UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION, KUMASI

EFFECT OF AGE AND HEIGHT ON THE PHYSICAL AND MECHANICAL PROPERTIES AND THE CALORFIC VALUE OF *Hevea brasiliensis*

ERNEST WENIA ACHANA

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A Dissertation in the Department of CONSTRUCTION AND WOOD TECHNOLOGY EDUCATION, Faculty of TECHNICAL EDUCATION, submitted to the School of Graduate Studies, University of Education, Winneba in partial Fulfilment of the requirements for the award master of Philosophy (Wood Science and Technology) degree.

JUNE, 2017

DECLARATION

STUDENT’S DECLARATION

I, ACHANA ERNEST WENIA declare that this Dissertation, with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work and it has not been submitted either in part or whole, for another degree elsewhere.

SIGNATURE…………………………….………….

DATE…………………………………..…………

SUPERVISOR’S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of Dissertation as laid down by the University of Education, Winneba.

SUPERVISOR’S NAME: **PROF. CHARLES ANTWI-BOASIAKO**

SIGNATURE…………………………….………….

DATE…………………………………..…………

ACKNOWLEDGEMENT

I humbly register my gratitude to God Almighty for guiding and steering me through a successful completion of this program.

I am highly indebted to my project supervisor, Professor Charles Antwi-Boasiako (the Head of Department of Wood Science and Technology, FRNR-KNUST) for his motivation, enthusiasm, advice and immense knowledge that guided me in coming out with this work.

Mr. Douglas Amoah (Department of Wood Science and Technology Laboratory Technician) FRNR-KNUST deserves my appreciation for his valuable pieces of advice during various stages of this work. Mention also has to be made of Mr. Andy Bayuko and Mr. Johnson Addai for their assistance with the conversion of the samples for the experiment. My profound gratitude also goes to my fellow Post Graduate students especially James Boakye Acheampong for always being there for me especially in difficult times.

I am equally indebted to my wife (Azantinlow Gloria) my children (Achana Rodney Wemochiga, Achana Ransley Wemoye and Achana Rosabel Wedoba) for all the patience they had for me during my engagement in this program. God richly bless everyone.

DEDICATION

To God for the gift of life and to my parents (Mr. Achana Lennox Wekem and Kudadim Beatrice) for raising and supporting me in life.

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ABSTRACT

Many of Ghana's commercial timber species are threatened due to high demand resulting to pressure on the traditional species. The need to investigate the potential utilization of some Lesser-used Timber Species to ascertain their suitability for use is very paramount. Some physico-mechanical properties and calorific value of 20, 30 and 40-year old *Hevea brasiliensis* were investigated. The moisture content (MC) ranged between 13.02% (base of 40-year old) and 15.26% (crown of 20-year old). All the ages (20, 30 and 40-years) recorded gradual increase in MC from their bases to their crowns (14.57 to 15.26%, 13.55 to 14.52% and 13.02 to 13.38% respectively). Density also increased along the boles of the various trees (495.28 to 529.38Kg/m^3 for 20-years, 502.28 to 546.88Kg/m^3 for 30-years and 553.07 to 558.14Kg/m^3 for 40-years). Longitudinal swelling and shrinkage both increased along the boles of the various trees (1.62 to 1.93% and 0.63 to 1.12%, 1.19 to 1.55% and 0.61 to 0.75%, 0.87 to 1.47% and 0.07 to 0.12% respectively) from the base to the crown. Tangential swelling and shrinkage ranged from 2.26 to 2.73% and 2.50 to 3.37% (20-years), 2.01 to 2.53% and 2.30 to 3.21% (30-years), 1.49 to 1.73% and 2.29 to 3.21% (40-years) increasing from the base to the crown and 20-years to 40-years respectively. Volumetric swelling and shrinkage both recorded increases along the boles of all the trees but reduced from age 20-years to 40-years (5.50 to 7.76% and 5.87 to 7.63%, 4.56 to 6.39% and 5.73 to 6.87%, 4.51 to 6.18% and 5.47 to 6.85%, respectively). The greatest resistance to compressional forces parallel and perpendicular to the grain were recorded by the 40-year old tree (34.51 to 35.24N/mm^2 and 4.79 to 5.30N/mm^2) followed by the 30-years (31.77 to 33.39N/mm^2 and 4.55 to 4.77N/mm^2) and 20-years (26.60 to 32.84N/mm^2 and3.78 to 4.40N/mm^2). MOR recorded an increase in values from age 20 to 40-years but reduced along the boles from base to crown (58.74 to 60.88N/mm^2, 59.07 to 66.60N/mm^2 and 59.56 to 67.24N/mm^2 respectively). The average calorific values recorded were 15.99, 18.09 and 18.17MJ/Kg respectively for the various ages making them good sources of firewood. In general the 20-year old tree and the crown portions of the 30 and 40-year old *H. brasiliensis* would be suitable for general light works such as tool handles, packaging and pencils due to their lesser densities and the great propensity to swell and shrink. The base and middle portions of the 30 and 40-year old trees were heavy and strong with less MC and would be ideal for furniture production and also as good fuel wood. This work intends to generate greater interests by stakeholders to move into massive cultivation of *H. brasiliensis* plantations leading to the creation of job opportunities and a source of constant supply of raw material to both the local and international markets.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Unger *et al.* (2001) indicated that wood is the oldest material used by human for constructional purposes after stone. Wood has useful properties, such as its natural and economic availability, ease of fabrication into an infinite variety of sizes (Hoadley, 2000). Kretschmann (2010) further noted that wood is renewable, it has an exceptional strength to weight ratio and a good insulator for heat and electricity. Although wood generally has good construction properties, Davidson *et al.* (2002) noted that design and conceptual differences in construction requires that the appropriate type of wood be used for the intended application. This is to prevent construction failure that contributes to high project budgets and delays in construction. However, in all cases, wood with higher mechanical and physical properties is desirable for construction. There is hardly a single use of wood that does not depend on at least one or more of its mechanical properties (Kollman and Cotê 1968).

The search for alternative wood to replace our traditional species is also based on the fact that the global supply of traditional timber is low, while demand for timber remains high, thus raising the costs of timber as well as housing construction. Within this field of research, there have been recommendations from environmental, economic and physical perspectives regarding rubberwood (*Hevea brasiliensis*) as a suitable alternative to traditional timber (Mathew, 2004; Zhang *et al.*, 2008).

To the environmentalist, rubberwood may be suitable due to its relatively faster natural replenishment. Kollert and Zana (1994) explained that while maturation of most timbers may take up to 60 years to fully mature for harvesting, it takes 25 to 30 years for a rubber tree to mature. From an economic viewpoint, Freeman (2011) asserted that the production cost per cubic meter of rubberwood is only about 30% of the cost of certain forest species such as *Milicia excelsa, Khaya ivorensis* and *Triplochiton scleroxylon*. Thus, it is portrayed as a cheaper alternative to most traditional timbers.

Hong and Dan Sim (1994) reported that rubberwood has comparable physical and mechanical properties with traditional timber. Simpson and Tenwolde (1999) found that it has similar physical characteristics as maple wood, whereas Ayrilmis *et al.* (2009) also discovered some similarities in the physical characteristics of rubberwood and those of oak. The basis for comparison has often been on the static bending properties, including the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) (Simpson and Tenwolde, 1995; Ayrilmis *et al.*, 2009). Relative to traditional wood, rubberwood has also been found to have comparable strength properties including MOR, work to maximum load in bending, compressive strength parallel to the grain, compressive stress perpendicular to grain, and shear strength parallel to grain (ASTM, 1995; Khokhar *et al., 2010*).

However, the general concern about rubberwood is that it has relatively high sugar content, which makes it more susceptible to fungal and insect attacks. Thus, it is commonly treated with insecticides such as chlorpyrifos, imidacloprid, fipronil, and chlorfenapyr as well as fungicides like chlorothalonil, copper oxine, benomyl and isothiazolinone (Gnanaharan and Mathew, 1982; Zhou *et al.*, 2009). This may account for its low patronage and utilisation in the tropics. In addition, while traditional timber has several species suitable for construction, for rubberwood, only *H. brasiliensis* is planted commercially. However, Freeman (2011) indicated that the *Hevea* plant has several clones with variable characteristics.

Ser (1990) and Zhou *et al.* (2007) indicated that rubberwood is largely used for making furniture in Malaysia, Indonesia and Thailand. According to Freeman (2011), rubberwood is a better substitute to conventional timber for furniture- making because its grain structure is very attractive and it is amenable to a variety of finishes and stains, for decorative purposes. In Thailand, Ser (1990) reported that rubber lumber is replacing teak lumber which is traditionally used for construction. In construction, Freeman (2011) maintained that it is more appropriate given that it is more resistant to splitting caused by nailing and can also be stained to shades of traditional forest timbers including teak, rosewood, mahogany and cherry.

In Africa, *H. brasilensis* is indigenous to Gabon, Liberia, Cameroon, Nigeria, Cote d'Iviore and Ghana (Balsiger and Bahdon, 2000; Killmann, 2001). Traditionally, rubber trees in these regions are harvested for their latex and also as a cheap source of wood fuel. However, it is only produced on a small scale in Liberia, and its cultivation in the African region is more significant in Nigeria, with about 300,000 ha (Balsiger and Bahdon, 2000). According to Kilmann (2001), the total land area for its cultivation in Africa is about 470,000 ha, which is about 5% of the global natural rubber tree production. *H. brasiliensis* is also the most dominant and cultivated species of rubber in Ghana, which either germinates in the wild or is produced commercially on plantations. According to Balsiger and Bahdon (2000), Ghana's total land area of rubber trees is less than 15,000 ha, of which Ghana Rubber Estates cultivates 13,010 ha, with the rest grown on smaller scales and some in the wild.

Although the traditional use of rubber in Ghana has been either for the production of crumb rubber for exports, the failing timber industry can be saved by lessening the dependency on traditional timbers and shifting demand for wood to the lesser-known species, such as rubberwood, *Amphimas pterocarpoides*, *Petersianthus africanus* and *Piptadeniastrum africanum*. Currently, rubberwood is produced as lumber by local lumber firms, including Western Veneer Company Limited, Samartex and Bibiani Logging and Lumber Company Limited. However, patronage for traditional timber remains high due to the general public perception that the traditional timbers, (including *Milicia excelsa*, *Khaya ivorensis*, *Triplochiton scleroxylon* and *Entandrophragma cylindricum*) have better physical and mechanical properties than the rather unpopular woods, such as rubberwood. In order to clarify such perceptions and to verify the viability of substituting traditional timber species with rubberwood, analyses of the latter's physical mechanical properties with the traditional timbers' including *Triplochiton scleroxylon*, *Chloroplora excelsa* and *Khaya ivorensis* need to be conducted.

1.2 Problem Statement

Historically, wood has been used as a major building material (Hoadley, 2000), due to its natural availability. Forest resources all over the world are being depleted at an alarming rate. In 1990, forest made up 31.6% of the world's total land area or some 4128 million ha. This changed to30.6% in 2015, or some 3999 million ha (FAO, 2015). The same report found the net annual rate of forest loss to have slowed from 0.18% in the early 1990s to 0.08% during the period 2010-2015. Ghana's original forests cover of 8.2 million ha at the beginning of the 20th century, only an estimated 1.6 million ha remain (FAO, 2010). The agricultural sector, which includes forestry, is the largest contributor (about 40% in 2000 - 2004) to GDP, while forestry alone contributed an estimated 4% to the GDP (World Bank, 2005). The formal Timber Industry accounts for 11% earnings in foreign exchange and 6% to GDP and directly employs 100,000 people (Marfo, 2010). The major factors responsible for deforestation and degradation are agriculture expansion (50%), wood harvesting (35%), urban sprawl and infrastructural development (10%), mining and exploitation (5%) leading to an annual loss of 135,000 ha representing 2.0% rate of deforestation (FAO, 2010) which has led to dwindling of commercial timbers. The constant decline in volumes of timber caused by over- exploitation needs to be addressed if the livelihood of forest communities and the continuous supply of raw materials for national development are to be sustained. Efforts therefore need be geared towards discovering alternative sources of timber with high potential of generating revenue in order to reverse the negative effect of the over exploitation and reliance on our traditional sources of timber. However, concerns have been raised that rubberwood with latex may have higher viscoelasticity and MOE that may improve the durability of the wood.

In Ghana, the depletion of traditional timber has contributed to high cost of wood in construction and housing; given that wood is often a major component in construction (Ayarkwa, 1998). However, *H. brasiliensis* is a plant that could be used as an alternative to traditional timber for structural and furniture works. Although, it is produced on a relatively smaller scale than traditional timbers, it is indigenous to

Ghana and its potential as a substitute to traditional timber may be established by establishing the comparability of rubberwood to the popular hardwoods, such as *Tectona grandis*, *Triplochiton scleroxylon*, *Millicia excelsa* and *Khaya ivorensis*.

1.3 Justification

Wood from *H. brasiliensis* was traditionally regarded as waste until the 1980s' when it found widespread utilization in the timber industry. Kamaruzaman and Yahi (2011) stated that more than 80% of the total rubber plantation areas are in Asia. However, Malaysia, Indonesia and Thailand cultivate almost 70% of the total rubber plantations in Asia. The UNSD (2008) indicated that Malaysia registered a total export value of almost US$1.3 bn from furniture made from rubber wood as compared to Indonesia's total export value of US$1.0 bn. Rubber wood has certain advantages over conventional timbers from the natural forest. This is because it is a plantation by-product which takes only 25 to 30 years to mature and is available at relatively low cost whiles its production cost per cubic meter is only about 30% of the production cost of other forest species (Kollert and Zana 1994). In 2013, natural rubber contributed US$2.2bn to Malaysia's total exports with rubber wood products contributing US$2.1bn (MRB, 2014). Out of Liberia's US$ 207 million in export earnings in 2010, 61% came from rubber with about 20,000 people employed by commercial rubber farms and up 60,000 smallholder households engaged in growing of rubber trees. However, it is very essential to consider its physico – mechanical properties to ascertain the effectiveness of these properties in relation to its utilization.

Although rubber wood is widely spread in West Africa with Nigeria, Liberia and Ghana noted for its cultivation, the concentration is on the extraction of latex for rubber production. Unfortunately, after the extraction of the latex, the rubber tree, which is contributing massive foreign exchange in terms of export in furniture products in Asia in particular, is not being utilized as a raw material for the timber industry but rather used as a source of fuel wood by local indigenes. It is therefore very important to ascertain its suitability for utilization in the timber industry in Ghana.

1.4 Main Objective

To assess the physical and mechanical properties of rubberwood along the boles of various ages as well as the calorific value for potential utilization.

1.4.1 Specific Objectives

1. To determine the Density and Dimensional stability along the stems of rubberwood at different ages (20, 30 and 40-years).
2. To examine the Mechanical properties
3. Determine the Calorific Value of various ages of rubberwood.

1.5 Hypotheses

The following hypotheses were tested by the study:

H_0: Rubberwood trees with greater ages have greater strength and calorific value than those with lower ages.

H_0: There is no difference between the compressive strength of rubberwood and other commercial woods such as *M. excelsa, khaya ivorensis and Triplochiton scleroxylon*

1.6 Significance of the Study

The study is intended to provide further insight into the viability of adopting cheaper rubberwood as a substitute for conventional timber by determining its physical and mechanical properties and the calorific values at different ages (20, 30 and 40 years). The results of the study would provide an opportunity to establish a practical way of reducing costs of construction through the introduction and adaptation of more rubberwood plantations for the sustainable supply of wood resources. Moreover, it can also instigate further research to add to the quest of finding a durable, but cheaper alternative to traditional sources of wood.

1.7 Scope of the Study

The study is limited to conceptual discussions on the physical, mechanical physical properties of wood and their energy levels. The surrogates for the physical properties are limited to density, moisture content, swelling and shrinkage, and the measurement of mechanical properties of wood to MOR, compressive strength parallel to the grain, compressive stress perpendicular to grain, and the calorific values.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the relevant literature on the physical and mechanical properties of wood. Empirical experiments that have been conducted to test these attributes are reviewed in line with their results and findings. Different models that underline specific tests of mechanical properties of wood specimens are also reviewed.

2.2 Physical properties of *H. brasiliensis*

According to Chunwarin (1990), there are about nine species of the genus *Hevea* (*H. sprceana, H. rigidifolia, H. microphylla, H. camporum, H. benthamiana, H. pauciflora, H. nitida, H. guianensis)* but the most popular is *H. brasiliensis*, which is cultivated commercially for natural rubber production. Originally, *H. brasiliensis* was indigenous to the Amazon Basin. However, the works of Sir Henry Wickham contributed to the spread of the *Hevea* in other areas including Bolivia, Peru, Ecuador, Columbia, Surinam and Venezuala as well as South East Asian countries like Malaysia, Indonesia and Singapore (Chirasatitsin, *et al*., 2005). *H. brasiliensis* is distinct from other types of wood physically and mechanically. In the wild *H. brasiliensis* can grow to over 30m, with a trunk diameter of up to 30cm (Balsiger *et al.*, 2000). On plantations, the trees are kept smaller, up to 24m tall and the trunks reach a diameter of about 20cm. Zhang *et al.* (2008) explained that the trees are kept shorter and thinner, so as to use most of the available carbon dioxide for latex production. Generally, however, *H. brasiliensis* is shorter in height and has narrower trunks than other hardwoods, like *Quercus* (oak) species, *Milicia excelsa* (Odum) and *Triplochiton scleroxylon* (Wawa/Obeche).

For example, Arung *et al.* (2005) indicated that under sheltered conditions and deep soil, oaks, such as Pedunculate oak (*Quercus rabur*) and Sessile Oak (*Quercus petraea*), can grow to 40m or more in height. Similarly, Lawson (1994) noted that *Triplochiton scleroxylon* (Wawa) can attain an average height of 70m and a trunk diameter of 60cm in 25-30 years, by which time, a fully matured *H. brasiliensis* would have a diameter of about 30cm. Moreover, *Milicia excelsa* grows to an average height of 50m and average diameter of about 1 to 1.5 metres (Arung *et al.*, 2005), which is much larger than the matured *H. brasiliensis.* This implies that *H. brasiliensis* will produce less timber than the other species.

Physically, *H. brasiliensis* is a light coloured hardwood and shows the general structure of hardwood with certain characteristics specific to the species. For example, Taylor (2003) indicated that *H. brasiliensis* is not rubbery, but rather moderately hard and stiff, with about the same density as ash or maple.

In comparison to other hardwoods like *Quercus rabur*, *Triplochiton scleroxylon* and *Milicia excelsa*, Bosshard (1966) classified rubberwood as light hardwood based on its density. Bosshard (1996) explained further that the basic density and density of rubberwood at 12% mc vary even in mature trees of the same age and plantations. It may vary from 435 to 626 kg/m^3 due to genetic or clonal differences. Meier (2013) also confirmed that at 12% MC, rubberwood has density of 600 to 620 kg/m^3. At 12% MC, the densities of other hardwoods such as *Eucalyptus delegatensis* (Alpine; 650kg/m^3), *Flindersia australis* (Ash, Crow's; 950kg/m^3), and *Milicia excelsa*

(Iroko/Odum; 660kg/m^3) are generally higher than that of *H. brasiliensis* (Meier, 2013). Similarly, Zhang *et al*. (2007) found that *H. brasiliensis* has a green density between 600-620kg/m^3, which is lighter than the green density of *Eucalyptus delegatensis* (Alpine; 1050kg/m^3) and *Flindersia australis* (Ash, Crow's; 1050kg/m^3).

Killmann (2001) described the physical properties of *H. brasiliensis* in terms of colour, which is important for its aesthetic value in terms of its adaptability to constructional and home use. Freshly sawn *H. brasiliensis* (green wood) is whitish yellow in colour and turns pale cream after drying. Lim *et al.* (2003) confirmed that rubberwood has a white to pale cream colour, but sometimes includes a pinkish tinge. However, Ratnasingam *et al.,* (2012) noted that the colour eventually changed to light straw or light brown, due to weathering. The colour of rubberwood is distinct from other hardwoods like *Milicia excelsa*, which Mathews (2004) described as yellow to golden or medium brown, with colour tending to darken over time.

Growth rings on *H. brasiliensis* are absent or ill-defined and the concentric marks, which resemble growth rings in the cross sectional view are false rings formed by the distribution pattern of tension wood in association with banded apotracheal axial parenchyma (Reghu, 2002). Mathews (2004) also indicated that the growth rings are usually indistinct and they often comprise narrow to medium rays, which are barely visible without lens. The concentric rings, combined with the large vessel elements, give the wood a clear figure on its longitudinal surface. Heartwood formation is not noticeable in rubber tree, because the sapwood is not distinct from the heartwood, unlike in other durable hardwood species like *Milica excelsa* and *Eucalyptus acmenoides* (Meier, 2013).

2.3 Importance of Physical Properties within Rubberwood for Construction

The physical properties of rubberwood have some distinct importance for construction and woodwork. The most evident feature of rubberwood in woodwork is the unique colour of the wood, which gives the finished product a distinct and attractive look. Balsiger *et al*. (2000) asserted that the light colour of the wood allows rubberwood panels to have a transparent finishing, emphasising the all-natural character of the product. On the other hand, the light colour of rubberwood makes it easy to be coloured with different paints, and it also makes it harmonious with other wood colours. Lim *et al.* (2003) observed that rubberwood has the beautiful texture, with smooth and uniform character, which also adds to the aesthetic value of the products.

Primarily, *H. brasiliensis* is used for rubber extraction after five years of cultivation. On the other hand, after 25 to 30 years of maturation, the trees can be used for other construction purposes (Kollert and Zana, 1994). However, for construction purposes, rubberwood needs to be treated to reduce the high depositions of carbohydrates, which makes the wood susceptible to fungal and insect attacks soon after felling (Zhou *et al.*, 2007). Pressure treatments and treatments with solutions, such as boric acid represent added time and costs to the production of rubberwood, while improper treatment of the wood puts the construction project at risk of failure (Ratnasingam *et al.*, 2012).

2.4 Mechanical Properties of Rubber Wood

Wood may be described as an orthotropic material, which means that, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential (Green and Rosales, 1996). The longitudinal axis (*L)* is parallel to the fibre (grain); the radial axis (*R)* is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis (*T)* is perpendicular to the grain but tangent to the growth rings. The orthotropic composition of wood therefore has implications for its mechanical properties, with respects to its elastic and strength properties. According to Forest Product Laboratory (2010), the importance of understanding the mechanical properties of wood lays in the fact that, a component member of a structure is often subjected to multi-axial stress state, as opposed to a simple stress state. Thus, an understanding of the mechanical behaviour of wood allows for more efficient design of structures.

2.4.1 Elastic Properties of Wood

The elastic properties of wood refer to the measure of stiffness of the wood. The elastic properties of wood are based on the theory of elasticity of anisotropic elastic body, developed by Lekhnitskii (1963). According to the theory, all bodies, on the whole, can be divided into homogeneous and non-homogeneous bodies, and isotropic and anisotropic as well. Wood, as presented by Perkins (1967), might be classified as a material that possesses some levels of homogeneity from the macroscopic structure to microscopic structure. Dinwoodie (2000) deduced from the theory that, there are four levels: macroscopic, microscopic, ultrastructural and molecular. Based on these levels, it can be explained that wood crushing and wood tensile strength could be related to the strength of the tracheids. Besides that, the components of stress, strain and elastic constants in different levels can be considered and the elastic properties would depend on the position in the tree. Moreover, the macroscopic constants (C_{ijkl}) are not necessarily equal to the microscopic constant (c_{ijkl}) or, equal to the average values. However, when the medium is macroscopically homogeneous and when the strains are small and relatively homogeneous, one could consider the material response as homogeneous and (C_{ijkl}) is approximately equal to (c_{ijkl}).

The theory of elasticity applied to wood is based on the hypothesis that wood has three mutually perpendicular planes. Bodig and Jayne (1982), in addition to this hypothesis, considered the material homogeneous. Therefore, the longitudinal-tangential surface is not a plane, but roughly cylindrical. However, they consider the other two surfaces, the longitudinal-radial and radial-tangential, as truthfully, more straight. Thus, wood may be treated as a cylindrical orthotropic body. Technically, Silker and Yu (1993) asserted that, twelve constants (nine are independent) are needed to describe the elastic behaviour of wood: three Moduli of elasticity E, three Moduli of Rigidity G, and six Poisson's ratios μ.

2.4.1.1 Modulus of Elasticity

The MOE (Young's modulus) a material property, that describes its stiffness and is, therefore, one of the most important properties of solid materials (Forest Product Laboratory, 1999). The MOE is established in the fact that mechanical deformation puts energy into a material and the energy is stored elastically or dissipated plastically. The way a material stores this energy is summarised in stress-strain curves. Stress is defined as force per unit area and strain as elongation or contraction per unit length. When a material deforms elastically, the amount of deformation likewise depends on the size of the material, but the strain for a given stress is always the same and the two are related by Hooke's Law (stress is directly proportional to strain). This can be expressed as;

$$\sigma = E.\ \varepsilon$$

Where:

σ is stress (MPa)

E is modulus of elasticity (MPa)

ε is strain

From the Hooke's law, the MOE is defined as the ratio of the stress to the strain, which is given as;

$$E = \frac{\delta}{\varepsilon} [MPa]$$

According to Winandy and Rowell (2005), stress is not directly measurable, but it can be calculated from different formulas for different types of loadings. Strain, however, is defined as the change in length divided by the original (initial) length, which is given as:

$$\varepsilon = \frac{\Delta l}{lo} = \frac{l1 - lo}{lo}$$

Where:

Δl is change in length

l_1 is length after elongation

lo is original (initial) length

Generally, the modulus of elasticity can be determined by tension, bending tests and natural frequency vibration tests. The tension and bending test are based on the principle of Hooke's law and they are called static methods, while the natural frequency of vibration gives dynamic MOE (Winandy and Rowell, 2005). The static method is based on pulling or bending a sample of the material in an instrument, which measures force and measuring the changes of the length.

A mechanical strain gauge is often used to measure the strain on the test piece, as it applied in the given formula:

$$\delta = \frac{\mathrm{F}}{\mathrm{A}}\,[\mathrm{MPa}]$$

Where:

F is applied force [N]

A is cross sectional area [m^2]

The gauge has two contacting points. One point is firm and the second is movable. This device should be a dial where the small straight motion of the point is transmitted into bigger rotary motion of the hand. Usually, there are two hands comprising a big hand showing divisions on main scale (centesimal or millesimal) and a small hand, showing whole millimetres on auxiliary scale. The change of the length is calculated as the difference between gauge reading in the state of loading and gauge reading in an unloaded state. The test piece is mounted in the tensile testing machine (Figure1), which allows measurable forces to be applied. The test piece is supported at either ends and a load (in a form of weights) is applied in the middle between the supports. Green *et al*. (2003) indicated that the change of the length is usually very small (tenths – hundredths of mm) and it is impossible to measure it by normal rules and therefore, extensometers are used to take measurements.

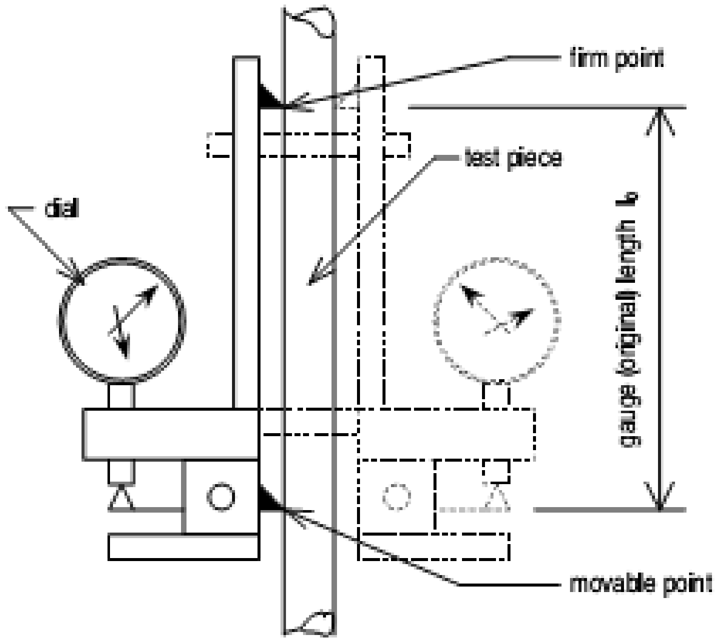

Figure 1: Mechanical strain gauge showing a mounted test piece

Source: Winandy and Rowell (2005)

The MOE of a wood specimen measures the ratio of stress placed upon the wood, compared to the strain or deformation that the wood exhibits along its length. In this approach, the relations between the MOE and Poisson’s ratios (LeVan and Evans, 1996) are expressed as;

$$\frac{\mathrm{\mu ij}}{\mathrm{Ei}} = \frac{\mathrm{\mu ij}}{\mathrm{Ej}}, \quad i \neq j, \quad i,j = L,R,T.$$

According to the model, elasticity implies that deformations produced by low stress are completely recoverable after loads are removed, but plastic deformation or failure occurs when the specimen is loaded to higher stress levels. The three MOE, which are denoted by E_L, E_R, and E_T, respectively, are the elastic moduli along the longitudinal, radial, and tangential axes of wood. However, the modulus of elasticity determined from bending, E_L, rather than from an axial test, may be the only modulus of elasticity available for a species. The E_L calculated includes an effect of shear deflection, but E_L

from bending can be increased by 10% to remove this effect approximately. This adjusted bending EL can be used to determine ER and ET based on the ratios. From this perspective, the elastic ratios (at 12% moisture content) of some common hardwood, such as oak/ *Quercus macrocarpa* (E_T /E_L = 0.082; E_R/E_L = 0.154) and Mahogany/ *Swietenia macrophylla* (E_T /E_L = 0.064; E_R/E_L = 0.107) can be calculated, as shown in Table 2.1.

Table 2.1: Elastic ratios of some common timber species

Species	**E_T / E_L**	**E_R/E_L**
Basswood (Tilia Americana)	0.015	0.046
Mahogany (Swietenia macrophylla)	0.050	0.111
Oak (Quercus macrocarpa)	0.082	0.154
Red maple (Acer rubrum)	0.067	0.140

Source: Forest Product Laboratory (1999)

The MOE of some common hardwoods, such as Iroko or *M. excelsa* (9.38GPa), Mahogany or *S. macrophylla* (9.56GPa), maple, oak or *Q. macrocarpa* (7.10GPa) and Wawa/Rosewood or *T. scleroxylon* (10.86GPa) are also calculated based on the bending properties of the wood. The MOE of rubberwood or *H. brasiliensis* (9.07GPa) is comparable with some of the common timber species such as *M. excels* and *T. scleroxylon* which indicate that rubberwood could also be applicable for construction members that may be subjected to multiple stress states.

2.4.1.2 Poisson's Ratio

When a member is loaded axially, the deformation perpendicular to the direction of the load is proportional to the deformation parallel to the direction of the load (Winandy, 1995). The ratio of the transverse to axial strain is called Poisson's ratio.

The Poisson's ratios are denoted (sigma) and named after Simeon Poisson (Winandy and Lebow, 2001). The first letter of the subscript refers to direction of applied stress and the second letter to direction of lateral deformation. For example, is the Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis. Two of the Poisson's ratios are very small and are less precisely determined than are those for other Poisson's ratios (Rowell *et al.*, 2005). Poisson's ratios vary within and between species and are affected by moisture content and specific gravity.

The Poisson's ratio of a stable, isotropic, linear elastic material cannot be less than −1.0 or greater than 0.5 due to the requirement that Young's modulus, the shear modulus and bulk modulus have positive values (Winandy, 1995). A perfectly incompressible material deformed elastically at small strains would have a Poisson's ratio of exactly 0.5, but Sliker (1993) indicates that most materials have Poisson's ratio values ranging between 0.0 and 0.5. The Poisson's ratios for some of the commonly used timber species are presented in Table 2.2. This can form a basis for comparison to the mechanical properties of *H. brasiliensis*.

Table 2.2: Poisson's ratio for some common timber species

Species	Mlr	µRL	µLT	µTL	µRT	µRT
Basswood (*Tilia americana*)	0.384	0.406	0.912	0.346	0.034	0.022
Mahogany (*Swietenia macrophylla*)	0.297	0.641	0.604	0.284	0.033	0.032
Oak (*Quercus macrocarpa*)	0.350	0.448	0.560	0.292	0.064	0.033
Red Maple (*Acer rubrum*)	0.424	0.478	0.774	0.349	0.065	0.037

Source: Forest Product Laboratory (1999)

2.4.2 Strength Properties

According to Green *et al*. (2003), the mechanical properties most commonly measured and represented as strength properties for design include MOR in bending, maximum stress in compression parallel to grain, compressive stress perpendicular to grain, and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain, and hardness.

2.4.2.1 Shear Force

Shear strength of wood is a measure of its ability to resists internal slipping of one layer relative to another along the grain, and it is defined by the maximum load per unit shear plane area (Wood Handbook, 1987). Panshin and de Zeeuw (1964) explained that the shear strength of wood results when one portion of the wood slides over the other on an application of external load. There are three types of shear which act on wood: vertical, horizontal and rolling. According to Boding and Jayne (1982), due to the extremely high shear resistance across the grain, shear testing of wood samples is restricted to failure only in the longitudinal direction. Shear strength is determined by dividing the maximum load by the shear area (Dinwoodie and Desch, 1996). Huggins *et al.,* (1964) found that beam shear strength and ASTM D143 shear were not different and that the former depends on the shear span, defined as the distance from support to the nearest concentrated load.

Keenam (1974) utilised a finite element method to predict the shear strength of full-size beams under four-point bending load conditions. It was realised that the shear strength of the beam decreased as the shear-span-depth ratio increases. Rammer (1996) proposed a test method for determining the shear strength of lumber using full-size spacemen; this is called the five-point bending test. He reported that this test can consistently produce shear failure from a wide range of lumber sizes, and the lumber shear strength is related to ASTM D 143 shear strength value.

2.4.2.2 Modulus of Rupture

The modulus of rupture (MOR) reflects the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Boresi *et al*. (1993), however, argued that, normals to the axis are not required to remain perpendicular to the axis after deformation. Therefore, the modulus of rupture is the highest stress experienced within the material at its moment of rupture. However, Gere and Timoshenko (1997) contended that the MOR does not apply true stress because the formula by which it is computed is valid only to the elastic limit.

Libai and Simonds (1998) explained that when an object formed of a single material, like a wooden beam, is bent, it experiences a range of stresses across its depth. At the edge of the object or on the inside of the bend (concave face) the stress will be at its maximum compressive stress value. At the outside of the bend (convex face) the stress will be at its maximum tensile value. These inner and outer edges of the beam or rod are known as the ‘extreme fibres’. Han *et al.* (1999) observed that most materials fail under tensile stress before they fail under compressive stress, so the maximum tensile stress value that can be sustained before the beam fails is its flexural strength or MOR. MOR is calculated from the following equation (Kollman and Cotê 1968):

$$MOR = \frac{3\mathrm{PL}}{2bh3}$$

Where:

P = Maximum load (N)

L = Length of test piece (mm)

b = Breath of test piece (mm)

h = Depth of test piece (mm)

2.4.2.3 Flexural Rigidity

Flexural rigidity is defined as the resistance offered by a structure while undergoing bending. Sankar (1993) noted that in Euler-Bernoulli's beam equation, the flexural rigidity (defined as *EI*) varies along the length as a function of *x* shown in the following equation:

$$EL\frac{\mathrm{dy}}{\mathrm{dx}}=\int_0^x M\ (x)dx+C1$$

Where:

E is the Young's modulus (in Pa),

I is the second moment of area (in m^4),

y is the transverse displacement of the beam at x, and

$M(x)$ is the bending moment at x.

Perre *et al.* (2002) observed that the flexural rigidity of a wood specimen can be approximated in many ways depending on the accuracy expected. Gross approximation of the rigidity under flexion is given by the formula:

$$R=E_L 4b\left(\frac{h}{L}\right)^3$$

Where:

R is the rigidity under flexion

L is the length of the sample

h is its thickness

b its width

E_L is its Young modulus.

A more accurate approximation based on variability principle shows that, in bending experiment, where the load is normal to the grain, the deflexion can be approximated by:

$$u = \frac{2\varepsilon^4 \pi^4 E_L}{3(1 - \nu_{LR}\nu_{RL})L^3} F$$

Where:

u is the displacement

$h = 2$ the thickness of the sample

L its length

E_L the young modulus

$_{LR}$ and $_{R}$ is the corresponding Poisson's ratio.

Thus, the flexural rigidity is given by the relation

$$R = \frac{2\varepsilon^4 \pi^4 E_L}{3(1 - \nu_{LR}\nu_{RL})L^3}$$

2.4.2.4 Work to Maximum Load in Bending

The work to maximum load (WML) stress represents the ability of a specimen to absorb shock with some permanent deformation and more or less injury to the specimen (Popper *et al.*, 2001). WML is, therefore, a measure of the combined strength and toughness of wood under bending stresses. WML is, thus, the amount of work needed to actually fracture or fail a material. It is a measure of the amount of energy required to fracture the material. According to Mathews (2004), toughness and work to total load are analogous properties, but their final limit state also includes energy absorbed beyond the ultimate failure. WML is calculated as the relation of the area under the stress to the strain curve from zero to the ultimate strength of the material.

Hodgkinson (2000) observed that the WML takes into account the Work to Proportional Limit (WPL), which is the measure of work performed, or the energy used, in going from an unloaded state to the elastic limit of a material. For a beam of rectangular cross section under centre point loading, WPL is calculated as the area under the stress in relation to the strain curve from zero to the proportional limit.

2.4.2.5 Compressive Strength Parallel to Grain

The compressive strength parallel to grain is the maximum stress sustained by a compression parallel-to-grain specimen (Groover, 2015). Winandy and Rowell (2005) indicated that, if wood is considered a bundle of straws bound together, then a compression parallel to the grain (*C*||) can be thought of as a force trying to compress the straws from end to end. The distance through which compressive stress is transmitted does not increase or magnify the stress, but the length over which the stresses are carried is important. If the length of the column is far greater than the width, the specimen may buckle. This stress is analogous to bending-type failure rather than axial-type failure. As long as specimen width is great enough to preclude buckling, *C*|| is solely an axial property. Rowell (2005) indicated that, compression-parallel-to-the-grain strength or the maximum crushing strength is derived at the ultimate limit value of a standard stress-strain curve. The strength of wood in $C\|$ is derived by the following:

$$C\| = P/A$$

Where:

$C\|$ is the stress in compression parallel to grain

P is the maximum axial compressive load

A is the area over which load is applied

According to the ATSM 695 (2008), the specimen is mounted in an Instron electromechanical load frame for compressive tests to be conducted. The setup offers a controlled situation where the force being applied, the area over which the load is applied and the moment of failure can be measured objectively. The setup also prevents the specimen from buckling, which allows for the measurement of the axial property of the specimen.

2.4.2.6 Compressive Stress Perpendicular to Grain

Compression perpendicular to the grain (C⊥) can be thought of as stress applied perpendicular to the length of the wood cell. Therefore, it depicts that the wood cells are being crushed at right angles to their length until the cell cavities are completely collapsed. According to Winandy and Lebow (2001), wood is not as strong perpendicular to the grain as it is parallel to the grain. However, once the wood cell cavities collapse, wood can sustain a nearly immeasurable load in C⊥. Because a true ultimate stress is nearly impossible to achieve, maximum C⊥ in the sense of ultimate load-carrying capacity is undefined and discussions of C⊥ are usually confined to stress at some predetermined limit state, such as the proportional limit or 4% deflection.

Compression-perpendicular-to-the-grain stresses are found whenever one member is supported upon another member at right angles to the grain. Examples of compression perpendicular to the grain are the bearing areas of a beam, truss, or joist. The C⊥ strength is derived by:

$$C_{\perp} = P/A$$

Where:

C⊥ = the stress in compression perpendicular to the grain

P = the proportional limit load, and

A = the area

For compressive perpendicular to grain, the data collected from the tests, using the Instron electromechanical load frame includes the length between supports (L), width (b) and depth (h) of specimen, load applied (P) and Strain. These are used in the following equations to calculate for (ASTM-695, 2008):

Cross-sectional area of the specimen (A) = $A = b \times h$

Deflection (Δ) = $Strain \times L$

Modulus of elasticity = $E = \frac{PL}{A\Delta}$

The compression perpendicular to grain and the compression parallel to grain is then calculated using the equation:

$$\frac{\Delta PL}{AE}$$

Where:

Δ = Deflection

P = Load

A= Cross-section area

E= Modulus of elasticity

2.4.2.7 Hardness

Hardness is generally defined as resistance to indentation using a modified Janka hardness test, measured by the load required to embed an 11.28-mm (0.444-in.) ball to one-half its diameter. It is therefore used to represent the resistance to indentation and/or marring (ASTM, 2003). While a material may be softer or harder in common vernacular, hardness, in engineering terms, is a material property that is measured using specified methods detailing sizes, sources, and test speeds. Beyond those specific test conditions, the term hardness when used in common language may have widely different meanings to different people (Rowell, 2005). The hardness of the surface of wood greatly impacts on its machinability. It is of great importance in plank flooring, furniture veneers as well as in kitchen and office furnishing (Herajarki, 2000). It is also a very important characteristic as far as wood intended for parquet manufacturing is concerned (Lutz 1977, Niema and Stubi 2000), it affects the resistance against scratching, wearing and abrasion. Hoadley (1980) stated that, hardness determines the material that can be suitably used for flooring, paving blocks and bearing blocks.

It can be derived from different forces such as compressive, frictional and shear forces (Kollman and Cotê 1968). Schueab (1990) concluded that the method according to Brinell (2011) is most suitable for testing the hardness of solid wood. The depth of indentation determined by the Brinell method is thought to produce fewer side effects than the Janka method (Bektas *et al;* 2001).

2.4.2.8 Shock Resistance

Shock resistance or energy absorption is a function of a material's ability to quickly absorb and then dissipate energy via deformation (McDonald, 1997). This is an important property for baseball bats, tool handles, and other articles that are subjected to frequent shock loadings. High shock resistance on energy absorption properties requires both the ability to sustain high ultimate stress and the ability to deform greatly before failing (Chirasatitsin *et al*., 2005). It can be measured by several methods. With wood, three of the most often used methods are work tests (to maximum load), impact bending tests, and toughness tests (Winandy and Rowell, 2005). The latter two test methods yield measures of strength and pliability, mutually referred to as energy absorption. These two measures of shock resistance are similar, but are not particularly relative to one another.

With the impact bending test, a hammer of given weight is dropped upon a beam from successively increased heights until rupture occurs or the beam deflects 152 mm (6 in.) or more. The height of the maximum drop, or the drop that causes failure, is a comparative value that represents the ability of wood to absorb shocks that cause stresses beyond the proportional limit (ASTM, 2003). All that is recorded is the height of drop causing complete failure in a beam such that for a different sized beam or a different mass of weight the measured value would most certainly change.

Toughness, however, is the ability of a material to resist a single impact-type load from a pendulum device (ASTM, 2003). Thus, toughness is similar to impact bending in that both are measures of energy absorption or shock resistance. Yet critical differences exist. Toughness uses a single ultimate load and impact-type bending, whereas impact bending uses a series of progressively increasing, multiple loads in which the earlier load history can certainly alter the eventual result. Although each test method defines a material characteristic, each measured property should only be compared within the limited definitions of that method. They should not be compared on a method-to-method basis nor compared if tested on differing sized or conditioned materials.

2.5 Natural Characteristics of Wood Affecting their Mechanical Properties

Clear straight-grained wood is used for determining fundamental mechanical properties; however, because of natural growth characteristics of trees, wood products vary in specific gravity, may contain cross grain, or may have knots and localised slope of grain. Natural defects such as pitch pockets may occur as a result of biological or climatic elements influencing the living tree. These wood characteristics must be taken into account in assessing actual properties or estimating the actual performance of wood products.

2.5.1 Anisotropic Behaviour of Wood

A material is said to be anisotropic if it has different physical properties in the direction of various structural axis. The cell wall exhibits definite anisotropy because of the structural organisation of the materials composing it (Panshin and de Zeeuw, 1980). Strength properties depend on the anisotropy of wood (Illstron, 1944). Compressive, tensile and shear strengths vary widely between the longitudinal and lateral directions of wood. For example, the ratio of compression parallel to the grain to the compression perpendicular to the grain varies from a minimum of 4 in hardwoods containing thick- wall fibres with small diameters, to a maximum of 12 in thin-walled tracheae in conifers. This means that wood is 4-12 times stronger in compression parallel to the grain than it is perpendicular to the grain (Panshin and de Zeeuw, 1980).

2.5.2 Cross Grain

Cross grain is a defect of wood (Boding and Jayne, 1982) and occurs when the longitudinal axis of the cells is no parallel to the edge of a piece of wood (Illstron, 1994). Hoadley (1990) explained that cross grain is measured quantitatively as a slope of grain, taken as the ratio of unit of deviation across the grain to the corresponding distance along the grain. The fibre deviation from a line to the sides of the wood (cross grain) reduces strength because wood is much weaker across the grain than parallel to it (Wilcox *et al,* 1991).

2.5.3 Knots

Knots are formed by the change of wood structure that occurs where limbs grow from the main stem of the tree (Illstron, 1994). Boding and Jayne (1982) indicated that knots introduce heterogeneity and therefore have major influence on the mechanical properties of wood. According to Hoadley (1990), knots reduce strength in two ways. Firstly, the knot itself has abnormal cell structure that runs at an angle to the surrounding grain direction. Also, the area around the knot usually contains cross grain that result in severe strength reduction.

Tensile strength is affected most by the knot but compression strength parallel to the grain is reduced too. The amount of reduction depends on where the knot is located on the beam (wood) across the section (Illstron, 1994). Boding and Jayne (1982) have, however, observed that not every property is adversely affected by the presence of knots. Overall strength and stiffness in compression perpendicular to grain as well as in shear along the grain benefit from the presence of knot.

2.5.4 Tension Wood

Tension wood is formed on the upper side of a leaning stem or branch of a hardwood, but a few kinds of trees form tension wood on their lower side (Onaka, 1949). Depending on its intensity, tension wood, according to Tsoumis (1991), has higher density than normal wood. The higher density may be explained on the basis of thicker walls of gelatinous fibres. When tension wood is present, the normal relationships of strength, MC and density do not apply. According to Panshin and de Zeeuw (1980), the few available data on the mechanical properties of this subnormal wood suggest that compression strength both parallel and perpendicular to grain, MOR, MOE in bending, and shear strength of tension wood are all lower than those of normal wood below the fibre saturation point.

2.5.5 Juvenile Wood

Juvenile wood refers to a typical wood formed around the pith during the first few years of growth. It is more pronounced in trees with unusually fast initial years of growth. In plantation-grown conifers, which grow quickly due to lack of competition, juvenile-wood formation often continues for 15 or more years, forming a core several millimetres (mm) in diameter. However, in other cases, juvenile wood is either restricted to a few rings adjacent the pith or it is virtually absent (Hoadley, 1990). The transition from juvenile wood to mature wood is gradual in some cases, abrupt in others. Juvenile wood may be lower than normal in density, especially in conifers. In some cases, they are pronounced, different in cell size, appearance and arrangement (Tsoumis, 1991). Wood from the first few growth rings should be compared to mature wood to get a sense of how different juvenile wood can be.

2.5.6 Specific Gravity

The substance of which wood is composed is actually heavier than water; its specific gravity is about 1.5 regardless of wood species. In spite of this, the dry wood of most species floats in water, and it is thus evident that part of the volume of a piece of wood is occupied by cell cavities and pores. Variations in the size of these openings and in the thickness of the cell walls cause some species to have more wood substance per unit volume than other species and therefore, higher specific gravity (Silker and Yu, 1993). Thus, specific gravity is an excellent index of the amount of wood substances contained in a piece of wood; it is a good index of mechanical properties as long as the wood is clear, straight grained, and free from defects. However, specific gravity values also reflect the presence of gums, resins, and extractives, which contribute little to mechanical properties. In fact, mechanical properties within a species tend to be linearly, rather than curvilinear, related to specific gravity (Silker *et al.,* 1994). Therefore, where data are available for individual species, linear analysis is suggested.

2.5.7 Calorific Value (CV)

Calorific value is the quantity of heat produced by the complete combustion of a given mass of a fuel, usually expressed as Joules per kilogram (J/kg). It is sometimes described as a measure of the heating power of a substance. It is the heat liberated when a unit mass of a fuel is combusted at constant volume in oxygen saturated in water with water vapour, with combustible products being carbon dioxide, oxygen and nitrogen (Antwi-Boasiako., *et al* 2012). The use of biomass for production of energy has been very crucial to the development of civilisation. Pressures on the global environment have led to calls for an increase in the use of renewable energy sources, in lieu of fossil fuels. Biomass is one potential source of renewable energy and the conversion of plant material into a suitable source of fuel is of much importance. The average area of forest and wooded land per inhabitant varies regionally. The variations are between 6.6 ha in Occeania, 0.2 ha in Asia, 1.4 ha in Europe and 0.8 ha in Africa (FAO, 2001). The bulk of energy supply in Ghana is met from wooded fuels, i.e. firewood and charcoal. Wood fuel account for about 71% of the total energy supply in Ghana and about 60% of the final energy demand (Trassero, FAO., 2002).

Fire wood can be procured as off-cuts from saw mills and other wood-using industries or directly from the forest. Although it is not difficult to acquire and process firewood for utilisation, its usage involves the release of harmful gases into the atmosphere posing a threat to the atmosphere leading to respiratory diseases (Antwi-Boasiako., *et al.,* 2012). The harvesting of tress as firewood also leads to deforestation and desertification (El- Hinnawi and Biswas, 1981). The use of *H. brasilienses* as a source of firewood after the extraction of latex becomes uneconomical due to advance age of the plant is popular among rural folks in communities where rubberwood plantations are common in Ghana. Haygreen and Bowyer (1982) noted that dense woods (such as oak) are by far better fuel sources than lighter species. Thus, high-density woods often exhibit higher energy contents than a large amount of less-dense woods (Antwi-Boasiako et al., 2012). Type of wood species and MC are other vital factors that affect the calorific value of wood apart from density.

The heat of combustion for fuels is expressed as the Higher Heating Value (HHV), Lower Heating Value (LHV) or the Gross Heating Value (GHV).

The estimating of the HHV of the samples is computed by applying correlation based on proximate analysis information. The measured HHV of fuel sample is determined as follows:

$$HHV = \frac{(q2 - q1)C}{m}$$

Where:

q_2 = galvanometer reading with sample,

q_1 = galvanometer reading without sample.

C = calibration constant, m = mass of fuel sample.

The estimated higher heating value (HHV) of fuel sample was computed as follows:

HHV = 0.3536 ($F.C$) + 0.1559($V.M$) + 0.0078(A) (MJ/kg)

Where:

$F.C$ = percentage of fixed carbon

$V.M$ = percentage of volatile matter

A = percentage of ash content

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 Materials

Rubberwood logs were obtained from 20- year old (young), 30- year old (mature) and 40-year old (old) trees from Asamankese in the Eastern Region of Ghana. The ages were surrogated for the latex content given that Freeman (2011) pointed out that young rubberwood has a high latex content, mature trees with little latex, while the old trees of about 40 years have little or no latex content.

3.2 Sampling Method

The rubberwood (*H. brasiliensis*) samples were taken from three sections of the boles of the trees, namely the base (1 to 10m from ground level), middle (10.1 to 20m from ground level) and the crown (20.1m above ground level). The dimensions of the samples, for each test, were based on the American Society for Testing and Materials (ASTMD) and the British Standard Institute (BSI), as given in Table 3.1.

Table 3.1: Samples and dimensions of specimens for the tests

Test	Samples	Dimensions	Standard
Moisture content	90	20x20x20mm	ASTM D4442-07
Density	90	25x25x25mm	BS 393 (1957)
Shrinkage	90	20x20x20mm	BS 393 (1957)
Compression parallel to the grain	90	60x20x20mm	ASTMD143-9 (2000)
Compression perpendicular to the grain	90	50x50x150mm	ASTMD 695 (2008)
Static bending	90	300x20x20mm	BS 373 (1957)
Calorific value	45	50x50x150mm	ASTMD2015- (1985)

3.2.1 Moisture Content

The Moisture content (MC) was determined using Oven-dry method at 103°C ± 2°C (or holding between 101°C to 105°C) near the drying endpoint (ASTMD 4442-07). The sensitivity of the balance (scale) that was used to weigh the samples was within a minimum of 0.1% of the weight of the sample being tested. Each sample (20x20x20mm) was weighed immediately, before any drying or re-absorption of moisture took place. After weighing, the samples were placed in an oven heated at 105°C and kept there until no appreciable weight change occurred in 4-hour weighing intervals. The constant or oven-dried weight and the weight of the specimen when cut were used to determine the percentage of MC using the formula:

$$\%MC = \frac{\mathrm{Ww} - \mathrm{Wd}}{\mathrm{Wd}}\, X\ 100\%$$

Where:

W_w = green weight of the sample,

W_d = oven-dried weight of the sample.

3.2.2 Density

The basic density was determined using the hydrostatic method (Chave, 2006). The specimen comprised sample wood from the three sections. Each sample was soaked in water in a container overnight in order for the samples to reach their maximum saturation points. The weights of the container and the water it contained were determined. The wood samples were submerged in water and the weight of the container plus specimen determined. The increase in volume of the water displaced by the swollen specimen recorded in cm^3. The blocks of wood were then oven dried at 105^oC until the weight was constant and the oven dry-weight was recorded. The basic density (kg/m^3) was calculated as follows (BS 393; 1957):

$$Density = \frac{\text{Oven} - \text{dried weight (kg)}}{\text{weight of water displaced by swollen specimen(m3)}}$$

3.2.3 Shrinkage

The samples were taken from the base, middle and crown portions of all ages of *H. brasiliensis.* They were tested using the standard oven dry method (Peng *et al.*, 2012). The initial dimensions (20x20x20mm) of the individual specimens were recorded and placed in a ventilated oven set at just above the boiling point of water (i.e.105^{o}C). The samples were kept in the oven for 24 hours. According to Peng *et al.* (2001), the new weight, called the oven dried weight, was then used to calculate the change in dimension in the sample, using the equation (BS 373; 1957):

$$Shrinkage = \frac{Decrease\ in\ dimension/volume}{Original\ dimension/volume} \text{ X } 100$$

$\beta_L = \frac{L_S - L_0}{L_S} \times 100$; for longitudinal direction,

$\beta_T = \frac{T_S - T_0}{T_S} \times 100$; for tangential direction,

$\beta_R = \frac{R_S - R_0}{R_S} \times 100$; for radial direction.

Volumetric shrinkage for each disc was calculated by the formula used by Mantanis *et al.*, (1994) as:

$$\beta \text{V} = \frac{\text{Ls} \times \text{Ts} \times \text{Rs} - \text{Lo} \times \text{To} \times \text{Ro}}{\text{Ls} \times \text{Ts} \times \text{Rs}} X\ 100$$

Where:

B_L = Longitudinal shrinkage of the spacemen; B_R = Radial shrinkage of the spacemen;

B_T= Tangential shrinkage of the spacemen; $L_{S=}$ Volumetric shrinkage of the spacemen Ls= Longitudinal dimension of the saturated spacemen; Ts = Tangential dimension of the saturated spacemen; Rs = Radial dimension of the saturated spacemen; Lo= Longitudinal dimension of the dried spacemen; Ro= Radial dimension of the dried spacemen and

To= Tangential dimension of the dried spacemen

3.2.4 Swelling

The dimensional change due to swelling of the specimen, represented by the volumetric swelling, was measured according to ASTM-1037 (1999). The weight gain of the samples was determined by soaking the oven-dried specimen in water at a temperature of 20 $\pm 1^{o}$C for 24 hours. The volumetric swelling coefficients were calculated according to the formula:

$$\text{Swelling} = \frac{Wda - Wdb}{Wdb} x\ 100$$

The volumetric swelling for each stake was determined from its longitudinal, radial, and tangential faces (Rowell and Young, 1981; Mantains *et al., 1994*) as:

Where: Wda =Wood dimension after immersion and Wdb = Wood dimension before immersion.

The volumetric swelling for each stake was determined from the values for their longitudinal, radial, and tangential faces (Rowell and Young, 1981; Mantanis *et al.*, 1994) as:

$$\text{Volumetric swelling (\%)} = \frac{\text{Sl x St x Sr} - \text{Dl x Dt x Dr}}{\text{Dl x Dt x Dr}}\ \text{x}\ 100$$

Where;

SI = Longitudinal dimension of stakes in swollen condition; St = Tangential dimension of stakes in swollen condition; Sr = Radial dimension of stakes in swollen condition,

DI = Longitudinal dimension of stakes in dry condition; Dt = Tangential dimension of staked in dry condition; Dr = Radial dimension of stakes in dry condition

3.3 Mechanical Properties

3.3.1 Compressive Strength Perpendicular to Grain

The compressive strength test was conducted using ASTMD 695 (2008). The Instron load frame was used to apply a load of 2000N m/s^2 to the specimens both at angles perpendicular to the grain and parallel to the grain until rupture or deformation. For compressive perpendicular to grain, specimens with dimensions 50 x 50 x 150mm were used. The samples were placed in the Instron electromechanical load frames such that the grains were perpendicular to the steel cylinder at the base. The samples ware then clamped between the upper jig and the lower jig, with the deflection gauge attached to the jigs. The load was applied starting from 200N m/s^2 with constant increments of 100N m/s^2 until failure of the specimen.

3.3.2 Compressive Strength Parallel to Grain

Samples with dimensions 60 x 20 x 20mm were used for the compression parallel to grain. Each sample was placed in the Instron electromechanical load frames such that the grains were parallel to the steel cylinder between the lower jig and the base of the samples. The sample was then clamped between the upper jig and the lower jig, with the deflection gauge attached to the jigs. The load was applied starting from 2000N m/s^2 with constant increments of 2000N m/s^2 until failure of the samples. The data collected from the tests included the length between supports (L), width (b) and depth (h) of sample, load applied (P) and Strain. These were used in the following equations to calculate for:

Cross-sectional *area of the specimen (A) = A = b x h*

Deflection (Δ) = Strain x L

Modulus of Elasticity $E = \frac{\mathrm{PL}}{\mathrm{A\Delta}}$

The compression was calculated using the equation:

$$\mathrm{CI} = \frac{\Delta \mathrm{PL}}{\mathrm{AE}}$$

Where:

Δ = Deflection (N/mm)

P= Load (N)

A = Cross-section area (mm^2)

E = Modulus of Elasticity (N/mm^2)

3.4 Static Bending

The MOR was used as the surrogate for the static bending and it was measured based on the experiments conducted by Treacy *et al.* (2000). In measuring the MOR, the ends of the sample were supported and a load placed on the centre of the sample. The test pieces were supported at the ends and in accordance with BS 373 (1957), the loading heads moved at a constant speed of 0.65 cm min^{-1}. The orientation of the annual rings in the 2cm standard test piece was parallel to the direction of loading. The deflection of the beam at mid-length was measured with reference to the outer points of loading in the central loading method. The MOR was determined (BS 373, 1957):

$$MOR = \frac{3\mathrm{PL}}{2\mathrm{bh}3}$$

Where:

P = Maximum load (Nm/s)

L = Length of test piece (mm)

b = Breath of test piece (mm)

h = Depth of test piece (mm)

3.5 Calorific Value

The specific gravity was determined in accordance with ASTM D2395-93 standard, which is determined by the formula:

$$\%S.G = \frac{\mathrm{Wwd}}{\mathrm{Wwt}}$$

Where:

W_{wt} = weight of the wood sample

W_{wd} = weight of water.

The volatile matter contents in the test sample were determined according to ASTM D3175-89:

$$\%V.M = \frac{\mathrm{Ms} - \mathrm{Mfd}}{\mathrm{Ms}}\ X\ 100\%$$

Where:

Ms = mass of air dried sample

Mfd = mass of sample after 10mins in furnace at 900^{o}C.

Determination of ash content in the test sample was carried out, according to ASTM D3174-89, in the electric furnace.

The percentage ash content (A) was determined as follows:

$$\%A = \frac{Mar}{Ms} X\ 100\%$$

Where:

Mar = mass of ash residue (g),

Ms = mass of air dried sample (g).

The fixed carbon content of each test sample was calculated by difference. The higher heating value (HHV) of these samples was determined (ASTM D2015, 1985) in an oxygen bomb calorimeter. The percentage fixed carbon (F.C) was determined by subtracting the sum of percentage volatile matter and ash content from 100 (ASTM D2015, 1985).

$$\%F.C = 100 - \%(V.M + A)$$

The estimating HHV of the sample was also computed by applying correlation based on proximate analysis information. That is, the measured HHV of fuel sample was determined as follows:

$$HHV = \frac{(q2 - q1)C}{m}$$

Where:

q_2 = galvanometer reading with sample,

q_1 = galvanometer reading without sample.

C = calibration constant, m = mass of fuel sample.

The estimated higher heating value (HHV) of fuel sample was computed as follows:

HHV = 0.3536 ($F.C$) + 0.1559($V.M$) + 0.0078(A) (MJ/kg)

Where:

$F.C$ = percentage of fixed carbon

$V.M$ = percentage of volatile matter

A = percentage of ash content

3.6 Data Analysis

After the data had been obtained from the sample tests, Single Factor One – way Analysis of Variance (ANOVA) of Microsoft Office Excel 2010 was employed to determine the significant difference ($P < 0.05$). Differences in the physical and mechanical properties of the specimen were tested using ANOVA. The analyses were summarised and presented in Table 4.1.

CHAPTER FOUR

RESULTS

4.1 Physical Properties within various Ages of *H. brasiliesnsis* at Dry State

4.1.1. Moisture Content

Within the 20-year old, the higher MC (15.26%) was recorded at the crown, while the base recorded 14.57%. The 30-year old had its highest MC (14.52%) also at the crown while its lowest value (13.55%) was recorded at the base section. A value of 13.38% was recorded at crown by the 40-year old *H. brasiliensis,* while its lowest value (13.02%) was recorded at the base (Table 4.1). The greatest MC amongst the three trees (15.26%) was recorded by the 20-year old *H.brasiliensis* at its crown section while the least value (13.02%) was recorded by the 40-year old at its base section. The crown portions of all the three age groups (20, 30, 40-years) recorded highest MCs (15.26, 14.52 and 13.38% respectively) followed by their middle portions (14.74, 13.83 and 13.19% respectively) while the base portions recorded the least values (14.57, 13.55 and 13.02% respectively). There were no significant differences in the MC ($p<0.05$) within and between the three age groups along their boles (20, 30 and 40-years) (Table 4.1).

4.1.2. Density

The 40-year old *H. brasiliensis* recorded the highest density at its base (558.14kg/m^3) and the lowest density (495.28kg/m^3) was recorded by the 20-year old at its crown (Table 4.1). It was observed that the bases of all the three ages (20, 30 and 40-years) had the greatest densities (529.38, 546.88 and 558.14kg/m^3 respectively), followed by the middle portions (512.81, 527.56 and 556.25kg/m^3 respectively) and the least

(495.28, 502.28 and 553.07kg/m^3 respectively) recorded at their crowns. There were no significant differences in the densities recorded ($p < 0.05$) between and within the various age groups (20, 30 and 40 years) along their boles (Table 4.1).

Table 4.1: Physical properties within the stem of *H.brasiliensis* of various ages

	Age								
Physical properties	**20 year**			**30 years**			**40 years**		
	Butt	**Middle**	**Top**	**Butt**	**Middle**	**Top**	**Butt**	**Middle**	**Top**
M. C	14.57^{ABC}	14.74^{AB}	15.26^{A}	13.55^{ABC}	13.83^{BCD}	14.52^{ABC}	13.02^{D}	13.19^{CD}	13.38^{CD}
Density (kg/m^3)	529.38^{ABC}	512.81^{BC}	495.28^{C}	546.88^{AB}	527.56^{ABC}	502.28^{C}	558.14^{A}	556.25^{AB}	553.07^{AB}
Long. swelling (%)	1.62^{AB}	1.79^{A}	1.93^{A}	1.19^{AB}	1.49^{AB}	1.55^{AB}	0.87^{B}	1.34^{AB}	1.47^{AB}
Tang. swelling (%)	2.68^{A}	2.71^{ABC}	2.73^{ABC}	2.01^{ABC}	2.31^{ABC}	2.53^{BC}	1.49^{BC}	1.64^{BC}	1.73$_{BC}$
Radial swelling (%)	1.97^{ABC}	2.46^{AB}	2.67^{AB}	1.55^{BC}	2.34^{AB}	2.75^{A}	1.17^{C}	1.97^{ABC}	2.35^{AB}
Vol. swelling (%)	5.50^{B}	6.^{95AB}	7.76^{A}	4.65^{B}	6.09^{AB}	6.39^{AB}	4.51^{B}	4.36^{AB}	6.18^{AB}
Lon. shrinkage (%)	0.63^{A}	0.82^{A}	1.12^{A}	0.61^{A}	0.72^{A}	0.75^{A}	0.07^{A}	0.68^{A}	0.12^{A}
Tan. shrinkage (%)	2.50^{B}	2.78^{AB}	3.37^{A}	2.30^{B}	2.67^{AB}	3.21^{AB}	2.29^{B}	2.62^{AB}	3.21^{AB}
Radial shrinkage (%)	2.88^{B}	3.05^{AB}	3.81^{A}	2.69^{B}	2.70^{B}	2.73^{B}	2.50^{B}	2.53^{B}	2.57^{B}
Vol. shrinkage (%)	5.87^{BC}	6.28^{BC}	7.63^{A}	5.73^{BC}	6.16^{BC}	6.87^{AB}	5.47^{C}	5.75^{BC}	6.85^{AB}

***Values in the rows with the same letter are not significantly different ($P<0.05$)**

4.2. Dimensional Stability within the various Ages of *H. brasiliensis*

4.2.1. Swelling

4.2.1.1. Longitudinal Swelling

The greatest longitudinal swellings (1.93, 1.55 and 1.47%) were recorded at the crown portions of the 20, 30 and 40-year old trees respectively with the base portions recording the least (1.62, 1.19 and 0.87% respectively). The values recorded for longitudinal swelling did not show any significant differences ($p<0.05$) within the boles and between the stems of each of the three ages (20, 30 and 40-years) (Table 4.1).

4.2.1.2 Tangential Swelling

Among the various year groups (20, 30 and 40 years), the greatest swelling (2.73%) was at the crown of the 20-year old whereas the lowest (1.49%) was at the base of the 40-year old (Table 4.1). The crown portions of all three year groups had their greatest tangential swelling (2.71, 2.53 and 1.73% respectively) while the bases had the least (2.68, 2.01 and 1.49% respectively). There were no significant differences in tangential swelling ($p<0.05$) between the various ages (20, 30 and 40 years) as well as within their boles (Table 4.1).

4.2.1.3 Radial Swelling

Radial swelling was greatest (2.75%) at the crown of the 30-year old tree whereas the least (1.17%) was recorded by the 40-year old at its base (Table 4.1). this was due to both and environmental variation. The trend was that the greatest radial swellings (2.67, 2.75 and 2.35%) were recorded at the crown portions of all the age groups while the bases recorded the least (1.97, 1.55 and 1.17% respectively). The values recorded for radial swelling for both intra and inter-tree variations showed no significant differences ($p<0.05$) (Table 4.1).

4.2.1.4 Volumetric Swelling

The greatest volumetric swelling (7.76, 6.39 and 6.18% respectively) was recorded at the crowns while the bases had the least (5.50, 4.65 and 4.51% respectively) for the 20, 30 and 40-year old trees. The greatest value amongst the three ages was recorded at the crown (7.76%) of the 20-year old tree while the least was at the base (4.51%) of the 40-year old tree (Table 4.1). Values recorded for volumetric swelling indicated no significant differences ($p<0.05$) along the stems of 30 and 40-year old trees and between all the trees (Table 4.1).

4.2.2 Shrinkage

4.2.2.1 Longitudinal Shrinkage

The greatest shrinkage (1.12%) among the three ages was at the crown of the 20-year tree while the least (0.07%) was at the base of the 40-year old tree. The trend was that, the greatest shrinkage among all three age groups (1.12, 0.75 and 0.63% respectively) occurred at their crowns. This was followed by the middle portions (0.82%, 0.72% and 0.68% respectively) with the least shrinkages (0.63%, 0.61% and 0.07% respectively) recorded at their bases. There were no significant differences in the values recorded for longitudinal shrinkage ($p<0.05$) along the boles and between the trees of all the ages (20, 30 and 40 years) (Table 4.1).

4.2.2.2 Radial Shrinkage

The greatest radial shrinkage (3.81%) was at the crown of the 20-year old tree whereas the least (2.50%) was at the base of the 40-year old tree (Table 4.1). The general trend was that the greatest radial shrinkage for all ages (3.81%) was at the crown of the 20-year old. This was followed by the 30 and 40 year olds (2.73% and 2.57% respectively) at their crowns. The least radial shrinkages among the three age groups (2.88, 2.69 and 2.50% respectively) were at the bases. There were no significant differences for radial shrinkage ($p<0.05$) within the boles of the 30 and 40-year olds and between all the three ages (20, 30 and 40 years) (Table 4.1).

4.2.2.3 Tangential Shrinkage

Among the various ages, the greatest tangential shrinkage (3.37%) was recorded at the crown of the 20-year old tree whereas the lowest (2.29%) was recorded at base of the 40-year old tree (Table 4.1). The trend was that the greatest tangential shrinkages were recorded at the crowns of all the age groups (3.37, 3.21 and 3.21% respectively) while the bases recorded the least (2.40, 2.30 and 2.29% respectively). There were no significant difference recorded for tangential shrinkage ($p<0.05$) within the boles of the 30 and 40-year olds and between all the three trees (Table 4.1).

4.2.2.4 Volumetric Shrinkage

The greatest value for volumetric shrinkages was recorded along the crowns (7.63, 6.87 and 6.85% respectively) for all the tree ages (20, 30 and 40-years) while the least was (5.87, 5.73 and 5.47% respectively) were recorded at their bases. There were no significant differences for volumetric shrinkage ($p<0.05$) within the boles of the 30 and 40-year old trees and between all the three trees ($p<0.05$) (Table 4.1).

4.3 Mechanical Properties

4.3.1 Compression Parallel to the Grain

The highest and the lowest compressions (35.24N/mm^2 and 26.60N/mm^2) were recorded at base and crown of the 40 and 20-year old *H. brasiliensis* respectively (Table 4.2). The trend was that all the three year groups (20,30 and 40-year olds) had their highest compressions parallel to the grain being recorded at their bases (32.84N/mm^2, 33.39N/mm^2 and 35.24N/mm^2 respectively) while the lowest compressions parallel to the grain for all the year groups were recorded at their crowns (26.60, 31.77 and 34.51N/mm^2 respectively). There were no significant differences for compression parallel to the grain ($p<0.05$) within the boles of the 30 and 40-year olds and between all the three ages (Table 4.2).

Table 4.2: Mechanical properties within the stems of *H. brasiliensis* of various ages

Age		**20 years**			**30 years**			**40 years**	
Stem position (Axial)	**Butt**	**Middle**	**Top**	**Butt**	**Middle**	**Top**	**Butt**	**Middle**	**Top**
Compression parallel to the grain	32.84^{AB}	28.24^{C}	26.60^{C}	33.39^{AB}	31.93^{B}	31.77^{AB}	35.24^{A}	35.17^{A}	34.51^{A}
Compression perpendicular to the grain	4.40^{BC}	4.21^{CD}	3.78^{D}	4.77^{ABC}	4.56^{BC}	4.55^{BC}	5.30^{A}	4.95^{AB}	4.79^{AB}
MOR	60.88^{BC}	60.04^{BC}	58.74^{C}	66.60^{A}	61.69^{BC}	59.07^{C}	67.24^{A}	63.78^{AB}	59.56^{BC}
Calorific value		15.99^{B}			18.09A			18.17^{A}	

***Values in the row with the same letter are not significantly different (P<0.05)**

4.3.2 Compression Perpendicular to the Grain

The maximum and minimum compressions for inter tree variations (5.30N/mm^2 and 3.78N/mm^2) were recorded at base and crown of the 40 and 20-year old trees respectively (Table 4.2). The trend was that the bases of all the year groups (20, 30 and 40 year olds) had the maximum compressions perpendicular to the grain while their crowns had the minimum compressions perpendicular to the grain. There were no significant differences for compression perpendicular to the grain ($p<0.05$) between all ages (20, 30 and 40-years) and within the boles of the 30 and 40-year olds (Table 4.2).

4.3.3 Modulus of Elasticity (MOR)

The highest Modulus of Rupture value (67.24N/mm^2) was at the base of the 40-year tree while the lowest (58.74N/mm^2) was at the crown of the 20-year old *H.brasiliensis.* The 30 and 40-year old tress had their highest MOR (66.60N/mm^2 and 67.24N/mm^2) at their bases while the lowest MOR (59.07N/mm^2 and 59.56N/mm^2) were at their crowns respectively (Table 4.2). The trend was that the bases of all the year groups had the greatest MOR (60.88N/mm^2, 66.60N/mm^2 and 67.24N/mm^2 respectively) while the least (58.74^2, 59.07N/mm^2 and 59.56N/mm^2 respectively) were recorded at their crowns. There were no significant differences for MOR ($p<0.05$) recorded between the three ages (20, 30 and 40-years) and within the boles of the 30 and 40-year olds (Table 4.2).

4.3.4 Calorific Value within the Stems of *H.brasiliensis.*

The greatest calorific value (18.17MJ/kg) within all three age groups (20, 30 and 40-year olds) was recorded by the 40-year old tree while the least (15.99MJ/kg) was recorded by the 20-year old. The 30-year old tree had (18.09MJ/kg) as its calorific value (Table4.2; figure 4.2). There were no significant differences for CV ($p<0.05$) between and within the boles of all the three age groups (20, 30 and 40-year old trees) (Table 4.2).

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter discusses the findings and opinions about the results. It is an undisputable fact that, identification and potential utilization of our lesser-used species (LUS) will ensure maximum conservation and sustainable development of the nation's forest resources including timber for the maintenance of environmental quality and the continues distribution of optimum benefits to all sectors of the society (Bih, 2006). This will also contribute towards the reduction in the excessive over-exploitation and dependence on some preferred traditional timber species (Chamberlain *et al.,* 2000). To determine the suitability of *H. brasiliensis* for timber production as well as a good source of fuel wood, it is important to understand their physical, mechanical and calorific properties.

5.2 Moisture Content

Strength properties of wood samples are related to their MCs (Kollman and Cotê 1968). Hence, it was imperative to determine the MC of all the samples obtained from the three age groups of *H. brasiliensis.* The MC at 12% increased from the 40-year old *H. brasiliensis* through to the 20-year old due to the differences in their ages, density and permeability (Haygreen and Bowyer., 1982). This is because stem growth is often rapid in the early years, when wood formation favours wide rings with a high proportion of juvenile wood which is known to contain greater percentage of moisture (Kimura *et al.,* 2014). The base, middle and crown portions of the three trees showed a consistent pattern of increase in MC along the bole due to the greater density at their bases than at the middles and crowns which conforms with studies by Lim and Khoo

(1986), Bakar *et al*. (1998) and Romulo and Arancon (1997) on date, oil and coconut palms where gradual increases in MC along trunk height and towards the central regions were detected. However, they explained that for the trunk height, there was a tendency for MC to increase from the base to the crown of the palms due to the effects of earth gravity, where the water distribution to the higher part of the trunk requires higher caviler pressure. This was also identified by Jamala *et al.,* (2012) for five commercial forest timber species studied: Iroko (*Melicea excelsa*), Mahogany (*Khaya ivorensis*) Obeche (*Triplochinton scleroxylon*), Apa (*Afzelia Africana*) and Ita (*Celtis mildbraedii*) where MC increased from the base to the crown and from the heartwood to the sapwood respectively. Shupe *et al.* (1995) further noted that the MC of heartwood at the green and dry states varied with height. This variability is dependent on the tree species, the section of the log, site, environment and genetic variations (Chowdhury *et al.,* 2007). Dinwoodie (2000) was of the view that the variability might be correlated with the year when the tree was felled. The different age groups (20, 30 and 40-year olds) revealed that there were no significant differences ($p > 0.05$) along the bole of each tree. This study is in accord with the trends reported by (Haygreen and Bowyer., 1982).

Lim and Khoo (1986), Romulo and Arancon (1997), Bakar *et al*. (1998), Dinwoodie (2000), Chowdhury *et al.*, (2007) and Jamala *et al.,* (2012) which is a positive indication that the bases and middle portions of the three age groups of *H. brasiliensis* could be denser, less susceptible to defects and more useful than their crowns.

5.3 Density within *H. brasiliensis*

Density is by far the most useful parameter for measuring wood quality (Ali *et al.,* 2011). It is positively correlated to mechanical strength and shrinkage of timber (Lim *et al,* 2003). Majumdara *et al.* (2014) found the density of 20-year old *H. brasiliensis* to range from 470 to 510kg/m^3, that for the 25-year old ranged from 500 to 560kg/m^3 and 30-year old was from 530 to 640kg/m^3. Lim *et al.* (2003) also discovered that the density of *H. brasiliensis* ranged from 480 to 650kg/m^3 at 12% MC depending on their ages. However, this study recorded values ranging from 495.28 to 529.38 kg/m^3 for the 20-year *H. brasiliensis,* 502.28 to 546.88 kg/m^3 for the 30-year old tree and 553.07 to 558.14 kg/m^3 for the 40-year old (Table 4.1). This makes all the portions of the various trees to be classified as low to medium and ideal for furniture works except the crown of the 20-year old which is regarded as low density and recommended for interior usage. Although, the findings of this work conform to those of Lim *et al*. (2003), there are slight variations with those of Mujumdara *et al.,* (2014) due to the age differences of trees used for the research. It was also found that density was higher at the base and decreased towards the crown portions of all age groups. These within tree variations may be due to small radial increases associated with the transition from juvenile to mature wood (Zobel and Sprague, 1998). Faith (2014) found that density decreases from heartwood towards the sapwood and over the stem height (from base to crown) at the dry state. Wood density normally decreases with height in the stem of a tree, greater at the base due to the greater compaction of the base tissues exerted by the overlapping cells along the bole than the tree crown (Donaldson *et al,* 1995) which usually correlate with MC, dimensional stability and influences wood quality.

Lim and Khoo (1986) noted that the density of oil palm trunk decreased linearly with the trunk height. This has been similar to the trend exhibited by the three age groups of *H. brasiliensis*. Similarly, Prayitno (1995) as well as Romulo and Arancon (1997) identified the base of oil and coconut palm trunks recording greater density, followed by the middle and crown portions. The densities of oil and coconut palm trunks ranged between 100kg/m^3–900kg/m^3. The current values of *H. brasiliensis* ranged from 495kg/m^3 – 558.14kg/m^3 for all the tree age groups. FAO (1985) reported that at 12% MC, wood should be graded as high (very heavy) if it records a density above 500kg/m^3, medium (350-500kg/m^3) and low densities having less than 350kg/m^3. There was a marginal decrease in density from the base to the crown for the three different age groups. No significant differences ($p<0.05$) in values recorded for density along the boles of all the three ages and between the individual trees.

5.4 Dimensional Stability within the Stems of *H. brasiliensis*

5.4.1 Swelling

Swelling is a characteristic of all elastic materials but it differs somewhat for different types of materials (Hernandez, 2007). Swelling of woods in liquids is of fundamental importance both from the scientific point of view and in the context of commercial processing including the usage of wood (Mantanis *et al.*, 1994). Kollman and Cotê (1984) were of the view that wood swells insignificantly along the longitudinal direction increasing from the base towards the crown portions.

Gryc *et al.* (2007) reported that the dimensional variations of swelling in wood were smallest in the longitudinal direction (0.1-0.4%), great in the tangential direction (3-6%) and the greatest variation in the radial direction (6-12%) which agrees with this study for, longitudinal swelling 0.87-1.93% being smallest, tangential swelling: 1.49-

2.73% as great and radial swelling greatest 1.17-2.75% for 20, 30 and 40-year old *H. brasiliensis* respectively. All the trees recorded values higher than the range identified by Gryc *et al.*, (2007) for longitudinal swelling.

However, the swelling is in conformity with reports by Kollman and Cotê (1984) that wood swells insignificantly along the longitudinal direction than the tangential and radial swelling. For tangential swelling, the values recorded by this study were slightly lower than those identified by Gryc *et al.*, (2007). There were no significant differences ($p<0.05$) in the values recorded along the boles (base, middle and crown) of all the tress and between the individual trees. Radial swelling within the three trees also recorded lower values than those identified by Gryc *et al.*, (2007) which could make them less liable to weathering. Their volumetric swelling ranged between 4.36-7-76% for the 20 and 40-year old trees. The various ages recorded less longitudinal swelling (0.87-1.93%) but greater radial (1.17-2.75%) and tangential (1.49-2.73%) swellings making them less susceptible to insects (termites and beetles) and decay (white rot, brown rot and soft rot). Values recorded indicated no significant differences ($p<0.05$) along the stems of all the trees except the base (5.50%) and the crown (7.76%) of the 20-year tree. The inter tree variations also showed no significant differences ($p<0.05$). Generally, the 40-year old tree recorded minimum swelling as compared to the 30 and 20-year old trees with the base portions also recording less swelling as compared to the middle and crown portions. *H. brasiliensis* is ideal for utilisation as timber for the production of furniture, panels, windows and doors as well as for internal decorative purposes. This will contribute to an increase in the raw material base in the timber industry of Ghana.

5.4.2 Shrinkage

Water in green or freshly sampled wood is located in the cell wall and cell lumen (Haygreen and Bowyer, 1982). The degree of shrinkage is caused by the amount of moisture lost by wood when its MC fluctuates between the oven dry state and the Fiber Saturated Point. Shrinkage increases generally from the tree base to the crown and from the heartwood to sapwood of most timber species (Shupe *et al.,* 1995; Mottonen and Loustarinen, 2006). This could be attributed to greater amount of extractives, lignin and less MC for the inner wood and the increase in specific gravity from the inner wood to outer wood. Shrinkage for *H. brasiliensis* by Majumdara *et al.* (2014) showed longitudinal shrinkage ranged from 0.12 to 0.15%, 4.32 to 6.10% for tangential, 2.24 to 3.20% for radial shrinkage at different height position for the 20-year. The 25-year old tree recorded values ranging from 0.13 to 0.18%, 4.15 to 5.03% and 2.10 to 2.56% whereas the 30-year old tree showed values ranging from 0.17 to 0.18%, 4.02 to 4.92% and 2.03 to 2.40% for longitudinal, tangential and radial shrinkage respectively. It was realized that tangential shrinkage was greater at every position for every year group. Sattar (1997) found the average tangential, radial and volumetric shrinkage to be 4.95, 1.99 and 8.35% within *H. brasiliensis.* Indian rubber wood showed longitudinal shrinkage ranging from 0.10 to 0.19%, tangential and radial shrinkage ranged from 5.7 to 6.5% and 2.6 to 3.1% along the bole respectively whiles volumetric shrinkage ranged from 10.1 to 12% (Anon., 2002). The difference in shrinkage in both the tangential and radial directions could be due to the restraining effect of fibril angle in the cell walls (Kollman and Cotê 1984). Scgniewind (1989) is also of the view that the variation between shrinkage of different surfaces was due to cellular structure and physical organization of cellulose chain molecules within the cell walls and the density and MC variations along the bole of *H. brasiliensis.*

This study showed longitudinal, tangential and radial shrinkage ranges from 0.63 to 1.12%, 2.50 to 3.37% and 2.88 to3.81% along the boles respectively for the 20-year old tree with volumetric shrinkage of 5.87 to 7.63%. The 30-year old tree ranged from 0.61 to 0.75%, 2.30 to 3.21 and 2.69 to 2.73% with volumetric shrinkage ranging from 5.73 to 6.87%. The 40-year old tree had values ranging from 0.07 to 0.68% for longitudinal shrinkage, 2.29 to 3.21% and 2.50 to 2.57% for tangential and radial shrinkage respectively whiles volumetric shrinkage was from 5.47 to 6.85% (Table 4.1). The tan

The 30 and 40-year old trees exhibited a trend where the tangential shrinkage was higher than the radial shrinkage which conforms to the works of Majumdara *et al.* (1984), Sattar (1997) and Anon (2002). However, the 20-year old *H. brasiliensis* recorded higher values for radial shrinkage than tangential shrinkage. Other previous studies by Sattar (1997) and Annon (2002) and Majumdara (2014) revealed slightly greater differences in values for *H. brasiliensis.* This could be attributed to the variations in ages, MC and basic density of the trees used for the tests. This study confirmed that shrinkage generally increases from the tree base to crown. Apart from the base (2.88%) and the crown (3.81%) of the 20-year old tree which recorded significant differences ($p<0.05$), the remaining sections and ages (20, 30 and 40 years) recorded no significant differences ($p<0.05$). The same trend was observed for tangential shrinkage for the 20-year old where there was a significant differences ($p<0.05$) in the values at the base (2.50%) and the crown (3.37%). Among the three trees, the 20-year had greater shrinkage followed by the 30 and 40 year old trees. This could be associated with the greater MC but less density within the 20 year tree than the 30 and 40 year tress. With greater density and less MC, wood could be more useful externally for structural purposes.

5.5 Mechanical properties of *H. brasiliensis*

5.5.1 Compression Parallel to the Grain

Majumdara *et al.* (2014) discovered the strength values of different age groups of *H. brasiliensis* as from 27.30-30.00N/mm^2, 29.90-31.00N/mm^2 and 31.10-32.60N/mm^2 for 20, 25 and 30-year old trees respectively for compression parallel to the grain. These findings are not significantly different ($p<0.05$) from the findings of the current study, which indicated the strength values ranging from 26.60-32.84N/mm^2 for the 20-year old, 31.77-33.39N/mm^2 and 34.51-35.24N/mm^2 for the 30 and 40-year old trees respectively. For within tree variations, there were no significant differences within the various sections of the 30 and 40 year *H. brasiliensis* which could be due to similar density and MC trends the three trees recorded. However, the 20 year tree recorded significant differences ($p<0.05$) between the base (32.84%) and the middle (28.24%) as well as the base and the crown (26.60%) sections but there were no significant difference ($p<0.05$) between the individual trees. It was discovered that the values for compression were greater at the base of each tree and decreased towards the crown portion. This is a positive indication that the bases of the trees could be more resistant to biodegradation, mass loss and other wood defects (warping, splitting, honey combing, case-hardening, etc.).

This study revealed less resistance to compression forces in the 20-year old tree but greater in the 30 and 40-year old. A similar trend was also discovered for within tree variations when the various sections of each tree were compared. The resistance is lesser at the crown portions and greater at the middle and base sections.

5.5.2 Compression Perpendicular to the Grain

The strength values for compression perpendicular to the grain for this study varied from 2.78-4.40N/mm^2 for 20-year old, 4.55-4.77N/mm^2 and 4.79-5.30N/mm^2 for 30 and 40-year old respectively. This conforms to works of Majumdara *et al.* (2014) who recorded values for 20- year ranged from 3.90-4.01N/mm^2, 25 and 30-year old recorded 4.27-5.06N/mm^2 and 4.62-5.30N/mm^2 respectively. The 20-year old was discovered to have less resistance than the 30 and 40-year old samples, which proved to have greater resistance to compressive forces. It was also discovered that the base portions of all ages recorded greater resistance to compression forces than the middle and crown portions. This could indicate their bases being acceptable for usage in areas where much strength is required than the middles and crowns. The 20-year old recorded 4.40, 4.21, and 3.78N/mm^2 for base, middle and crown portions respectively. The 30-year had 4.77, 4.56, 4.55N/mm^2 whilst the 40-year old recorded 5.30, 4.95, and 4.79N/mm^2 for the base, middle and crown portions respectively. There were no significant differences ($p<0.05$) along the 30 and 40-year old trees. However, there were significant differences ($p<0.05$) between the base (4.40%) and the crown (3.78%) of the of the 20-year *H. brasiliensis.*

5.6 Modulus of Rupture (MOR)

This study recorded MOR values varying from 58.74-60.88N/mm^2 for 20-year old, 59.07-66.60N/mm^2 for 30-year old and 59.56-67.24N/mm^2 for 40-year old. It was realized that apart from the 20-year old tree, which recorded lesser MOR values than those reported by Lee (1986) and Anon (2002), the 30 and 40-year old trees showed close similarities in static bending. The MOR of 20-year old trees had (49.70-53.30N/mm^2), 46.30-48.70N/mm^2 for 25-year and 30-year (62.60-67.80N/mm^2)

(Majumdara *et al.,* 2014). Malaysian rubber wood showed an average MOR around 66N/mm^2 (Lee, 1982) whereas Indian rubber wood recorded 75.60N/mm^2 (Anon., 2002).

Whereas there were no significant differences ($p<0.05$) in the values recorded for the three sections of the 20-year old, there were significant differences ($p<0.05$) between the base (66.60%) and the middle (61.69%), and between the base (66.60%) and the crown (59.07%) of the 30 year old tree. The 40-year old also recorded a significant difference ($p<0.05$) between the base (67.24%) and the crown (59.56%). Comparatively, this study equally revealed that the ability of the various sections of the trees to withstand the tendency to rupture was greater at the base and decreases along the stem of the tree from the middle to the crown. This is an indication that the bases of the three trees as well as the older trees of *H. brasiliensis* could be more useful for projects where adequate strength is required like bridges, timber stairs, doors and roofing.

5.7 Calorific Value

Calorific value or heating value of a substance (a fuel or food) is the amount of heat released during complete combustion of a specific amount of it. Wood fuel use has increased in the developed world, and more attention is being given to finding sustainable wood fuel for use in the developed world (FAO 2010). Approximately 60% of the world’s total wood removals come from forest and outside forest are used as energy purposes with about 80% of households in Ghana depending on woodfuels for cooking, heating in addition to commercial and industrial use (Trassero, FAO, 2002). Hydro and fossil fuels are generally becoming unreliable, expensive and a threat to the environment. Onuegbu *et al.* (2011) found the calorific value of *Khaya senegalensis (18.24MJ/kg), Gmelina arborea* (18.60MJ/kg), *Milicia excels* (18.56MJ/kg), *Terminalia superba* (18.22MJ/kg) and *Ceiba pentandra (16.93MJ/kg).* These values compare favourably with current results recorded: 15.99MJ/kg for the 20-year old, 18.09MJ/kg for 30-year old and 18.17MJ/kg for the 40-years old. The Gross Calorific Value (GCV) of six tropical hardwood species studied by Mitchual *et al.* (2014) revealed the following; *C. mildbread* (20.16MJ/kg), *T. superba* (22.22MJ/kg), *A. robsta* (20.89MJ/kg), *T. scleroxylon* (21.60MJ/kg) *africana* (22.17MJ) and *C. pentandra* (20.33MJ/kg) while Mahlia *et al* (2001) recorded calorific values (18.00MJ/kg, 15.40MJ/kg) for palm kernel shells and palm fibre respectively. Werther and Ssaenger (2000) recorded 18.41MJ/kg for rubberwood. These findings conform with this current study. The GCV of all three age groups (20, 30 and 40-years) are considered adequate to be used as wood fuels. Since mature *H. brasiliensis* trees are usually cut down to make room for replanting due to lack of latex production, aging trees should be channelled for use as woodfuel.

5.8 The Use of H. *brasiliensis* after Latex Extraction as They Age

Wood has always served man and contributed decisively to his survival all through the development of civilization as a raw material for several products including furniture, flooring, sleepers, dowels and bridges compared to other competitive materials such as metals, cement (concrete) and plastics (Tsoumis,1991). H. *brasiliensis* wood could be used for wood products after their latex have been extracted. Traditionally, H. *brasiliensis* has been useful as cheap sources of firewood and charcoal but research has proved otherwise. Salleh (1984) reported that H. *brasiliensis* wood could be used for furniture, panelling, parquet, kitchen stools as well as particle boards and veneer. This study accords with Salleh, (1984) and Tsoumis, (1991) that wood from H. *brasiliensis* is excellent material for structural and minor usage based on the results of their physico-mechanical properties studied.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

- The base and middle portions of the 30 and 40 year old trees are ideal for exterior and medium structural purposes such as furniture, panelling, stairs, doors and windows. This is due to their less MC, good swelling and shrinkage qualities and greater densities, ideal compressive strength and MOR.
- The crown portions of the 30 and 40 year old trees and the entire 20 year tree are ideal for minor or light works such as stools, pencils, tool handles, and interior decoration of rooms as well as packaging. This as a result of their greater MCs, greater swelling and shrinkage but less density, good compression strength and MOR.
- All three age groups of trees are recommended for use as wood fuel although the 30 and 40 year trees provide higher energy capacity than the 20 year tree.

6.2 Recommendations

- Further research should be conducted on *H. brasiliensis* from two or more ecological zones in Ghana to ascertain the level of variations if any in their properties.
- Government agencies such the Forestry Commission should be well resourced and mandated to undertake the cultivation of rubberwood plantations not only for the production of rubber but timber and timber products in order to encourage the private sector to venture into this highly profitable venture.

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