Biomechanics, an aspect of the relationships between Wood Anatomical Parameters and Mechanical Strength in Ten Nigerian Timber species

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Abstract-Wood anatomical characteristics of ten commercial timbers of Nigeria: *Ceiba pentandra; Diospyros mespiliformis; Afzelia africana; Brachystegia nigerica; Gossweilerodendron balsamiferum; Periscopsis elata; Khaya ivorensis; Milicia excelsa; Mansonia altissima* and *Gmelina arborea* were determined and their potentials in the prediction of five strength parameters: compression; cleavage; shear; indentation and tensile were assessed. The anatomical characteristics showed variations in fibre length; fibre diameter; fibre lumen diameter; fibre cell wall thickness; number of fibres per field of view; number of vessels per field of view; vessel diameter in the tangential direction and in the derived values: Runkel ratio; slenderness ratio and coefficient of flexibility. Variations occurred also among the species in all the strength parameters assessed, which include compression; tension; indentation; cleavage and shear. The statistical analysis showed significant differences among the means tested for in the ten timber species (P= 0.05). Anatomical parameters with highly significant correlations - positive or negative were of good strength predictive potentials. The strength prediction equation ($\hat{Y} = bx + a$) was derived for each of the strength parameters assessed and the validity of these equations determined. When the mean of any of the anatomical parameters (x) is substituted in the equation, the corresponding strength could be worked out. Species with longer fibres offered less resistance to compression, indentation and tensile forces. Fibre diameter showed no significant correlations with any of the strength parameters and therefore was not of any predictive value. Species with narrower fibre lumina offered more resistance to compression, cleavage and tensile forces. Timber species with thicker fibre walls were more resistant to compression and tensile forces, but less resistant to indentation force. Species with more fibres per field of view were more resistant to compression and cleavage forces. Timber species with many vessels per field of view offered more resistance to compression, indentation and tensile forces, but low resistance to cleavage force. Timbers whose vessel diameters are wider in the tangential directions offered lower resistance to compression, cleavage and tensile forces. Among the three derived fibre values assessed, slenderness ratio had no strength predictive potential. The other two, coefficient of flexibility and Runkel ratio had good strength predictive potentials which seemed antagonistic in nature. While species with high coefficient of flexibility offered low resistance to compression, cleavage and tensile forces but high resistance to indentation force. Species with high Runkel ratio gave high resistance to compression, cleavage and tensile forces
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Key words: Biomechnics, Anatomical parameters, Strength parameters, Nigeria, Fibre diameter, Runkel ratio, Timber

INTRODUCTION:

Wood has served man since he appeared on Earth, and has decisively contributed to his survival and to the development of civilization. Moreover, wood continues to be the raw material for a large number of products even in modern times, although other competitive materials (metals, cement, plastics etc.) are available. The value of wood is preserved in many traditional uses, and grows steadily with its use in new products to meet the increasing needs of man [24].The astonishing material progress in the 20th century not infrequently, results in the consumer, seeking to satisfy a particular need, being completely bewildered because the choice is so wide. The quality of the many alternatives is so overwhelming, that the material faces very stiff competitions. The progress made in wood utilization is as a result of much painstaking research, often not directed primarily to solving practical problems. Research into the properties of timber is one of the most pertinent factors that endowed wood to hold its own today, second to none, for so very a wide range of quite different end-uses. The practical significance of our new knowledge of wood is, however, yet to be fully appreciated and generally applied. It is too often assumed that generations of practical experience have taught users all there is to know about a material in such general use [7].

Timber is obtained exclusively from conifers and dicotyledonous trees termed softwood and hardwood respectively, though the terms do not necessarily reflect the true strength of the materials. There is considerable variability in the structure and strength properties of timbers and the problems which this poses to the utilization of the material in a situation where uniformity and stability are desirable is rather challenging. This great variability in the structure and strength properties of the timber is due to the fact that the material is obtained from a once living entity which underwent the various life processes of the living tree which were affected by the prevailing environmental conditions (seasonal changes, wind, sunshine, rainfall and natural disasters).

After harvesting in the forest, the wood is converted into a great number of products by sawing, slicing, gluing, chipping, pulping, modification by impregnation with chemicals, or chemical processing. Products of primary industrial processing include poles, particleboards, fibreboards, posts, lumber, laminated wood, veneer, plywood, pulp and paper-and, in turn, these are made into products for final end-use, for example in furniture, construction, etc. Products of chemical processing are synthetic fibres, photographic films, explosives, chemicals, and many others.[24]

Wood is also an important fuel material for cooking, heating, and production of steam, hence wood may be utilized as a source of energy. About half of the world's production of wood is used as fuel. With the existing energy problems, wood as a renewable product of nature, is acquiring a greater importance as fuel.These multiple services are due to certain advantages: wood, as aesthetically unrivalled as a material [8], because it is available in a great variety of colours, textures, and figures. It gives a feeling of "warmth" to touch and sight, which is not possessed by other competitive materials. It is very strong mechanically in relation to its weight; it is insulating to heat and electricity, and exhibits little thermal contraction and expansion, and has good acoustic properties (utilized in making musical instruments). It does not oxidize (rust) and shows considerable resistance to mild concentrations of acids. It may be easily machined with small consumption of energy; nailing or bonding with metal connectors, as well as gluing, are easily achieved. Wood is the main source of cellulose, which is the base of numerous products. It is found in most parts of the world, and is a renewable source in contrast to petroleum, metal ores, and coal, which are gradually but steadily being exhausted [11]. It is also biodegradable. Wood has disadvantages as well. It is hygroscopic ie. it holds moisture when in contact with liquid water or water vapour. The gain or loss of moisture, within certain limits, results in dimensional changes (Timber Movement). It is an anisotropic material (i.e., it presents differential mechanical strength and differential dimensional changes in different structural directions). It may burn and decay. It has variable structure and properties, because it is a product of biological processes. It is produced by many tree species, and its production is influenced by environmental factors and heredity. As with any other material, sound knowledge of its advantages and disadvantages is prerequisite to sustainable utilization of wood. Such knowledge allow for improvement of the quality of wood produced in the forest, better use of the numerous available species, making products of the best possible quality, and reduction of waste. A good knowledge of such physical properties as shrinkage and expansion will serve as a guide to builders in selection of timber species for specific jobs. This will go a long way in solving such problems as dislodging of joints which could eventually lead to accidents. Since wood is an anisotropic material and presents differential mechanical strength (i.e. a piece of wood may be strong in compression strength, but weak in another strength parameter), it is only proper to have a good knowledge of the various strength parameters of individual commercial timbers; how a particular strength parameter is related to the anatomical structure and content of the various species. It is when this is done that a safe and economical use of the timber will be achieved. Moreover, a good understanding of the wood structure and chemical composition will in no small measure help in actualizing the full strength potentials of the numerous constructional timber materials, in order to utilize their optimal potentials. To determine the strength properties of wood, two standard alternative test methods are available [7]. These are the service tests and the laboratory methods. Service tests are carried out under conditions to which timber is exposed in service, and such conditions which are however nearly limited, cannot be exactly reproduced in the laboratory. The data take longer to collect. External factors likely to influence strength properties are more difficult to control. The decentralization of the tests increases their cost. In the laboratory methods, two classes of tests are made; namely: test on small, clear specimens and test on timbers of structural sizes. The former is of value for comparative purposes, and they provide an indication of the different strength properties of the individual timbers. The tests are designed to avoid the influence of knots and other defects in which case the results do not indicate the actual loads structural members can carry, unless a reduction factor is applied to obtain safe working stresses. Test on timber of structural size more nearly reproduce service conditions and they are of particular value because they allow for defects such as knots and splits. They have the disadvantage of being costly, because of the large amount of timber material required, and the length of time needed to load larger-sized test-pieces to the point of failure. What is clearly evident from the above is that the available testing methods (service and laboratory) for the engineering properties of wood are rigorous, slow and capital intensive. In the circumstance, the need arises for a quick, less expensive, indirect but largely reliable approach for identifying, selecting or grading constructional timber materials in order to save time, maximize cost and optimize profit. The present study is aimed at examining the possibility of an anatomical approach to achieve this goal. Providing the essential background, [9], indicated that the composition of the xylem tissue and the structural arrangement of the component elements, considerably determine the physical properties of woods and their suitability for commercial uses. The author further pointed out that such factors as fibre content of wood, fibre length, fibre cell wall thickness, vessel abundance and distribution, percentage ray volume, growth layer width and proportion of late wood had direct or indirect influence on specific gravity and strength properties of woods. The relationships were, however, not spelt out for specific timber species. In a related development, [14]opined that the structure of wood may, however, be understood not only in terms of the arrangement of its cells, but also and more fundamentally, on the basis of the organization and chemistry of the cell wall substance. The author further pointed out that the primary and secondary cell walls are composed of three major constituents: cellulose and hemi-cellulose, both polysaccharides, and lignin, an aromatic polymer derived from phenyl-propane building blocks (C6-C3 units).In consideration of an anatomical option for timber identification and grading, the present study was designed to investigate the anatomical characteristics of ten commercial timbers of Nigeria and five of the specific strength properties for such timbers. The objectives of the study are to:

1. Characterize anatomically the woods of ten timber species using the ordinary light microscope, focusing on the quantitative characteristics.

2. Determine the resistance to tensile, compression, indentation, cleavage and shear strength properties of the timber species using the laboratory method.

3. Trace aspects of relationship (positive and negative) between some anatomical parameters and strength properties.

4. Produce strength prediction equations using the anatomical parameters.

5. Make meaningful recommendations for the commercial utilization of the wood types.

Materials and Methods:

Source and Collection of Samples

All the 10 species are widely distributed in the natural rain forest zones in Nigeria and elsewhere in West Africa, where the annual rainfall is about 1500mm and above. The wood samples were supplied by the Forestry Departments in Enugu, Anambra and Abia States of Nigeria. The timbers supplied were of marketable size. The timber species were further authenticated by Professor J.C. Okafor of the Department of Applied Biology, Enugu State University of Science and Technology.

Table 1. The timber species used in this study and their families.

	Species	Family	Location of collection
1	*Ceiba pentandra* (Linn.) Gaerth.	Bombacaceae	Nsukka
2	*Diospyros mespiliformis* Linn.	Ebenaceae	Ikom
3	*Afzelia africana* Sm.	Fabaceae	Nsukka
4	*Brachystagia nigerica* Hoyle & A.P.D. Jones	Fabaceae	Aba
5	*Gossweilerodendron balsamiferum* (Verm.) Harms.	Fabaceae	Nsukka
6	*Periscopsis elata Harms.*	Fabaceae	Nsukka
7	*Khaya ivorensis* A. Chev.	Meliaceae	Onitsha
8	*Milicia excelsa* (Welw.) Cl Berg.	Moraceae	Nsukka
9	*Mansonia altissima* A. Chev.	Sterculiaceae	Enugu
10	*Gmelina arborea* Roxb.	Verbenaceae	Nsukka

A preliminary identification of the samples was made following the guidelines of [24]; [3]; [12]; [7].A confirmatory identification of the samples was made through the microscopic studies of their sections. The features observed were compared with those given by [24] and [7]. [2], identified seventeen hardwood timber species using wood microstructure.

Preparation of samples for anatomical studies:

Small blocks of wood samples from the 10 timber species were fixed in F.A.A. (Formalin-Aceto-Alcohol). This solution contains 90ml of 70% ethanol, 5ml of glacial acetic acid and 5ml of formaldehyde. This preserves the blocks and their cell contents for a long period and also softens the blocks for easy sectioning with the microtome [18].The transverse section (T.S.), the tangential longitudinal section (T.L.S.) and the radial longitudinal section (R.L.S.) of the samples were made with the aid of a Reichert sledge microtome. Each of the sections was 18-30μm thick. These were stored in distilled water in separate petri-dishes. Microscopic studies were made by mounting the various samples on a slide in water, staining with the appropriate stains and viewing under the microscope. The staining was done with following:

i. Phloroglucinol and concentrated hydrochloric acid (conc.HCl.).

ii.1% aqueous Iodine solution.

Various methods of making a permanent section have been described by [12]; [18] and [16].The method adopted in this study is as outlined by [20] and the method is as follows:

a. Sections were stained in 1% aqueous Safranine for five minutes.
b. The Safranine was drained off and the materials washed with three changes of distilled water.
c. The sections were then washed twice in absolute (98-100%) alcohol.
d. The sections were next stained with 1% Fast-green for two minutes.
e. The Fast-green was drained off and the sections washed with two changes of absolute alcohol.

f. The sections were then cleared with pure xylene for five minutes and finally mounted in Canada balsam.

Staining with Safranine and Fast-green differentiates lignified (red staining) and unlignified (green staining) tissues.

All the preparations were then examined under an ordinary light microscope at various magnifications. Photomicrographs of the preparations were taken with Ortholux binocular microscope.

Wood maceration was done using 5% potassium chlorate solution in concentrated nitric acid [12] In this method, chips of wood of 2mm thick were placed differently in long test-tubes bearing the names of the various wood samples. The test-tubes were secured in test-tube racks. Two grammes of 5% potassium chlorate (KCLO3) crystals were added to each of the test-tubes. Ten ml. of concentrated nitric acid (conc.HNO3) were carefully introduced to the test-tubes. The set-up was allowed to react in a fume cupboard, until the chips softened and bleached.

Potassium chlorate, being a strong oxidizing agent causes an instant reaction with the nitric acid to effect maceration. In tubes where the reaction was slow, the racks were put in an oven and heated to 60^0 C for several hours. This enhances the reaction and maceration of the chips.After the reaction, excess solution was decanted from the test-tubes, and the softened bleached chips washed several times in distilled water to prevent further reaction. The softened chips were then separately transferred into well-labelled specimen bottles – two bottles (A and B) for each sample. A solution made of phenol and glycerin was poured into the bottles. The phenol protects the fibres from fungal decay, while the glycerin removes air bubbles from the bottles. The chips in the bottles were shaken with glass beads. This helps the fibres to tease out and fall apart. The fibres were then stained in brilliant crystal blue and safranine for bottles A and B respectively for each of the wood samples. The stained fibres and vessels were mounted on slides in 30% glycerin, and were carefully covered with cover slips. Examinations and measurements were made under the light microscope.

Measurements

The following quantitative measurements were made with the aid of an eye – piece micrometer fitted to the eye-piece tube of the light microscope.

The counting of wood elements from the permanent slides are as follows:

(a) The number of fibres per field of view at 400x magnification. Fibres of the 10 samples were counted in the (T.L.S). A total of twenty five fields of view were counted for each sample and their means noted.

(b) The number of cells in the widest part of the largest ray cell for a particular field of view was noted, and this was done for twenty five fields of view. The means of these values were noted and the percentage ray volumes determined.

(c) The number of vessels per field of view at 100x magnification was counted. This as in the above cases was done twenty five fields of view and their mean noted.

(d) Vessel diameters in both the axial and tangential directions were measured for the 10 timber species at 100x mag. Twenty five measurements were made and their means noted.

Fibre Dimensions

The fibre dimensions were measured using a KYOWA TOKYO JAPAN monocular microscope to which an ocular micrometer was fitted. The ocular micrometer was first calibrated using a stage micrometer of 2mm range. This was done by mounting the stage micrometer on the stage of the microscope, and aligning its zero-mark with that of the ocular. The unit of the ocular, which aligns with a given unit of the stage micrometer at a given magnification, was noted. This was used as the conversion factor in the subsequent measurements.

The conversion factors were worked out as follows:

At 40× magnification,

45 unit of ocular = 1.6mm of stage,

1 unit of ocular = 1.6/45 = 0.035mm. So, the conversion factor at 40× magnification = 0.035mm.

At 100× magnification,

50 units of the ocular = 0.74mm of the stage,

1 unit of the ocular = 0.74/50 = 0.0148mm. So, the conversion factor at 100× = 0.0148mm.

At 400× magnification,

71 units of the ocular = 0.25mm of the stage,

1 unit of the ocular = 0.25/71 = 0.0035mm. So, the conversion factor at 400× = 0.004mm.

The dimensions measured were:

(i) Fibre length (L).

(ii) Fibre diameter (D).

(iii) Fibre lumen diameter (l)

(iv) Fibre cell wall thickness (C).

(v) Vessel diameter in the tangential direction (VD).

Other measured quantities include: number of vessel per field of view and number of fibres per field of view.

Twenty five fibres were measured for each of the ten timbre species. From the dimensions got from the measurements, derived values were calculated. The formulae used in the various calculations were:

(a) Runkel ratio (RR) = 2C/l.

(b) Coefficient of flexibility (CF) = l/D.

(c) Slenderness ratio (SR) = L/D.

The various fibre dimensions and the derived values of the timber species were analysed and then compared with their compression strength, tensile strength, shear strength, cleavage strength and indentation strength. This was aimed at determining if any of the measurable or derived fibre values could serve as an anatomical indicator of strength (i.e. along the grain in the above named strength parameters).

Strength parameters

The preparation of the samples for the various strength tests was based on the British Standard BS 373 (1957) 'Methods of Testing Small Clear Specimens of Timer', which is currently used in most International Timber Research Centres. This was equally recommended in the Bulletin of the Forest Research Laboratory, NO.50 (1969), and in the Technical Note NO. 10 of the Princess Risborough Laboratory entitled "The Strength of Timber" (1977). The samples were cut using a BOSCH JIG –SAW machine (model GST 85 PBE 500W). These clear samples were oven-dried at 103^0C for several hours and weighed at intervals until no further differences in weight were recorded. The cuttings were done as follows:

Compression Strength

Twenty five clear small samples of each of the timber species were cut to the dimension 60×20×20mm from the heartwood portion of each of the ten timber species. These were oven-dried at 103^0 C for several hours and weighed at intervals until no further differences were recorded. The samples were wrapped in plastic bags to protect them from absorbing moisture from the atmosphere. They were tested to know the maximum amount of force (in Newtons), which would cause the samples to fail structurally. This was read off from the graph plotted by the Hounsfield tensometer as the tests were performed. The Hounsfield Tensometer machine used in this work is of the Civil Engineering Department of University of Nigeria Nsukka.

Tensile Strength

Twenty five clear small samples of each of the timber species were cut to the dimension 300mm in length, with a cross section of 20mm at the ends, waisted to 6×3mm. These were cut from the heartwood portion of the timber species. They were equally treated as in the case of compression strength, but were tested using a different adapter specifically designed for tensile strength tests with the tensometer.

Shear Strength

Twenty five clear small samples of each of the ten timber species were cut to the dimension 20mm×20mm×20mm feated as in the case of compression test, but were tested using the adapter for shear strength test with the tensometer.

Cleavage strength

Twenty five clear small samples of each of the ten timber species were cut to the dimension 45mm×20mm×20mm cut from the heartwood portion of the timber species. The samples were cut at one end to accommodate the grips of tensometer adapter.

Indentation test

Twenty five clear small samples of each of the tem timer species were cut to the dimension 20mm×20mm×20mm as in the shear test from the heartwood portion of the timber species. This assesses the resistance of wood to the impregnation of a special hardened steel tool (Janka) rounded to a diameter of 11.3mm embedded to half its diameter.

Statistical analysis

Correlation analysis was ran between wood anatomical parameters and the various strength parameters using the SPSS and GenStat statistical packages. A correlation matrix table was generated in respect to these comparisons. Regression analysis was also ran in the same manner as with correlation, and prediction equations derived.

Results

. Quantitative anatomical characteristics of the Timber species:

The mean measurable anatomical characteristics of the ten timber species are given in Table 2

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Table 2: Mean dimensions values of the elements studied (mm)

Species	Mean fibre length	Mean fibre diameter	Mean fibre lumen diameter	Mean fibre cell wall thickness	Mean Runkel ratio
CEI	0.613	0.036	0.026	0.005	0.448
DIO	0.920	0.018	0.009	0.005	1.211
AFZ	1.482	0.040	0.015	0.007	1.215
BRA	1.375	0.019	0.010	0.005	1.036
GOS	1.289	0.033	0.023	0.005	0.492
PER	1.219	0.021	0.007	0.007	2.107
KHA	1.628	0.023	0.012	0.006	1.334
MIL	1.271	0.020	0.012	0.004	0.883
MAN	1.007	0.021	0.012	0.005	0.910
GME	1.217	0.033	0.025	0.005	0.390

LSD (0.05) Between 2 species means.	0.1255	0.0104	0.0029	0.00087	0.3607

CEI=*Ceiba pentandra* DIO=*Diospyros mespiliformis* AFZ=*Afzelia africana* BRA= *Brachystegia nigerica* GOS=*Gossweilerodendron balsamiferum* PER=*Periscopsis elata* KHA=*Khaya ivorensis* MIL= *Milicia excelsa* MAN=*Mansonia altissima* GME=*Gmelina arborea.*

Table 2. (Contd.): Mean dimensions values of the elements studied (mm).

Species	Mean Coefficient of flexibility	Mean Slenderness ratio	Mean vessel dia. in tang.dir.	Mean no. of fibres per view.	Mean number of vessels per field of view
CEI	0.699	47.074	0.223	7.040	5.440
DIO	0.471	50.622	0.097	19.400	14.800
AFZ	0.511	53.705	0.198	17.240	5.200
BRA	0.514	60.282	0.167	30.760	5.560
GOS	0.693	41.785	0.170	14.880	5.000
PER	0.342	56.999	0.096	16.360	34.400
KHA	0.492	75.507	0.158	17.920	12.000
MIL	0.566	62.533	0.200	25.600	4.920
MAN	0.560	47.206	0.089	11.640	64.600
GME	0.736	38.411	0.162	18.000	5.960
LSD (0.05) Between 2 species means	0.0593	8.4079	0.0253	2.7196	3.1278

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The strength parameters of the ten timber species are given in table 3.

Table 3. **Mean strength values of the timber species (N).**

Species	Cleavage	Compression	Shear	Tensile	Indentation
CEI	148.400	1792.800	914.800	601.600	719.400
DIO	456.710	6710.400	1546.000	1248.800	571.200
AFZ	417.200	8358.400	2452.000	1156.400	458.200
BRA	307.700	6177.600	939.600	878.400	743.020
GOS	301.400	4963.200	1542.800	931.200	711.700
PER	345.100	8240.800	1855.200	1136.400	735.690
KHA	362.300	5440.800	1122.000	930.400	511.900
MIL	198.100	6214.400	1641.200	761.200	779.100
MAN	209.520	6892.800	1181.200	1201.200	812.600
GME	311.600	5153.600	1955.600	1038.800	748.400
LSD (0.05) Between 2 species means.	44.2965	448.6733	239.1415	121.9304	57.3434

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A correlation matrices table between the anatomical and strength parameters are given in table 4. The prediction equations for strength using the anatomical parameters are given in Tables 5 to 9. Figure1. shows a photomicrograph of macerated pulp of *Gmelina arborea* wood, which was one of the timber species worked on.

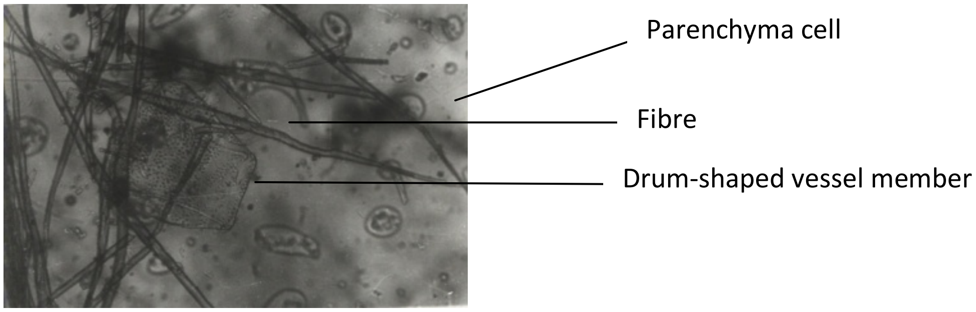

Fig. 1 showing parenchyma cells, fibres and a large drum-shaped vessel.
a= parenchyma cell, b = fibre cell and c = vessel member

Table 4.**Correlations of anatomical and strength parameters the timber species**.

	Fibre length	**Fibre diameter**	**Fibre lumen diameter**	**Fibre cell wall tickness**	**Coefficient of flexibility**	**Runkle Ratio**	**Slenderness ratio**	**No. of fibres/field of view**	**No. of vessels/field of view**	**Vessel dia. in tang. dir**	**Compression strength**	**Cleavage strength**	**Shear strength**	**Indentation strength**	**Tensile strength**
Fibre length	1														
Fibre diameter	.093	1													
Fibre lumen diameter	.176**	.331**	1												
Fibre cell wall thickness	.122	.047	- .211**	1											
Coefficient of flexibility	.063	.223**	.821**	- .548**	1										
Runkle Ratio	- .036	- .140*	- .621**	.672**	- .839**	1									
Slenderness ratio	.420**	- .074	- .511**	-. 045	- .436**	.287**	1								
No. of fibres/field of view	- .047	- .151*	- .338**	-.099	- .164**	.091	.195**	1							

No. of vessels/field of view	- .383**	- .149*	- .292**	.028	- .242**	.210**	- .054	- .275**	1						
Vessel diameter in tangential direction	.373**	.085	.269**	.091	.228**	- .176**	- .003	.038	- .510**	1					
Compression strength	- .287**	- .105	- .546**	.231**	- .495**	.408**	.118	.296**	.338**	- .348**	1				
Cleavage strength	- .092	.000	- .227**	.107	- .291**	.234**	.042	.188**	- .129*	- .217**	.399**	1			
Shear strength	- .119	.083	.020	.181**	- .082	.087	- .108	- .026	- .107	- .025	.403**	.302**	1		
Indentation strength	- .128*	- .023	.070	- .230**	.165**	- .104	- .099	.010	.267**	- .082	- .177**	- .429**	- .204**	1	
Tensile strength	**- .299****	**- .040**	**- .267****	**.138***	**- .273****	**.213****	**- .053**	**- .004**	**.339****	**- .420****	**.467****	**.379****	**.240****	**- .127***	**1**

**.Correlation is significant at the 0.01 level (2-tailed) *.Correlation is significant at the 0.05 level (2-tailed)

Table 5. Prediction equations: prediction of compression of strength using the anatomical parameters $\hat{Y}$= Compression Strength. X= Anatomical parameters.

Anatomical parameters	Prediction equations: $\hat{Y}$= bx + a	Correlation coefficient	Slope(b)	Intercept(a)	Validity
Fibre length	-1788.778x + 8323.755	-0.287	-1788.778**	8323.755**	+
Fibre diameter	-10339.411x + 6269.632	-0.105	-10339.411^{ns}	6269.632**	-
Fibre lumen diameter	-129135.685x + 7938.230	-0.546	-129135.685**	7938.230**	+
Fibre wall thickness	239198.633x + 4693.239	0.222	239198.633**	4693.239	+
Runkel ratio	993.206x + 4998.565	0.408	993.206**	4998.565**	+
Coefficient of flexibility	-6204.527x + 9458.840	-0.495	-6204.527**	9458.840**	+
Slenderness ratio	12.713x + 5315.472	0.118	12.713^{ns}	5315.472**	-
Vessel diameter in tangential direction	-10756.265x + 7671.433	-0.348	-10756.265**	7671.433**	+
No. of fibres per field of view	73.006x + 4688.842	0.296	73.006**	4688.842**	+
No. of vessels per field of view	34.202x + 5454.494	0.338	34.202**	5454.494**	+

*= Significant at 5% α-level; **=Significant at 1% α-level; ns=Not significant; (+) =Valid prediction equation; (-) = Not valid prediction equation.

Table 6. Prediction equations: prediction of Cleavage strength using the anatomical parameters $\hat{Y}$= Cleavage Strength. X= Anatomical parameters.

Anatomical parameters	Prediction equations: $\hat{Y}$= bx + a	Correlation coefficient	Slope(b)	Intercept(a)	Validity
Fibre length	-35.676x + 363.158	-0.092	-35.676^{ns}	363.158**	-
Fibre diameter	-5.379x + 306.846	0.000	-5.379^{ns}	306.846**	-
Fibre lumen diameter	-3328.879x + 356.809	-0.227	-3328.879**	356.809**	+
Fibre wall thickness	6973.426x + 268.768	0.104	6873.426^{ns}	268.768**	-
Runkel ratio	35.316x + 271.290	0.234	35.316**	271.290**	+
Coefficient of flexibility	-226.508x + 433.176	-0.291	-226.508**	433.176**	+
Slenderness ratio	0.284x + 291.547	0.042	0.284^{ns}	291.547**	-

Vessel diameter in tangential direction	-416.955x + 371.708	-0.217	-416.955**	371.708**	+
No. of fibres per field of view	2.880x + 255.191	0.188	2.880*	255.191**	+
No. of vessels per field of view	-0.812x + 319.522	-0.129	-0.812*	319.522**	+

*= Significant at 5% α-level; **=Significant at 1% α-level; ns=Not significant; (+) =Valid prediction equation; (-) = Not valid prediction equation.

Table 7. Prediction equations: prediction of Shear strength using the anatomical parameters $\hat{Y}$= Shear Strength. X= Anatomical parameters.

Anatomical parameters	Prediction equations: $\hat{Y}$= bx + a	Correlation coefficient	Slope(b)	Intercept(a)	Validity
Fibre length	-238.041x + 1825.008	-0.119	-238.041^{ns}	1825.008**	-
Fibre diameter	2641.283x + 1444.750	0.083	2641.283^{ns}	1444.750**	-
Fibre lumen diameter	1489.560x + 1492.619	0.020	1489.560^{ns}	1492.619**	-
Fibre wall thickness	61463.641x + 1180.678	0.177	61463.641*	1180.678**	+
Runkel ratio	67.914x + 1446.941	0.087	67.914^{ns}	1446.941**	-
Coefficient of flexibility	-330.344x + 1699.491	-0.082	-330.344^{ns}	1699.491**	-
Slenderness ratio	-3.754x + 1715.544	-0.108	-3.754^{ns}	1715.544**	-
Vessel diameter in tangential direction	-250.944x + 1554.163	-0.025	-250.944^{ns}	1554.163**	-
No. of fibres per field of view	-2.047x + 1551.654	-0.026	-2.047^{ns}	1551.654**	-
No. of vessels per field of view	-3.492x + 1570.165	-0.107	-3.492^{ns}	1570.165**	-

*= Significant at 5% α-level; **=Significant at 1% α-level; ns=Not significant; (+) =Valid prediction equation; (-) = Not valid prediction equation.

Table 8. Prediction equations: prediction of indentation strength using the anatomical parameters $\hat{Y}$= Indentation Strength. X= Anatomical parameters.

Anatomical parameters	Prediction equations: $\hat{Y}$= bx + a	Correlation coefficient	Slope(b)	Intercept(a)	Validity
Fibre length	-62.266x + 760.201	-0.128	-62.266*	760.201**	+
Fibre diameter	-175.406x + 488.664	-0.023	-175.406^{ns}	488.664**	-

Fibre lumen diameter	1295.049x + 659.628	0.070	1295.049^{ns}	659.628**	-
Fibre wall thickness	-19325.055x + 784.095	-0.230	-19325.055**	784.095**	+
Runkel ratio	-19.899x + 699.075	-0.104	-19.899^{ns}	699.075**	-
Coefficient of flexibility	162.257x + 588.523	0.165	162.257*	588.523**	+
Slenderness ratio	-0.836x + 723.790	-0.099	-0.836^{ns}	723.790**	-
Vessel diameter in tangential direction	-197.170x + 709.861	-0.082	-197.170^{ns}	709.861**	
No. of fibres per field of view	0.194x + 675.652	0.010	0.194^{ns}	675.652**	-
No. of vessels per field of view	2.120x + 645.646	0.267	2.120**	645.646**	+

*= Significant at 5% α-level; **=Significant at 1% α-level; ns=Not significant; (+) = Valid prediction equation; (-) = Not valid prediction equation.

Table 9. Prediction equations: prediction of Tensile strength using the anatomical parameters. $\hat{Y}$= Tensile Strength. X= Anatomical parameters.

Anatomical parameters	**Prediction equations: $\hat{Y}$= bx + a**	**Correlation coefficient**	**Slope(b)**	**Intercept(a)**	**Validity**
Fibre length	-278.325x + 1350.863	-0.299	-278.325**	1350.863**	+
Fibre diameter	-586.108x + 1004.037	-0.040	-586.108^{ns}	1004.037**	-
Fibre lumen diameter	-9420.589x + 1130.239	-0.267	-9420.589**	1130.239**	+
Fibre wall thickness	22037.453x + 868.733	0.138	22037.453*	868.733**	+
Runkel ratio	77.432x + 910.797	0.213	77.432**	910.797**	+
Coefficient of flexibility	-510.788x + 1273.644	-0.273	-510.788**	1273.644**	+
Slenderness ratio	-0.854x + 1034.046	-0.053	-0.854^{ns}	1034.046**	-
Vessel diameter in tangential direction	-1934.809x + 1290.055	-0.420	-1934.809**	1290.055**	+
No. of fibres per field of view	0.140x + 985.947	0.004	0.140^{ns}	985.947**	-
No. of vessels per field of view	5.123x + 907.559	0.339	5.123**	907.559**	+

*= Significant at 5% α-level; **=Significant at 1% α-level; ns=Not significant; (+) = Valid prediction equation; (-) = Not valid prediction equation.

Discussion

In the present work, the anatomical characteristics showed variations in fibre length; fibre diameter; fibre lumen diameter; fibre cell wall thickness; number of fibres per field of view; number of vessels per field of view; vessel diameter in the tangential direction and in the derived values: Runkel ratio; slenderness ratio; coefficient of flexibility (Table 2). Variations occurred also among the species in all the strength parameters assessed (Table 3). This conforms to the report of Wilson and White (1986), who showed that no two pieces wood, even if cut from the same tree, are exactly alike. The strength parameters tested equally varied significantly among the timber species.

The composition of the secondary xylem (wood) tissue and the structure and arrangement of the component elements determine the physical properties of the wood and their suitability for commercial uses [10], [19]; [9]. These properties are manifold and not necessarily correlated, so that a given wood may be strong with reference to one force and weak with reference to another [9]; [24].

According to [9], the specific gravity is probably the most important single characteristic that gives an indication of strength of wood. In an absolutely dry wood, specific gravity depends on the volume of wall material and its chemistry. The specific gravity of the wall material has been calculated to be between 1.40 and 1.62, but because of variable proportions of walls in the different woods, their specific gravity may be as low at 0.04 and as high at1.46 [19].According to [5] [22] [21] and [15] the relationship between mechanical and anatomical properties of plant tissues has been the subject of considerable speculation because it is evident that, aside from their physiological functions, every tissue type contributes in some way to the mechanical behavior of organs. Correlation analysis shows a highly significant negative relationship between fibre length and compression, indentation, and tensile strengths. This mean that timbers with long fibres have low resistance to compression, indentation and tensile forces. In the foregoing, *Diospyros mespiliformis* and *Mansonia altissima* with fiber lengths of 0.920mm and1.007mm respectively are expected to perform better against these forces than the rest of the species whose fibre are quite long. Fibre diameter size had no significant correlations with any of the five strength parameters, even though negative relationships exist between it and compression, indentation and tension and positive relationships with shear and cleavage. This is in contrast to the report of [13], where it was reported that the proportion of large fibres influence strongly but negatively the density, cleavage, hardness and shear strengths.

Fibre lumen diameter showed highly significant negative correlations with compression, cleavage and tensile forces. This means that the narrower the fibre lumen, the more resistant the timber is to this three forces. *Periscopsis elata* and *Diospyros mespiliformis* lumen diameters of 0.007 mm and 0.009 mm respectively are expected to perform better than the other timbers whose fibre lumina are wider. Fibre cell wall thickness had highly significant positive correlations with compression and tensile strengths and a highly significant negative correlation with indentation strength. This implies that the thicker the fibre cell wall, the timbre resists compressive and tensile forces; while it becomes more vulnerable to indentation forces. In other words *Afzelia africana* and *Periscopsis elata* with fibre cell wall thickness of 0.007 mm and 0.007mm respectively to perform better than the rest whose fibre cell wall thickness are lower against compression and tension, but will show the least resistance to indentation force. [25] reported that wood cell walls consist of three main components which affect its performance as a material.The number of fibres per field of view had a highly significant positive correlation with compression and cleavage strengths and as such an increase in the number of fibres results to an increase in the resistance of the timber to compressive and cleavage forces. *Brachystegia nigerica* and *Milicia excelsa* with 30.760 and 25.600 fibres per field of view respectively are expected to perform better than *Gmelina arborea* and *Mansonia altissima* with 7.040 and 11.640 fibres, with respect to compressive and cleavage forces.[6], reported that fibre-wall volume and mean thickness of individual fibre wall had a rough relation to strength.

The number of vessels per field of view gave highly significant positive correlation with compression, indentation and tensile strengths, while giving a highly significant negative correlation with cleavage strength. So, the more the number of vessels per field of view, the more the resistance of the timber to compression, indentation and tensile forces, while the resistance to cleavage force reduces. *Mansonia altissima* and *Periscopsis elata* with 64.600 and 34.400 respectively are expected to give better resistance to compression, tension and indentation forces than *Milicia excelsa* with 4.920 and the rest the species, but both will give low resistance to cleavage. The vessel diameter in the tangential direction had highly significant negative correlation with compression, cleavage and tensile strength. This is to say that the narrower the tangential vessel diameter, the higher the resistance of timbers to these forces. *Mansonia altissima*, Periscopsis elata and *Diospyros mespiliformis* with tangential vessel diameter of 0.089 mm, 0.096 mm and 0.097 mm respectively are expected to offer higher resistance to compressive, cleavage and tensile forces than the rest of the timbers with wider tangential diameters.In the three derived fibre values: slenderness ratio showed no significant correlation; coefficient of flexibility and Runkel ratio showed highly significant correlations which seemed almost antagonistic in nature. While coefficient of flexibility showed a highly significant negative correlation with compression, cleavage and tension, and a highly significant positive correlation with indentation strengths, Runkel ratio showed high significance positively with compression, cleavage and tension. These mean that increase in coefficient of flexibility reduces the resistance of timber to compressive, cleavage and tensile forces, but increases its resistance to indentation; an increase in Runkel ratio results in a corresponding increase in resistance of the timber compression, cleavage and tensile forces. *Periscopsis elata* and *Diospyros mespiliformis* with coefficient of flexibility of 0.342 and 0.471 respectively are expected to show better resistance to compression, cleavage and tension than the rest of the species, but lower in resistance to indentation force. [1], observed that positive correlations exist between static bending strength of timbers and fibre cell wall thickness, fibre Runkel ratio, fibre slenderness ratio and fibre content. They equally observed negative correlations between static bending strength of the timbers and fibre length, fibre diameter, fibre lumen diameter, fibre coefficient of flexibility, vessel diameter, and vessel length of the same timbers.

In conclusion, the above reports point to the fact that timber is a highly variable material. In contrast to metals and other materials of homogeneous structure, wood exhibits mechanical properties in different growth directions (axial, radial and tangential) - and therefore, is mechanically anisotropic. So, in order to make a proper selection of timber in structural and other constructional works, there is the need to have sound knowledge of the nature of the strength of the various timber species options that are available. The present study considered anatomical options in the grading of timbers using anatomical indices. Structural problems in wooden structures like creeping in wooden book shelves, distortions in the roof of houses, collapse of mine-props etc. could be significantly reduced when the mechanical properties of wood materials used in their erection are known. The strength parameters of relatively unknown species could be worked out, using their anatomical parameters based on the prediction equations produced.

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