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Modeling of Physical and Mechanical Properties of five Wood Species growing in North Darfur with Anatomical Properties.

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Abstract

The strong relationship between anatomical properties of wood and many of its other properties was known for some time but it was not possible to quantify these relationships due to the difficulty in the past to make quantitative analysis for wood anatomy. With the discovery of the stereological techniques which facilitated the quantitative analysis of wood anatomy it became possible to establish mathematical models relating physical, mechanical and other wood properties to anatomical properties. The main objective of this study was to determine some anatomical, physical, mechanical, and technological properties of the studied wood species and establish relationships between anatomical properties, as independent variables, and the other properties, as dependent variables, in the form of mathematical models with which we can predict physical and mechanical properties from anatomical properties and find the most important anatomical properties affecting the other properties. All anatomical properties were determined from macerated fibers. The physical properties tested comprised density, moisture content and shrinkage. Static bending was also carried out for determining modulus of rupture (MOR) and modulus of elasticity (MOE). This, in addition to compression parallel to the grain (COM). All physical and mechanical properties were carried out according to standard procedures. Analysis of variance, correlation analysis, simple regression and multiple regression analysis were carried out to achieve the objectives. The results of the analysis of variance revealed significant differences in most of the properties studied – anatomical, physical and mechanical between the five species. The details of these results are given in the first paper.

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Key Words: Anatomical Properties; Physical Properties; Mechanical Properties; Modelling.

Introduction

Measurements of various characteristics of wood cells are made for driving structure- property relationships. The fiber dimensions measured include fiber length, cell diameters, lumen diameter and cell wall thickness. Many methods have been used for direct measurement of the above structural characteristics. All these methods were tedious and not adequately accurate. Recently quantitative characterization of wood structure using stereological techniques has been used for establishing structure- property relationships (Nasroun, 1978). Stereology is a body of methods for the exploration of three dimensional spaces, when only two dimensional sections through solid bodies or their projections on a surface are available. These were introduced as fast and adequately accurate methods for quantitative characterization of wood. The techniques rely on counts rather than direct measurements. In such investigations systematic point counts, boundary intersection counts and feature counts are used (Nasroun, 1997). Stereological methods were used to evaluate different characteristics and avoid the disadvantage of manual methods which are time – consuming and laborious. Quantitative characterization involves the application of geometrical- statistical formulae. The principles and techniques of stereology are applied to transverse microtome sections of wood or to randomly distributed macerated wood fibers deposited on microscope glass slide. Stereology as a method of quantitative microscopy has been described by Underwood (1970). In many studies the images of transverse sections of wood or randomly mounted wood fiber were examined. Wood density and wood specific gravity both indicate the amount of actual wood substance present in a unit volume of wood (Nasroun, 2005; Zobel and Jett, 1995). Wood density is not a simple characteristic. It is affected by the cell wall thickness, the cell diameter, the earlywood to latewood ratio and the chemical content of the wood (Cave and Walker, 1994). Density of wood is its single most important physical property. It is considered the best single index for overall wood quality. Most mechanical properties of wood are closely correlated with density. The anatomical variations between hardwood species has significant effect on physical, mechanical and other properties and hence their utilizations. All wood properties are affected by the anatomical structure of wood. Because the relationships are so close it was important to quantify them in the form of mathematical models for predicting other wood properties from their anatomical structure. Ifju *et al* (1978) investigated the relationships between anatomical properties of seven tropical hardwood species growing in Sudan and their papermaking properties. They found that the relationships varied with beating time. In case of unbeaten pulp, fiber length and proportion of fiber lumen were the principles factors influencing breaking length. The model of unbeaten pulp indicated that the fiber length negatively influenced breaking length. In case of pulp beaten for 110 minutes however, breaking length and fiber length were positively related.

This paper aims at establishing relationships between each of the physical and mechanical properties as a dependent variable and the anatomical properties as independent variables. This, in turn, will indicate the most important anatomical properties affecting each of the physical and mechanical properties under study.

Materials and Methods

Material

Table1 shows a list of the wood species used in this investigation given by their scientific names, common names and their families.

Table 1. The list of wood species under investigation

Family	Species	
	Scientific name	Common name
Balanitaceae	1-Balanites aegyptiaca	Heglig
Myrtaceae	2-Eucalyptus camaldulensis	Kafour
Mimosaceae	3-Acacia nilotica	Sunt
	4-Acacia seyal	Talh
Leguminosae	5-Faidherbia Albida	Hraz

Methods

Determination of Anatomical Properties

All anatomical properties were determined from macerated fibers, as described in details in Mohammed, *et al* (2019). The fiber length was determined using stereological techniques on macerated fiber. The other anatomical characteristics measured included fiber length (FLmm), fiber diameter (FD μ m), fiber lumen diameter (FLD μ m), double cell wall thickness (DCWT μ m), rankles ratio (RR), coefficient of cell rigidity (CR), and fiber flexibility (FF).

Physical and Mechanical Properties

The physical properties tested comprised density, which was determined using Sudanese Standard 1512-2:2015: *Wood – determination of density for physical and mechanical tests*. and shrinkage in accordance to Sudanese Standard 1748:2013 *Wood – determination of radial and tangential shrinkage*. Static bending was also carried out for determining modulus of rupture (MOR) and Modulus of elasticity (MOE) according to the Sudanese Standard 5176: 2012. *Wood – determination of ultimate strength in static bending*. This, in addition to compression parallel to the grain (COM), which was carried out according to ISO Standard 3787 – 1976 *Wood – determination of ultimate stress of compression parallel to the grain*. More details of these methods are given in Mohammed *et al* (2019).

Statistical Analysis

Analysis of variance and Duncan's Multiple Range Test (DMRT) were conducted looking for significant differences in all studied properties between the species and separating the means. This was followed by correlation analysis to estimate the degree to which two variables vary together, and indicate the significant relationships between pairs of dependent and independent variables. This helped in conducting simple

regression analysis to find the key anatomical properties affecting the different physical and mechanical properties. Finally these relationships were modeled by multiple regression analysis.

Results and Discussion

The results of the analysis of variance revealed significant differences in most of the anatomical properties between species (More details in Mohammed, *et al*, 2019)). Fiber length ranged between 2.28mm for kafour to 1.45mm for haraz. Fiber diameter, on the other hand ranged between 16.75µm for sunt to 14.11µm for haraz. Fiber lumen diameter was highest for haraz (7.83µm) and lowest for talh (6.12µm). Double cell wall thickness, on the other hand, ranged between 8.95µm for sunt and 6.22µm for haraz. Runkle ratio, however, was highest for talh (1.83) and lowest for haraz (0.84). For coefficient of cell rigidity talh was highest (0.29), while haraz was the lowest (0.22). Fiber Flexibility ranged between 0.55 for haraz and 0.43 for Kafour. Table 2 in the first paper also revealed significant differences in volume fractions of cell types (Vessels, fibers and parenchyma) and cell components (cell walls and cell lumens). Most of these results were comparable to what was obtained Nasroun (1978) except for fiber length which was longer, in average than that of Nasroun. The physical properties in table 3 in the first paper showed that density ranged from 0.95g/cm³ for sunt to 0.50g/cm³ for haraz. The densities of sunt and talh were in the upper end of the range and were higher than what was obtained by Nasroun (2005). Shrinkage, however, showed no significant variation between the species. The mean values for tangential shrinkage ranged between 12.20% for kafour and 11.12% for talh, while radial shrinkage was highest in haraz (5.56%) and lowest in talh (5.21%). In general the shrinkage values were higher than those of Nasroun (2005). Kafour, however, showed comparable shrinkage values with that obtained by Nasroun and Alshahrani (1998).

With regards to mechanical properties (table 3 in the first paper) modulus of rupture ranged between 139.7 MPa for sunt and 68.7 MPa for haraz. Compression parallel to the grain ranged between 68.4 MPa for sunt to 35.8 MPa for haraz, while modulus of elasticity for bending was highest for sunt (12873.6 MPa) and lowest for haraz (6507 MPa). Modulus of elasticity for compression parallel to the grain, on the other hand, ranged between 2413.5 MPa for talh and 1000.8 MPa for haraz. Most of the mechanical properties were lower than the results recorded by Nasroun (2005).

Structure-property Relations

Correlation analysis

Table 1 shows the results of correlation analysis between dependent variables (MOR, COM, MOE, MOC and DEN) and the independent variables (anatomical properties). Only the significant correlations were recorded in order to be used in both simple regression and multiple regressions. The table indicated that Modulus of Rupture was positively correlated with fiber diameter ($R=0.33658$, $P=0.0096$), double cell wall thickness ($R=0.591$, $P<0.0001$), rankle ratio ($R=0.03539$, $P=0.0045$) and Coefficient of Cell Rigidity ($R=0.04033$, $P=0.0045$), but negatively correlated with the fiber flexibility ($R=-0.4299$, $P=0.0020$). It also showed that compression parallel to the grain was positively correlated with double cell wall thickness ($R=0.5481$, $P<0.0001$), coefficient of cell rigidity ($R=0.3748$, $p=0.00084$) and rankle ratio ($R=0.03575$, $P=0.0136$), while it is negatively correlated with the fiber flexibility ($R=0.40299$, $P=0.0034$). Modules of Elasticity from bending and modulus of elasticity from compression parallel to the grain showed the same trends as MOR.

Finally density showed positive correlations with fiber diameter ($R=0.4121$, $P=0.0029$), double cell wall thickness ($R=0.6090$, $P<0.0001$) rankle ratio ($R=0.3716$, $P=0.0101$) and coefficient of cell rigidity ($R=0.4260$, $P=0.0020$).

Table 1. Results of Correlation Analysis.

	MOR	COM	MOE	MOC	DEN
FD	R=0.3658 P= 0.0096		R=0.4121 P= 0.0029		R=0.3121 P= 0.0158
DCWT	R=0.5915 P= 0.0001	R=0.5481 P=0.0001	R=0.6090 P= 0.0001	R=0.3555 P=0.0113	R=0.5400 P= 0.0001
RR	R=0.3539 P= 0.0015	R=0.3575 P= 0.0136	R=0.3716 P= 0.0101	R=0.3467 P=0.0147	R= 0.3374 P= 0.0204
CR	R=0.4033 P= 0.0045	R= 0.3748 P= 0.0080	R=0.3396 P=0.0170	R=0.3742 P=0.0074	R=0.3074 P= 0.0316
FF	R= -0.4299 P= 0.0020	R=-0.4062 P= 0.0034	R=-0.4260 P=0.0020	R=-0.4260 P=0.0020	
PpCW	R=0.5841 P=0.0001	R=0.7294 P= 0.0001	R=0.6579 P= <0.0001	R=0.5778 P=0.0001	R=0.6636 P=0.0001
PpCL	R=-0.6029 P=0.0001	R=-0.7359 P=0.0001	R=-0.6440 P= 0.0001	R=-0.5842 P=0.0001	R=-0.6482 P=0.0001

*** Where:**

MOR= Modulus of Rupture, COM= Compression parallel to the grain, MOE= Modulus of Elasticity for bending, MOC = modulus of elasticity for compression, DEN = Density, FD = fiber diameter, LD = lumen diameter, RR = rankle ratio, CR = coefficient of cell rigidity, FF = coefficient of cell flexibility, PpCW = volume fraction of total cell wall, PpCL = Volume fraction of total cell lumen.

Results of simple regression

Tables 2a – 2e show the results of simple regression analysis. It shows equations relating each dependent variable to different individual independent variables with R- squares and the significance levels. Although all models were significant at different levels, R-square values were quite low.

Table 2a shows the results of simple regression analysis for MOR with important anatomical factors. It indicated that the most important anatomical factors affecting MOR are DCWT, PpCL and PpCW in this order of importance according to the values of R-square. These were followed by CR, FF, RR and FD. DCWT, PpCL and PpCW however, affect MOR to a lesser degree than they affect the other properties below.

Table 2a: Simple regression analysis of modulus of rupture

No	Regression models	R - square	Significant level (%)
1	MOR=33.22+5.02FD	0.1316	P=0.0096
2	MOR=10.32+12.30DCWT	0.3833	P=0.0001
3	MOR=69.70+31.81RR	0.1397	P=0.0075
4	MOR=13.07+354.96CR	0.2190	P=0.006
5	MOR=188.32-171.37FF	0.1890	P=0.0016
6	MOR=58.32+88.43Pp CW	0.3411	P=0.0001
7	MOR=149.01-92.40PpCL	0.3635	P=0.0001

Table 2b shows the results of simple regression analysis for MOE with anatomical properties. The models showed similar trends as with MOR (table 2a), with slight change in the order, whereby PpCW and PpCL had higher R – square values than those obtained with DCWT.

Table 2b. Simple regression analysis of modulus of elasticity from bending with anatomical properties

No	Regression models	R - square	Significance level
1	MOE=662.46+1120DCWT	0.3776	P=0.0001
2	MOE=1840.50+518.00FD	0.1666	P=0.0033
3	MOE=6221.48+2748.63RR	0.1267	P=0.0112
4	MOE=2001.11+28261CR	0.1648	P=0.0034
5	MOE=16032-13810FF	0.1457	P=0.0062
6	MOE= 4424.22+9141.41PpCW	0.4328	P=0.0001
7	MOE= 1358-9058.52 PpCL	0.4147	P=0.0001

Table 2c shows the results of simple regression analysis for compression parallel to the grain with anatomical properties, with similar trends as the above models. However, the values of R-square increased with PpCW and PpCL, indicating that these two properties affect compression parallel to the grain more than they affect MOR and MOE. The reverse was the case with DCWT, whose effect on compression was less than its effect on MOR and MOE. Unlike tables 6a and 6b the effect of FD on compression was not significant, therefore the model disappeared from this table.

Table 2c: Simple regression analysis of compression with anatomical properties.

No	Regression models	R-square	Significant level (%)
1	COM=89.91-74.35FF	0.1544	P=0.0048
2	COM=12.13+160.52CR	0.1944	P=0.0014
3	COM=36.87+15.18RR	0.1376	P=0.0080
4	COM=16.25+4.88DCWT	0.2626	P=0.0001

5	COM=79.08-54.13 PpCL	0.5415	P=0.0001
6	COM=25.29+53.00 PpCW	0.5320	P=0.0001

Table 2d shows the results of regression analysis for modulus of elasticity from compression test (COM) with anatomical properties. Here the results are quite different from the above mentioned tables. First, because DCWT seems to have a negligible effect on MOC as can be seen from the extremely small value of R-square. This, in spite of the fact that the correlation between the two properties as shown in table (1) was much better. Moreover, the relation with FD was not significant and the model did not appear in the table. Like in all the above tables PpCW and PpCL were the most important anatomical factors affecting MOC.

Table 2d Simple regression analysis for modulus of elasticity from compression with anatomical properties.

No.	Regression models	R -square	significance level %
1	MOC=831.32 + 128.71 DCWT	0.0795	P = 0.0475
2	MOC=1003.69 + 709.28 RR	0.1311	P = 0.0098
3	MOC= 152.31 + 7501 CR	0.1852	P = 0.0018
4	MOC= 3399.98 – 3298.85 FF	0.1326	P = 0.0093
5	MOC= 575.37 + 2286 PpCW	0.4342	P=0.0001
6	MOC= 2890.63 – 2302.59PpCL	0.4329	P= 0.0001

Table 2e shows the results of simple regression for density with anatomical properties. Only four models were significant, with PpCW and PpCL being the most important properties affecting density, followed by DCWT and finally CR. The models with FD, RR and FF were not significant.

Table 2e: Simple regression analysis of density with anatomical properties

No	Regression models	R - square	Significance level
1	DEN=0.2027+0.0680DCWT	0.2599	P=0.0002
2	DEN=0.2626+10783CR	0.1224	P=0.0127
3	DEN= 1.04-0.67TCL	0.4201	P=0.0001
4	DEN= 0.3640+0.68TCW	0.4403	P=0.0001

Mathematical Models

Table 7 shows the results of multiple regressions. The results represent the models relating the individual dependent variables (physical and mechanical properties) to the independent variables (the anatomical characteristics). Model 1 in the table shows the relationship between modulus of rupture (MOR) and all anatomical characteristics which are significantly correlated to MOR. They included FD, DCWT, PpCW and PpCL. They all appeared as being positively related to MOR, while PpCL should be negatively related to it. This may be due to the fact that PpCL is highly and negatively correlated to PpCW. This is why the negative sign was moved to the intercept. This model explained only 53% of the variation in MOR. By dropping PpCL from this model R-square percent increased from 53% to 62% as shown in model 2 in the table. As FD is positively correlated to DCWT model 3 was derived by dropping FD with the same R-square percent. Therefore model 3 represents the best model for MOR, with DCWT and PpCW representing the most important anatomical characteristics influencing MOR. From this model we can predict the value of MOR as a function of these two independent variables, which gives a better prediction than the simple regression equations. This is explained by higher R^2 value and the significant level.

Model 4 shows the relationship between MOE and the correlated anatomical properties, namely: FD, DCWT, PpCW and PpCL. They all appeared as positively related to MOE including PpCL which is negatively correlated to MOE, as appeared from the correlation analysis and simple regression. However, the negative sign appeared in front of the intercept instead of PpCL. The model is highly significant and contributes about 61% of the variation in MOE.

Model 5, on the other hand, shows the relationship between compression parallel to the grain (COM) and the same anatomical properties in model 4. They represent the most important anatomical factors affecting compression parallel to the grain. The model is highly significant and explains about 68% of the variation in compression parallel to the grain and can be used for predicting its value. The relationship between modulus of elasticity from compression (MOC) and the correlated anatomical properties is shown in model 6. The independent variables are the same as those in MOE (bending) model except that the negative sign is in front of FD while in model 4 it was in front of the intercept. The model had the lowest R^2 value as it explains only 49% of the variation in MOC.

Model 3 shows the relationship between density (DEN) and the correlated anatomical properties, which comprised: DCWT, PpCW and PpCL and represent the most important anatomical properties influencing DEN. The model is highly significant and explains about 65% of the variation in DEN.

Table 3: Multiple regression equations.

Model no	Regression models	R ² percent	Significant level (%)
1	MOR= -26.25+0.20FD+5.65DCWT + 116.43PpCW+42.78 PpCL	53	P =0.0001
2	MOR = 11.48 + 0.00095 FD+ 53.97DCWT+ 2348 PpCW	62	P =0.0001
3	MOR = 11.48 + 5.95 DCWT + 88.15 PpCW	62	P =0.0001
4	MOE = -7463 + 95.98FD + 448.58DCWT + 15407PpCW	61	P =0.0001
5	COM = 44.51 - 0.28FD+1.20 DCWT+2978PpCW- 25.67PpCL	68	P =0.0001
6	MOC = 1511 - 96.61FD +54.12 DCWT + 2386.PpCW + 39.53 PpCL	49	P=0.0001

Conclusions and recommendations

- All models except MOC model (number 6) were highly significant and explain more than 60% of the variation in the respective dependent variables.
- The models can predict the values of these dependent variables with reasonable accuracy.
- MOC model (model 6) had the lowest R² value (49%) and this could not be improved by trying all combinations of the correlated independent variables.
- Relationships between dependent and independent variables were slightly different with regards to R² values and significance level. It is, therefore recommended that when selecting the independent variables for multiple regression to look at both correlation and simple regression results.

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