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Experimental Investigation On The Mechanical Properties Of African Fan Palm (Borassus Aethiopum)

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Abstract
This study investigated the mechanical properties of African fan palm for its applicability in reinforced concrete works. The African fan palm is characterised as mart wood and its variability to stress and strain (longitudinal, radial and tangential) like other timber species necessitates an understanding of its mechanical properties. Therefore, the objective of this study was to experimentally determine the uniaxial tension, three-point bending, compression and Poisson's ratio of the African fan palm. The Poisson's ratio was obtained through the comparison of the transverse strain against the longitudinal strain when the fan palm bar was tensioned on a 2000kN capacity Universal Tensile Machine (UTM). Three sample specimens were used to obtain the average value of the Poisson's ratio calculated as 0.382. This gap in literature was critical to allow its use in finite element analysis such as ANSYS and ABAQUS software. Six sample specimens for tensile strength were tested. Three of these samples of 20mm had an average tensile strength of 94.67N/mm^2 and an average Young's modulus of 20kN/mm^2, whilst the other three specimens of 12mm had an average tensile strength of 84.33N/mm^2 and a Young's modulus of 26.71kN/mm^2. For the three-point bending test, seventeen specimens were used longitudinally for each of the bottom and middle portions of the tree trunk measured from the base of the tree. The average modulus of ruptures (MOR) and modulus of elasticity (MOE) were 98.37N/mm^2 and 17.78kN/mm^2, and 43.99N/mm^2 and 8.27kN/mm^2, respectively for the bottom and middle sections. Equally, seventeen samples were used for longitudinal compressive strength with mean results of 77.87N/mm^2 and 59.49N/mm^2 for bottom and midsections of the trunk respectively. The relatively greater mechanical properties of the bottom portions emphasize the need to use the matured bottom part in structural works. These results of the various tests conducted suggest that the African fan palm had good mechanical properties for use as reinforcement in structural concrete members.

Keywords: *Tensile strength, compression strength, MOR, MOE, deformation, Poisson's ratio*

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I. Introduction

Steel, a nonrenewable reinforcing material for structural concrete members has offered, arguably the most suitable properties for reinforced concrete works compared to other renewable materials. However, it is not only causing unbearable strain on developing countries in terms of cost for importation and the eventual finish cost of projects, but its effect and contribution towards environmental degradation is worrisome. Empirical studies have outlined a range of eco-friendly materials with less impact on the environment that have been recommended as substitutes for reinforcement such as raffia palm by Kankam (1997), babadua by Kankam and Odum-Ewuakye (2000), rattan palm by Adewuyi et al. (2015), bamboo by Kankam et al. (1988), Ferreira et al. (2016), Adom-Asamoah et al. (2017), and Wei et al. (2020). These investigations delved and confirmed the suitability, strength and mechanical properties (referenced in Table 4) of these materials through various tests as substitute reinforcement. Amongst these renewable materials are the African fan palm.

The mechanical properties of the African fan palm were examined for its applicability in reinforced concrete members. The fan palm is characterised as mart wood and its variability to stress and strain (longitudinal, radial and tangential) like other timber species necessitates an understanding of its mechanical properties. This eco-friendly mart plant is mostly found in semi-arid and sub-humid zones of Sub-Saharan Africa (ICRAF, 1992; Ayarkwa, 1997). The fibres of the fully grown mart wood are densely compacted and hard offering it resistance to decay, chemical attack or fungal attack when in contact with water (Joshua, 1997). This species is one of the most difficult timber materials to work with both machines and hand tools because of its sharp needle-like fibre. Several researches reported significance progress undertaken on the mechanical properties of fan palm. These studies focused mainly on strength properties such as flexural, bending and compression (Samah et al., 2015;

Asibe et al., 2013; Ngargueudedjim et al., 2015; Kone et al., 2021). Audu and Raheem (2015) presented the use of blocking agents as a means of reducing deflections in beams. Their study revealed an enhanced deflection resistance of beams with fan palm reinforcement bars coated with hydroxylamine as compared with the beams with uncoated fan palm bars for periods above 270 days. Raheem and Audu (2013) on the other hand experimented on the durability of fan palm by using alkaline media. They observed that epoxy coated fan palm bars had improved durability. However, coating of fan palm bars could reduce the bond strength of structural members.

In the course of extensive review of existing literature on fan palm, there is no evidence that investigations relating to Poisson's ratio of fan palm have been documented. In today's use of design softwares, the value of the Poisson ratio is fundamental for modelling (e.g. ABAQUS). It is also an important parameter on the bond between the reinforcing bar and concrete in their composite action. This mechanical property defines the lateral strain against the longitudinal strain when a material is stressed and generally for longitudinal tensile stress and accompanying compression lateral strain, the value falls within the range of 0 – 0.5. Though auxetic materials such as polyurethane foam contradicts this narrative with negative Poisson's ratio as they expand transversely when tensioned and decreases when compressed (Carneiro et al., 2013).

The deformational changes due to stresses when load is applied on isotropic and anisotropic materials defer, due to the former exhibiting uniform properties in all directions whilst the latter show different properties in any of its directions (Tokmakova, 2005).

The adoption of eco-friendly concrete reinforced materials, requires a comprehensive understanding of their behaviour to enhance performance in structural work. Other researchers presented mechanical properties of wood and documented findings on their strength properties and Poisson's ratios (Green et al., 1999; Gao et al., 2016). Figure 1 illustrates the moduli of rupture and elasticity of some of the hardwoods and softwoods species by Ayarkwa (1997) and Green et al. (1999). Amongst these species, the African fan palm offered the maximum bending stress prior to yielding which could be attributed to its densely compacted fibres when fully matured. It also possessed a good resistance to elastic deformation. Findings from Ayarkwa (1997) drew similarities on the strength properties of fan palm with Milicia Excelsa (Odum) in terms of density, bending strengths, compression and shear strength.

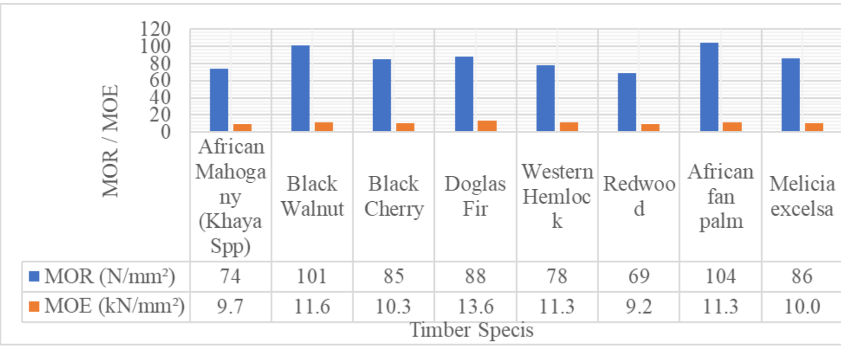


Figure1: MOR and MOE of some wood species (Green et al., 1999; Ayarkwa, 1997).

Many investigators presented Poisso's ratios of several timber materials that are illustrated in Figure 2 by Green et al. (1999) and Gao et al. (2016). Green et al. (1999) presented a comprehensive discussion on the mechanical properties of wood in their published hand book. Amongst these materials presented, it is observed that the Black Walnut will exhibit large elastic deformation compared to Bamboo as in Figure 2.

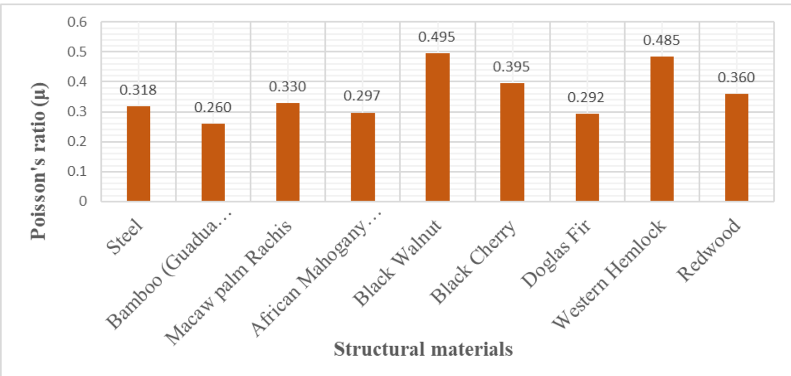


Figure 2: Poisson's ratio of structural materials (Green et al., 1999; Gao et al., 2016)

II. Materials

The African fan palm

Fan palm materials used were obtained mainly from fully grown mart trees from Kintampo, a farming village with rich cultural heritage in the Bono East Region of Ghana. Four fan palm trees of average height of almost 20 to 25 meters were felled and each tree was cut from the base into three lengths of 2 meters each and three lengths of 1.5 meters each with a chain saw. The middle part was also cut for sample analyses. These trunks (bottom and middle parts) were converted into quadrants and later transported to the KNUST (Kumasi, Ghana) Faculty of Natural Resources at the carpentry workshop for conversion into marketable sizes for beams, slabs and columns. Most of the middle and top parts were not used due to the high concentration of sap. However, sample specimens were analysed and found to contain cementitious compounds for use as pozzolanic material so as to avoid wastage of the rest of the material.

Conversion and Air- Seasoning

Two edges of each quadrant were planed square using the combined surface planer and thicknessing machine prior to ripping of the bars to sizes of 12mm x 12mm x 1500mm; 16mm x 16mm x 2000mm; 20mm x 20mm x 2000mm; 25mm x 25mm x 2000mm and 25mm x 35mm x 2000mm. The converted pieces were stacked carefully inside the workshop for air-drying for a duration of 2 months. Samples specimens from the seasoned stack were weighed and the wet weights compared to the dry weights to obtain a 12% moisture content.

Mechanical test Methods

Tensile test

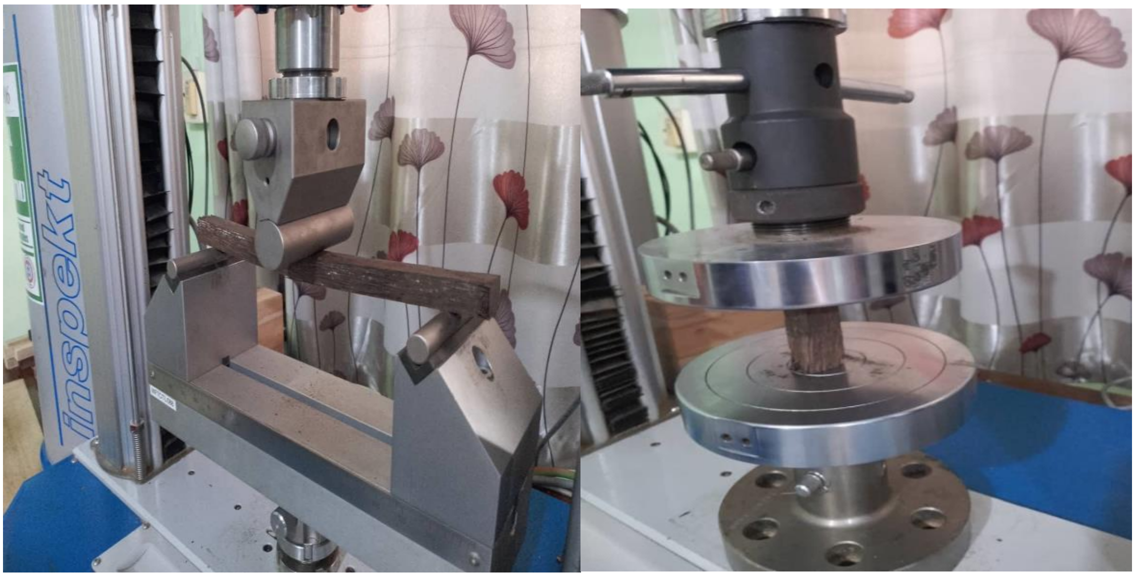
Samples used for the tensile strength test were selected from scantlings of Borassus Aethiopum of square cross-sectional areas of 12mm x 12mm and 20mm x 20mm. A total sample size of 6 scantlings (3 from each cross-section) were randomly selected from the stack of seasoned fan palm bars and cut to lengths of 600mm. These specimens were subjected to a computerized Universal Testing Machine (UTM) with a load capacity of 2000kN in accordance with the British Standard BS EN 1008 (2002) at the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Kumasi, Ghana. The test specimens were gripped inside a 150mm long hollow metal bar at both ends using epoxy mixture of resin and hardener and allowed to dry for 24 hours (Figure 3a). The epoxy resin had an excellent bond property with other materials when dried with less shrinkage. The glued metal bars enhanced the grip and prevented crushing of the fibres of the fan palm bars during the test process, thus eliminating the tendency of premature failure leading to incorrect results. An extensometer with a 50mm gauge length was attached (Figure 3b) to the test specimen gripped into the jaws of the UTM. The extensometer was then connected to the computer monitor and as load was applied, the latter automatically recorded the ultimate failure load and elongation as well as the stress versus strain curve and the Young's modulus of the test specimen.

(a) Grip enhancement mechanism (b) extensometer attached to the fan palm bar
Figure 3: (a) Sample specimens and (b) Specimen clamped into the UTM

Flexural three-point bending and compression test

A three-point flexural bending test and compression were conducted at the Wood and Furniture Testing Centre of the Forestry Research Institute of Ghana (FoRIG), Kumasi Ghana, using a Universal Testing Machine with a 50kN capacity and an initial speed of 10min/sec. These two tests were performed on the same UTM but with different fixtures. Seventeen (17) samples of bottom and middle specimens of fan palm sizes of 25mm x 25mm x 450mm were prepared and tested between span supports of 300mm as illustrated in figure 4 a. The test was conducted to determine both the modulus of rupture (MOR) and modulus of elasticity (MOE) respectively.

In accordance with the American Standard ASTM D143 - 2022, the compression test samples of seventeen (17) specimens were prepared with cross-sectional area of 25 millimeters square and a length of 60mm and the testing is illustrated in figure 4b.



(a) Three-point bending test (b) Compression test

Figure 4: Three-point bending and compression test set-up

Poisson's ratio test

Three sample specimens of 600mm length x 20mm cross-sectional area of fan palm bars were machined and measured with varying diameters of 15.69, 15.58 and 15.67mm using the Lathe Machine at the KNUST Mechanical workshop. These sample specimens as illustrated in figure 5b were gripped the same way as the tensile specimens. Specimen sample were secured in the jaws of UTM of capacity 2000kN and subjected to tensile loading. The longitudinal strain was obtained from the computerised UTM with a 50mm gauge length extensometer attached to the fan palm bar, while a venier calliper was used to measure the lateral deformation. Sample specimens for testing were not loaded to failure so as to ensure that the Poisson's ratio measurement would be ensured within the elastic response region of the fan palm. The value of the Poisson ratio for circular bars were then calculated using:

$$lateral\ strain = \frac{\delta \mathrm{d}}{\mathrm{d}} \ldots\ldots\ldots\ldots\ldots (1)$$

where, d is the diameter of the bar and δd is the change in diameter after the load was applied. The longitudinal strain was calculated as:

$$longitudinal\ strain = \frac{\delta \mathrm{l}}{\mathrm{l}} \ldots\ldots\ldots\ldots\ldots (2)$$

where, l is the original length and δl being the change in length after elongation. Hence, the Poisson ratio (μ):

$$\mu = -\frac{\delta \mathrm{d} \, . \mathrm{l}}{\mathrm{d} \, . \delta \mathrm{l}} \ldots\ldots\ldots\ldots\ldots (3)$$

The negative sign mirrors objects which when stretched longitudinally give a decrease in lateral dimension.

(a) Fan palm bar being prepared on a lathe machine

(b) fan palm bar grip (c) specimen for a tensile pull using UTM

Figure 5: Preparations of specimen for the Poisson ratio test using UTM

III. Results And Discussions

Results

A summary of the results of the experimental investigation are presented in Table 1 - 3 and Figures 6 – 9. The tensile strength results presented in Table 1 are in agreement with those in Table 4 by the past researchers. A plot of the tensile stress-strain curve in Figure 6 showed linear relationship for all six specimens with mean ultimate tensile failures and Young's modulus of elasticity of 94.67N/mm^2 and 20kN/mm^2 for the 20mm fan palm bars and 84.33N/mm^2 and 26.71kN/mm^2 for the 12mm bars respectively. Similar findings were reported by Samah et al. (2015, Kone et al. (2021) and Adedeji (2020) as shown in Table 4.

Table 2 and Figures 7 and 8 present a three-point flexural bending results with mean values of MOR and MOE as 98.32N/mm^2 and 18kN/mm^2, and 45.63N/mm^2 and 8.48kN/mm^2 for both the bottom and middle parts respectively. The low tensile values of both MOR and MOE of the middle part of the fan palm render it unsuitable for use as reinforcement. Furthermore, the middle part is lighter in weight due to a lot of sap concentration, and could easily be subjected to decay or undergo significant moisture movement if used as reinforcement as well as being vulnerable to insect attack (Kone et al., 2021; Adedeji, 2020).

The compression test was conducted parallel to the grains, and from Table 3 and Figure 9, it can be seen that the compressive strengths for the bottom ranges from 54.93 – 98N/mm^2 with a mean value of 77.87N/mm^2 and standard deviation of 12.18N/mm^2, whilst the middle part ranges from 39.32 – 77.16N/mm^2 with a mean value of 59.49N/mm^2 respectively.

The experimental results of the Poisson's ratio test from the three-sample varied slightly from 0.382, 0.379 and 0.384, giving an average mean score of 0.382. The result is close to those obtained by Green et al. (1999). This result could be classified under high Poisson's ratio as categorized by Belyadi et al. (2017). They investigated the Poisson's ratio of harder materials (rocks) and concluded that materials with low Poisson's ratio 0.1 – 0.25 does not fracture easily under load, compared to high Poisson's ratio of rocks ranging from 0.35 – 0.45 which were harder to fracture. High Poisson's ratio signifies that the fan palm material will undergo large deformation longitudinally compared to those with lower Poisson's ratio values. Generally, the results obtained by Oliveira et al. (2018) on matured macaw palm rachis (0.22 – 0.35) could be compared with the one obtained in this test (0.382), since these materials are botanically fibrous.

Table 1 Tensile strength and Young's modulus results

Specimen ID	Bar Dimensions	Tensile Strength (N/mm^2)	Young's Modulus (kN/mm^2)
A20		90.00	16.44
B20	20mm	117.00	20.40
C20		77.00	22.14
Mean Ave.		**94.67**	**20.00**
A12		81.00	24.12
B12	12mm	95.00	36.01
C12		77.00	20.00
Mean Ave.		**84.33**	**26.71**

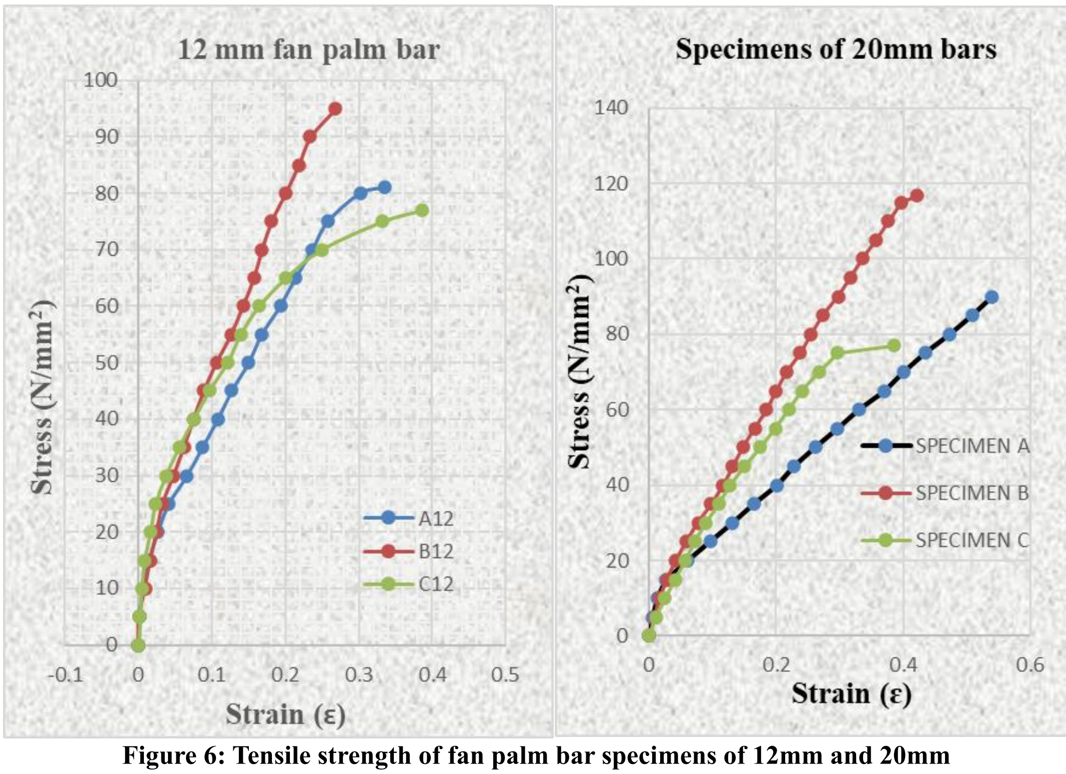


Figure 6: Tensile strength of fan palm bar specimens of 12mm and 20mm

Table 2 Three-point Bending Test

Specimens ID	Bottom Parts		Middle Parts (N/mm²)	
	MOR (N/mm²)	MOE (kN/mm²)	MOR (N/mm²)	MOE (kN/mm²)
1	83.29	15.21	37.17	7.94
2	100.51	13.13	62.96	12.85
3	109.29	17.65	75.09	12.35
4	125.17	16.82	65.92	12.08
5	120.68	15.15	58.69	7.71
6	77.11	18.52	36.19	5.72
7	97.47	16.42	37.30	6.25
8	127.58	19.54	46.25	8.56
9	82.49	23.50	38.66	6.85
10	108.47	21.69	32.76	8.16
11	79.24	16.39	36.38	5.52
12	78.53	18.80	42.14	8.20
13	94.05	16.67	62.66	13.69
14	126.72	17.03	34.82	7.12
15	94.84	19.33	37.46	7.28
16	85.26	20.67	33.98	7.13
17	80.74	19.55	37.26	6.69
	1671.43	**306.07**	**775.67**	**144.10**
Mean	**98.32**	**18.00**	**45.63**	**8.48**
STDV	**18.21**	**2.59**	**13.63**	**2.59**

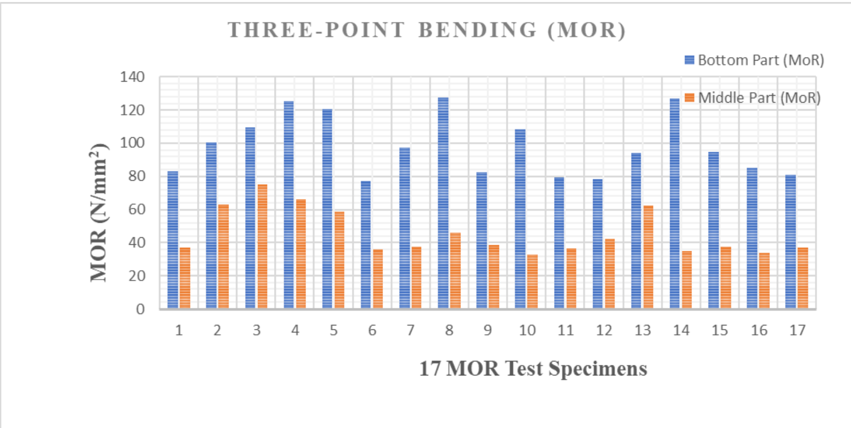


Figure 7: Modulus of rupture of fan palm.

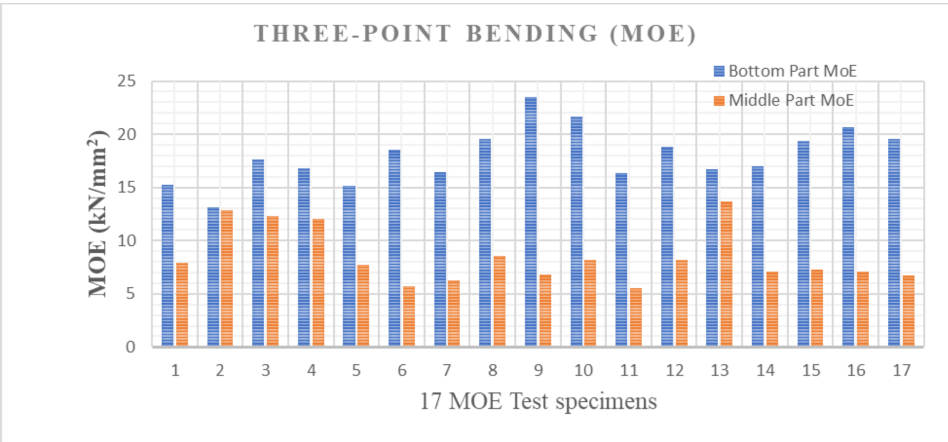


Figure 8: Modulus of elasticities of the bottom and middle parts.

Table 3 Compression Test

Specimens ID	Compressive Strength Test	
	Bottom Part (N/mm²)	**Middle Part (N/mm²)**
1	66.39	51.76
2	89.20	54.67
3	61.57	58.40
4	73.19	60.30
5	69.52	63.03
6	98.01	39.32
7	54.93	52.35
8	90.96	67.67
9	84.58	68.77
10	78.94	51.25
11	68.31	60.21
12	89.09	76.38
13	66.59	68.84
14	80.30	52.35
15	84.46	40.06
16	92.28	77.16
17	75.50	68.78
	1323.82	**1011.3**
Mean	**77.87**	**59.49**
STDV	**12.18**	**11.11**

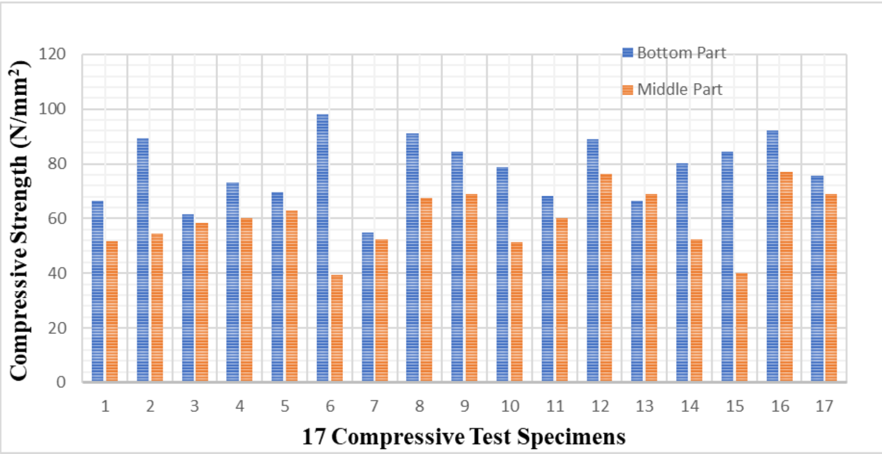


Figure 9: Compressive test results of the bottom and middle parts.

Discussions

According to the results from previous researchers in Table 4, the strength properties of African fan palm showed excellent load bearing capacity. Table 1 and Figure 6 presents the ultimate failure loads of sample specimens of 12mm and 20mm fan palm bars. The ultimate failure loads denote the consistency, irrespective of the size of the bars, the failure loads remain within a close range (84.33 – 94.67N/mm^2). However, the modulus of elasticity shows variance denoting ease at which 12mm bars could be stretched and deformed as compared to the 20mm bars.

Table 2 and Figures 7 and 8 depict the observed results of the MORs and MOEs of the three-point bending whilst Table 3 and Figure 9 present the compression results of the bottom and middle parts of the fan palm bars. The results reveal the stiffness and tendency of the bottom parts ability in sustaining longer loads than the middle parts. Similar results of the MOR, MOE, tensile, and compressive strengths were reported by Gbaguidi-Aisse et al. (2011) and Belyadi et al. (2017).

None of the currently reviewed journals was able to publish the Poisson's ratio of the African fan palm, despite wide recommendations for the material to be used as a reinforced material. The results of the Poisson's ratio allow enable its use in Finite Element Analysis such as in ANSYS and ABAQUS software. The Poisson's ratio effects are found on composite action between reinforcing bars and concrete. When the Poisson's ratio is large, it affects the bond between the bars and concrete due to the tendency of the tensile reinforcement bars breaking away from the concrete as the bar contracts.

This study was able to experimentally contribute towards calculating the average value from three test results as 0.382. This result is close to the values of some of the hardwood species described in Figure 2 and slightly higher than a similar fibrous Macaw palm rachis, with a value of 0.330 presented by de Oliveira et al. (2018) as well as being close to steel with Poisson's ratio of 0.318 found by Gao et al. (2016). Thus, the high value of the fan palm's Poisson's ratio of 0.382 could be attributed to its closely dense and cemented fibres of the fully grown tree.

Table 4: Mechanical properties of the African fan palm

Reinforcement Material	Tensile Strength in Flexure (N/mm^2)	Compressive Strength (N/mm^2)	Bending		Shear strength (N/mm^2)	Basal Density (kg/m^3)	Author(s)
			MOR (N/mm^2)	MOE (kN/mm^2)			
African Fan Palm		58.00	104	11.30	7.8	670	Ayarkwa (1997)
	300		190	17.20		690	Gbaguidi-Aisse et al., (2011)
		62.90	120	17.13	11.64	793.30	Asibe et al., (2013)
	103.20	86.54	180.01	15.04		894.40	Ngargueudejim et al., (2015)
	105	92.50	91.40				Samah et al., (2015)
	103.70	60.73	108.23	3.39	8.13	965	Kone et al., (2021)
Bamboo	124.6 (+ Nodes)	49.2					Kankam et al., (1988)
	194.5 No (- Nodes)	45.7					
	108.20			13.10			Ferreira et al., (2016)
	126.72			16.75			Adom-Asamoah et al., (2017)
	131.18	105.2		15.6			Wei et al., (2020
Babadua (Thalia) Geniculata)	75-125 (+nodes)						Kankam and Odum-Ewuakye (2000)
	150-200 (-nodes)						
Rattan palm (Calamus Deerratus)	335.23						Adewuyi et al., (2015)
Raffia palm (Genus Raphia)	75 – 113.8			12 - 25			Kankam (1997)

Note: (+ nodes) Specimens with nodes), (- nodes) Specimens without nodes).

IV. Conclusion

An experimental investigation was conducted to evaluate the mechanical strength properties of the African fan palm through axile traction (tensile), three-point bending (flexion) and axial compression. Two tensile tests were performed, the first to predict the ultimate tensile failure load of the material and the second for the Poisson's ratio. For the latter, the materials were loaded within their elastic range for an accurate measurement of the Poisson's ratio. The experimental results pointed to the fact that the tensile strengths, MORs, MOEs and compression strengths of the bottom parts of fully matured fan palm are recommended for structural works.

Previous investigators of Poisson's ratio of some materials used for reinforced concrete members have their Poisson's ratios characterised as high (0.35 – 0.45). The African fan palm thus presented a high value Poisson's ratio of 0.382 which could be attributed to its closely dense and cemented fibres of the fully grown tree.

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