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# Assessment of the effects of density on the mechanical properties variations of Borassus aethiopum

Asafu-Adjaye Osei Asibe, Frimpong Mensah Kwasi and Darkwa Nicholas Albert

Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology, FRNR-KNUST, Kumasi-Ghana

## ABSTRACT

The effect of density variation on the mechanical properties of Borassus aethiopum was assessed. Five trees were selected from the transitional zone in Ghana. "Wood" samples were collected from the three distinct zone of the tree: the dermal zone, sub-dermal zone, and the central at 15%, 30%, 45%, 60%, 75% and 90% of the tree merchantable height. One-half of the boards were used in the green state and the other half air dried for the dry tests. Mechanical strength test specimens and Density were prepared and tested in accordance with the British Standard BS 373:1957. The mean basic density and [density at 12%MC] for each of the zones in Kg/m<sup>3</sup>were 636.0 [793.3], 476.4 [579.1], and 251.2 [293.9] respectively. The mean strength values in N/mm<sup>2</sup> in the 'green' [and dry] conditions for the dermal zone, sub-dermal zone, and central zone were carried on Modulus of Rupture, Modulus of Elasticity, Compression parallel to the grain, Shear parallel to the grain: 8.53 [11.64], 5.36 [7.74], and 1.15[1.80]; Hardness in kNW here as the "wood" density and mechanical properties increased from the central zone to the dermal zone, they however decreased from base to top at any particular height. There was a good correlation between the Density and the various mechanical strength values at (p < 0.001).Hence "wood" density can be used in predicting the mechanical properties of Borassus aethiopum wood.

Keywords: Borassus aethiopum, Density, Mechanical properties

## INTRODUCTION

The increasing trend in timber utilization has contributed over the years to the neglect of other non-timber forest products, which play important role in the domestic economy in forest management [1]. In Ghana, the average consumer of wood believes that hardwoods give the best results when utilized for timber construction and hence have laid more exploitation emphasis on these woods at the expense of several potentially useful monocotyledonous species that the country is endowed with. Although, tree-like monocotyledonous species do not produce wood in the usual sense of the word, their stems are physically hard, can grow to about 20-60cm in diameter and hence are potential source of raw materials for use in the manufacture of several wood products [5]

*Borassus aethiopum*, a non-timber forest product and a Palm, belongs to the family Arecaceae or Palmae[13]. *Borassus aethiopum* is an unbranched Palm growing to 20-30m tall and characterized by a crown up to 8m wide [12]. *Borassus aethiopum* with over 25 years old have a swelling of trunk at about 12-15m above ground. It is mostly found in Tropical and Southern Africa, Savannah and Open forests; specifically in Semi-arid and Sub-humid Zones. *Borassus aethiopum* is known for its high sap content which is normally extracted for drink [3]. However, the

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"wood" is not efficiently utilized and most often left to the mercy of wood deteriorating organisms. Assessing the strength properties of the "wood" would form theoremise for all sustainable management activities for stakeholders. Small clear straight-grained specimens are used for determining fundamental mechanical properties [11]. The methodutilizes small, clear, straight-grained test specimens which represent the maximum qualitythat can be obtained [4]; [2]. The method remains valid for characterizing newtimbers [6].Density serves as a measure for the mechanical properties [15]. In the absence of any other data about the properties of a particular species, wood density is used as a guide to its utilization [17]. Some strength properties show a very marked correlation with density; naming compression strength parallel to the grain, bending strength and hardness [6].

Understanding the effect of density variation on the variations in the mechanical properties of *Borassus aethiopum* is fundamental to its efficient utilization. This study presents the effect of density on the mechanical properties variations of *Borassus aethiopum*.

#### MATERIALS AND METHODS

Five *Borassus aethiopum* trees were extracted from the transitional zone in the Ashanti Region - Ghana in a 28 year old stands. Each fell tree was cut into 6 logs at 15%, 31%, 47%, 63%, 79% and 95% of the tree merchantable height. A cross section through the stem of the bolts showed three distinct layers: the dermal zone which is the most periphery portion just below the cortex. The sub-dermal zone is the transitory zone between the dermal and the central zones, and the central zone.

#### **Conversion, Sampling and Air Drying**

Each portion of the three zones was converted into boards with bandsaw. Strips of dimensions  $25 \times 25 \times 1500$  mm and  $55 \times 55 \times 1500$  mm were prepared from the boards representing each section of the trees sampled. The green test specimensfor the density and the mechanical properties were cut into sizes and orientations required by the [4]. Strips for the dry test were however stacked for air-drying under shed. After these strips were fully dried, test specimens for the dry test samples for the mechanical testing were prepared to the standard sizes and orientations required by the British Standard BS 373:1957. Strips were prepared from the dermal, sub-dermal, central zones and the bulge areaand conditioned (at controlled temperature of  $20 \pm 3^{\circ}$ C and relative humidity of  $65 \pm 2$  %) to about 12% moisture content. The final mean moisture contents were used in adjusting the dry mechanical values of the specimens to the standard mechanical strength at 12% moisture content. Static bending test (MOE and MOR), Compression and Shear parallel to the grain tests, and Hardness test were conducted using the Universal testing Machine, Instron4482. Thirty (30) replicateseach of the dermal zone, sub-dermal zone, and central zone were used for each mechanical test.

#### Analysis

Analysis of variance was carried out to determine the level of significance among the varioustreatment means at 0.05% probability level. Means separation was done using Duncan'sMultiple ComparisonTest.Correlation and regression analysis were conducted to determine therelationship between density and mechanical properties of *Borassus aethiopum*wood.

#### **RESULTS AND DISCUSSION**

In general, all the stems studied exhibited common characteristics: the dermal, sub-dermal and the central zones in their cross section. This zonal variation in *Borassus aethiopum* was also found in a study on wood characteristics and properties of *Cocosnucifera*[16]. The analysis of variance (ANOVA) of the properties studiedrevealed that the variation between the various zones in each of the trees was highly significant at P<0.05

#### Density

The overall average basic density and [density at 12% MC] for each of the dermal zone, sub-dermal zone, and central zone of the trees were 636.0Kg/m<sup>3</sup>[793.3Kg/m<sup>3</sup>], 476.4Kg/m<sup>3</sup>[579.1Kg/m<sup>3</sup>], and 251.2Kg/m<sup>3</sup> [293.9Kg/m<sup>3</sup>]respectively (Table 1). The mean basic density and density at 12% MC decreased significantly at P<0.05 from the bottom (15%) of the trees to the top of the trees (95%). [7] reported similar pattern of decrease in density with increasing height in the stem of *Pinusradiata*. The mean basic density and density at 12% MC alsoincreased radially from the central zone to the sub-dermal zone and to the dermal zone as depicted in Table 1.

[8] found similar trend in *Cocosnucifera*, and pointed out that a typical stem at one meter height would have about ten bundles/ $cm^2$  in the central portion and about 50 bundles/ $cm^2$  near the outside or periphery.

			Height of Mechantable bole of Borassus aethiopum					
Physical	Radial	15%	30%	45%	60%	75%	90%	Pooled
Properties	Position	$Mean \pm S.D$	$Mean \pm S.D$	$Mean \pm S.D$	$Mean \pm S.D$	Mean ±S.D	$Mean \pm S.D$	Mean± S.D
	Dermal	$717.2 \pm 12.9^{a}$	683.9 ±24.9 <sup>b</sup>	635.6±28.3°	618.4±27.2 <sup>d</sup>	599.2±29.1 <sup>e</sup>	561.4±386 <sup>f</sup>	$636 \pm 59.8$
Bascdensity	Sub-Dermal	595.4±21.0 <sup>fg</sup>	$536. \pm 39.2^{h}$	486.1±44.9 <sup>i</sup>	$460 \pm 40.3^{j}$	$409.3 \pm 44.1^{k}$	$370.9 \pm 55.8^{1}$	$476.4 \pm 90.3$
$(kg/m^3)$	Central	$341.8\pm29.9^{m}$	291.5±29.9 <sup>n</sup>	$260.5 \pm 25.1^{\circ}$	$238.7 \pm 24.4^{p}$	$196.8 \pm 18.5^{q}$	177.3 ±24.3 <sup>r</sup>	$251.2 \pm 66.1$
	Dermal	$906.8 \pm 18.4^{a}$	859.6±35.1 <sup>b</sup>	792.1±39.1°	$768.5 \pm 37.5^{d}$	$742\pm39.7^{e}$	$690. \pm 52.4^{\rm f}$	$793.3 \pm 82.8$
Density at 12%	Sub-Dermal	736.9±28.6 <sup>eg</sup>	$657.2 \pm 52.3^{h}$	$590.6 \pm 58.7^{i}$	556.6 ±52.8 <sup>j</sup>	$490.9 \pm 56.4^{k}$	$442.4 \pm 70.9^{1}$	579.1 ±118.2
MC (kg/m <sup>3</sup> )	Central	$405.8 \pm 36.6^{m}$	342.1±38.2 <sup>n</sup>	$305.0 \pm 30.1^{\circ}$	278.1 ±29.7 <sup>p</sup>	$228.6 \pm 21.5^{q}$	$204.7 \pm 28.6^{r}$	$293.9 \pm 80.7$

Table 1: Mean	Values of basic density	and density at12%MC	in Relation toHeight and	Positions f Borassus aethiopum
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Each value is the mean and standard deviation of 5 replicates sampled trees of Borassus aethiopum. Means with different superscript are significantly different (p < 0.05)

## Modulus of Elasticity (MOE)

The overall average green MOE and MOE at 12% MC for each of the dermal zone, sub-dermal zone, and central zonewere 14725.0N/mm<sup>2</sup>[17127.3N/mm<sup>2</sup>],5272.1N/mm<sup>2</sup>[9704.12N/mm<sup>2</sup>],and 1150.9N/mm<sup>2</sup> [1698.6N/mm<sup>2</sup>] respectively(Tables 2 and 3). The MOE decreased significantly along the bole height from the bottom (15%) of the trees to the top of the trees (95%) at P< 0.05. [20]Classified strength of species based on the MOE at 12% moisture content as follows: 'Very High' [19,000 N/mm<sup>2</sup> and more], 'High' [14,000-19,000N/mm<sup>2</sup>], 'Medium' [11000-14,000 N/mm<sup>2</sup>], 'Low/ Medium' [9,000-11,000 N/mm<sup>2</sup>], and 'Low' [below 9,000 N/mm<sup>2</sup>]. The above classificationindicates that the various portions within the tree vary in terms of stiffness and the classification is 'High' in the dermal zone, 'low/Medium' in the sub-dermal zone, and 'Low' in the central zone The overall order of decreasing MOE of the various sections of the trees was as follows: Dermal zone > Sub-dermal zone.

#### Modulus of Rupture (MOR)

Similarly, the mean static bending strength, the Modulus of Rupture (MOR), varied significantly at P<0.05 (Table 2 and 3) in the radial position and longitudinally from the base (15%) of the trees to the top (95%) of the trees for each zone. The mean MOR for each of the dermal zone, sub-dermal zone, and central zone in the green and at 12% MC was respectively 89.8N/mm<sup>2</sup> [120.5N/mm<sup>2</sup>], 45.2N/mm<sup>2</sup> [63.8N/mm<sup>2</sup>], and 7.5N/mm<sup>2</sup> [11.9N/mm<sup>2</sup>]. The MOR of small clear specimen at 12% MC according to [9] is rated very low when is under 50N/mm<sup>2</sup>, low if it ranges from 50–85N/mm<sup>2</sup>, medium if it ranges between 85-120N/mm<sup>2</sup>, high and very high if it ranges from 120-175N/mm<sup>2</sup> and over 175N/mm<sup>2</sup> respectively. The preceding classification points out that the dermal zone is rated high, that of the sub-dermal zone is rated low, and very low in the case of the central zone. The overall order of decreasing MOR of the various sections of the five trees was as follows: Dermal zone > Sub-dermal zone > Central zone.

#### **Compression Parallel to the Grain (Comp llg)**

The mean maximum crushing strength for the dermal, sub-dermal and the central zones for the green and [at 12% MC] in all the trees were 48.4 N/mm<sup>2</sup>[62.9N/mm<sup>2</sup>], 24.7 N/mm<sup>2</sup>[34.7 N/mm<sup>2</sup>], and 4.9 N/mm<sup>2</sup>[7.7 N/mm<sup>2</sup>] respectively (Tables 2and 3). For each of the zones, the maximum crushing strength decreased significantly at P<0.05 at the radial position from the dermal zone to the central zone and longitudinally from the base (15%) of the trees to the top (95%) of the trees sampled. Compressive strength parallel to the grain have been classified according to [9], as very low, low, medium, high, and very high when the strength values are under 20N/mm<sup>2</sup>, ranging from 20-35N/mm<sup>2</sup>, 35-55N/mm<sup>2</sup> and over 85N/mm<sup>2</sup> respectively. This classification consequently rates the dermal zone as high, low in the sub-dermal zone and very low in the central zone. Overall order of decreasing Compression Strength Parallel to the Grain of the sections in the five trees was as follows: Dermal zone > Sub-dermal zone.

#### **5.2.4 Shear Parallel to the Grain**

The overall average Shear strength parallel to the Grain of the trees sampled in the green and at 12% MC for the dermal, sub-dermal and the central zones were respectively 8.53 N/mm<sup>2</sup>[11.64 N/mm<sup>2</sup>], 5.36 N/mm<sup>2</sup>[7.74N/mm<sup>2</sup>], and 1.15 N/mm<sup>2</sup>[1.80 N/mm<sup>2</sup>] (Tables 2 and 3). The mean green Shear strength Parallel to the Grain varied significantly at P<0.05 at the radial position and longitudinally from the base of the tree (15%) to the top (95%) of the trees for each zone. The overall order of decreasing Shear strength Parallel to the Grain for the various sections in the five trees was as follows: Dermal zone > Sub-dermal zone > Central zone.

#### 5.2.5 Hardness

The overall average for the dermal zone, sub-dermal zone, central zone and the bulge area were 7.23kN[10.49kN], 4.46kN[6.79kN]and0.57kN[1.27kN], respectively (Tables 2 and 3). The average Hardness for each zone at a given height varied significantly along the bole and the hardness strength decreased significantly at P<0.05at the radial position and longitudinally from the base (15%) of the trees through to the top (95%) of the trees. The overall order of decreasing Hardness for the various sections was as follows: Dermal zone > Sub-dermal zone > Central zone. Evidently, these results demonstrate a stark difference in the ability of the various parts of the same tree to resist indentation.

			Height of Mei	rchantable bole	of Borassus ae	ethiopum		
Mechanical	Radial	15%	30%	45%	60%	75%	90%	Pooled
Properties	Position	Mean $\pm$ S.D	Mean $\pm$ S.D	Mean $\pm$ S.D	$Mean \pm S.D$	Mean $\pm$ S.D	$Mean \pm S.D$	Mean± S.D
	Dermal	$127.2\pm13.3^{\rm a}$	106.0 ±13.9 <sup>b</sup>	$96.6 \pm 12.9^{\circ}$	$84.4 \pm 15.7^{d}$	$69.2 \pm 17.8^{e}$	$55.7 \pm 16.6^{\rm f}$	$89.8\pm28.0$
MOR	Sub-Dermal	$76.3 \pm 17.5^{g}$	$61.8\pm15.4^{\rm h}$	$50.0 \pm 13^{i}$	$36.2 \pm 6.5^{j}$	$27.6 \pm 7.1^{k}$	$19.5 \pm 6.8^{1}$	$45.2 \pm 22.9$
N/mm <sup>2</sup>	Central	$16.4 \pm 2.4^{m}$	$8.9 \pm 1.5^{n}$	$6.5 \pm 1.6^{\circ}$	$5.5\pm1.9^{\rm op}$	$4.4 \pm 1.6^{pq}$	$3.1 \pm 1.3^{\mathrm{qr}}$	$7.5 \pm 4.7$
	Dermal	$199 \pm 28.7^{a}$	176.5 ±33.7 <sup>b</sup>	152.2 ±36.5°	127.5±34.9 <sup>d</sup>	98.5 ±30.6 <sup>e</sup>	$78.6\pm27.8^{\rm f}$	138.7±52.8
MOE x 100	Sub-Dermal	113.5±27.9 <sup>g</sup>	$90.8\pm33.6^{\rm h}$	$71.7\pm28.8^{\mathrm{i}}$	$49.9 \pm 16.6^{j}$	$36.4 \pm 12.0^{k}$	$25.0 \pm 10.6^{1}$	64.5±38.6
N/mm <sup>2</sup>	Central	$26.4\pm8.0^{\mathrm{lm}}$	$12.4 \pm 3.1^{n}$	$8.6\pm2.6^{\rm o}$	$7.1 \pm 2.8^{p}$	$5.0 \pm 2.1^q$	$3.6 \pm 1.7^{\mathrm{r}}$	10.5±8.6
	Dermal	12.2±0.9 <sup>a</sup>	10.1±0.9 <sup>b</sup>	8.9±1.2 <sup>c</sup>	$8.0{\pm}1.4^{d}$	6.7±1.3 <sup>e</sup>	$5.2 \pm 1.0^{f}$	8.5±2.3
Shear llg	Sub-Dermal	$8.6 \pm 1.3^{\text{cg}}$	$7.4 \pm 1.2^{\rm h}$	$5.8\pm1.5^{\rm i}$	$4.8 \pm 1.4^{j}$	$3.4{\pm}1.4^{k}$	$2.2 \pm 1.0^{1}$	5.4±3.1
N/mm <sup>2</sup>	Central	$2.4\pm1.2^{\rm lm}$	$1.6\pm0.5^{n}$	$1.0\pm0.6^{\rm o}$	$0.8\pm0.1^{\rm op}$	$0.7\pm0.2^{\rm opq}$	$0.5 \pm 0.2^{pqr}$	$1.2 \pm 0.7$
	Dermal	$69.6 \pm 11.4^{a}$	57.6±9.06 <sup>b</sup>	50.6±1.1°	$44.7 \pm 10.0^{d}$	39.3±8.9 <sup>e</sup>	$28.5 \pm 6.8^{f}$	48.4±16.2
Comp llg	Sub-Dermal	43.5±8.4 <sup>dg</sup>	36.9±7.4 <sup>eh</sup>	26.7±5.2 <sup>fi</sup>	19.1±6.1 <sup>j</sup>	$12.7 \pm 5.8^{k}$	9.2±4.1 <sup>kl</sup>	24.7±14.4
N/mm <sup>2</sup>	Central	$9.1 \pm 1.6^{klm}$	$6.6 \pm 1.9^{klmn}$	$4.8 \pm 1.5^{no}$	4.3 ±1.3 <sup>nop</sup>	$3.0\pm1.2^{\text{nopq}}$	$1.6\pm0.7^{opqr}$	$4.9 \pm 2.0$
	Dermal	10.6±1.4 <sup>a</sup>	8.9±1.1 <sup>b</sup>	$7.8 \pm 1.0^{\circ}$	$6.7 \pm 1.1^{d}$	5.6 ±0.9 <sup>e</sup>	$3.8 \pm 0.8^{\mathrm{f}}$	$7.2 \pm 2.9$
Hardness kN	Sub-Dermal	7.7 ±1.3 <sup>cg</sup>	6.3±1.2 <sup>dh</sup>	5.1±1.1 <sup>i</sup>	3.8±0.7 <sup>fj</sup>	$2.5 \pm 0.7^{k}$	$1.4 \pm 0.5^{1}$	$4.5 \pm 2.6$
	Central	$1.2\pm0.2^{lm}$	$0.8 \pm 0.2^{lmn}$	$0.5 \pm 0.2^{no}$	$0.4\pm0.1^{\text{nop}}$	$0.3 \pm 0.1^{opq}$	0.2 ±0.1 <sup>opqr</sup>	$0.6 \pm 0.3$
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Table 2: Mean Values of green Mechanical Properties of Borassus aethiopum in Relation to Height and Positions

Each value is the mean and standard deviation of 5 replicates sampled trees of Borassus aethiopum.

Means with different superscript are significantly different (p < 0.05)

#### Table 3: Mean Values of Mechanical Properties at 12% MC of Borassus aethiopum in Relation to Height and Positions

			Height of Me	chantable bole	of Borassus aet	hiopum		
Mechanical	Radial	15%	30%	45%	60%	75%	90%	Pooled
Properties	Position	Mean $\pm$ S.D	$Mean \pm S.D$	Mean $\pm$ S.D	Mean $\pm$ S.D	Mean ±S.D	Mean $\pm$ S.D	Mean± S.D
	Dermal	171.6±15.3 <sup>a</sup>	$143.8 \pm 10.6^{b}$	125.2 ±8.4 <sup>c</sup>	$112.3 \pm 11.4^{d}$	95.1 ±12.8 <sup>e</sup>	$73.3 \pm 14.9^{f}$	120.2±34.3
MOR								
N/mm <sup>2</sup>	Sub-Dermal	110.6±16.2 <sup>dg</sup>	$82.7 \pm 9.5^{h}$	$65.8 \pm 10.4^{i}$	$52.4 \pm 9.2^{j}$	$41.8 \pm 10.0^{k}$	$29.1\pm7.8^{1}$	63.8±29.1
	Central	$25.8 \pm 3^{m}$	14.7±3.3 <sup>n</sup>	11.3±2.7°	$8.5 \pm 2.0^{p}$	5.7±1.9 <sup>q</sup>	4.6±1.1 <sup>qr</sup>	$11.3 \pm 4.7$
	Dermal	286.1±55.4 <sup>a</sup>	225.9±34.7 <sup>b</sup>	187.2±32.6°	$168.4 \pm 37.9^{d}$	131±43.4 <sup>e</sup>	$102.8 \pm 37.9^{f}$	183.6±72.7
MOE x 100								
N/mm <sup>2</sup>	Sub-Dermal	187.0±43.7 <sup>cg</sup>	130.7±27.8 <sup>eh</sup>	$110.3\pm30.7^{1}$	79.2±25.1 <sup>j</sup>	$60.2 \pm 18.0^{k}$	$38.4 \pm 15.3^{1}$	101±56.7
	Central	$38.7 \pm 7.3^{lm}$	$21.5\pm5.8^{n}$	$16.7 \pm 4.9^{\circ}$	$12.5\pm5.8^{p}$	$7.2 \pm 3.1^{q}$	$5.63 \pm 2.2^{r}$	17±11.9
	Dermal	17.3±1.1 <sup>a</sup>	$13.9 \pm 1.3^{b}$	$11.9 \pm 0.8^{\circ}$	$10.6 \pm 0.5^{d}$	$8.7 \pm 0.8^{e}$	$7.3 \pm 1.0^{t}$	$11.6 \pm 3.4$
Shear llg					c	1	1	
N/mm <sup>2</sup>	Sub-Dermal	$11.9 \pm 1.2^{g}$	$10.2\pm1.2^{n}$	$8.4 \pm 1.4^{\circ}$	$7.0 \pm 1.5^{ij}$	5.1 ± 1.1 <sup>K</sup>	$3.8 \pm 1.2^{\circ}$	7.7±3.1
	Central	3.6 ±1.5 <sup>m</sup>	2.3±0.7"	$1.7 \pm 0.8^{\circ}$	$1.3 \pm 0.6^{p}$	$1.1 \pm 0.40^{pq}$	$0.8 \pm 0.4^{q_{\rm f}}$	$1.8 \pm 1.2$
					<b>.</b> .			
<b>a</b> "	Dermal	88.7±7.5 <sup>a</sup>	$74 \pm 9.4^{\circ}$	66.2±11.1°	58.7±10.7 <sup>ª</sup>	51.6±10.1°	38.5±6.3 <sup>4</sup>	62.9±18.4
Comp lig		50.0 < 5dg	AC A T Ach				110 60	045 160
N/mm <sup>2</sup>	Sub-Dermai	58.0±6./**	$49.4 \pm 7.4^{-10}$	35./±/.2"	$30.0 \pm 6.2^{\circ}$	$20.8 \pm 7.0^{\circ}$	$14.2 \pm 6.9^{\circ}$	34./±16.8
	Central	$13.2 \pm 3.2^{m}$	$10.7\pm2.8^{mm}$	8.2±2.4"	$6.7 \pm 2.9^{\circ p}$	$4.8 \pm 2.6^{Pq}$	2.7±1.34	7.7±4.4
	D	12 4 2 78	110.22	10 4 1 09	01.1.0	77,15°	57.17 <sup>f</sup>	105.20
II	Dermai	$15.4\pm 2.7^{\circ}$	$11.9\pm2.5^{\circ}$	$10.6 \pm 1.9^{\circ}$	$9.1 \pm 1.0^{-1}$	$1.1 \pm 1.5^{\circ}$	$5.1 \pm 1.1^{-1}$	$10.5\pm2.9$
Hardness	Sub-Dermal	$10.0 \pm 2^{-8}$	$9.2\pm1.4^{-1}$	$8.1\pm1.2^{\circ}$	$0.8 \pm 1.2^{\circ}$	$5.0 \pm 0.7^{\circ}$	$3.4 \pm 0.5$	$0.8 \pm 2.6$
KIN	Central	$2.4 \pm 0.4^{-10}$	$1.7 \pm 0.2^{\circ}$	$1.2 \pm 0.1^{\circ}$	$1 \pm 0.1^{\circ p}$	$0.8 \pm 0.2^{opq}$	0.5±0.2 <sup>pq</sup>	1.3±0.6

Each value is the mean and standard deviation of 5 replicates sampled trees of Borassus aethiopum.

Means with different superscript are significantly different (p < 0.05)

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#### **Correlation between Density and Mechanical Properties**

The correlations between the densities and mechanical properties of the three distinct layers or zones of the trees are presented in Table4A to 4F for the green and dry conditions respectively. The correlations revealed that there was a good correlation between density and the mechanical strength values for the dermal, sub-dermal and the central zones. The densities and mechanical properties for the green condition and dry condition in square brackets were highly correlated at 98.4% ~ 99.8% [97.1% ~ 99.9%], 98.6% ~ 99.7% [94.9% ~ 99.7], and 92.4% ~ 99.8% [94.8% ~ 99.9] respectively for the dermal, sub-dermal and the central zones. The correlation coefficient between wood density and mechanical properties was highly significant (p < 0.001).

Table4A: Correlation between the basic density and the green mechanical strength values for the Dermal zone.

	Basic	Green	Green	Green	Green	Green
	Density	MOR	MOE	Comp.llg	shear.llg	Hardness
Basic Density	1					
Green MOR	0.985*	1				
Green MOE	0.978*	0.991*	1			
Green Comp.llg	0.992*	0.995*	0.982*	1		
Green shear.llg	0.992*	0.998*	0.985*	0.999*	1	
Green Hardness	0.990*	0.992*	0.997*	0.990*	0.991*	1

\*significant (p < 0.001) probability level

Table4B: Correlation between the density and the mechanical strength values at 12% MC for the Dermal zone.

	Density at 12% MC	MOR at 12% MC	MOE x 100 at 12% MC	Comp.llg at 12% MC	shear.llg at 12% MC	Hardness at 12% MC
Density at 12% MC	1					
MOR at 12% MC	0.993*	1				
MOE x100 at 12% MC	0.991*	0.997*	1			
Comp.llg at 12% MC	0.990*	0.999*	0.995*	1		
Shear.llg at 12% MC	0.989*	0.995*	0.988*	0.991*	1	
Hardness at 12% MC	0.980*	0.986*	0.996*	0.984*	0.971*	1

<sup>\*</sup>significant (p < 0.001) probability level

#### Table4C: Correlation between the basic density and the green mechanical strength values for the Sub-dermal zone.

	Basic Density	Green MOR	Green MOE x100	Green Comp.llg	Green shear.llg	Green Hardness
Basic						
Density	1					
Green MOR	0.993*	1				
Green MOE x100	0.990*	0.999*	1			
Green Comp.llg	0.990*	0.997*	0.998*	1		
Green shear.llg	0.997*	0.992*	0.991*	0.992*	1	
Green Hardness	0.988*	0.988*	0.987*	0.988*	0.996*	1

\*significant (p < 0.001) probability level

#### Table4D: Correlation between the density and the mechanical strength values at 12% MC for the Sub-dermal zone.

	Densityat 12% MC	MOR at 12% MC	MOE x 100 at 12%	Comp.llg at 12%	shear.llg at 12%	Hardness at 12%
Density	1					
Dry MOR	0.993*	1				
Dry MOE x 100	0.994*	0.992*	1			
Dry Comp.llg	0.996*	0.989*	0.991*	1		
Dry shear.llg	0.997*	0.986*	0.996*	0.997*	1	
Dry Hardness	0.975*	0.952*	0.978*	0.975*	0.986*	1
		*cionifica	at(n < 0.001) probabil	ity land		

\*significant (p < 0.001) probability level

	Basic Density	Green MOR	Green MOE	Green Comp.llg	Green Shear.llg	Green Hardness		
Basic Density	1							
Green MOR	0.940*	1						
Green MOE	0.924*	0.998*	1					
Green Comp.llg	0.993*	0.961*	0.946*	1				
Green Shear.llg	0.959*	0.990*	0.983*	0.976*	1			
Green Hardness	0.977*	0.944*	0.927*	0.980*	0.978*	1		
*significant ( $p < 0.001$ ) probability level								

Table4E: Correlation between the basic density and the green mechanical strength values for the Central zone

Table4F: Correlation between the density and the mechanical strength values at 12% MC for the Central zone.

	Density at 12%	MOR at 12%	MOE at 12%	Comp.llg at 12%	Shear.llg at 12%	Hardness at 12%	
	МС	MC	МС	МС	МС	MC	
Density at 12% MC	1						
MOR at 12% MC	0.966*	1					
MOE at 12% MC	0.971*	0.999*	1				
Comp.llg at 12%MC	0.995*	0.948*	0.953*	1			
Shear.llg at 12% MC	0.965*	0.998*	0.996*	0.952*	1		
Hardness at 12% MC	0.986*	0.955*	0.956*	0.992*	0.963*	1	

\*significant (p < 0.001) probability level

## Relationship between wood density and mechanical properties

Earlier studies examined the predictability of some wood mechanical properties from density on various hardwood species such as *Eucalyptus globulus*, *E. nitens* and *E. regnans*[21] and Teak [13]. These studies reported density as a good estimator of mechanical properties. Figures 1A-3B shows the functional relationships between density and the measured mechanical properties of the different zones of *Borassus aethiopum*. Regression equations (Tables5-7) were derived with co-efficient of determination ( $\mathbb{R}^2$ ) values ranging between 0.96 – 0.99, 0.95 – 0.99 and 0.95 – 0.99 respectively for the dermal, sub-dermal and the central zones. The density of *Borassus aethiopum* in the green and at 12% MC for the dermal, sub-dermal, and central zones is a good estimator of measured mechanical properties. Hence, in almost all the evaluations, the coefficient of determination ( $\mathbb{R}^2$ ) was more than 90 %. For the dermal, sub-dermal and central zones for approximately 93% of the variations in the mechanical properties studied.

Table 5: Functions relating mechanical properties to density (basic and 12% MC) grain for theDermal zone

Mechanical Property	'Green' wood		Wood at 12% MC	
	Density (x)	R <sup>2</sup>	Density (x)	R <sup>2</sup>
	Strength (Y)		Strength (Y)	
	Relationship		Relationship	
MOE (N/mm <sup>2</sup> ) x 100	Y = 0.698x - 310.9	$R^2 = 0.957$	Y = 0.602x - 306.8	$R^2 = 0.982$
MOR (N/mm <sup>2</sup> )	Y = 0.447x - 194.6	$R^2 = 0.969$	Y=0.440x - 229.3	$R^2 = 0.986$
Compllg (N/mm <sup>2</sup> )	Y = 0.250x - 111.0	$R^2 = 0.984$	Y=0.220x - 112.1	$R^2 = 0.980$
Shear llg (N/mm <sup>2</sup> )	Y = 0.043x - 19.20	$R^2 = 0.984$	Y = 0.045x - 24.50	$R^2 = 0.978$
Hardness KN	Y = 0.039x - 17.23	$R^2 = 0.979$	Y = 0.034x - 16.69	$R^2 = 0.960$

<b>Table 6: Functions</b>	relating mechanical	l properties to density	(basic and 12% MC)	for the sub-dermal zones
	0			

Mechanical Property	Green' wood		Wood at 12% MC	
	Density (x)	R <sup>2</sup>	Density (x)	R <sup>2</sup>
	Strength (Y)		Strength (Y)	
	Relationship		Relationship	
MOE (N/mm <sup>2</sup> ) x 100	Y=0.421x -134.8	$R^2 = 0.984$	Y = 0.429x - 151.9	$R^2 = 0.987$
MOR (N/mm <sup>2</sup> )	Y = 0.260x - 78.66	$R^2 = 0.986$	Y = 0.272x - 93.82	$R^2 = 0.986$
Comp llg (N/mm <sup>2</sup> )	Y=0.163x - 53.17	$R^2 = 0.979$	Y = 0.154x - 54.80	$R^2 = 0.992$
Shear llg (N/mm <sup>2</sup> )	Y=0.029x - 8.708	$R^2 = 0.993$	Y = 0.028x - 8.450	$R^2 = 0.993$
Hardness kN	Y= 0.027x - 8.081	$R^2 = 0.976$	Y = 0.021x - 5.275	$R^2 = 0.951$



Table 7: Functions relating mechanical properties to density (basic and 12% MC) for the Central zones

Figure 1A: Relationship between Basic density and green strength - Dermal zone

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Figure 1B: Relationship between density at 12% MC and strength at 12% mc –Dermal zone



Figure 2A: Relationship between basic density and green strength – Sub-dermal zone



Figure 2B: Relationship between density at 12% MC and strength at 12% MC– Sub-dermal zone



Basic Density Kg/m<sup>3</sup>

Figure 3A: Relationship between Basic density and green strength - Central zone



Figure 3B: Relationship between density at 12% MC and strength at 12% MC – Central zone

## Comparison of the studied mechanical properties of Borassus aethiopum toother species.

Comparison of the mean mechanical properties determined for *Borassus aethiopum*(Dermal zone, Sub-dermal zone, and Central zone) to other commercially important timber species of (Table 8) reveals that the mechanical properties of the dermal zone compares favourably with Afromosia (*Pericopsiselata*), Dahoma (*Pepdiniastrumafricanum*), Teak (*Tectonagrandis*), and Sapele(*Entandrophragmacylindricum*).

 Table 8: Comparison of the mean mechanical properties of Borassus aethiopum (Dermal zone, Sub-dermal zone, and Central zone) to other commercially important timber species.

						Hard-
	MC	MOR	MOE	Comp	Shear llg	ness
	(12%)	$(N/mm^2)$	$(N/mm^2)$	llg(N/mm <sup>2</sup> )	N/mm <sup>2</sup>	kN
Dermal Zone	Green	89.8	13358.6	48.4	8.5	7.2
	12%	120.2	17127.3	62.9	11.6	10.5
Sub-dermal Zone	Green	45.2	6573.4	24.7	5.4	4.5
	12%	63.8	9704	34.7	7.7	6.8
Central Zone	Green	7.5	1051.5	4.9	1.2	1.3
	12%	11.8	1698.6	7.7	1.8	0.6
Afromosia**						
(Pericopsiselata)	Green	102	12,200	51.6	11.5	7.1
	12%	126.9	13,400	68.5	14.4	6.9
Balsa (Ochromapyramidale) **	Green	-	-	-	-	-
	12%	21.6	3,400	14.9	2.1	-
Ceiba(Ceibapentandra)**	Green	15.2	2,800	7.3	2.4	1
	12%	29.6	3,700	16.4	3.8	1.1
Dahoma*	Green	85.8	9,399	37	13.4	4.99
	12%	109.6	10,897	54.2	20.4	6.22
Mahogany						
(Khaya spp.) **	Green	51	7,900	25.7	6.4	2.8
	12%	73.8	9,700	44.5	10.3	3.7
Obeche (Triplochitonscleroxylon) **	Green	35.2	5,000	17.7	4.6	1.9
	12%	51	5,900	27.1	6.8	1.9
Sapele(Entandrophragmacylindricum						
) **	Green	70.3	10,300	34.5	8.6	4.5
	12%	105.5	12,500	56.3	15.6	6.7
Teak (Tectonagrandis)**	Green	80	9,400	41.1	8.9	4.1
	12%	100.7	10,700	58	13	4.4

Source: \*[17] and \*\*[10]

Also, the strength properties of the sub-dermal zone in terms of MOE, Compression parallel to the grain, and Hardness compare favorably with that of Mahogany (*Khayaspp*). The strength properties of the Central zone are relatively low in respect of Balsa, Ceiba, and Obeche.

#### CONCLUSION

Analysis of variance of the density and mechanical properties of these zones indicate that there is significant difference at P<0.05 between the zones. The effect of stem height on "wood" physical properties and mechanical properties for each of the zones were significant at P < 0.05. The density and the strength properties decreased significantly at P<0.05 at the radial position and longitudinally from the butt of the trees to the top of the trees for each of the zones. Density is a good predictor of the mechanical properties of the dermal zone, sub-dermal zone and central zone. The mechanical properties of the dermal zone compare favorably with Pericopsiselata, Pepdiniastrumafricanum, Tectonagrandis, and Entandrophragmacylindricum hence an indication that this monocot giant, Borassus aethiopum, is a good substitute for these timber species.

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