent respectively than *Anigeria adolfi-ferederici* and *Eucalyptus globulus* which are widely used for construction purposes. MOE of bamboo is also higher by 23 per cent and 11 per cent per cent than the above mentioned tree species. On the other hand, the compression strength of *O.abyssinica* shows 40 per cent and 32 per cent high values respectively than *A. adolfi-ferederici* and *E. globulus*. Since this bamboo has solid culms and has fast growing characteristics than any woody species, it can be used as an alternative raw material for substituting hardwoods in construction and other sectors.

Table 12. Comparisons of mechanical properties of 3-year-old *O.abyssinica* with some commercially important tree species in Ethiopia

No	Species	Density (kg/m^3)	MOR (N/mm^2)	MOE (N/mm^2)	Compression parallel to the grain (N/mm^2)	Tangential shrinkages (%)	Radial shrinkages (%)
1	*Cordia African**	410	64	6996	29	-	-
2	*Juneperus procera**	513	87	9081	38	-	-
3	*Podocarpus falcatus**	520	77	6704	40	4.6	2.0
4	*Cupressus lustanica**	430	64	6145	33	1.36	0.52
5	*Anigeria adolfi-feredericí**	560	93	10029	46	6	3.4
6	*Eucalyptus globulus**	780	124	11655	52	6.84	6.35
7	*Oxytenantheraabyssinica*	535	190	13052	76	8.34	7.14

Source Anon, 1995b

CONCLUSION

The physical and mechanical properties of *O. abyssinica* are affected by anatomical variables such as vascular bundles size, fiber length, fiber diameter and fiber wall thickness. In addition to this bamboo age and culm height showed highly significant effects on anatomical variables and on physical and mechanical properties of bamboo.

Density, moisture content, fiber length, fiber diameter and vascular bundles size are the most important variables to determine the properties of *O. abyssinica.*When compared with commercially important timber species in Ethiopia, the average density and strength values of this solid culm bamboo possess higher values. Thus, *O. abyssinica* can be used as an alternative raw material for the manufacture of various bamboo products such as pulp, fiber boards, particleboards, flanges for laminated composite beams, furniture and structural applications.

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