Sudan University of Science and Technology
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Relationship between Anatomical Properties and some Physical and Mechanical properties for Five Wood Species Growing in North Darfur- Sudan

علاقة الخصائص التشريحية ببعض الخواص الفيزيائية والميكانيكية لخمس أنواع أخشاب نامية في شمال دارفور – السودان

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بسم الله الرحمن الرحيم

إستهلال(AYAH)

قال تعالى : (وَلَقَدْ رَآهُ نَزْلَةً أُخْرَى (13)عِنْدَ سِدْرَةِ الْمُنْتَهَى (14)عِنْدَهَا جَنَّةُ الْمَأْوَى (15)
إِذْ يَغْشَى السِّدْرَةَ مَا يَغْشَى (16)مَا زَاغَ الْبَصَرُ وَمَا طَغَى (17)لَقَدْ رَأَى مِنْ آيَاتِ رَبِّهِ
الْكُبْرَى (18))

صدق الله العظيم

النجم (الأية 13-18)

DEDICATION

To my loved parents, who taught me how life could be:

To my Brothers, sisters for their encouragement.

To my daughters.

To my First love Nazek

To all those who love the forest in the world.

I dedicate this humble work with greater love.

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Relationships between anatomical properties and some physical and mechanical properties for five wood species growing in North Darfur, Sudan.

Abstract

This study was conducted to assess the Relationships between anatomical properties and some physical and mechanical properties of five wood species growing in North Darfur, Sudan. which consist of the following species (*Acacia seyal* (Talh), *Acacia nilotica* (Sunt), *Balanites aegyptiaca* (Heglig), *Eucalyptus camaldulensis* (Kafour), and *Faidherbia Albida* Haraz). 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. Wood chips from the five wood species were macerated by boiling them in concentrated nitric acid for ten minutes. The liberated fibers were stained in safranin for five minutes, washed by alcohol and water and mounted on glass slides ready for examination and measurements. The fiber length was determined using stereological techniques on macerated fiber. The other anatomical characteristics measured included fiber length (FLmm), fiber diameter (FDµm), fiber lumen (FLDµm), double cell wall thickness (DCWTµm), rankles ratio (RR), coefficient of cell rigidity (CR), and fiber flexibility (FF). The physical properties tested comprised density, moisture content and shrinkage. Static bending was also carried out for determining modulus of rupture (MOR MPa) and Modulus of Elasticity (MOE MPa).This, in addition to compression parallel to the grain (COM MPa). As well as Modulus of Elasticity from compression (MOC MPa) . All physical and mechanical properties were carried out according to standard procedures. The results of the analysis of variance revealed significant differences in most of the anatomical properties between species. Fiber length ranged between (2.28mm) for kafour and (1.45mm) for haraz. Fiber diameter, on the other hand ranged between (16.7470µm) for sunt to (14.113µm) for hraz. Fiber lumen diameter was highest for haraz (7.832µm) and lowest for talh (6.122µm). Double call wall thickness, on the other hand, ranged between (8.95 µm) for sunt to 6.22 µm for haraz.

Rankles ratio, however, was highest for talh (1.834) and lowest for haraz (0.842). For coefficient of cell rigidity talh was highest (0.288), while haraz was the lowest (0.223). Fiber Flexibility ranged between (0.55) for haraz to (0.433) for Kafour. Modulus of Rupture ranged between (139.701) for sunt to (68.736) for haraz. Compression parallel to the grain ranged between (68.409) for sunt to (35.864) for haraz. While modulus of elasticity ranged from (12873.6) sunt to (6507) for haraz. Density ranged from (0.95g/cm3) for sunt to (0.50g/cm3) for haraz. Shrinkage, however, showed no significance variation between the species. The correlation analysis revealed significant correlations between MOR, MOE, COM, MOC and density on one hand and some anatomical characteristics, namely FD, DCWT, rankles ratio, coefficient of fiber rigidity, volume fraction of cell lumen(P_PCL) and fraction of cell wall(P_PCW). When these correlated variables were used in simple regression with individual physical and mechanical properties as dependent variables and correlated anatomical properties as the independent variables, they revealed that P_PCW , P_PCL and DCWT was the most important anatomical properties affecting the dependent variables (MOR, MOE, COM,MOC and DEN), followed by FD, RR,CR and FF. The multiple regression used for modelling these relationships showed that the most important independent factors affecting the dependent variables (MOR, MOE, COM, MOC, and DEN) were the same namely: P_PCW, P_PCL, DCWT, FD, RR, CR. R-square for MOR model was 0.6219 at $P<0.0001$significant level; for MOE model R-square was 0.6057 at $P< 0.0001$; while for COM model R-square was 0.6774 and $P< 0.0001$. Hence R-square for model of MOC was 0.589 at $P<0.0001$significant level. However the principal factors influencing density were DCWT and CR with R-square = 0.6539 and $P<0.0001$.

علاقة بعض الخصائص التشريحية ببعض الخواص الفيزيائية والميكانيكية لبعض أنواع الأخشاب النامية في شمال دارفور – السودان

الملخص

إستهدف هذا البحث علاقة بعض خصائص الأخشاب التشريحية ببعض الخواص الفيزيائية والميكانيكية مع لبعض الأخشاب الصلدة النامية في ولاية شمال دارفور والتي إشملت على الأنواع التالية: سنط،طلح، هجليح،كافوروحراز. كل الخصائص التشريحية تم تحديدها من الألياف المحررة عن بعضها البعض عن طريق غلى حبيبات خشبية في حمض النتريك المركز في حمام ماء لمدة عشرة دقائق ومن ثم صبغها بمادة السفرانين وغسلها بالكحول والماء وتحميلها على شرائح زجاجية وإجراء القياسات المطلوبة بإستخدام المجهر. تم تحديد طول الألياف بإستخدام الوسائل الإسترولوجية أما الخصائص التشريحية الأخرى فقد تم قياسها على مجهر إلكترونى عاكس وهي أقطار الألياف وأقطار الفراغات الخلوية للألياف ومنها تم قياس سمك الجدار الخلوي للألياف ونسبة رانكل ومعامل قساوة الألياف ومعامل مرونة الألياف . وتم تحديد الخصائص الفيزيائية- المحتوى الرطوبى ومعدلات الإنكماش حسب مواصفات قياسية كما تم تحديد معامل الإنحناء الإستاتيكى لتحديد معامل الإنحناء ومعامل المرونة للأخشاب المدروسة أيضا تم وفق الإختبارات القياسية . وتبع ذلك إختبار مقاومة الإنضغاط الموازي للألياف أيضا حسب طرق إختبار قياسية .وأظهرت نتائج تحليل التباين فروق معنوية في معظم هذه الخصائص بين الأنواع المختلفة . ففي الخصائص التشريحية تفاوت طول الألياف من2.28ملم للكافور إلى 1.45 ملم للحراز .كما تفاوتت أقطار الألياف من16.75مكرون للسنط إلى 14.11مكرون للحراز, وكان قطر الفراغ الخلوي أعلاه في حالة الحراز 7.83 مكرون وأقله في حالة الطلح 6.12 ميكرون.أما ضعف سمك الجدار الخلوي فكان أعلاه سجل في السنط 8.95 مكرون أقله في الحراز6.22 مكرون، وكانت نسبة رانكل ومعامل قساوة الألياف أعلاها للطلح (1.83و0.288) على التوالى وأقله للحراز(084 و0.233 على التوالى). بينما كان معامل مرونة الألياف أعلاه في حالة الحراز(0.55 ميقا باسكال) وأقله في حالة الكافور (0.42 ميقا باسكال). وفيما يلى الخصائص الفيزيائية تفاوتت الكثافة (عند محتوى رطوبى 7%) مابين 0.95جم\سم^3 للسنط و0.50 جم\سم^3 . أما معدلات الإنكماش فلم تظهر أي فروق معنوية بين أنواع الأخشاب المختلفة. وأظهر تحليل الترابط علاقات معنوية بين مقاومة الإنحناء ،معامل المرونة ،معامل المرونة من للإنضغاط ،مقاومة الإنضغاط الموازي للألياف والكثافة من جهة وبعض الخصائص التشريحية من جهة أخرى. وعندما أختبرت هذه الروابط بإستخدام تحليل الإنحدار الخطي البسيط وضح أن الفراغ الخلوي ،الجدار الخلوي وضغف سمك الجدار الخلوي كانت أكثر الخصائص التشريحية تأثيرا على المتغيرات التابعة. يليه كل من قطر الألياف ونسبة رانكل ومعامل قساوة الألياف ومعامل مرونة الألياف . وعندإختبار هذه العلاقات بإجراء تحليل الإنحدار الخطى المتعدد تم الحصول على سبعة نمازج رياضية بدرجة عالية من المعنوية وكان قيمة R^2 في النموزج الخاص بمقاومة

الإنحناء (MOR) 0.6219 ودرجة معنوية$p<0001$. أما في حالة معامل المرونة (MOE) كانت قيمة R^2 يساوى 0.6057وبدرجة معنوية تساوى $p<0001$. وبلغت قيمة R^2 لنموزج مقاومة الإنصغاط الموازي للألياف(COM) 0.6774 ودرجة معنوية $p<0001$. والنموزج الخاص بمعامل المرونة من الإنضعاط فكان $R^2=0.587$ ودرجة معنوية$p<0001$.

وقد إشملت هذه النمازج السبعة كافة المتغيرات المستقلة الخمسة المزكورة أعلاه . بينما شمل النموزج الخلص بالكثافة أربع متغيرات مستقلة وهي ضعف سمك الجدار الخلوي(DCWT) ، معامل مرونة الألياف ،الفراغ الخلوي(PPCL) والجدار الخلوي (PPCW) وبلغت قيمة R2 0.6539 بدرجة معنوية بلغت$p<0001$.

List of tables

List of abbreviations used in this study and their definition

Abbreviations	definition
V_V	Volume fraction per unit test volume.
A_A	Area per unit test area
L_L	length per unit length

p_p	Points per unit test points.
N_L	Number of point interceptions per unit length.
P_L	Number of point intersections per unit length.
S_V	Surface area per unit test volume (surface density)
N_A	Number of feature per unit test Area
DCWT	Double cell Wall Thickness
FD	Fiber Diameter
LD	Fiber lumen Diameter
CWT	Cell wall thickness
MOR	Modulus of Rupture.
MRC	Material Research Center
DBH	Diameter at Breast Height
COM	Compression parallel to the grain
MOE	Modulus of Elasticity
MOC	Modulus of elasticity from compression
FL	Fiber length
RR	Rankles Ratio
CR	Coefficient of Cell Rigidity
FF	Fiber Flexibility
DEN	Density
TS	Tangential Shrinkage
RS	Radial Shrinkage
LS	longitudinal Shrinkage
FRC	Forest Research Center
PPCL	volume fraction of cell lumen
PPCW	volume fraction of cell wall

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CHAPTER ONE

INTRODUCTION

North Darfur State is located in the western part of Sudan; the Greater Darfur region occupies an area equals to the size of Burkina Faso. North Darfur is the home of 2.25 million people, 80% of them live in rural areas where their livelihoods rely on natural resources especially woody plants. The total area of North Darfur is about 296 thousand square kilometers, which is equals to 296 million hectare representing 12% of total area of Sudan and 57% of total Darfur region (Practical Action,2016).Generally the climate of North Darfur is arid in the north and semi- arid in the southern parts.

Like most of the other parts of Sudan, the forests in Northern Darfur are natural degraded forests. They are stocked mostly with secondary species which are not in use. Research on wood has proved that the climatic conditions of the area in which the species grow has a significant effect on the properties of the wood. (Roqu, 2004; Alevs and Angyalossy-Alfonso 2000; Wimmer, 2002; Desch and Dinwoodie, 1996). Wood is a raw material of variable structure. Wood properties vary between and within species as well as between different parts of the same tree.

Understanding the extent of the variability of wood is important that is why the use of each type of wood is related to its characteristics; moreover, the suitability or quality of wood for specific purpose is determined by the variability of one or more of these characteristics, which is directly affected by its structure, and its physical properties (Panshin and de Zeeuw, 1980). However, to use wood to its best advantage most effectively in the various implementations, all characteristics must be considered (Miller, 1999). The versatility of the wood is demonstrated by the wide variety of wood products. This variability is a result of a wide spectrum of desirable physical characteristics or properties between many species of wood. Virtually all wood properties are affected by its anatomical structure. Ideally, the extent of this wide difference needs to be fully investigated. In many cases, more than one property of wood is important to the end use. Efficient utilization means that species should be matched to end- use requirements through an understanding of their properties (Simpson and Tenwolde, 1999).

The anatomical, physical and mechanical characteristics of wood are considered the fundamental basis for timber use. Studies of wood properties have a special significance in promoting quality research in wood products by studying some anatomical properties, density, hardness and other strength properties of wood. Tree stems have a considerable economic value as raw materials. The prediction of changes in wood characteristics is challenging because, in addition to growth conditions, the wood structure and chemical composition can differ between genotypes, within a tree, among trees and with the age of a tree (Butterfield, 2003). Juvenile wood is produced by young cambium. Therefore form a continuous cylinder around the pith and occupies a larger proportion in the higher parts of the stem than in the lower part with a larger stem diameter. Juvenile wood occupies around the first 10-15 growth rings (Butterfield 2003, Bonham and Barnett 2001).

Virtually all wood properties are affected by their anatomical properties. Previously these properties were analyzed qualitatively by describing the wood structure without having to make any measurements because of the difficulty of dealing with microscopic features. In the absence of quantitative data, it was not possible to establish mathematical models relating anatomical properties to other wood properties. The appearance of stereological techniques, however, made it possible to make easy quick measurements and obtain quantitative data for the anatomical properties. This made it possible to subject these data to statistical analysis leading to the establishment of the relationships we are after (Nasroun and Alshahrani, 1998).

These models will be used for predicting different wood properties from their anatomical properties. This type of modeling emerged as a new area of research in the field of wood science and technology.

General objective

The main objective of this study is to investigate some basic properties of the studied species and establish relationships between anatomical properties as independent variables and its individual physical and mechanical properties as dependent variables.

Specific objectives

1-To determine some physical and mechanical properties of five wood species growing in Northern Darfur.

2- To carry out quantitative analysis of the anatomical structure of the selected species using stereological techniques.

3-To establish relationships between each of the physical and mechanical properties of the five species with their anatomical properties in the form of mathematical models.

4-To find the most important anatomical properties affecting each of the physical and mechanical properties under study.

CHAPTER TWO

LITERATURE REVIEW

2-1General

Wood has been considered an important renewable resource due to its sustainability in production, abundance and universal use such as building, energy, transportation structures and various wood industries (Nasroun, 2005; USDA, 2010).

Thus wood differs from other construction materials because it is produced in a living tree. As a result, wood possesses material properties that may be significantly different from other materials normally encountered in structural design. Although it is necessary to have an in-depth knowledge of wood properties, it is necessary for the engineer to have a general understanding of the properties and characteristics that affect the strength and performance of wood in construction. This includes not only the anatomical, physical, and mechanical properties of wood as a material, but also the standards and practices related to the manufacture of structural wood products, such as sawn lumber and glued laminated wood, plywood (Nasroun, 2005).

In the broadest terms, trees and their respective lumber are classified into two general classes, hardwoods and softwoods. Hardwoods normally have broad leaves that are shed at the end of each growing season, in some species. Softwoods have needlelike leaves that normally remain green all year round. The classification as hardwood or softwood has little to do with the comparative hardness of the wood. Several species of softwoods are harder than many low- to medium-density hardwoods. With few exceptions the structural wood products used in bridge applications are softwoods. Although hardwoods are not widely used at this time, structural grading procedures for hardwoods have been developed recently, and their use is increasing worldwide(Panshin and Zeeuw, 1980).

2.2Anatomical Properties

In hardwoods, the cells that make up the anatomical organization are the vessels, fibers, parenchyma cells and the wood rays. Fibers are the principal elements that are responsible for the strength of the wood (Panshin and Zeeuw, 1980).

Wood density is an important wood property for both solid wood and fiber products (De Guth, 1980). It is affected by the cell wall thickness, the cell diameter, the early wood to latewood ratio and the chemical content of the wood (Cave and Walker, 1994).

2.2.1. Fiber characteristics

Hardwood fibers are typically long, slender, straight cells whose ends taper to a point. Fibers can be separated into two types: libriform fiber and fiber tracheid. The fiber wall thickness varies among different species; wall thickness has a direct effect on the density of wood and through its density mechanical performance. The increase in the length of the fiber is due to its very marked elongation at the tips (Desch and Dinwoodie, 1996).

In paper industry, special attention is paid to the length of the fiber and the extent to which neighboring fibers overlap and joined to one another. Fiber length affects the strength and surface bonding properties of fiber products and is therefore of interest for many purposes. Long fibers are more desirable than short ones (Dadswell and Nicholls, 1959).The percentage of fibers in hardwood may reach 50% or more of total wood volume. Fibers are most specialized as supporting elements. Density and thus strength of hardwood are generally related to the portion of wood volume occupied by fibers (Hayergreen and Bowyer, 1989)

2.2.2. Vessels

In softwoods the functions of conduction and support are both carried out by the tracheid, where as in most hardwoods these functions are performed by different cell types. Vessels only occur in hardwoods. In wood tissue an indefinite number of vessel members are connected endwise to form a pipe-like structure of indeterminate length which is called vessel. In cross-sections, vessels appear as called pores (Desch and Dinwoodie, 1996). The distribution of pores over the cross-section depends on the tree species and can be diffuse (homogeneously), or concentrated in ring-like structures called semi ring- porous or ring-porous.

The size of vessel members varies widely in ring-porous hardwoods; differences within a growth ring are much greater than differences between species. Vessel members are the most massive wood cells. Instead of tracheid's, vessels serve to transport water to wood fibers assume the mechanical function of supporting the tree. The vessels play a very important role as a conductive element in the living tree (Lundqvisst, 2002).

2.2.3. Parenchyma Cells

Parenchyma cells are thin-walled, storage units; in hardwoods, longitudinal form of parenchyma is often divided into a number of smaller cells through the formation of cross walls during the process of cells maturation (Haygeen and Bowyer, 1989,).

Longitudinal parenchyma is relatively rare in the softwood species, usually not more than 1-2% of volume of those woods in which it occurs. The longitudinal form of parenchyma is often quite significant in hardwoods. Some hardwoods have up to 24% of their volume made up of longitudinal parenchyma cells; however, certain species of hardwoods contain no longitudinal parenchyma (Panshin and De Zeeuw, 1980).

2.3 Cell Wall Structure

At the molecular level the wood cell wall is composed of cellulose, hemicellulose and lignin, as the major constituents of the cell wall. These Components are arranged in most intricate manner which gives strength to the wood material. The structure resembles the concrete structure in building where the cellulose chain combine to make microfibrils which represent the steel bars that make the general frameworks and is strengthened by hemicelluloses.

Lignin, on the other hand, represents the concrete mixture which fills the spaces within the framework making a strong structure (Nasroun, 2005).

At the cellular level the walls of wood cells are made up of the primary wall and the secondary wall. The neighboring cells are separated by the middle lamella. The secondary wall is composed of three layers, S1, S2 and S3. The S1 layer is the layer closest to the primary wall, while the S3 layer is the layer closest to the cell lumen. Haygreen and Bowyer (1996) also reported that because the S2 layer is much thicker than the S1 or S3 layers, it has the greatest effect on the cell and hence the wood behave. Microfibrils are the structural units of plant cell walls. Each microfibril contains a number of cellulose chain molecules bundled together, and is surrounded by low molecular weight hemicelluloses.

Since S2-layer constitutes most of the fiber and has the largest amount of cellulose, its microfibrillar angle (MFA) has a great influence on the mechanical properties of wood. If the S1-layer is still present and relatively intact after pulping and subsequent operations, fibers' mechanical properties are not solely dominated by the S2-layer). However, in general, the lower the microfibrillar angle, the stronger and stiffer a fiber is. With low MFA and cellulose chains are loaded in the direction of cellulose chains when tension is applied more force will be in the longitudinal direction. When the microfibrillar angle increases, the fibrils are loaded more and more to their lateral directions, which have inferior mechanical properties compared to the chain direction. Study of how the tensile stiffness of individual fibers is affected by the microfibrillar angle is needed. Reiterer *et al* (1999) found great decrease in tensile strength and tensile stiffness and a significant increase in fiber breaking strain as a function of increasing microfibrillar angle.

Low MFA makes fiber stress-strain curves almost linear; at higher angles one can observe significant non-linearity. This has been shown by Page and El-Hosseiny (1983). They found that when fibers are subjected to tension for a time periods of 12-48 hours, fibrillar orientation towards fiber axis increases (MFA decreases).

This leads to increased fiber strength and elastic modulus, as do many other fiber properties; MFA varies between fibers from the same tree. Latewood fibers usually have slightly lower MFA than early wood fibers (Lichtnegger *et al*, 2000). MFA also varies between growth rings. In growth rings far from the pith the MFAs were from 6° to 10°. Similar values are measured by Lichtenberger *et al*, (2000), even measuring MFAs very close to 0° for some early wood fibers.

2.4. Quantitative Wood Anatomy

Measurements of various characteristics of wood cells are made for driving structure- property relationships. The fiber dimensions measured include fiber length, cells diameters, lumen diameter and cell wall thickness. Many methods have been used for measuring each of above structural characteristics. For instance methods previously employed for measuring the fractional cell wall area included cutting and weighting cell lumen in photomicrograph or under the microscope. Cell dimensions were also measured in various ways ranging from simple techniques using scales in the ocular of a microscope to electronic device.

A method of obtaining the transverse cell wall dimensions, while avoiding many of sources of artifacts, are suggested by Stamm, (1964). Ifju and Labosky, (1972) also determined the cell thickness by counting the number of cell per unit area. This method, however, had limited applications. These are some of the attempts made to quantity wood structure without the use of the conventional direct methods. The vast majority of methods were by direct measurement.

Recently quantitative characterization of wood structure using stereological techniques has been used for establish 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 distribute 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.

A point count is usually carried out on each micro-structural element such as fibers, vessels, longitudinal parenchyma and radial parenchyma on transverse sections. Each sampling point on wall or lumen of the cell in question is counted. The point fraction p_p is then calculated. Each point fraction representing a random static which is unbiased estimator of the area fraction A_A or volume fraction V_V of particular feature in the structure of wood.

The volume fraction of any feature can be defined as the number of test point falling on the feature as a fraction of the total test points. Test points in most cases are the points of intersection of the horizontal and vertical lines of the square grid(Nasroun and Alshahrani, 1998; Nasroun, 2005). Here are some of the stereological equations:

$V_V = A_A = L_L = P_P$………………………………………………….. (1)

Statistical measurement of the cell area and average size of cell require the knowledge of interception count (N_L) or intersection count (P_L) in addition to the number of feature per unit area (N_A).

$N_L = 2P_L$……………………………………………………………… (2)

These accounts are obtained by superposition of direct line segments in the form of grid upon the microscopic section images. A count of the number of times that the line segments intersect with cell boundary divided by test line length gives P_L. This count is an unbiased estimator of half the surface area per unit volume (S_V) as said by DeHoff and Rhine,(1968). The stereology equation relating the intersection count PL to specific surface of cells is as follows:

$S_V = 2P_L$……………………………………………………………… (3)

The average number of cells per unit area in the cross section (N_A) will be measured by counting the number within the grid and dividing it by the test area. The quantity N_A leads to calculating the average area occupied by cell (A) using the following equation:

$\bar{A} = A_A / N_A = P_P / N_A$ …………………………………………………… (4)

The intersection count (P_L) is related to the average length of leaner features per unit area (L_A) as bellow (Underwood, 1970).

$L_A = (\pi/2)\, P_L$ …………………………………………………………….(5)

The average fiber length (L) can be calculated from counts made on macerated fiber as follows:

$L = \Pi P_L / 2N_A$ ………………………………………………………….(6)

$L = \pi\bar{d}$ ……………………………………………………………….(7)

Where (P_L) is the Number of intersections with cell boundaries per unit line, (N_A) is the number of features (cells) per unit test area.

And average cell diameter (d^-) can be calculated from:

$(\bar{d}) = N_L / N_A = PL / 2N_A$ …………………………………………………………………… (8)

Where: N_L= is the average number of interceptions of feature per unit test line.

Average lumen diameter (LD^-)

$$LD^- = \frac{\sqrt{4pp(\text{lumen})}}{\pi\, NA}$$ ………………………………………….. (9)

Where $p_{p\ (\text{lumen})}$ is the average point fraction for the cell lumen.

N_A= number of cells per unit area.

Then double cell wall thickness (DCWT) calculated as follows:

$DCWT = d^- - LD$ ……………………………………………………….. (10)

Fiber length (FL) is estimated from counts on randomly mounted macerated fibers the average length is estimating according to the following: $FL= \pi P_{/2} N_A$ ……………………………………………...(11)

Where:

FL= Fiber length

P_L= points of intersections with fiber boundaries per unit line
N_A = the number of fibers per unit area

Rankle ration = DCWT/ LD^- ……………………………………….(12)

Co- efficient of cell wall rigidity = DCWT/ FD^-……………………….(13)

Fiber density index (FDI) $= \frac{PP-cell\ wall}{pp-cell\ lumen}$………………………...(14)

Fiber Flexibility = LD/ FD ………………………………………..(15)

2.5. Physical Properties

2.5.1. Wood density

Density is defined as the amount of wood substance per unit volume. Density of wood is a function of the cell wall thickness and also depends on the level of cell wall development. Koch (1985) reported that wood density is the mass or weight of wood and its contained water per unit volume. Chafe, (1991) reported that high cellulose content in wood is a good for indication of high density and low lignin content.

Density of solid wood substance which is represented by cell wall material is approximately 1.54 g/cm³ which is the same in all wood species (Nasroun, 2005). However, there are great differences between the different species. This is due to the differences in the cell wall to lumen ratios between the different species.

Density varies greatly depending on the anatomical structure of the wood. Tsoumis (1991) pointed out that density is the best and simplest index of the strength of clear wood; with increasing density, strength also increases. This is because density is a measure of the amount of cell wall materials contained in a given volume of wood. Therefore, higher density denotes larger amount of cell wall available to resist external forces. It serves as a measure for the mechanical properties such as bending and represents the simplest and the best indicator of wood quality (Kubler, 1980).

Increasing density results in corresponding increases in all strength properties, except for axial tension (Dinwoodie, 1989). For elasticity and shock resistance properties, density is less correlated. High density is associated with thick fiber walls and a higher proportion of fibres. These are the very qualities which contribute to strength and in the absence of any other data about the properties of a particular species, wood density is used as a guide to its utilization (Shrivastava, 1997). Desch and Dinwoodie, (1996) also elucidated that some strength properties show a very marked correlation with density namely compression strength parallel to the grain, bending strength and hardness.

They added that the density of a piece of wood is determined not only by the amount of wood substance present, but also by the presence of both extractives and moisture. The presence of moisture in wood not only increases the mass of the timber, but also increases the volume. Donaldson, *et al*., (1995) reported that density usually decreases with height in the stem.

Wood density and wood specific gravity both indicate the amount of actual wood substance present in a unit volume of wood (Nasroun, 2005; Jett, 1995). Wood density is not a simple characteristic. It is affected by the cell wall thickness, the cell diameter, the early wood to latewood ratio and the chemical content of the wood (Cave and Walker, 1994). Density of wood is a 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. Density also affects hygroscopicity, shrinkage, and swelling, mechanical, thermal, acoustic, electrical, and other basic wood properties, as well as properties related to the industrial processing of wood (Davis 1961; Barefoot *et al*., 1970; Lewark, 1979).

Wood density is one of the most important properties since it correlates well many other physical and mechanical properties (Tsoumis, 1991; Knapic *et al*. 2007). Thus wood density is a good indicator for the estimation of all other material properties. Wood density (or specific gravity) depends upon the size of the cells, the thickness of the cell walls, and the interrelationship between the numbers of cells of various kinds. Wood density is not distributed evenly along the stem radius. Its distribution is related to the growth ring structure. Each growth ring consists of lighter early wood and darker latewood. Latewood is made of cells which have thicker walls and smaller Lumina in comparison to early wood. This results in a higher density of latewood (Fromm *et al*. 2001) and explains why the density of wood increases with increasing proportion of latewood (Panshin and de Zeeuw, 1980; Tsoumis, 1991).

Where an increase of growth ring width is associated with an increase of latewood proportion, thus density also increases. According to decreasing ring width with the age of a tree it is obvious that higher density should be in the central part of a tree stem of ring-porous species. Deguth (1980) added that wood density is an important wood property for both solid wood and fiber products in both conifers and hardwoods.

2.5.2 Moisture content

It is well known that moisture content influences the strength and stiffness of wood specimens subjected to bending. Strength and stiffness increase with a decrease in moisture content. One of the most important factors that affect the mechanical properties of timber is its moisture content (Schniewind,1989).The strength of clear timber rises approximately linearly as moisture content decreases from the fiber saturation point and may increase 3-fold when the oven-dry state is reached. However, at moisture contents of around 15%, the strength would be approximately 40% higher than that at fiber saturation point, depending on the type of wood (Baradan, 2003).

The mechanism of the strength increase is similar to that of shrinkage in concrete; the contraction results in decreased inter-fiber spacing and, therefore, stronger bonding between fibers (Taylor, 2000; Baradan, 2003; Widehammar, 2004).

2.5.3 Wood shrinkage

The shrinkage of inadequately seasoned lighter structural members such as house farming is highly important. Shrinkage of framing members particularly the joists causes the central parts of the building to drop if tolerances are not adequate. Green lumber may shrink in service and loosen fastening and glued joints in furniture and other structures. The strength of joints is seriously affected by shrinking and swelling of wood members.

A wood handle set into a metal head such as an ax or hammer tightens with swelling and loosens with shrinkage. Tangential shrinkage is the shrinkage which occurs tangentially to the growth rings and perpendicularly to the fiber, and hence micro-fibrils, direction (Panshin and de Zeeuw, 1980). Density has positive relationships with both Tangential and Radial shrinkage (Pliura, etal, 2005).

Radial shrinkage is the shrinkage which occurs perpendicularly to the fibers and micro-fibrils direction and radially parallel to the rays, its value is usually higher than the longitudinal shrinkage and lower than tangential shrinkage (Panshin and de Zeeuw, 1980).

Longitudinal shrinkage (S_L) is the shrinkage that occurs parallel to the grain or micro-fibrils and its value is usually very small compared to tangential and radial shrinkage (Panshin and de Zeeuw, 1980).(Pliura, etal, 2005) reported that density has negative correlation with longitudinal shrinkage.

2.6. Mechanical Properties

Wood is highly anisotropic in its strength properties i.e. it has different property values in longitudinal and lateral directions. This is due to its cellular structure and the physical organization of the cellulose chain molecules within the cell walls (Schniewind, 1989). The good mechanical behaviour (strength) of wood expresses the efficiency and ability of wood to resist external loads that change its dimensions and shape. Green *et al*. (1999) stated that, mechanical properties are commonly measured and presented as “strength properties” for design including modulus of rupture in bending, maximum stress in compression parallel to the grain, compressive stress perpendicular to the grain, and shear strength parallel to grain.Hardness is a measure of the resistance of wood to the entrance of foreign bodies in its mass (Tsoumis, 1991).

The hardness of wood varies with the direction of the wood grain. Testing on the surface of a plank, perpendicular to the grain is said to be of "side hardness". Testing the cut surface of a stump is called a test of "end hardness". This resistance is higher up to about double in the axial direction than sidewise, but the difference between radial and tangential surfaces are seldom important. Hardness is related to the strength of wood, to abrasion and scratching with various objects, as well as to the difficulty or ease of working wood with tools and machines (Tsoumis 1991).

Desch and Dinwoodie, (1996) found that wood density is one of practical importance in its utilization and as a good indicator of strength properties. Evans (1991) concluded that the pattern of wood density variations have impact on the variations of most strength properties. Dinwoodie,(1996. reported that density and mechanical properties decrease from the tree base to the top whereas it increases from the inner wood to the outer wood at any particular height and the density has a strong positive correlation with the mechanical properties of wood, and can therefore be used in predicting its strength properties.

As described by Kretschmann (2010) wood may be considered as an anisotropic material has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal (L), radial (R), and tangential (T). He further explained that there are twelve constants needed to describe the elastic behaviour of wood. These constants are three models of elasticity E, three models of rigidity G, and six Poisson's ratiosμ. When wood material is able to resist extreme external load without deformation in the shape, this wood material can be classified as stiff material and in all cases wood elasticity is measured by modulus elasticity (MOE) while the wood resistance against failure is measured by modulus of rupture (MOR) (Rammer 2010; Kretschmann 2010).

2-6-1 Compression strength parallel to the grain

The compressive strength is obtained by dividing the load to failure by cross-sectional area. The compression strength parallel to the grain is up to 10 times higher than compression perpendicular to the grain. When a force or load tends to shorten or crush a wood, there is said to be compressive stress and the strength of wood is said to be compressive strength (Panshin *et al*., 1964). Wilcox *et al*., (1991) have also stated that, compression strength parallel to grain indicates maximum load that each square millimetre of wood can be expected to support as a column with the load being applied to the end grain, in the grain direction.

Wood is very strong in compression parallel to the grain and this is seldom a limiting factor in furniture design. It is considerably weaker in compression perpendicular to the grain. An example of this type of compression would be the pressure that chair legs exert on a wooden floor. If the applied pressure (weight) exceeds the fibre stress at proportional limit for the wood, permanent indentations will result in the floor. The sample size is 20×20×60mm and the load is applied to the piston of the cage at a rate of 0.01mm/s. (Desch and Dinwoodie, 1996).

Nasroun, (1979) mentioned that among 21 species, the lowest compression strength values parallel to the grain were obtained by *Faidherbia albida* (383kg/cm^2) while *Acacia nilotica and Khaya senegalensis* had the highest values(854cm^2 and 753kg/cm^2 respectively). The value of compression of *Balanities aegyptiaca* was 520kg/cm^2.Nasroun and Al Zaki (1987) worked on the relationship between anatomical structure and some physical and mechanical properties of eight hardwood species growing in Sudan. They found that the compression strength parallel to the grain was significantly influenced by volume fraction for cell wall material and fiber length.

2-6-2 Compression strength perpendicular to the grain

This test is rarely carried out and this strength is estimated from hardness test of timber since it has been established that there is high correlation between hardness and Compression strength perpendicular to the grain (George, 2009).

2-6-3 Tensile strength parallel to the grain

Due to difficulties in testing and the limited use for such data, tension parallel to the grain has not been extensively measured and/or reported. Desch and Dinwoodie, (1996) reported that the test has a little practical significance sine most of failures that occur in practice are cleavage failures originating at one side, rather than true tensile parallel to the grain failures.

Strength in tension appears to be much more sensitive to angle of grain than either bending or compression and at angles exceeding 8% there is a marked decline in tensile strength.

Desch,(1981) reported that the tensile strength is much more reduced by cross grain than bending or compressive strength.

2-6-4 Tensile strength perpendicular to the grain

Tensile stress perpendicular to the grain is useful for quantifying resistance to splitting. Examples of such stress include splitting firewood, driving nails, and forcing cupped boards to be flat.

Wood is relatively weak in tension perpendicular to the grain but it is very strong in tension parallel to the grain (visualize a board being pulled from both ends).

2-6.5 Shear parallel to the grain

Panshin *et al*., (1964) reported that shear strength of wood results when one portion of the wood slides over the other on application of external load. According to Bodig and Jayne (1982) because of the extremely high shear resistant across the grain, shear testing of wood is restricted to failure in the longitudinal direction only. Shear strength is determined by dividing the maximum load by the shear area.

2-6.6. Static bending

Defined as "an index of the maximum load a bending member can be expected to support before failing, weighted for the effects of span, width and depth(Wilcox et al.,1991).Bending strength results from a combination of all the three primary strengths (compression, shear and tension); they cause flexure or bending in the wood (Panshin *et al*, 1964).

Static bending test specimens are 20×2 0× 300 mm. The test is usually carried out on air-dry small clear specimens. The bending strength of wood is usually presented as modulus of rupture (MOR) which is the equivalent stress in the extreme fibres of specimen at a point of failure. MOR is calculated from equation (16) below. The ratio of stress to strain within the elastic range below the proportional limit is an estimate for the modulus of elasticity (MOE) (Kollmann and Cote, 1984). MOE can be calculated from equation.

$MOR = 3PL/2bd^2$…………………………………………… (16)

Where MOR is the Modulus of Rupture.

P= is maximum load, at failture.

L = is the length of span, in mm.

b =is the width, in mm.

d = is depth, in mm.

$MOE = P'L^3/4\Delta bd^2$…………………………………………….. (17)

Where:

MOE = is the modulus of elasticity in bending, in mm.

P´= is the load, in N, at the limit of proportionality.

L = is length of span, in mm.

Δ' = is the deflection, in mm at the limit of proportionality.

b = is the width of sample, in mm.

d = is depth of sample, in mm.

2-6-7 Modulus of Elasticity (MOE)

Hooke's Law states, that the ratio of stress to strain for a given piece of wood within the elastic range is a constant. The ratio is called the modulus of elasticity. Also known as Young's Modulus and usually abbreviated as MOE or simply E (equation 17). This ratio equals the stress divided by the resulting strain. It can be calculated by choosing any set of values of stress and resulting strain, although the stress and strain values at the proportional limit are conventionally used (Hoadley, 2000).The relative slope of the stress-strain curve, as indicated by the modulus of elasticity, E, gives a measure of a relative stiffness; the steeper the slope, the higher is the 'E' value and stiffer the wood. Moreover, the higher the E value, the lower is the deformation under a given load (Hoadley, 1990).

2.6.8 Anisotropic behavior of wood

A material, which has different physical properties in the different directions of various structural axes, is said to be anisotropic. The cell wall exhibits definite anisotropy because of the structural organization of the materials composing it. Strength properties depend on the anisotropy of wood (Illstron, 1994). Compressive, tensile and shear strengths vary widely between longitudinal and the lateral directions in wood. For example, the ratio of compression parallel to grain to the compression perpendicular to grain varies from a minimum of 4 in hardwoods, containing thick-walled fibres with small diameters, to a maximum of 12 in thin-walled trachieds in conifers.

This means that wood is 4-12 times stronger in compression parallel to grain than it is perpendicular to grain Tension parallel to the grain, on the other hand, is 40 times tension perpendicular to the grain (Panshin and de Zeeuw, 1980).

2.7. Factors Affecting Wood Strength

The existence of a linear relationship between wood density and strength has been demonstrated by several investigators. Similarly, it has been found that within the range of specific gravity found in most species, an approximately linear relationship exists between strength and specific gravity. Thus, Mitchell (1963) reported that a 0.02 change in specific gravity represents a change of about 70 kg/ cm^2 in the modulus of rupture of clear wood. On the other hand the relationship between specific gravity and stiffness (modulus of elasticity) is poor (Anon, 1980). Cave and Walker (1994) also found that density was a poor indicator of cell wall stiffness. Natural defects like pitch pockets may occur as a result of biological or climatic elements influencing the living tree.

The wood characteristics must be taken in to account in assessing actual properties or estimating the actual performance of wood products (George,2009). Form the point of view of economics, a defect in wood is any feature that lowers its value on the market. It may be an abnormality that decreases the strength of the wood or a characteristic that limits its use for particular purpose. There is certain amount of risk in classifying an abnormality as defects because what is judged to be definitely unsuitable for an application may prove to be ideal for a different application of special use (Kollman and Cote, 1968).

2.7.1 Natural Defect

Timber contains natural growth features which have an influence in reducing their strength. The most important single factor influencing strength and stiffness of timber is its density, but there are many other variables some anatomical in origin such as knots, slope of grain and micro-fibrillar angle, and some environmental factor such as moisture content and temperature, duration of load, which plays significant role in determining the strength and stiffness of the wood (Zobel and Van Buijtenen, 1989) and (Panshin and de Zeeuw, 1980).

2.7.1.1 Knots

Knots are the most commonly encountered defects. Cell structure in branches is significantly different from that of trunk cells, and alignment of longitudinal cells in branches is at an angle to cells in the tree trunk. In addition, longitudinal cells in the trunk must deviate around the branch base which causes localized grain alterations. Knots can adversely influence mechanical properties because of the heterogeneity they introduce, and create stress concentrations due to interruption of the continuous, parallel arrangement of the trunk cells. Frequently, checks occur around the knots during the drying process (Nasroun, 2005).

The influence of a knot on the mechanical properties of a wood member is due to the interruption of continuity and change in the direction of wood fibers associated with the knot. The influence of knots depends on their size, location, shape, and soundness; attendant local slope of grain; and type of stress to which the wood member is subjected (Dinwoodie, 1996) and (Hoadley, 1990). The shape (form) of a knot on a sawn surface depends upon the direction of the exposing cut. A nearly round knot is produced when lumber is sawn from a log and a branch is sawn through at right angles to its length (as in a flat sawn board (https://www. Sloping Grain, retrieved in 2016).

A conservative approach to predicting strength reduction is to consider knots as empty holes, and then total strength is assumed to come from what solid wood remains. Influence of grain deviation is more difficult to visualize but is equally significant because it compounds strength reductions over that of empty holes.

Knots on the top or bottom edge of a beam are more critical than the same knots located near the center (Illstron, 1994).Tensile strength is more affected by knots than compression strength (Desch and Dinwoodie, 1996, and Jayne, 1982).

2-7-1-2 Slope of grain

Slope of grain in structural timber can result from diagonal sawing, sawing a log with significant taper, sawing logs with poor form or with spiral or twisted grain. Definitions of slope of grain as given are firstly for sloping grain:" an arrangement of fibers or other longitudinal elements at an angle to the longitudinal axis of the piece." and secondly for spiral grain: "An arrangement in which fibers or other longitudinal elements take a spiral course about the axis of the tree (Wilcox et al., 1991)." Slope of grain is measured by the angle between the direction of the fibers and the edge of the piece, with the angle being expressed as a slope.

When both sloping grain and spiral grain are present the combined slope of grain is taken as the effective slope (Simonho, et al, 2004,).

Grading rules generally allow the slope of grain associated with a permissible knot to be ignored. The strength ratio is the percentage reduction that is applied to permissible stresses for pieces with a particular slope of grain relative to pieces with zero slope of grain. In some wood products applications, the directions of important stresses may not coincide with the natural axes of fiber orientation in the wood. This may occur by choice in design, from the way the wood was removed from the log, or because of grain irregularities that occurred while the tree was growing. The term slope of grain relates the fiber direction to the edges of a piece. Grain angle (slope of grain) affects strength and severe slope of grain decreases strength strongly (Glos, 2004) and (Hankinson, 2009).

However, slope of grain shows only a weak correlation with strength, which is explained by the fact that severe slope occurs very seldom (Glos, 2004). The effect of the slope of grain may depend greatly on species. In straight grained timber, the fibers or tracheid's are more or less parallel to the vertical axis of the tree. Moreover to contributory factor in strength, straight-grained timber makes for ease of machining and reduces waste. On the other hand, it gives rise to ornamental figure. In irregular grained timber, the fibers are at varying, and irregular inclinations to the vertical axis, when excessive, seriously reduce strength, besides accentuating difficulties in machining. Irregular grain, however, often gives rise to an attractive figure (Desch and Dinwoodi, 1996).

Spiral grain is a very common defect in a tree, and when excessive renders the timber valueless for use except in the round. It is produced by the arrangement of the wood fibers in a spiral direction about the axis instead of exactly vertical. Timber with spiral grain is also known as "torse wood." Spiral grain usually cannot be detected by casual inspection of as tick, since it does not show in the so-called visible grain of the wood, by which it is commonly meant a sectional view of the annual rings of growth cut longitudinally. It is accordingly very easy to allow spiral-grained material to pass in specion, thereby introducing an element of weakness in a structure. There are methods for readily detecting spiral grain. The simplest is that of splitting a small piece radially. It is necessary, of course that the split be radial, that is, in a plane passing through the axis of the log, and not tangentially (Sydney, 1985).

In the latter case it is quite probable that the wood would split straight, the line of cleavage being between the growth rings Effect of slope of grain on strength properties is much greater in structural sizes than in small clear specimens. Grading rules for slope of grain in relation to strength of hardwood or softwood are formulated (Sunley, 1968).

2-7-1-3 Fissures

The strength of timber affected by fissures which include shakes splits and check. A check is separation of the fibers along the formation of a crack or fissure in the timber across the growth rings and radial direction. The causes of checks are unequal shrinkage which takes place when moisture content is reduced during seasoning. The cause of shakes is uncertain but they rarely develop unless they were present to a certain extent before the tree was felled (Koch, 1985).

A split is the separation of the fiber long the grain forming a crack or fissure that extends through the piece from one surface to another. They affect shear stress only, but have no effect on other mechanical properties (Desch and Dinwoodi, 1996).

2.7.2 Factors other than defects

2.7.2.1 Density

Almost all mechanical properties of wood are closely related to density, some more other than others. In fact density is most likely the best single predictor of mechanical properties of clear, straight defect-free wood. In wood, density is a reflection of the amount of cell wall material present per unit area, and this in turn is a function of the type and size of cells and the amount of latewood versus early wood in the piece under consideration, among other factors. In general, species with a high specific gravity have correspondingly high strength value.

Specific gravity is affected by anatomical structure which, in turn affects strength properties as well as other physical properties (Nasroun and AL zaki1987), (Nasroun and Alshahrani, 1999). For the wood technologist, wood density is important, as an increase in its value can result in higher timber strength and a greater yield of pulp (Elliot, 1970).These studies reported density as a good estimator of mechanical properties in some species .In general, the higher the density the harder is the wood (addis et al, 1995, Walker and Buttereleld, 1996).

However, in some cases, species with high density may have lower hardness strength than other species with lower density (Wagenfuhr, 2007). Thus, in this case, species with the lower density (Sessile oak) has the higher hardness strength. Density has a positive relationship with both radial and tangential shrinkage but also has a negative correlation with longitudinal shrinkage (Pliura, etal, 2005).

2.7.2.2 Moisture Content

The moisture content of a piece of wood is defined as the mass of water in the piece expressed as the percentage of the oven-dry mass of the wood. It has influence on all the strength properties of wood (Desch and Dinwoodie, 1996). It is well known that moisture content influences the strength and stiffness of small clear wood specimens subjected to bending. Strength and stiffness increase with a decrease in moisture content**.**

The hygroscopic behavior of wood describes the adsorption and desorption of moisture to maintain equilibrium depending on the surrounding climate in particular relative humidity and temperature. The adsorption of moisture occurs in two steps in the range from 0 % to 30 % where the moisture is transferred into the cell walls of the wood. Above 30 % moisture content, the cell walls are completely saturated and the moisture is transferred into the cavities of the cells. The moisture content of 28 – 30 % is called fiber saturation point. The fiber saturation point varies depending on the wood species.

Changes in the moisture content below the fiber saturation point affect the physical, mechanical and rheological properties of wood, like the shrinking and swelling, the strength values or the modulus of elasticity or rigidity. The dimension changes are different in the three material axes (longitudinal, tangential or radial) as a principle in wood properties variations. Increasing the moisture content increases the density of wood. Both of the weight and volume of wood increase with increasing moisture content below fiber saturation point resulting increase in moisture content over oven dry density.

2-7-2-3 **Temperature**

In general, the mechanical properties of wood decrease when wood is heated and increase when cooled (Gerhard, 1982). At a constant moisture content and below approximately 150ºC (302ºF), mechanical properties are approximately linearly related to temperature. The change in properties that occurs when wood is quickly heated or cooled and then tested at that condition is termed an immediate effect. At temperatures below 100ºC (212ºF), the immediate effect is essentially reversible; that is, the property will return to the value at the original temperature if the temperature change is rapid.

This illustrates the immediate effect of temperature on modulus of elasticity parallel to grain, modulus of rupture, and compression parallel to grain, 20^{o}C (68^{o}F), based on a composite of results for clear, defect-free wood. The permanent decrease of modulus of rupture caused by heating in steam and water is shown as a function of temperature and heating time.

The effect of temperature is more pronounced with the some strength properties compared with others: thus the longitudinal compression strength increases almost three folds with a drop in temperature from 180-15c°. It should be appreciated that long –term exposure to elevated temperature results in a market reduction in strength, stiffness and toughness, the effect been greater in hardwood than softwood. (Moor, 1984). Dinwoodie (1996) reported that there is an interaction between temperature and moisture content. Thus at high moisture content toughness decrease with decreasing temperature while at low moisture content toughness will increases with decreasing temperature.

2-7-2-4 **Duration of load**

Increase in the rate of load application in a mechanical test result in increased value of strength and stiffness. The effect is greater in testing “green” wood where strength value can increase by 50 percent at moisture content higher than those of wood at 12 percent moisture content. Wood exhibits the unique property of carrying substantially greater maximum loads for short durations than for long periods.

The shorter the duration of load, the higher is the ultimate strength of the wood. Long-term tests have also shown that a series of intermittent loads produce the same cumulative effects on strength as a continuous load of equivalent duration. For example, a load applied for alternating years over a 50-year period would have the same effect as the same load applied continuously for 25 years. For structural applications, wood strength values are based on assumed normal load duration of 10 years (George, 2009).

2-8 **Wood Quality**

Wood quality can be defined in terms of attributes that make it valuable for a given end use (Jozsa and Middleton, 1994). In general, density and micro-fibril angle (indicators of strength and stiffness respectively) are reputed to be the key determinants of wood quality.

For the saw miller, wood quality is reflected in the value of mill production and depends on grade out-turn and the value for each grade (Addis *et al*., 1995). Wood quality for the structural engineer means wood with a high stiffness level, an attribute which is most important for beams, joists and purlins. Strong wood is required for studs and trusses (Addis et al, 1995).

Wood density is an important wood property for both solid wood and fiber products in both conifers and hard woods. Density is a general indicator of cell size and a good prediction of strength, stiffness, ease of drying, machining, hardness (de Guth, 1980, Panshin and de Zeeuw (1980). The density is one of the most important properties influencing the use of timber and hence it's Quality.

It is the important trait within species wood characteristic because knowledge about it allows the prediction of a greater number of properties than any other trait (Bowyer and Smith, 1998).

2.9 **Structure- property relationships**

Koch (1985) reported that 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 paper making 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. Barkas (1949) reported that vessel diameters tend to decrease with increasing distance from the pith. McDonal (1995) cited that the extreme radial increase in specific gravity was associated with increase in fiber wall thickness, decease in fiber diameter and decrease in fiber lumen diameter.

Zhang (1992) found that specific gravity was closely related to tissue proportion, among which was vessel proportion was the most important, and will be directly determined by percentage of cell-wall material. The wood relative density is highly correlated with cell wall area and basic density with cell wall thickness (Quirk, 1984).

2-9.1**The relationship between wood shrinkage and wood anatomy**

The anisotropy of shrinkage in late-wood, and in sapwood and heartwood of gymnosperms and angiosperms was directly proportional to the differences in intensity of lignification between radial and tangential walls of tracheids or fibers. Lignin has a bulking effect on the cell-wall and reduces its tendency to shrink in thickness (Boyd, 1974).

The ratio of tangential to radial linear shrinkage was significantly affected by width of fiber and structure and size of rays. It was also found that groups with irregular rays had the greatest shrinkage anisotropy (Mariaux and Narboni, 1978). The broad ray tissue shrank less than other tissue; cell-wall shrinkage was greater than lumen shrinkage for parenchyma (McGinnes *et.al,* 1976).

The most important structural parameters which influence the specific gravity of wood were the average volume fraction for cell wall material, the average fiber volume fraction for rays, and average fiber length. While compression strength parallel to the grain was found significantly influenced the average volume fraction for cell wall and fiber length (Nasroun and Al Zaki, 1981).

Thus the most important anatomical parameters affecting Shrinkage were vessel diameter, diameter of parenchyma cell, lumen fraction and diameter of fiber lumen (Nasroun and Al shahrani1999).

CHAPTER THREE

MATERIALS AND METHODS

3. The study area

The wood species used in this study was collected from North Darfur State natural forests. The state lies between latitudes 13˚ - 14˚ N and longitudes 25˚ - 26˚ E. The mean annual rainfall is 218mm; mean temperature 36.6˚C, altitude is 740m above sea level (FAO, 2012). Generally the climate of North Darfur is arid in the north and semi- arid in the southern parts.

The dominant vegetation types in the area are: *Balanites aegyptiaca*, *Acacia senegal*, *Boscia senegalensis, Maerua crassifolia*, *Acacia tortilis, Acacia mellifera, Acacia nilotica, Acacia seyal, Eucalyptus camaldulensis, (in plantation forest) Faidherbia albida, and* other Acacia species as well as many important shrubs (Ibrahim, 1984).

The study site is located at Kuttum locality western part of North Darfur State about 100 kilometers from El-Fasher.

3.2 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
Blanitaceae	*1-Balanites aegyptiaca*	Heglig
Myrtaceae	*2-Eucalyptus camaldulensis*	Kafour
Fabaceae Sub f mimisoideae	*3-Acacia nilotica*	Sunt
	4-Acacia seyal	Talh
Leguminosae	*5-Faidherbia Albida*	Haraz

There are five varieties of heglig distributed throughout Africa (Sands, 2001). The only variety recorded to appear in Sudan is variety aegyptiaca (EL Feel, 2004).

Wood material was collected from fifteen hardwood tree species belonging to four families. These species are heglig, kafour, sunt, talh and haraz. From each of tree species, three normal (Healthy & Mature tress) were selected in central and Northern Rural Fattabrno.

General description of tree and wood, distribution and uses of the study species are given in the following sections.

1- *Balanites aegyptiaca* Del (Heglig): Family: Blanitaceae

Heglig is an armed tree about 8-10 m high (El Amin 1990) and 10 cm and rarely over 15 cm in diameter (Vogt 1995). Wood pale yellow, coarse grained; hard (Thirakul 1984). It is an evergreen tree adapted to various climatic conditions especially in arid regions with extremely high temperatures and scarce water; thus it was advised to be promoted for combating desertification (Gour and Kant (2012). Its wood is used for local furniture, agriculture implements, joinery, and walking sticks. Good for firewood and charcoal (Thirakul, 1984).

2- *Eucalyptus camaldulensis* Dehn. (Kafour):Family: Myrtaceae

Tall tree up to 30 m high. Bark smooth, deciduous, (El Amin 1990).The wood is hard and durable, resistant to termites (Thirakul, 1984, Vogt, 1995). It is native of Australia grown in forest plantations in Darfur region, Blue Nile and as shelterbelts in Khartoum Green Belt (El Amin, 1990). Fiber length 0.812 mm, diameter 0.010 mm, double wall thickness 0.005 mm and runkle ratio 1.000 (Nasroun and Elzaki, 1987). It’s used in local construction, sleepers or for nonstructural purpose (Thirkul, 1984).

3- ***Acacia nilotica*** **L. Willd (Sunt): Family: Mimosaceae**

Sunt is an extremely variable species. Usually up to 15 m high. Fibers of medium wall thickness, or very thick-walled, and helical thickenings absent (Neumann et al. 2000). Fibers are non-septate (Neumann et al. 2000, Yousif 2000). Fiber pits simple to minutely border. (Neumann et al. 2000). It is used as firewood, railway sleepers and for fencing posts. The bark exudes an edible gum and is used medicinally as reported by(Van Wyk et al, 2000).

4-*Acacia seyal* .var. seyal Del. (Talh): Family: Mimocaceae

Talh is atypical tree of African semi-arid zones (Von Mey dell 1990). It is locally known as Talh and belongs to the family mimoscaceae. Talh is a tree 3-17 m high. Wood is white cream hard (Thirakul 1984). Vascular or vasicentric tracheids sporadic to absent (Neumann et al. 2000). Fibers of medium wall thickness; or very thick-walled and helical thickenings absent (Neumann et al.2000), fibers non- septate (Neumann et al. 2000, Yousif 2000). Fiber pits simple to minutely bordered, mainly restricted to radial walls (Neumann et al. 2000). It produces good fuel wood and charcoal. The timber is used in construction but is susceptible to insect attack (Vogt 1995). It’s used as cosmetic material in rural areas especially in Darfur region. It is also widely used for women saunas.

5- *Faidherbia Albida*: (Haraz) Familly: Mimocaceae

Haraz is widely distributed throughout the dry zones of tropical Africa

(Pelissier, 1980). The identification classification and the first botanical determination of the species under the name *Acacia albida* Del. was made by Delille in (1813) and was based on a specimen obtained in Egypt.

3.3 Methods

3.3.1 Sampling

Three trees were selected randomly for each species. The sample trees were collected from different areas of North Darfur the three tree of sunt were collected randomly from Dawa Forest, while the three trees of talh were collected from Tarma Forest. However, trees of heglig, kafour and haraz were selected from Fattabarno Forest. The distances between selected trees in each forest were more than 100 meter. The tree height and diameter at breast height were measured using a caliber and sunto clinometers, as shown in table 2. Logs 1.5 meters long were cut from the base of each tree for the purpose of this investigation. These logs were sawn into boards and random sample were taken from these boards for preparing test specimens for determining the different properties. So the sample size was 250 sidles per species.

Table: 2 Characteristics of the sample trees

Forest	species	Tree No	Height(m)	DBH(cm)
Dawa	Sunt	1	8.89	14
		2	9.25	15
		3	6.5	13
Tarma	Talh	1	6.80	19
		2	7.90	18
		3	9.13	17
Fattabrno	Kafour	1	13.11	16
		2	12.20	15
		3	14.7	17
	Haraz	1	12.50	15
		2	10.80	13
		3	12.22	15
	Heglig	1	8.20	14
		2	6.90	12
		3	7.00	17

3.3.2. Anatomical Structure

The anatomical investigations were conducted in Forest Research Centre (FRC at Soba and Material Research Centre (GIAD). The determination of anatomical properties was based on macerated fibres. The maceration procedure developed by Shultze as cited in Jane (1970) was used to liberate the fibres from each other. To do this wood chips from each species were boiled in concentrated nitric acid (60%) in a water bath for 10 minutes. Liberated fibres were washed several times to remove relics of nitric acid and then left for about 10 minutes in distilled water. When the fibers settled down, excess water was gently drained away, the macerated material was placed in Petri dishes, stained by few drops of safranin dye for ten minutes and then rewashed using a series of alcohol concentrations (50%, 70%, and 95%) and water.

The prepared macerated materials were placed on glass slides with one drop of Canada balsam on the slide. Each slide was then covered gently with a cover slip measuring 2.2x2.2cm.The prepared slides were left to dry gradually for three days after which they were ready for examination and determining the different fibre characteristics

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3.3.2.1Fiber length determination

Stereological technique was used for determining the fiber length. To do this the macerated fibers were projected from the stage of a projecting microscope through a digital camera onto a computer screen with a square grid 20x20cm with seven equidistant horizontal parallel lines. Then stereological counts for determine the fibers length were carried out. These counts included the number of points of intersections with fiber boundaries per unit line (P_L) and the number of fiber per unit area (N_A). The magnification used was108x. These stereological parameters were used to calculated fiber length from the following equation.

$FL= \pi P_L/2N_A$…………………………………………………...(19)

This part of the investigation was conducted at the Forest products Division at the Forest Research Center (Soba).

3.3.2.2. Cross-sectional measurements

The transverse measurements of fibers included, fiber diameter, fiber lumen diameter and double cell wall thickness. All of these properties were measured using an image analyzer (model: kross) using 10x magnification. This part of the study was carried out at the Material Research Center (GIADs). The measurements obtained from this machine were fiber diameter (FD) and fiber lumen diameter (LD).

From these two parameters the double cell wall thickness was calculated using the following equation:

1- DCWT = FD - LD……………………………………………(20)

Where:-

DCWT= Double cell wall thickness (µm)

FD= fiber diameter (µm)

LD= Fiber lumen diameter (µm)

From the three above parameters the following ratios were calculated. Coefficient of Cell Rigidity (CR), Rankles Ratio (RR) Fiber Flexibility (FF) from the following formulae:

2-CR= DCWT /FD ……………………………………………………(21)

Where:

CR=Cell Rigidity

3-RR= DCWT/LD………………………………………………………(22)

Where:-

RR= Rankle Ratio

DCWT= Double cell wall thickness (µm),

LD= Fiber lumen diameter (µm).

4- FF= LD/ FD …………………………………………………………(23)

FF= Fiber Flexibility

3.2.3 Volume fractions for cell types and their components

From temporary cross-sectional slides were prepared from randomly selected samples from each species using sliding microtome. The section were stained by soaking them in safranin for five minutes and washed by several alcohol concentrations and water. The sections were mounted on glass slides using Canada balsam as temporary slides. The slides were allowed to dry and examined under microscope for cell type’s proportions and their components using stereological techniques. The techniques involved projecting the image of the slides was projected from a microscope stage through a camera on to a computer screen with square grid imposed on the projected image. The grid was 10×10cms with four equidistant horizontal lines criss-crossing four vertical lines resulting in 16 intersection points representing the total test points.

A point count was made for components of cell types: vessel wall, vessel lumen, fiber wall, fiber lumen, and parenchyma wall and parenchyma lumen. The point count represents the number of test points falling on a feature divided by the total test points (p_p). From the proportion of cell components the proportion of cell types (vessels, fibers, and parenchyma) was worked out, in addition to the proportions of total cell walls and total cell lumens.

3.3.3. Physical properties

3.3.3.1. Density

The wood density was determined using Sudanese Standard 1512-2:2015 *Wood – determination of density for physical and mechanical tests*. Density was determined at equilibrium moisture content (7%). So they used 150 samples per species.

3.3.3.2. Shrinkage

The wood Shrinkage was determined between 30-0 moisture content using Sudanese Standard 1748:2013 *Wood – determination of radial and tangential shrinkage* (adopted from ISO Standard).

3.3.4 Mechanical properties

The wood for mechanical properties determinations was air dried at equilibrium moisture content (7%). The tests were carried according to Sudanese Standards.

Static bending was determined according to the Sudanese Standard 5176: 2012. *Wood – determination of ultimate strength in static bending.* The size of the test specimens was 2cm×2cm×30mm. They were at equilibrium moisture content (7%) the machine used for static bending test was the Universal Testing Machine (Model WDW -100). The Modulus of rupture (MOR) and Modulus of Elasticity (MOE), were calculated using the following equations:

1- $MOR = 3PL/2bd^2$ …………………………… (25)

P= Maximum load at failure

L = length of span (mm)
b = width of specimen (mm)
d = depth of specimen (mm)

2- $MOE = PL^3/4\Delta bd^3$ ………………………….. (26)

Where:

E= is the modulus of elasticity in bending in N/mm^2

P ´= is the load, in N, at the limit of proportionality.

L =is length of span, in mm.

Δ =´ is the deflection, in mm at the limit of proportionality.

b = width of specimen (mm)
d = depth of specimen (mm)

Compression strength parallel to the grain, on the other hand, was carried out in accordance to ISO Standard 3787 – 1976 *Wood – determination of ultimate stress of compression parallel to the grain*. Using Universal Testing Machine (model WDW-100). Specimens were at equilibrium moisture content (7%) and measuring 2cm×2cm×6cm using.

3.3.5 Statistical Analysis

In this study SAS software 2011were used to carrying out analysis of variance, followed by Duncan's Multiple Range Test (DMRT) looking for significant differences beteween 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 confirm these relationships and find the key anatomical properties affecting the different physical and mechanical properties. Finally these relationships were modeled by multiple regression analysis

CHAPTER FOUR

RESULS AND DISCUSSIONS

4.1 Anatomical Properties

Table 1 shows the anatomical characteristic and mean test for separation the five studied species. They include the fiber length FL in mm, Fiber Diameter (FDμm), fiber lumen diameter (FLDμm) double cell wall thickness (DCWTμm), runkles ratio (RR), coefficient of Cell rigidity (CR) and Fiber flexibility (FF). Analysis of variance showed significant differences in all properties between species.

Table4.1 Fiber dimensions of the five species studied.

Common name	**FL**mm	**FD**μm	**FLD** μm	**DCWT μm**
Sunt	2.10A	16.75A	7.80A	8.95A
Talh	1.45B	14.97B	6.12B	8.38A
Kafour	2.28A	14.50B	6.17B	8.0A
Heglig	1.77B	14.17B	6.87A	8.10A
haraz	1.58B	14.11B	7.83A	6.28B

Means with same letter in same column are not significantly different at 0.05.

* Where:

FL= fiber length, FD= Fiber Diameter, FLD = Fiber Lumen Diameter,

DCWT= Double cell Wall Thickness,

4.1.1Fiber Length

The analysis of variance showed that there was significant variations in fiber length among species (p =0.0002). The results of Duncan's Multiple Range Test (DMRT) shown in table4.1. revealed that kafour had the highest mean value (2.28mm), followed by sunt (2.10mm), without a significant difference between them but with significant differences from all other species.

These were followed by heglig (1.77mm), haraz (1.58 and .lastly talh which had the shortest fiber length value among the five species (1.45mm) without any significant difference between the three but with significant differences from kafour and sunt. These results were in agreement with that reported by Nasroun and Alshahrany (1998); Yosif (2001); Osman (2000).Who reported significant variations among species in fiber length. However, the mean fiber length values of kafour were slightly lower than what was found by Nasroun and Al shahrani (1998).

4.1.2Fiber Diameter

The results of analysis of variance for fiber diameter in table4.1 revealed that there were significance variations in fiber diameter among the five species (p=0.0226). The highest mean value of fiber diameter was recoded for sunt (16.75um) with significance differences from all other species, this was followed by talh (14.97um), heglig (14.17um), kafour (14.50um) and the lowest value was found in, haraz(14.11um) without significant difference from each other, but with significance difference from Sunt. the results were close to those found by Nasroun and Al shahrani (1998); Gamal (2007).

4.1.3Fiber Lumen Diameter

Variations in Fiber lumen diameter were significant between the five species (p=0.0195). haraz had the highest mean value (7.83um) Followed by suntraz (7.80um), heglig (6.87um) without any significant difference between the three species, but with significant difference from all other species .

These were followed by kafour (6.17um), and talh (6.12um) both of which had significantly lower FLD than the first three species but without any significant differences between them. Hence the results were slightly in agreement with that found by Nasroun and Alsharany (1998).

4.14 Double Cell Wall Thickness

The analysis of variance in Table4.1 showed significant variations in the values of DWTC among species (P= 0.0002). The highest mean values of (DCWT), were recorded for sunt, (8.95um) followed by talh (8.38um), heglig (8.10um) and kafour (8.00um) respectively without significant differences between them, but with significant difference from haraz, which had the lowest mean value (6.28um). The results were close to those found by Nasroun and Al sharany (1998).

Table4.2 Fiber rations of the five species studied.

no	Common name	**RR**	**CR**	**FF**
1	Sunt	1.16A	0.53A	0.46B
2	Talh	1.83A	0.56A	0.44B
3	Kafour	1.33A	0. 55A	0.43B
4	Heglig	1.27A	0.57A	0.46B
5	Haraz	0.84B	0.45B	0.55A

Means with same letter in same column are not significantly different at 0.05

Where:

RR= Rankles Ratio,CR= Coefficient of cell Rigidity, FF= Fiber Flexibility.

4.1.5 **Rankle Ratio**

Analysis of variance showed highly significant variation (P=0.0026) in Rankle ratio (RR) among the five species. Table4.2 shows that with regards to (RR) talh had the highest mean value (1.83), this was followed by Kafour (1.33), heglig (1.27) and sunt (1.16) without any significant difference between them, but all of them were significantly different from haraz (0.84). The results were slightly in agreement with that found by Nasroun and Al sharany (1998).

4.1.6Coefficient of Cell Rigidity

Based on analysis of variance there were highly significant variations in coefficient of cell rigidity between the five species (P= 0.0006). Table 4.2 shows that talh had the highest value(0.28), followed by Kafour (0.28), heglig (0.27) and sunt (0.26), without any significant difference between them but with significant difference from haraz (0.22) which had the lowest value with significant difference from all other species. The results were also close to those found by Nasroun and Alshahrani (1998).

4.1.7.Fiber Flexibility

The analysis of variance indicates highly significant variation in Fiber Flexibility among species (P= 0.0014). With regards to Fiber flexibility (FF). haraz had highest value (0.55) with significant difference from all other species. Followed by sunt (0.462), heglig (0.457B), talh (0.442), and kafour (0.433). The results were also close to those found by Nasroun and Alshahrani (1998).

DCWT, RR and CR showed the same trend with regards to the order of the species, while FF showed the opposite trend. That is, the species with the lowest value with regards to the first three parameters (haraz) had the highest value in FF and vice versa.

4.1.8 **Volume fraction of different cell types and their components.**

With the regard to point fraction for vessel (P_PV) in table 2 the result shows highest value was found in heglig (0.25) with the significant difference from all other species. These were followed by talh (0.14), kafour (0.14) and sunt (0.12)without any significant differences between the them. While haraz (0.038) had lowest value with significant difference from all other species.

With the regard to point for Fiber (P_PF) highest value was found sunt (0.70) Followed by talh (0.64), kafour (0.60) without the significant difference between them. These were followed by haraz (0.56), which had lowest value with significant difference from (sunt talh, kafour), but without any significant difference from heglig (0.48).

Based on the result of the point for Parenchyma (P_PP) highest value was found in haraz (0.40) with significant different from other species. Followed by kafour (0.28), hegliege (0.21), talh, (0.21) and lowest mean value registered by sunt without any significant difference between them, but with significant different with haraz.

With the regard to point fraction for cell lumen (P_PCW) highest value was found in sunt (0.68) this Followed by talh (0.61) without any significant difference between them, but with significant difference with all other species. Hence haraz, heglig and kafour they registered the same value without any difference between them but with significant differences with first two species (sunt,talh).

For volume fraction for total cell wall (P_PCW) the highest value was found in sunt followed by talh without any significant difference between them, but with significant difference with haraz, and kafour.

The result of point fraction of total cell lumen(P_PCL) reveled that kafour (0.47) had a highest mean value followed by karaz(0.46),heglig(0.46) and talh(0.39) without any significant differences between them, while sunt had lowest value sunt.(0.26) with significance difference from all other species. Woody cells, like any plant cells, are composed of cell walls and cell lumens.

This is why the volume fraction of total cell walls and volume fractions of total cell lumens at up to 1.0. Or close to 1.0.

Table 4:3 Volume fractions of different cell types and their components

Common name	P_PV	P_PF	P_PP	P_PCW	P_PCL
Heglig	0.25 A	0.48 C	0.21 B	0.53 B	0.46 A
Talh	0.14 B	0.64 AB	0.21 B	0.61 AB	0.39 A
kafour	0.14 B	0.60 AB	0.28 B	0.52 B	0.47 A
Sunt	0.12 B	0.70 A	0.16 B	0.68 A	0.26 B
Haraz	0.029 C	0.56BC	0.40 A	0.54 B	0.46 A

Means with same letter in same column are not significantly different at 0.05

4.2. Physical characteristics

4.2.1. Density

Table 3 shows the investigated physical properties for the five species. It indicates that there were highly significant variations in Density among the species ($P<0.0001$).

The results of Duncan's Multiple Range Test (DMRT) in table3 revealed that the highest density value recorded was for sunt (0.95g/cm^3), followed by talh(0.91g/cm^3) with no significant difference between them, but with significant difference from all other Species. These were followed by Heglig (0.78g/cm^3), with significance difference from all other species. Then kafour (0.58g/cm^3), with significance difference from all other species, as well as haraz (0.50g/cm^3), which had the lowest value with significance difference from all other species.

Densities for haraz and kafour were close to what was obtained by Nasroun (2005) while the other three species were slightly higher. Species with high density such as sunt(0.95g/cm^3), talh(0.91g/cm^3),and heglig (0.77g/cm^3) are expected to have high strength values accordingly cloud be recommended for such end uses as heavy constructions, as railway sleepers, flooring and other load-bearing structures. kafour (0.57g/cm^3), and haraz (0.50g/cm^3), associated with moderately heavy density values.

4.2.2. Shrinkage

According to analysis of variance no significant differences were observed in shrinkage (Tangential, Radial, longitudinal) values between the tree species (table 3).

The highest value for tangential shrinkage was associated with kafour (12.15%), followed by talh(11.77%),sunt (11.62%), and heglig (11.53%), while the lower shrinkage value was found in haraz(11.13%).In radial shrinkage the results revealed that Kafour had highest value (6.26%).followed by heglig (5.62), talh(5.32%),and sunt (5.28%). The lowest mean value associated with haraz (5.22%).

The results also revealed that heglig had highest value in longitudinal shrinkage (1.59%), these were followed by haraz (1.32%), kafour (1.19%), Lastly sunt and talh had a lowest mean value (0.89%, 1.09). The shrinkage values obtained were higher that what obtained by Nasroun (2005)

Table:4.4 Density and shrinkage of the five wood species

Common Name	Density g/ cm^3	Shrinkage		
		Tangential	Radial	Longitudinal
Heglig	0.78B	11.53A	5.62A	1.59A
Kafour	0.58C	12.15A	6.26A	1.19A
Sunt	0.95A	11.62A	5.28A	0.86A
Talh	0.91A	11.77A	5.32A	1.09A
Haraz	0.50D	11.13A	5.22A	1. 32A

Means with same letter in same columnn are not significantly different at 0.05

4.3. Mechanical properties

The ANOVA Test showed that the variation between species in Modulus of Rapture (MOR) was highly significant ($P < 0.0001$). Compression parallel to the grain (COM) also showed highly significant variation between species ($P<0.0001$).

Modules of elasticity (MOE) from bending showed the same trend highly significant differences between species ($P<0.0001$), and so as modulus of elasticity from compression (MOC).

4.3. Static Bending

4.3.1 Modulus of Rupture

Table 4 shows the results of the mean separation test for the five wood species. The table revealed that sunt had the highest value in MOR, with significant differences from all other species (140.70Mpa). followed by talh (125.31Mpa), with significant difference from all other species.

While heglig (107.13Mpa), and kafour (99.03), had close value with no significant difference between them but with significant difference from all other species. Lastly haraz had the lowest value (68.74) with significant difference from all other species.

Table 4.5 Mean values of mechanical properties of the five wood species

Common name	MOR MPa	MOE MPa	COM MPa	MOC MPa
Sunt	140.70A	12873.6A	68.47A	2166.3AB
Talh	125.31B	11092.0B	65.65A	2413.5A
Kafour	99.03C	8503.4C	57.00B	1727.5C
Heglig	107.13C	8813.4C	47.47C	1959.7BC
Haraz	68.74D	6507.8D	35.86D	1000.8D

Means with same letter in same column are not significantly different at 0.05.

* Where:

MOR= Modulus of Rupture, MOE= Modulus of Elasticity.

COM= Compression Parallel to the Grain MOC= Modulus of Elasticity from Compression,

4.3.1 Modulus of Rupture (MOR)

Table4: showed that sunt (140.70) had a highest value with significance difference from all other species. This was followed by talh (125.31), with significant difference from all other species.

While heglig (107.13), and kafour (99.03), had a same value with significant difference from all other species, but without any significance variation among them.

Lastly haraz had lowest value (68.74) with significant difference from the all other species. The results were slightly close to what was obtained by Nasroun (2005)

3.3.3. Modulus of elasticity for bending (MOE)

With regards to Modulus of Elasticity for bending the results showed that sunt had the highest value (12873mpa), with significant difference from all other species (table4.5). This was followed by talh (11092mpa), also with significant difference from all other species. heglig (8813mpa), and kafour (8503.4mpa), without any significant difference between them but significantly different from other species.

Lastly haraz (6507.8 MPa) had the lowest mean value with significant difference from all other species. Hence the result slightly different from what obtained by Nasroun (2005)

4.3.2 Compression Parallel to the grain (COM)

The analysis of variance indicated highly significant variations in Compression Parallel to the grain between species ($P < 0.0001$). Table4.5 also shows the separation of means for Compression Parallel to the grain. The table showed that sunt had the highest value (68.45 MPa) followed by talh (65.65 MPa) without any significant difference between them, but with significant differences from all other species.

These were followed by kafour (57.00 MPa) with significant variation from all other species. Followed by Heglig (47.47 MPa), with significant from all others species. Lastly haraz had given the lowest value (35.86 MPa) with significant difference from all other species. The result was close to what found by Nasroun (2005).

3.3.4. Modulus of elasticity from compression (MOC)

With regards to modulus of elasticity for compression the results showed that talh had the highest value (2413.5MPa), Followed by sunt (2166.3 MPa) without any significant difference between them. But with the significant difference from all other species (table4.5). These were followed by heglig (1959.7 MPa), and kafour (1727.5 MPa), without any significant difference between them. Lastly haraz (1000.8 MPa) had the lowest value with significant difference from all other species.

The result of compression parallel to the grain agrees with what found by Nasroun and Alzaki (1987).

4.4. Structure-property Relations

4.4.1. Results of correlation analysis

Table 5 shows results of correlation analysis between dependent variables (MOR, MOE, COM, MOC and DEN) and the independent variables (anatomical Features). 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 volume fraction of cell wall(P_PCW (r= 0.5841, P<0.0010), fiber diameter (r =0.3658, P= 0.0096), double cell wall thickness (r =0.5915, P<0.0001) Rankle ratio (RR) (r=0.3539, P=0.0015) and Coefficient of Cell Rigidity (rR =0.4033, P=0.0045), but negatively correlated with the fiber flexibility (r=-0.4299, P=0.0020) and volume fraction of cell lumen (r= -0.6029, P<0.0001). Modulus of Elasticity from bending and modulus of Elasticity from compression showed the same trends as MOR. It also showed that compression parallel to the grain was positively correlated with

(FD)(r=5481,P<0.0001), (RR) (r=0.3748, P=0.00084) and (DCWT)(r=03575, P=0.0136),while it's negatively correlated with the fiber flexibility (CR)(r=0.40299, 0.0034).

Finally density had positive correlation with (P_PCW) (r=0.6636) (P<0.0001), (FD) (r=0.3121, P=0.0158) (DCWT) (r=0.5400, P<0.0001), (RR) (r=0.3374, P=0.0204) and (CR)(r=0.3074.P=0.0316). While negatively correlated with volume fraction of cell lumens (P_PCL) (r = -0.6482) (P<0.0001).

Table:5. Results of Correlation Analysis between all properties studied

Dependent independent	MOR MPa	MOE MPa	COM MPa	MOC MPa	DEN g/cm^3
FD	r=0.3658 P= 0.0096	r=0.4121 P= 0.0029	r =0.5481 P<0.0001	r = 0.3555 P=0.0113	r = 0.3121 P= 0.0158
DCWT	r=0.5915 P= 0.0001	r =0.6090 P= 0.0001	r =0.3575 P= 0.0136	r =0.3467 P=0.0147	r =0.5400 p <0.0001
RR	r=0.3539 P= 0.0015	r=0.3716 P= 0.0101	r= 0.3748 P= 0.0080	r =0.3742 P=0.0074	r =0.3374 P= 0.0204
CR	r=0.4033 P= 0.0045	r=0.3396 P=0.0170	r=- 0.4062 P= 0.0034	r =-0.4260 P=0.0020	r =0.3074 P= 0.0316
FF	r=-0.4299 P= 0.0020	r=-0.4260 P=0.0020	r=0.7294 P= <0.0001	r =0.5778 P=<0.0001	NS
P_PCW	r=0.5841 P<0.0001	r=0.6579 P<0.0001	r=-0.7359 P=<0.0001	r =-0.5842 P=<0.0001	r =0.6636 P<0.0001
P_PCL	r=-0.6029 P<0.0001	r=-0.6440 P <0.0001	r=0.5481 P<0.0001	r =0.3555 P=0.0113	r =-0.6482 P<0.0001

Where:

MOR= Modulus of Rupture, MOE= Modulus of Elasticity for Bending COM= Compression parallel to the grain, MOC Modulus of Elasticity in compression, DEN = Density FD= Fiber diameter, LD= lumen diameter RR, rankle ration, CR= coefficient of cell rigidity, P_PCW= volume fraction of cell wall P_PCL= volume fraction of cell lumen.

4.4.2. Results of simple regression

Table: 6a-6e shows the results of simple regression analysis. Its shows equations relating each dependent variable to different individual independent variables with R- square and the significant level. Although all models were significant at different levels, R-square values were quite low because of small sample size.

Tables 6a to 6e show the results of simple regression analysis for MOR with important anatomical factors affecting MOR are DCWT, P_PCL and P_PCW in this order of important accordance to the values of R- square. These were followed by CR, FF, RR and FD. DCWT, P_PCL P_PCW however affect MOR to a lesser degree than they affect the other properties blew.

Table6a: simple regression analysis for modulus of rupture

No	Regression model s	R- Square percent	Significant level)
1	MOR=33.22+5.02 FD	13	P=0.0096
2	MOR=10.32+12.30 DCWT	38	P<0.0001
3	MOR=69.70+31.81RR	14	P=0.0075
4	MOR=13.07+354.96 CR	22	P=0.006
5	MOR=188.32-171.37 FF	19	P=0.0016
6	MOR=58.32+88.43 p_pCW	34	P<0.0001
7	MOR=149.01-92.40 p_pCL	36	P<0.0001

The table 6a: shows the results of simple regression analysis for MOE with anatomical properties the models showed similar trends as with MOR (table 6b), with slight change in the order, whereby P_PCW, P_PCL had higher R- square values than those obtained with DCWT.

Table6b: simple regression analysis for modulus of elasticity from bending with anatomical properties

No	Regression models	R- Square percent	Significance level
1	MOE=662.46+1120DCWT	38	P<0.0001
2	MOE=1840.50+518.00FD	17	P=0.0033
3	MOE=6221.48+2748.63RR	13	P=0.0112
4	MOE=2001.11+28261CR	16	P=0.0034
5	MOE=16032-13810FF	15	P=0.0062
6	$MOE=4424.22+9141.41P_PCW$	43	P<0.0001
7	MOE=1358-9058.52TCL	41	P<0.0001

The table 6b shows the results simple regression analysis for compression parallel to the grain with anatomical properties, with similar trends as above models.

However, the values of R-square increase with P_PCW and P_PCL, indicating that these two properties affect compression parallel to the grain more than affect MOR and MOE. The reverse was case with DCWT, which effect on compression was less than its effect on MOR and MOE. Unlike table 6a and 6b the effect of FD on compression was not significant; therefore the model disappeared from the table.

Table 6c: simple regression analysis for compression with anatomical properties.

No	Regression models	R- Square percent	Significant level
1	COM=89.91-74.35FF	15	P=0.0048
2	COM=12.13+160.52CR	19	P=0.0014
3	COM=36.87+15.18RR	14	P=0.0080
4	COM=16.25+4.88DCWT	26	P<0.0001
5	COM=79.08-54.13P_PCL	54	P<0.0001
6	COM=25.29+53.00P_PCW	53	P<0.0001

Table 6d: shows the results of regression analysis for modulus of elasticity from compression test (COM) with the anatomical properties. Here the results are quite different from the above mentioned depended variables. First because DCWT seen to have a negligible effect on MOC as can be seem from the extremely small value of R-square. This is in spite of fact that correlation between the two properties as shown in table 5 was much better.

Moreover the relation with FD was not significant and the model did not appear in the table. Like in all above variable P_PCW and P_PCL were the most anatomical factors affecting MOC.

Table 6d: simple regression of Modulus of elasticity from compression with anatomical properties.

No	Regression models	R- Square percent	Significance level
1	MOC= 831.32+128.71DCWT	0.8	P<0.0473
2	MOC=1003.69+709.28RR	13	P<0.0098
3	MOC=-152.31+75.01CR	19	P<0.0018
4	MOC=3399.98-3298.85FF	13	P<0.0093
5	MOC=575.37+2286P_PCW	43	P<0.0001
6	MOC=2890.63-2302.59P_PCL	43	P<0.0001

Table 6e shows the results of simple regression for density with the anatomical properties. Only four models were significant, with P_PCW and P_PCL being the most important properties affecting the density, followed by DCWT and finally CR. The models with FD, RR and FF were not significant.

Table 6e: simple regression of density with anatomical properties

No	Regression models	R-Square percent	Significance level
1	DEN=0.2027+0.0680DCWT	26	P=0.0002
2	DEN=0.2626+10783CR	12	P=0.0127
3	DEN= 1.04-0.67TCL	42	P<0.0001
4	DEN= 0.3640+0.68TCW	44	P<0.0001

4.4.3. Mathematical Models

Table7 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, P_pCW and P_pCL. 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 P_pCW. 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^2value and the significant level.

Model 4 shows the relationship between MOE and the correlated anatomical properties, namely: FD, DCWT, P_pCW and P_pCL. They all appeared as positively related to MOE including P_pCL 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 P_pCL. 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 7 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.

4.4.4. Results of multiple regression

Table 7: Multiple regression equations.

Model no	Regression models	R^2 percent	Significant level
1	MOR= -26.25+0.20FD+5.65DCWT + 116.43P_PCW + 42.78 P_PCL	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 + 15407P_PCW	61	P< 0.0001
5	COM = 44.51 - 0.28FD+1.20 DCWT+2978P_PCW-25.67P_PCL	68	P<0.0001
6	MOC = 1511 - 96.61FD +54.12 DCWT + 2386.P_PCW + 39.53 PpCL	49	P< 0.0001
7	DEN = -0.63 + 0.01DCWT + 1.59P_PCW + 0.85P_PCL	65	P< 0.0001

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

-All models except MOC model (model 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 R^2 value (49%) and this could not be improved by trying all combinations of the correlated independent variables.

5.2 Recommendations

Relationships between dependent and independent variables in simple regression were slightly different with regards to R^2 values and significance level. It is, therefore recommended that when selecting the independent variables for multiple regressions to look at both correlation and simple regression results.

To repeat this study using large samples of species with samples from different sites.

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