UNIVERSITY OF EDUCATION, WINNEBA

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THE PHYSICAL AND MECHANICAL PROPERTIES OF PLANTATION GROWN TEAK IN DIFFERENCE AGES FROM KAKUM IN CENTRAL REGION OF GHANA

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DECEMBER, 2020

DECLARATION

STUDENT'S DECLARATION

I, TIMOTHY ACQUAH, declare that this project report, with the exception of quotations and references in published works which have all been identified and duly acknowledged, is entirely my original research and that no part of it has been presented for another degree in this university or elsewhere.

SIGNATURE: ……………………………………………..

DATE: ………………………………………………………

SUPERVISOR'S DECLARATION

I hereby declare that the preparation and presentation of this work were supervised in accordance with guidelines and supervision of project report as lay down by the University of Education, Winneba.

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DEDICATION

I dedicate this thesis to my mother madam Adjoa Anto and My wife Akua Amoakowaa. May God richly bless them with long and healthy living.

TABLE OF CONTENT

CONTENT **PAGE**

DECLARATION ii
ACKNOWLEGEMENTS....iii
DEDICATION....iv
TABLE OF CONTENT v
LIST OF TABLES....viii
LIST OF FIGURES ix
ABSTRACT....x
CHAPTER ONE: INTRODUCTION 1
1.1 Background of the Study....1
1.2 Statement of the Problem 3
1.3 Purpose of the Study 4
1.5 Significance of the Study 5
1.6 Delimitation....5
CHAPTER TWO: LITERATURE REVIEW 6
2.1 Introduction 6
2.2 Teak Management....11
2.3 Biology of Teak....20
2.3.1Classification and Distribution of Teak....22
2.4 Teak as a Building Material 23
3.5 Tectona grandis plantations worldwide....24
2.5.1 Plantation Teak and Native Teak....27

2.5.2 Teak in Panamá 28

2.5.3 Tectona grandis plantations in Costa Rica 30

2.5.4 Management tools and guidelines for *Tectona grandis* plantations 33

2.6 Wood quality 39

2.7 Teak and Markets 41

2.8 Management of Natural Teak Forests 44

2.8.1 Planted Teak Forests for High-Quality 44

2.9 Teak is Well-Suited for Smallholders 45

2.10 Wood Quality and Uses of Teak 46

2.11.1 Moisture Content 47

2.11.2 Location of Water in Wood 48

2.11.3 Density of Wood 48

2.11.4 Shrinkage and Swelling 49

2.15.2 Sapwood and Heartw*ood* 51

CHAPTER THREE: MATERIALS AND METHODS 53

3.1 Materials 53

3.2 Sample Preparation for Physical Properties Determination 53

3.2.1 Moisture Content 54

3.2.2 Density Determination 58

3.2.3 Dimensional Stability Test 58

3.5.3. Data Analysis 60

CHAPTER FOUR: RESULTS AND DISCUSSION 61

4.1 Density 61

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATION 67

5.1 Conclusions 67

5.2 Recommendations 67

REFERENCES 68

APPENDICES 84

LIST OF TABLES

TABLE **PAGE**

1: Air-dry density at 12% moisture content and mechanical properties of 10, 15 and 20- year-old teakwood... 622

3: Correlation matrix of wood density at 12% moisture content and mechanical properties of teak.. 666

LIST OF FIGURES

FIGURE **PAGE**

1: Plantation teak wood in Jukwa in kakum national park 100

2: Newly planted teak seedling 122

3: Desiccation of unprotected tropical soils 155

4: Ten-year-old teak stand with no thinning 19

5: Cross-section of a plantation grown teak log with its darker heartwood................................ 40

6: Heartwood proportion of teakwood from the deciduous ecological zone 54

7: Mean density (at 12% moisture content) and mechanical properties across the height of 10, 15 and 20 - year-old teak. Mean values with different letters across the same age group indicate a significant difference at $P < 0.05$ 56

8: Mean density (at 12% moisture content) and mechanical properties across the axial position of 10, 15 and 20 - year-old teak. Mean values with different letters across the same age group indicate a significant difference at $P < 0.05$.. 57

ABSTRACT

The increasing demand for timber in Ghana has placed much pressure on some of the species whose technical information is known. The incumbent trend of deforestation has posed a threat on sustainability of the country's timber resource in the near future if adequate measures are not put in place to curb the problem. To this effort many exotic species have been introduced into the country and raised in plantation both on and off reserves to supplement the timber in the natural forest. Among these exotic species is the *Tectona grandis* (Teak). Despite the establishment of these hardwood species in plantation, wood users do not have adequate information which will encourage the maximum utilization of the species. The study was undertaken to evaluate the physical and mechanical properties of Teak wood at ages 10, 15, and 20-years grown in Jukwa in Hemang Lower Dankyira District. Six trees were selected from the plantation for the study. These trees were cut into three height portion (butt, middle and top) and wood samples selected for the test. Eighteen pieces of Teakwood were taken for the sample. Six pieces each for 10, 15 and 20 year-old teakwood. Twelve samples each were taken along the radial direction of the stem (heartwood and sapwood). The heartwood and sapwood were clearly sawn from the Teakwood. The sapwood samples were taken from 3 cm from the bark of the trees whereas the heartwood samples were taken from the range of 5 cm to the pith of each portion of the woods. The findings show that, maximum compressive strength, hardness and shear strength of the teak wood were found to increase with age of species. Teak wood at age 10 and 15 did not show any significant differences with respect to air dry density. On average, MoR of 20 years old Teak wood was 106 N/mm2, which was about 33% and 38% higher in the 20-year-old Teak wood than the 15 and 10 year old respectively. Modulus of elasticity (MoE) was 9% and 32% higher in 20 year than in the 15 and 10-year-old teak wood respectively. Relationship between teakwood properties and age of tree was not apparent. This suggests that other factors may influence the wood properties of teak tree. In general wood properties of 10 and 15-year- old Teak were not inferior to ones from 20-year-old Teak.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

In Ghana many people are interested of getting their own building. The nature of building and structure in Ghana cannot be done without wood. Wood which can be defined as the hard-fibrous material that forms the main substance of trunk or a branches of a tree or scrub used for fuel or timber according to Chudly and Greeno (1998) Building Construction handbook. Though there are other building materials like metal, plastic etc. which are now used to replace wood but still most builders and landlords still prefer the use of wood for their building instead of metal, plastics and grass. Based on the above statement it means wood is an indispensable and essential material for our buildings.

But when we consider the degradation of our forest and the desertification which are caused by agricultural expansion (e.g. permanent cultivation, free range cattle reaching shifting cultivation, traditional slash and burn), Wildfire, logging and fuel wood harvesting, Mining and Infrastructure development (e.g. road, settlement), builders are now finding it very difficult to get hard wood like Odum (Iroko) Sapele, Mahogany, Wawa (Obeche) Cedar, Emire, Ofram and others for their construction work. Because of these there a need to get replacement for the wood mentioned above. Teak (tectona grandis Linn F Verberance) has been considered by the researcher as a good replacement of our local hard wood Odum, Mahogany and others.

Teak is a high quality deciduous timber species, native to India, Burma, Indonesia and Colombia. It is now one of the important plantation species both in the high forest and the savannah zones of Ghana. The species was introduced into Ghana between 1900 and 1910 (FAO and UNEP 1981). Teak has since acclimatized well and has been widely grown in both industrial plantation and small community wood lots. Large scale plantation programmed that was initiated with the help of the Food and Agriculture Organization (FAO) of the United Nations (Prah 1994) Teak was introduced in Hemang Lower Denkyira District in early 1990s by small scale farmers

Teak has a high degree of natural durability is moderately hard and heavy with low stiffness and shock resistance but an excellent decay resistance (Thaiusta 1999). Currently, teak tree were cut at different ages. Growers have different opinion on optimal age of teak for various wood product but little scientific data are available to these view. In Ghana teakwood is being harvested from 10 to 30-year-old and above .The optimal age of teak for high quality products to ensure maximum timber productivity is unknown (Midgley et al 2007). One species that has been widely established in plantations throughout the tropics because of its good growth and stem form and its ability to produce high quality timber is the *Tectona grandis* (teak). Teak grows very fast and survives a wide range of climatic conditions. It thrives best in fairly moist regions (Thaiusta, 1999). Many factors including site, seed supply and seed quality affect the success of teak planting.

There are three main practices that can be observed in order to regenerate harvested *T. grandis* plantations (Kadambi, 1972; Street, 1962). These practices are by seeding, coppicing and root-shoot cutting. Coppiced teak trees tend to grow faster than seeded teak trees so Ghanaians are now tending to use coppice teak trees for regeneration instead. There is limited information on properties of teak at different age of plantation. According to Jha (1999) teak rotation at 20-years gives higher beneficially return as well as acceptable wood quality. After ten years of planting these species, people started using it as electric poles, for construction of wattle structures, fencing, rafter, fuel wood, stake and wind breaks without taking into consideration the mechanical and physical properties

Report indicates that teak rotation age was prevalent at 35-years while traditional Teak plantation rotation was previously 50 years or more (Bhat and Priyer, 2004). They reported that wood density, dimensional stability and strength properties of 35 and 50-year-old teak were not significantly different. The research done by Batt and Priyer is on higher ages, 35 and 50. Therefore this research seek to evaluate the physical and mechanical properties of teakwood at age 10, 15, and 20 since many peoples uses teak wood at early ages

1.2 Statement of the Problem

Wood which is one of the essential materials for building are now becoming more and more expensive and scarce. In 1920s Ghana forest reserve was about 1.6million hectares according to (Oduro et al, 2012). At the time there were large areas of forest reserves across the country. Now our forest reserves have reduced and depreciated to about 30% (Dauda 2015). Based on these, planting of tree has become very necessary. Planting trees will help Ghana to get enough wood for our construction project. Teak which was introduced in Ghana in the early 1930s has become most popular. In Hemang Lower Dakyira District where Kakum rain forest is located, even these place builders are finding it very hard enough before getting our local hard wood like Odum, Sapele, Wawa, Cedar and Mahogany for their construction work.

So now the attention has shifted to the use of Teak. Many are using teak wood for construction work e.g. areas like door frames and doors, window frames and window, ceiling joist, roof truss electric pole furniture's and many more but the problem is that, there is limited information on the properties of teak at different age of plantation, people use teak wood anyhow without taking into account it strength. Because of this, study is undertaken to assess the strength of teak wood at ages 10,15, and 20 grown in cape coast north district because the people just use the teak wood any how without considering the strength.

1.3 Purpose of the Study

The purpose of the study was to evaluate the physical and mechanical properties of 20, 15, and 10-years-old teak plantation in the Jukwa in Twifo Hemang Lower Dankyira District

1.4 Research Objectives

The objectives of the study were to:

- Know the physical properties of teakwood (moisture content, density and dimensional stability)
- Compare the bending strength MoE and MoR of plantation teak of age 10, 15 and 20 years.

1.5 Significance of the Study

The research work will help the teak tree users to know the specific year in which teak wood will be mature enough to use for construction work and other project. The research will also help to test the strength of teak by their base, middle and top

It is also going to provide adequate information about the mechanical physical properties of a teakwood.

1.6 Delimitation

This research work will only take into consideration the bending stress, density, MoC and MoE of plantation teak tree. The study only test for the str-ength of the base, middle and the top. It will also considered only three difference years 10years, 15 year and 20 twenty years.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Teak, *Tectona grandis* (L.f.), Verbenaceae from the Verbena Family, is one of the most valuable tropical woods in the world. Because of its strength, straightness, workability, and resistance to many pests and diseases, teak is used as a standard to which other timbers are compared (Bhat, 2011; Weaver, 2013; Pandey and Brown, 2010; Kumar et al, 2017; Keogh, 2009; Parameswarappa, 2015). The Spanish name for teak is “teca”. Both the Burmese and Greek translate this word to “carpenter’s proud” (Béhagel, 2017; de Vriend, 2008, Bhat and Ok Ma, 2014).

Teak *(Tectona grandis)* is one of the globally most important tropical timber species both in natural forests and in plantations. It grows in different geographical regions under different environmental conditions, and variation can be observed in characters like leaf morphology, drought resistance, stem form and branch characteristics, growth increment, soil preference, the proportion of heartwood, wood structure, fiber length, strength, specific gravity, durability, wood extractives, wood colour, contents of minerals, and resistance to pests and diseases. The variation is a combination of genetic differences (among populations and among individuals within populations) and differences in the growing environments (soils, climate, and silviculture practices).

Since the 2nd World Teak Conference held in Bangkok in May 2013 the international partners IUFRO, FAO, and TEAKNET have been promoting the initiation of a large scale international research, development and cooperation program to strengthen the conservation and sustainable use of teak genetic resources for the benefit of teak growers, forest industries, investors and local communities. In the same year, the 38th Session of the FAO Conference adopted the Global Plan of Action for the Conservation, Development and Sustainable Use of all Forest Genetic Resources. It identified the use of new technologies within the framework of bio-economy as a strategic priority to be supported by the international community. The envisaged Global Teak Support Program will build upon this initiative and contribute to the implementation of the Global Plan of Action.

The report "State of the World's Forest Genetic Resources" published by FAO in 2014 lists tree species that are considered national priorities by the reporting countries for the conservation and management of forest genetic resources. Teak (*Tectona grandis* Linn. F.) takes the top rank in this list in more than 20 countries. Economic value (including value of timber, pulp, food, wood energy, and non-wood forest products) is one of the main reasons for nominating the species as a priority for conservation and management. Though currently teak takes only a minor position in the total volume of world timber production and trade, it competes in the high-value hardwood markets and is a major strategic element in the forestry economies of many tropical countries.

Natural teak forests are estimated to cover ca. 29 million ha in India, Lao PDR, Myanmar and Thailand, of which almost half are located in Myanmar. The available old growth, high-quality teak resources are under threat due to over-exploitation and conversion to other land-uses. The supply of quality teak logs originating from old growth natural teak forests in Myanmar to overseas markets is in decline due to the impact of the log export ban in force since 1st April 2014, the decline of harvestable area in natural teak forests and the deterioration of the quality of naturally-grown teak. This has led to increased interest in establishing and sustainably managing planted teak forests.

Planted teak forests have attracted large investments from the private sector in Africa, Asia and Latin America. Globally, planted teak is the only valuable hardwood that constitutes an emerging forest resource. Planted teak forests according to various estimates cover between 4.35 to 6.89 million ha, of which more than 80% grow in Asia, ca. 10% in Africa, and ca. 6% in tropical America. Teak is known to exhibit a wide geographic variation in wood characteristics. Hence, in order to produce good quality teak in planted forests breeding programs have been established, mainly in Latin America and Asia, focusing on the selection of the desired wood-quality traits, including growth performance, clear straight bole, colour, grain, texture, stability, strength and durability. However, it is noteworthy that most planted teak forests are currently established using germ plasm that is based on a very limited number of clones mainly originating in Costa Rica, Malaysia or Thailand.

The situation given with natural and planted teak forests calls for the implementation of a program for the conservation, development and sustainable use of teak genetic resources on a global level in order to preserve the still existing native teak resources before they decline further and to strengthen the understanding and knowledge of teak genetic resources, promote their sustainable use and management and contribute to the development and strengthening of in-situ and ex-situ conservation programs through research collaboration at national, regional and global levels. In the long-term, the program is to help broaden the genetic base of available teak planting stock and thus to contribute to the establishment of resilient, high quality teak plantations. Overall, the implementation of the Global Teak Support Program (GTSP) will contribute towards achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development as well as the Aichi Biodiversity Targets of the Convention on Biological Diversity.

The global teak study presented in this report provides an analysis and evaluation of the current situation of the conservation and management of teak in both its natural range and in teak plantations. With the help of Global Teak support program (GTSPs), and government of Ghana many farmers in Heman lower Denkyira have develop interest in Teak plantation. Typical example is fig 1.

Figure 1: Plantation teak wood Kakum National Park Heman lower Denkyira district.

2.2 Teak Management

Optimum silviculture prescriptions for Panamá are not yet available because of teak's short history and limited growth analysis in the country. Occasionally, it is necessary to make use of Central American and Caribbean information in the short term when information specific to Panamá is not available (de Camino, 2017). Management prescriptions are therefore based on the mix of information that best fits Panamá. Teak seeds have acclimated to the soils and climate in Panamá. Through the seed division of the Ministry of the Environment (ANAM) in Panamá, special landraces are used and sold throughout the country. This division has tested recently introduced seed provenances of excellent varieties from Tanzania and Thailand. However, these seeds have responded poorly outside their native area. Introduced teak landraces specifically adapted to this region are the best seed provenances to use (Ramirez, 2009; Krisnapillay, 2010; Sarre and Ok Ma, 2014; Bermejo et al, 2014; Kaosa-ard, 2008).

Planting happens at the onset of rainy season. Teak may be planted by directly sowing the seeds, with containerized seedlings, or with bare-root nursery stock. Planting depths of at least 25 centimeters are required for seedlings. For a plantation, it is not recommended to sow directly because of high mortality rates and added labor costs. Instead, containerized seedlings have a higher survival rate because of their developed root systems. However, stump plantings (root and shoot pruned plants) can be most effective. In Central America, seedlings are planted in beds where they grow for one year. When seedlings reach one and a quarter to two centimeters in diameter and five to fifteen centimeters in height with roots fifteen to twenty-five centimeters in length, stumps are then cut. These can be transported over large distances, are quicker to plant, and their growth is more vigorous (Chaves and Fonseca, 2011; Weaver, 2013; Keogh, 2017; Bentacourt, 2017).

Figure 2: Newly planted teak seedling

Growth rates that exceed an average of twenty cubic meters per hectare per year over twenty years are unlikely to be encountered (Romeijn, 2009). Growth rate tables for Central America have many discrepancies and errors. The translation of growth rates based on experimental plots to field conditions has been inadequate (Varmola and Carle, 2012). This has led people in many countries to believe that growth rates will be higher than what is physically possible under field conditions. Most practicing foresters in the tropics would be content to encounter an average annual growth rate of ten to fifteen cubic meters per hectare per year over twenty years on all their plantation sites (Arias, 2013; Centeno, 2017; Pandey and Brown, 2010).

Management practices vary depending on whether teak is grown on short or long rotations. An important feature of all teak yield tables is the early peak of mean annual volume increment (MAI), generally between six and twenty years (Pandey and Brown, 2010). Rotations of more than twenty-five years show internal rate of returns lower than 12%, rotations of less than twenty-five years have higher internal rates of return (de Camino et al, 2012). Strength and heartwood density of young teak trees are not inferior to older ones, thus rotation age can be shortened. Panamá has rotations between twenty and thirty years with an ideal final stocking of 200 to 300 stems per hectare (Chaves and Fonseca, 2011).

Estimates of annual average increases are 1.3 centimeters in diameter, two meters in height and twelve cubic meters per hectare. The total volume at 25 years is estimated as 300m^3/ha and the commercial volume as 250m^3/ha (Moran, 2008). Teak in Panamá reaches 200 m^3/ha in twenty years on the best sites (ANAM, 2004). The financial rotation age does not depend on maximum volume productions, but on the value of the final product (Bhat, 2008; Bermejo et al, 2014; de Camino et al, 2012; Keogh, 2009).

The number of seedlings to plant depends on a combination of the desired final product and initial investment costs. Literature provides information on spacing that ranges from one meter by one meter to an irregular spacing of three meters by six meters (Alfaro et. al., 2017; Schmincke, 2010; Pandey and Brown, 2010).

According to most literature and personal interviews, the most common spacing for initial planting is three meters by three meters or 1,111 trees per hectare (Bermejo et al, 2014; de Camino et al, 2012).

The closer the spacing of teak, the more expensive are the establishment costs with seedling purchase and planting labor. Nevertheless, higher stocking allows for early mortality rates without a decline in later stand quality and provides an opportunity for selecting the better individuals during thinning operations. This silviculture treatment aids in early selection that can release the better individuals to achieve better growth rates (Pandey and Brown, 2010). Wider spacing reduces initial investment costs. However, the wider the spacing, the more weeding and pruning needs to be done during the initial years. Over the long run, costs will be about the same as closer spacing except that the costs for plantations with wider spacing will be spread out over the first five or six years (Keogh, 2017; Anoop et al, 2014).

Diameter at breast height (dbh) and specific gravity increased with increased spacing between trees while merchantable height, stem volume and basal area decreased. No matter which spacing is chosen, it is of utmost importance that the land be managed properly. Stocking rates and management will affect commercial growth (Ola-Adamas, 2010; Bhat, 2008). Teak is shade intolerant. It is sensitive to root competition and requires full light for proper development (Troup, cited in Romeijn, 2009; Weaver, 2013). Straight, commercial teak is contingent upon keeping the stand free from competition. When teak is first planted, an entire hectare or more of land is cleared. Also, because native flora competes with teak, weeding is mandatory in the first four years until the closure of the canopy finally shades out any understory. However, during future thinning the understory will regenerate but, by this time, the teak should be large enough to not be in danger of competition. This new understory can be beneficial to protect the soil from erosion. One of the weeding regimes suggests that cleaning should be done three times in the first year, twice in the second year, and once in the third and fourth years (Keogh, 2017; Romeijn, 2009). Another weeding treatment demands cleaning twelve times in the first two years, and twice in the third, fourth, and fifth years (De Vriend, 2008; Alfaro et al, 2017).

Teak needs a deep, porous and nutrient-rich soil to grow. With unprotected soil from heavy weeding, the hot tropical sun, fire, and heavy rain, erosion is inevitable (Chaves and Fonseca, 2011). Hot tropical sun desiccates bare soil and heavy rains leach out nutrients. This can cause stunted growth in teak plantations.

Figure 3: Desiccation of unprotected tropical soils

Erosion is a problem within teak plantations. Extensive erosion occurs when teak is planted on a hillside. It is recommended not to plant on hillsides with more than a 20% slope. To prevent heavy erosion, spacing on a hillside should be set wider apart to allow an understory to grow. Plantation fires are caused by uncontrolled field burning set by farmers practicing slash and burn agricultural techniques. Fire lanes can be cut to protect a stand from fire (de Camino et al, 2012; Chaves and Fonseca, 2011; Keogh, 2017; Herrera Durán, 2011).

Disease is not pervasive in teak, however problems still do exist. Leaf-cutter ants *Atta spp.,* have attacked many teak plantations. They can be controlled with organic deterrents or chemical pesticides. After fire a tree is more susceptible to fungal attacks. Therefore, preventive methods are necessary to protect the stand from fire and damage. Wind damage is another problem that can ruin a teak plantation. Dense stands thinned too late and plantation edges are affected by wind damage. Shallow roots from trees that have recently been released can create conditions where blow over or breakage occurs. To offset wind damage, good site selection and timely thinning is important (Keogh, 2017).

Pruning is required to keep the teak trunk free from knots that reduce quality and to increase its merchantable height (Keogh, 2017; Briscoe and Nobles, 2016). It is best to prune teak before the branches get too thick and produce large knots. Teak should be pruned directly after it has produced leaves. This will decrease the number of new branches and stems that form on the bole (Chaves and Fonseca, 2011; Schmincke, 2010). Consequently, labor costs are saved with timely pruning. Three pruning are recommended (Cordero 2016; Perez, 2016). The first pruning should take place between ages two and three when the majority of trees reach five meters in height and have a diameter of six centimeters. On average, half of the total height of the tree should be pruned. Anything more can damage the total photosynthetic capacity and, consequently, growth will slow (Alfaro et al, 2017). The second pruning should take place in the fifth year or when the trees reach ten meters in height. The last pruning should remove 60% of the total height when a tree reaches twelve meters or seven years.

For optimum development of a stand, thinning is essential. Thinning is a silviculture treatment to reduce size differences and increase stand uniformity. Fertilization is not needed to increase the diameter growth of trees, instead timely thinning is recommended (Keogh, 2017; Bermejo et al, 2014). Thinning is based on the number of trees in a hectare and the rotation age. Thinning should start at the onset of competition (Redes, 2008). Indicators of competition include the touching of crowns and mortality of lower branches. This competition occurs when trees reach seven to nine meters in height when planted with three by three meter spacing. Three to five thinning are the average number based on optimum Central American growth rates (Bermejo et al, 2014; Alfaro et al, 2017; de Camino et al, 2012). The first two thinning should reduce the number of trees by 50%; thereafter thinning is based on basal area (Miller, 2009; Redes, 2008; Pandey and Brown, 2010). When basal area is used, thin when the plantation reaches 20 to 25 m^2/ha and is reduced to 14 to 17 m^2/ha (Krug and Ruiz, 2013). The first thinning does not usually result in merchantable material and should be considered a sanitary cut to get rid of unhealthy or damaged trees. Thinning is not as important when teak matures because it does not need as much growing space. This occurs approximately when teak reaches age twelve (Keogh, 2009, de Camino et al, 2012; Kumar et al, 2017; Schmincke, 2010; Alfaro, 2010).

Most smallholders do not want to thin because of additional costs with no returns. Also, most do not have the technical knowledge of teak management and see a loss in their investment. Thinning, though, is not by definition a harvest. Instead a thinning favors growth of the best individuals (de Camino et al, 2012; Varmola and Carle, 2012). Unfortunately, with no thinning during the first ten years, the smallholders end up losing the tree's productive potential. In the short term, there is a limited supply of better quality logs. In the long run, this competition results in small diameter classes that reduce the price each log can generate. Also, if trees are shaded for too long, any type of management cannot rescue the tree's growth potential. Under these circumstances it is best to cut the stock and to start all over again. The consequence of no thinning is low to negative financial returns (Keogh, 2017).

Figure 4: Ten-year-old teak stand with no thinning

If the utilization of thinning and pole-sized wood improved financial conditions, teak plantation owners would benefit. Early returns from these first thinning would motivate smallholders to manage their stands for optimal growth. Since there is no international market for these small sizes, it is necessary to create a domestic market. Costa Rica uses teak from plantations first thinning to produce furniture parts and small flooring boards. Products such as broom handles, glue-edged boards, edging strips, furniture, and doors have been made from thinning materials. A domestic end-product market is needed to take advantage of these early thinning (Krisnapillay, 2010; Pandey and Brown, 2010; Keogh, 2017; Bermejo et al, 2014; de Vriend, 2008).

Forest plantations in the tropics have failed due to natural causes or human error. Unforeseen occurrences are the risks involved when working with a natural resource. These include natural catastrophes, insect infestations, weather phenomena, and fire. Human error can be avoided with careful planning and with consideration for distance to the market, infrastructure and transportation costs, site quality, and financial constraints. Also, short term gains based on intensive selective logging reduce the long term financial gain. To obtain a reasonable financial gain, it is pertinent to thoroughly understand all variables included from production to sale and the projected market for teak (Schmincke, 2010; Weaver 2013; de Vriend, 2008).

2.3 Biology of Teak

Teak is one of the best known tropical woods in the world. This large broad-leafed, deciduous tree ranges from 30 meters in height with a girth over one meter on good sites to twelve meters in height on poor sites. It develops a tall cylindrical bole and has a buttressed trunk at maturity. Leaves reach up to 50 centimeters in length and 25 centimeters in width (Weaver, 2013; Keogh, 2009; Betancourt, 2017; Ross, 2009). Teak grows naturally on over 23 million hectares in India, Laos, Myanmar, and Thailand and has been naturalized in the Philippines, Java, Indonesia and some of the smaller islands in the Indonesian Archipelago. It grows between latitudes from twenty three degrees north to ten degrees south with temperatures ranging from 16º to 40º Celsius. It requires an altitude between sea level and 1200 meters and rainfall of 500 to 5000 millimeters per year (Pandy, 2016; Pandey and Brown, 2010; Weaver, 2013; Keogh, 2007; Bermejo et al; 2014; de Camino et al, 2012).

Highly productive sites generally have higher rainfall. A dry period is still crucial for teak's development; teak grown without a dry period has weaker timber. Thus, teak requires monsoon climates with a distinct dry period of at least three months (Ghosh and Singh, 2011; de Vriend, 2008; Keogh, 2007; de Camino et al, 2012; Chaves and Fonseca, 2011). Teak grows best on fertile, well-drained, alluvial soils with a neutral or slightly acid pH. Limiting factors include shallowness, hardpans, waterlogging, compaction, or heavy clays with low contents of calcium, magnesium, and phosphate (Weaver, 2013). Growth is stunted when the slope is above 20 percent or elevation exceeds 1000 meters (de Camino et al, 2012). The best sites for teak have a soil depth of 90 centimeters or more and are located on medium to flat slopes at the base of a mountain or in valleys where there are no strong winds (Pandey and Brown, 2010; Keogh, 2007; Chaves and Fonseca, 2011).

Teak is a cross-pollinating species with monoecious flowers that are 45 to 60 centimeters long. Occasionally, self-pollination occurs but germination is poor (Weaver, 2013). In Panamá, flowering initiates between ages five and eight. This occurs at the beginning of rainy season and the fruits mature during dry season (Chaves and Fonseca, 2011). Germination is a plant's ability to initiate reproduction. Teak seeds are larger in areas that are more humid. Larger fruits have more seeds and positively increase germination numbers (Weaver, 1993). Also, scarification is used in Costa Rica to speed up germination (Chaves and Fonseca, 2011; Ramírez, 2009).

Teak is a coppicing species. Coppicing benefits smallholders who might not have the funds available to purchase more seeds, especially after a fire. Teak, however does use up much of the soil nutrients and unless fertilized the coppicing sprouts can be stunted and susceptible to disease (Weaver, 2013; Hase and Foelster, 2015).

2.3.1Classification and Distribution of Teak

Teak (*Tectona grandis* Linn. f.) is one of the tropical hardwood species from the family verbenaceae. It is an important timber species with worldwide reputation (Banik, 2013). It is naturally endemic to Thailand, Peninsular India, Myanmar and Laos. Teak was first introduced in plantations in Java (White, 2011) and also cultivated in the South and South-East Asia, South and Central America, the Pacific, Africa and the Caribbean Islands (Tewari, 2012). This tree can grow to a height of 30 – 40 cm. It has fluted bole and sometimes possess slight buttress (Keay, 2009). Teak has been successfully established and rated as one of the fastest growing timber species in many other countries of the world including Ghana. Teak can grow up to an age of 100 years. It sheds its leaves annually at dry season as part of its cycle of life. Its world-wide demand is attributed to its high quality timber on account of the attractiveness and sturdiness of the wood it produces (Goh *et al*., 2007; Sarre and Ok-ma, 2014).

The tree has a straight trunk, thick base, a spreading crown, and four-sided branch lets. The leaves, rough in texture, are opposite or whorled, and every branch ends in many small white flowers. The heartwood is golden – yellow colour, has a pleasant and strong aromatic fragrance. Its beautiful colour darkens into brown and mounted with darker streaks when seasoned.

2.4 Teak as a Building Material

Wood properties of *T. grandis* include its resistance to all kinds of weather or non-corroding properties, its solid fiber and elasticity, facilitate eases of working. The durability of Teak products is the oil in its heartwood. This special oil content makes the wood always seen gleam and maintains this glow when left outside for a long period of time. In addition, Teak wood will not be brittle due to its anti-bacterial characteristics. Machining is relatively straight forward. Boring, gluing, molding, nailing, planning, sawing, veneering, and turning do not present major problems (Keogh *et al*., 2011).

T. grandis has numerous end uses including ship building, marine construction and furniture making. It is suitable for carving and lasts long in contact with the ground. Its high resistance to chemicals makes it ideal for laboratory benches. The wood is ideally for constructional works where exposed to the weather e.g. Doors, windows, frames, trellis work, garden furniture etc. (Keogh *et al*., 2011). *T. grandis* wood, which is certified on the basis of social and environmental practices throughout its entire forest and wood chain, has a bright future as an industrial raw material. For this reason, the species is likely to retain its importance as the major high grade plantation species for tropics into the foreseeable future and adequate information on their strength properties is required for maximum utilization especially those from off reserve areas (Keogh *et al*., 2011).

3.5 Tectona grandis plantations worldwide

The excellent properties and versatile nature of teak (*Tectona grandis* L. f.) timber and its eminent suitability for an array of uses is well documented. The potential for growing and managing teak in different ecological zones and under different situations (objectives) is being increasingly recognized, leading to intensive domestication and cultivation of the species in countries/regions beyond its natural habitat. Despite the value of teak timber and its increasing demand, its full potential for providing direct revenue as well as value-added down-stream processing and for contributing to the national income has not been fully utilized.

With the ever-increasing demand for this high-quality wood, more people than ever want to take part in the teak plantation industry. Plantations, in general, have been established in most developed countries to cover dwindling stocks of natural forests (FIRA, 2016). Similarly, teak is a plantation species that can aid a developing tropical country to augment diminishing hardwood forests. Teak plantations can now be found in most tropical countries (Pandey and Brown, 2010; Bermejo et al, 2014; Keogh, 2009).

Despite all the efforts invested in reforestation, i.e. 5.7 million hectares planted worldwide in year 2000 according to the FAO (2010), the currently available *Tectona grandis* (teak) timber resources are far below the needs of the huge worldwide market demand (Ball et al. 2010). In the last TEAKNET (Asia-Pacific

Network) meeting held in 1999 in Chiang Mai (Thailand), the lack of planting stock, especially of superior quality, was identified as the primary cause of the teak timber deficit. Increased yield, higher uniformity and shorter rotations are strong incentives for developing the intensively managed *T. grandis* plantations, which are gaining a worldwide reputation due to the attractiveness and durability of teak wood. Market demands have prompted the establishment of plantations within and beyond its native countries (Hoare and Patanapongsa 2008, Monteuuis and Goh 2009, Bhat 2010).

Although several research projects have refined many aspects of teak silviculture, there are gaps in what is known about managing and use, growing teak in such vital aspects as site requirements, stand dynamics, short-rotation intensive management, wood processing, grading rules and product marketing. The importance of stocking density, for instance, is still vague as thinning intensities and periods have not been properly defined in relation to production objectives. Very often administrative decisions prevail over technical criteria and stands are thinned either too late or less intensively than recommended, causing a negative effect on individual and stand growth. Most of the tree plantations in the tropics grown for saw timber require early, heavy and repeated thinnings in order to sustain their characteristic rapid diameter growth (Galloway et al. 2011). Delaying thinning or carrying out slight interventions at early stages prompts inter-tree competition. On the contrary, too early or too strong interventions, although not common, cause site under-occupancy and the consequent loss in stand productivity.

Teak occurs naturally in parts of India, Myanmar, Laos and Thailand. It has been naturalized in Java, where it was probably introduced some 400-600 years ago (Troup 2011, Kadambi 2012, White 2012). Early introductions of teak outside Asia were made in Nigeria, with the first plantations being of Indian origin in 1902 and subsequently of Burmese origin (Horne 1966). Teak planting in what is now eastern Ghana started around 1905 and a small plantation of teak was established in Côte d'Ivoire in 1929 from plantation seeds obtained from then Togoland. Teak was introduced to countries of Tropical Africa to supplement local timber supplies because of its excellent timber properties. Perhaps the first pure teak plantation in Tropical America was established in Trinidad in 1913 with seeds from Burma. Teak planting in Honduras, Panama, and Costa Rica started between 1927 and 1929 (Ball et al. 2010).

Teak is the world's most cultivated high-grade tropical heartwood, covering approximately 6.0 million hectares worldwide (Bhat and Hwan Ok Ma 2014). Of this net area of teak plantations, about 94% are in Tropical Asia, with India (44%) and Indonesia (31%) contributing the bulk of the resource. Other countries of the region contribute significantly with 17% in total (Thailand, Myanmar, Bangladesh, Sri Lanka). About 4.5% of the teak plantations are in Tropical Africa and the rest are in Tropical America, mostly in Costa Rica and Trinidad and Tobago (Pandey, 2008). The Asian Pacific region (5.3 million hectares) have been managed under 35 to 80-year rotations , yielding annual productivities of 5 to 20 m3 ha-1 year-1, while teak plantations in Africa (310,000 hectares) are harvested at shorter rotations of 20 years, yielding between 4 and 13 m3 ha-1 year-1 (Bhat and Hwan Ok Ma 2014). Central and South American teak plantations (205,000 ha) are being managed under similar short rotation scenarios of 20-25 years, however they have shown higher yields of up to 40 m3 ha-1 year-1 (average of 20-25 m3 ha-1 year-1 on medium and high quality sites).

Teak has been grown under plantation conditions for 150 years. In the last decade, its high value as timber of excellent appearance and mechanical resistance, and the appearance of strong markets for teak products which parallels an increasingly declining stock of natural stands, have attracted particular attention to the potential of teak plantations as a high return investment possibility (Ball et al. 2010).

2.5.1 Plantation Teak and Native Teak

Plantation teak establishment began in countries where it occurs naturally. It was not until the late 1800s that teak plantations were introduced to countries outside its native area (Pandey and Brown, 2010; Keogh, 2009; Weaver, 2013). Teak is now grown in many tropical countries. Teak was first brought to Trinidad from Burma in 1880 but not established in a plantation until 1913. Ninety-two percent of the plantation teak is in tropical Asia with 43% in India and 31% in Indonesia. Tropical Africa holds 4.5% with most plantations in Côte d'Ivoire, Nigeria, Sierra Leone, Tanzania, and Togo. The Caribbean, Central and South America have 3% of global teak plantations in Trinidad and Tobago, Costa Rica, El Salvador, Panamá, Columbia, Ecuador, Venezuela, and Brazil. Most teak producers export the logs, processed timber, or final products globally. The number of countries now producing teak has risen in the last decades. Future trends show increasing production of teak in plantations (Weaver, 2013; Bhat and Ma, 2014; Pandey and Brown, 2010).

2.5.2 Teak in Panamá

Panamá, located between 7.5º and 10º North latitudes, is three degrees south of teak's naturally occurring range. However, teak grows well in Panama's climate. Teak was brought to the Summit Botanic Gardens in Panamá in 1926 with a seed provenance from Sri Lanka. The teak from these gardens provided most of the seed for Central American and Caribbean teak (de Camino et al, 2012; Picado, 2017). Growth depends on site quality, plantation density, management, and age of trees. Sites are classified according to their growth potential. Keogh's (2009) regional site classification chart for Central America states that teak will attain a mean top height of nearly 30 meters on the best sites (Class I) and twelve meters on the poorest sites (Class IV). Highly productive sites will have a dominant height of 21.7 meters in ten years.

Sites with a dominant height lower than 18.1 meters at ten years are classified as low productivity (de Camino et al, 2012; Kumar et al, 2017; de Vriend, 2008). Site quality describes how well a plant or tree will grow in a specific location. In 1956, Holdridge and Budowski distinguished more than a dozen life zones in Central America. These life zones were further subdivided into associations of land use or vegetation cover and local environmental conditions affected by altitude. The four zones of life for eastern Panamá are: Tropical-Dry Forest 15%, Pre-mountainous Humid Forest 27%, Tropical Humid Forest 44%, and Pre-mountainous Very Humid Forest 14% (Adames, 2011).

To define a plant's growth requirements Holdridge (2011) developed a classification system to examine the impact of climate on natural vegetation. Rainfall and bio temperature (based on the growing season length and temperature) are measured to classify broad vegetation categories. Eastern Panama's climate classification is 62% sub-humid with approximate average annual temperatures of 24º C (75º F), 36% humid with average annual temperatures above than 24º C, and 2% humid with average annual temperatures below 24º C. The average annual precipitation is 2300 millimeters with an average dry season of three months and an average annual temperature of 26º C (Adames, 2011). Teak's growth variability is dependent on soils, altitude, and climate. Out of all of these, climatic factors are the most important. The main climatic variables are annual rainfall and humidity (Pandey, 2016).

If the goal of the plantation farmer is to produce commercial logs then it is important that the climate variables for the region match those required for optimum teak production. Eastern Panamá meets teak's physiological requirements for climate, temperature and altitude. Eastern Panamá has three main soil groups. Soils derived from igneous rock that are found closer to the mountains in the San Blas and Majé mountain ranges tend to be more acidic and low in fertility but more resistant to erosion. The second group originates from sedimentary rock. These soils are high in organic material and fertility but limited by relatively high erosion. Unless already eroded, they can sometimes be found on slopes of at least 30%. The last major groups found in eastern Panamá are the alluvial soils. These soils found in the floodplains close to the major rivers and tributaries are known for their fertility and depth but may become waterlogged (Adames, 2011).

Teak requires deep, fertile and well-drained soils that range between a neutral to acidic pH (Chaves and Fonseca, 2011). Teak's soil requirements are satisfied in eastern Panamá. However, seasonal field conditions should be considered. For example, if a site is susceptible to waterlogging during the year if an area is already highly eroded and will not satisfy specific nutrient requirements then another site should be chosen (Keogh, 2017).

2.5.3 *Tectona grandis* plantations in Costa Rica

Fast-growing, high-yield tree plantations are an increasingly significant source of wood in the tropics. In these areas, the improvement of wood productivity is an important economic goal. In Costa Rica and other countries in Central America most of the tree plantations, especially those of advanced age, have not had the expected productivity. The main causes for this have been bad site selection, use of non-improved genetic planting material, and lack of appropriate silviculture management (Torres et al. 2015, De Camino et al. 2008, Castro and Raigosa 2011).

T. grandis was introduced in Costa Rica and other countries in Central America between 1927 and 1929. Until the year 2000, approximately 223,000 ha of *T.*

grandis plantations were established in this region (Pandey and Brown 2000). In the past 10 years, Costa Rica has steadily increased the annual plantation rate of several species to an approximate total of 11,000 hectares per year. In 2000, the total area of plantations reached 178,000 hectares, of which 30,300 ha (17.0%) corresponded to *Tectona grandis* (FAO 2010).

Governmental incentive programs have encouraged the establishment of commercial tree plantations in Costa Rica, reaching 140,000 ha by the year 2000 (Sage and Quiros 2011). Projects and private companies in Central America urgently need relevant growth and yield information for those species most widely used in reforestation projects. Determining the production throughout the rotation is particularly necessary in the case of advance-aged plantations (over 20 years).

The important property requirements of end-users in fast-grown *T. grandis* are straight, least-tapered boles with reduced flutes/buttresses and knots, low proportions of juvenile and tension wood, high proportions of heartwood, and optimum wood density and strength. The two mayor factors that influence sawn wood grade and recovery are unsound hollow knots and deep flutes in the logs (Bhat 2008). However, no scientific-based recommendations are available in the literature and many silviculture activities, such as pruning and thinning, are carried out, in most cases, based on visual assessment and common sense. No studies are available on the maximization of wood quality properties by means of intensive teak plantation management in Central America.

Linking forest management to timber industry is fundamental. Connections between silvicultural management and wood quality are limited, providing only size-related characteristics (girth and height growth, stand volume) as useful information. Particular grading rules set up by international markets for natural teak obtained in Asia, are currently limiting the selling options of several forest companies in Central and South America due to difficulties in meeting such stringent demands, mainly those having to do with minimum log dimensions and wood defects. Therefore, efficient management practices leading not only to maximum per-hectare volume production but also to a desirable individual-tree commercial volume production are strongly needed. Lack of sufficient financial information to evaluate the profitability of *T. grandis* plantations is discouraging new projects willing to invest in reforestation.

Several studies on growth and silviculture management are available for teak plantations in the Tropics, however, they have been somewhat scattered and without practical or conclusive results. Available management prescriptions and growth projections lack high-quality supporting data, complementary studies on stand competition, volume projections, merchantable volume estimates, information on the effect of different management regimens (on growth, yield , and quality), reforestation and management costs, wood prices and market grading, and financial analyses justifying the investment.

Within the next 10 years, most of the teak plantations in Costa Rica will be thinned for a second, third, or forth time, or even harvested at rotation ages between 20 and 30 years. Final yield (total and merchantable volume according to market requirements), total management costs, wood prices, and management options are urgently needed to inform owners, investors, and consumers about the real stock of commercial timber available at present and future, and the possible expected value of their plantations. The present study focuses on management scenarios developed according to production objectives, plantation quality classes, and rotation periods, aiming at producing high quality timber. The study does not cover all the factors influencing a tree plantation system, as they are numerous and some are very complex, e.g. genetic and climatic resources, fertilization regimens, land preparation, site conditions and soil quality, wood processing industry, among others.

Pruning and thinning are key silviculture activities, and together with the rotation length, are decisive factors for achieving different levels of quality and yield of round wood products. In this study, round wood is the last stage of the chain of production; further processing into board feet or furniture is not considered, as the many possible products and insufficient information make a deeper analysis difficult to achieve. A financial analysis complements the set of growth scenarios with different possible economic returns.

2.5.4 Management tools and guidelines for *Tectona grandis* plantations

T. grandis is suitable for multiple end-uses, including construction, furniture and cabinets, railway sleeper cars, decorative veneer, joinery, ship and vehicle body building, mining, reconstituted products, etc. The quality of teak timber, which could be improved by high input management, depends partly on tree form and partly on basic wood structure and strength properties. The major structural factors that should receive attention are, among others: stem size, bole shape, knot size and frequency, and heartwood-sapwood proportions (Bhat, 2010). Evidence of similitude in wood mechanical properties between new (21 years) and old (65 years) *T. grandis* trees offers scope for reducing the rotation age of fast-grown wood without affecting timber strength. Nevertheless, the available data on the effects of spacing and thinning regimens on wood quality are insufficient for designing an efficient management strategy (Bhat 2010).

High proportions of heartwood and high dry density are the two most desired wood characteristics for plantation-grown teak (Tewari, 2009, Baillères and Durand, 2010). Several studies report the heartwood content and the variations in dry wood density, from pith to bark, with stem height, age, stand density, and climatic conditions for teak in different countries (Nair and Chavan 2015, Bhat 2015, Brennan and Radomiljac 2008, Trockenbrodt and Josue 2008, Priya and Bhat 2009, Bhat et al. 2011). A few similar studies have been carried out for younger teak (< 10 years) in Costa Rica and documented by Moya (2010), Arce (2011), Moya (2011), as well as for mature teak (26 years), documented by González et al. (2009). Most mature trees contain a central core of heartwood usually darker in color than the surrounding sapwood, which often darkens considerably when the cut surface is exposed to air. The transformation from sapwood usually occurs abruptly over a few rows of cells (Hillis, 2007).

In Costa Rica, teak trees present a heartwood proportion of 55% of the total volume at 30 years, increasing logarithmically with increasing age and consequently with DBH. Arce (2011) found heartwood proportions of 33-37% in 10-year-old teak grown in a dry region of Costa Rica. Cross-sectional area of heartwood at DBH has been reported to increase with increasing age (up to 80-90%), this at ages greater than 30 years on plantation-grown teak in different regions of the world (Bhat 1995, Kokutze et al. 2004). Little importance has been given to the proportion of heartwood in many countries where teak forests are older than 50 years, since this characteristic is not a matter of discussion for older trees (over 40 years of age) containing over 90% of cross-sectional area of heartwood at DBH. Lately, the need to produce fast growing teakwood in a maximum of 20-30 years increased the importance of producing high heartwood content, which is considered a determinant factor during visual assessment and wood valuation.

In timber with clearly demarcated sapwood and heartwood, those trees with higher percentages of heartwood will yield more saleable timber; conversely, a high proportion of sapwood is not a problem in treated poles because it is easily penetrated by preservatives and thereafter may be more resistant to pests and fungal infections than the heartwood itself (Oteng-Amoako 2004). In Costa Rica and other Central American countries, grading rules are based mostly on visual assessment, i.e. on quality characteristics such as wood defects and heartwood color. Heartwood color and content determine, in most cases, whether the log will be valued as high or poor-quality wood, with a corresponding gain/loss of up to 50% of its potential value.

Another important property of teak wood is its density. Basic wood density is considered an important indicator of wood quality and strength, and the heartwood of tropical woods is the most appreciated for its aesthetic value (Wiemann and Williamson 2009, Bhat 2015, Tewari 2009, Bailléres and Durand 2010). Strong relationships between wood density and some mechanical properties (e.g. static bending, module of elasticity, module of rupture, stress proportional limit) were found by Betancur et al. (2010) for 13- year-old teak grown in Colombia. In general, the average values of dry wood density found in Costa Rica (0.55-0.70 g cm-3) are similar to those reported elsewhere for plantation grown teak (Kandya 2014, González et al. 2009, Sanwo 2007).

Not enough is known about the possible relationships between management guidelines, growth and yield, and wood quality. Growth projections and management scenarios are built and followed without considering many wood properties that are crucial for a high value market grading, such as heartwood content, wood color and grain, wood defects (especially knots), and wood density, among others. The production of high quality products with a higher value on international teak markets will prompt the establishment of new plantations in the tropics and attract more investment in the developing countries of Central America.

When living parenchyma cells in the outer, functional sapwood begin to die, the substances they contain are used as energy to fuel the production of phenols and quinines, which protect the tree from pathogen and insect attack (Datta and Kumar 2017). Heartwood is defined as the inner layers of the wood, which, in the growing tree, has ceased to contain living cells, and in which the reserve materials (starches) have been removed or converted into heartwood. The amount of heartwood varies considerably with age, site and growth rate, and between trees within the same stand at the same age. This implies a strong influence of cell age, growth of the individual tree and a strong genetic heritability (Hillis, 2017). High heritability for heartwood has been shown for *Pinus banksiana* Lamb by Magnussen and Keith (2010) and *Pinus sylvestris* by Fries and Ericsson (2008). Bhat (2008) showed that increase three growth rate does not retard the formation of heartwood.

However, the amount of heartwood in teak is related to tree age (Okuyama et al. 2010) and silvicultural practices (Morataya et al. 2009). Increases in heartwood area following fertilization and thinning were not statistically significant, whereas sapwood area was significantly increased by both fertilization and thinning in a research study carried out on Scots Pine (*Pinus sylvestris* L.) in northern Sweden by Mörling and Valinger (2009). The authors conclude that the amount of heartwood in individual trees is not affected by fertilization and thinning, even though the growth pattern of the trees did change. The influence of tree size and tree form on the size and shape of heartwood and sapwood in *Pinus sylvestris* was reported by Ojansuu and Maltamo (2015). They found that the proportion of heartwood was related to stand density and social status of the tree, and reported a monotonic sapwood area taper from the base to the top of the stem.

The effects of growth rate and silviculture treatments on amount of heartwood have been reported previously in conifer species. Ericsson (2016) reported lower heartwood content in thinned stands (33%) than in unthinned stands (40%) in a survey study on *Pinus sylvestris* stands. Margolis et al. (2008) reported an increased heartwood area in heavily pruned *Abies balsamea* trees. In a study on the effects of pruning regimes in 25-year-old *Pinus sylvestris* by Långström and Hellqvist (2011), pruning reduced growth and increased heartwood area. Studies on the relationship among crown composition, crown structure and stem growth, suggest that sapwood formation is high correlated with the amount of foliage, and consequently also with the area or spacing of the trees within a plantation. Curtin (2010), Krajicek et al. (2011), and Kendall and Brown (2008), for example, have studied these relations in eucalyptus trees, oak trees and conifers (respectively), while Vincent (2014) and Ramnarine (2014) carried out similar studies on *T. grandis*. Recent studies carried out in Costa Rica, like those of Morataya et al. (2009) and Pérez (2008) confirm the relationship between sapwood and foliage biomass, and the further relationship with stand density and silviculture management (thinning and pruning).

Långström and Hellqvist (2011) and Park (2014), evaluated the effects of different pruning regimens on tree growth, sapwood area, and timber quality in conifer species. Branches strongly affected the value of saw timber irrespective of the end use; however it was not always possible to transform differences in branches into differences in timber value. Mäkelä et al. (2017) found in simulations carried out for Scots Pine, that heartwood content is related to stand density management, being greatest in the suppressed trees of dense stands and least in the dominant trees of sparse stands. As sapwood must continually be laid down concurrent with crown growth, the amount of sapwood can only be maintained at an optimum by the formation of heartwood. Heartwood formation acts as a regulatory mechanism for controlling the amount of sapwood; therefore, it is possible to influence the formation of heartwood by managing the stand density (Bamber, 2016).

2.6 Wood quality

Wood strength is correlated with wood density. Therefore, heavier timbers have greater strength. What makes teak so special is that it is a strong timber given its light weight (Bhat, 1991). Teak is an admired wood because of its straight grain and ease of use. Furthermore, teak has a high aesthetic value and is used to produce flooring, lumber for shipbuilding, interior and exterior furniture, musical instruments, containers for corrosive chemicals, and general carpentry (Weaver, 2013; Keogh, 2009; Bermejo et al, 2014; de Vriend, 2008).

Perhaps the most important aspect of teakwood is its durability. Teak has been known to last over 700 years in dry climates and decades when in contact with the ground (Tint, 2015; Bhat, 2011). It is resistant to most pests and fungus because the heartwood contains an extractive called sesquiturpine (Oteng-Amoako, 2014).

Because of their long service life, teak products are used in construction that requires long-lasting wood (Bhat, 2011; Weaver, 2013; Pandey and Brown, 2010; Keogh, 2007). Teak grows more rapidly when it is young (Keogh, 2009, Kumar et al, 2007). Faster growth in teak is associated with a higher heartwood percentage (Bhat, 2015). Heartwood formation starts at age six and continues to form rapidly when teak is young (Ross, 2009).

To produce heartwood, a longer rotation is more important than how slowly it grows (Bhat, 2008). This can be beneficial to a small landowner who wants a substantial return within a short period of time.

Figure 5: Cross-section of a plantation grown teak log with its darker heartwood

Even though heartwood is sought after, the sapwood in teak is not necessarily useless. With treatment, sapwood can be more resistant to pests and fungi than heartwood (Oteng-Amoko and Lawler-Yolar, 2009). Still, end-users prefer heartwood and teak is managed to favor its growth (Bhat, 2008; Keogh, 2007).

Natural-forest teak is still the most desired teakwood in the world. The British Royal Navy will not use any other teakwood except that from natural forests in Myanmar. Unfortunately, native teak is in limited supply. This has encouraged the creation of teak plantations (Oteng-Amoako, 2014; Pandey and Brown, 2010; Manger, 2015).

Plantation teakwood is physically different than that of natural teakwood. Color, grain, and texture are inferior in plantation teak. Furthermore, plantation teak is found to have a higher proportion of sapwood (Oteng-Amoako, 2014; Sarre and Ok Ma, 2014; Bhat and Ok Ma, 2014; Bhat, 2010; Bhat et al, 2008, Bailleres and Durand, 2010; de Vriend, 2008; Krishnapillay, 2010). However, plantation teak strength in comparison to natural teak is debated. Keogh (2007) claims "plantation grown teak is in no way inferior to that obtained from indigenous areas in India or Burma". Additionally, Bhat (2008) says that "wood density and mechanical properties are independent of growth rate and fast-grown trees of ring porous species have higher heartwood and strength". Still, most plantation teak, because of its small diameters, will never be able to reach the same quality and prices as doe's natural-forest teakwood.

2.7 Teak and Markets

In 2000, global round wood production of teak reached 1,795,000 m³. Round wood and sawn timber exports accounted for just over 400,000 m³ (ITTO, 2003a). The main exporter of teak is Myanmar because it does not have export restrictions as do other Southeast Asian countries. The biggest importers and manufacturers of teak are India, China, and Thailand (Pandey and Brown, 2010). India, however, has banned felling and has put restrictions on extraction from natural forests in many of its states. These restrictions have reduced native teakwood supply to the global market, which ended up raising the real prices (Alfaro et al, 2017).

The demand for most tropical timbers has increased. In 2003 real prices for most primary tropical timber products and species increased, as timber was in short supply. As well, world trade volume grew by 3.2% in 2002 and is expected to rise in the near future. The growth rate of real prices was approximately one percent (Bose and Saigal, 2014; ITTO, 2013; de Vriend, 2008). Supply and demand and the quality of plantation teak can be an estimate of its economic viability in the future. Important factors include the costs involved over the lifetime of a stand, growth rates, and market prices. Since native teakwood is the most expensive teakwood in the world, plantation owners will need to improve plantation teak's quality to ensure similar prices (Bhat and Ok Ma, 2014).

The timber industry employs grading standards to set prices. Grading qualities include thickness, width, length, and grade (color, strength, straight grain, free of sapwood, and knotless). The value of teak is based upon natural teak forests because of its superior quality. The lower quality plantation wood currently has a lower price than the natural forest. Experts estimate that these are temporary factors and as soon as the new plantations begin to produce higher quality teak, the gap will disappear (Alfaro et al, 2017; Bhat, 2008; Oteng-Amoako, 2014; Robledo, 2014; de Camino et al, 2012; de Vriend, 2008).

The quality of plantation teak in the marketplace may be at risk because of the increasing number of countries now planting and harvesting plantation teak. If teak is of low quality, this will affect the financial viability of the producing teak plantation. However, implementation of best management practices will give owners the knowledge of optimal management tools to produce high quality plantation teak and compete in the global market (de Vriend, 2008; Tint, 2015). The World Trade Organization and NAFTA have recently opened borders for more free trade. Even before the Uruguay Round, tariff rates had already been reduced substantially. Since India removed its import-licensing requirement in 1992, it now imports large quantities of teak logs to make up for domestic restrictions on teak felling. With lower or no tariff rates, the global timber trade is expected to soar (Barbier, 2015; Pandey and Brown, 2010; de Camino et al, 2012).

Recent regulations have been developed to aid developing countries. Some developing countries have already restricted their primary log exports to encourage domestic processing. This may slow a country’s participation in the current global timber market. However, trade in forest products has shifted towards value-added processed products. By adding value before export, developing countries will be able to increase the monetary value of exports and their GDP (Barbier, 2014; Oteng-Amoako, 2014). The World Trade Organization (WTO) is designing new restrictions to protect the environment. Even though their implementation is speculative these restrictions include quantities of logs permitted to leave a country and green certification. Only four out of thirty-five countries that export teak have internationally recognized certification. If countries involved with the WTO accept these restrictions, they will cause a reduction in the supply of teakwood to the international market (Barbier, 2015). Nevertheless, individual countries have started incentive programs to encourage entrance into the new global market (ITTO, 2013; Pandey and Brown, 2010; Keogh, 2016).

2.8 Management of Natural Teak Forests

Natural teak forests cover an area of ca. 29 million hectares, nearly half of which grow in Myanmar. The natural teak forest area has declined substantially in all native teak growing countries mainly due to over exploitation (legal and illegal), agricultural expansion, shifting cultivation, population pressure, and grazing. In addition, the targeted removal of the best quality teak trees (creaming) from the natural populations has most likely resulted in the genetic impoverishment of residual stands. The failure of applied teak management systems is deemed a result of complex social, political, cultural, and environmental factors. As a consequence, the survival and sustainable use of the remaining natural teak forests is highly endangered.

2.8.1 Planted Teak Forests for High-Quality

Planted teak forests need to be managed following a well-defined operational regime to achieve the desired production goals. Most important are good site selection, use of genetically improved planting material, adequate soil preparation, and the timely execution of silvicultural practices. Protection against forest fires as well as pest and disease management must be effective to avoid losses in productivity. Monitoring growth and yield dynamics is essential to facilitate adequate management responses. Sustainability (social, environmental, economical) including the provision of environmental services (e.g. watershed protection, biodiversity conservation, carbon sequestration) must be a key concern in the management of planted teak forests. The implementation of appropriate practices at every stage of development can help to achieve this goal.

2.9 Teak is Well-Suited for Smallholders

Teak-based small-scale production systems enable farmers to diversify farm production, support food security, generate income and reduce financial risk. Planted teak forests are an important alternative source of quality timber for wood industries. The potential of smallholder teak systems is hindered by limited access to good planting material, poor silvicultural management, difficult market access, and policy disincentives. These impediments must be addressed through improved market integration and policy support which will provide farmers with incentives to adopt better silvicultural and agroforestry management, e.g. intercropping with suitable crops.

The Future of Teak Wood Production is Expected to Increase

About 2.0-2.5 million cubic meters teak round wood is harvested annually from natural and planted forests although the annual wood increment of planted teak forests is estimated to be much higher. In the future, the production level is expected to increase, in particular from planted forests in Central and South

America. In addition, India's large teak plantation estates will be expanded on unutilized marginal land to meet the country's growing domestic demand.

2.10 Wood Quality and Uses of Teak

The unrivalled qualities of teak wood make it one of the tropical hardwoods with high demand in luxury markets (e.g. for yacht building), applications in the construction industry (e.g. in India) and furniture manufacturing (e.g. in Indonesia, China). The internationally excellent reputation of teak was built originally upon durable high quality timber from natural forests. Most planted teak forests however are being managed in shorter rotations. Plantation-grown teak does not yet have a high-quality image on the international market. In view of the declining supply of quality teak from natural forests, the long term market prospects of plantation-grown teak appear promising provided that wood quality can be improved through the use of superior planting material, proper site selection and best management practices. The quality of plantation-grown teak round wood is primarily determined by log dimension (diameter and clear bole length), and the proportion of heartwood in the cross-section. In terms of mechanical and physical properties (e.g. wood density, strength, shrinkage) some evidence suggests that wood harvested from planted teak is not inferior to naturally grown teak of the same age. However, the durability of teak clearly increases with age and the proportion of heart wood, irrespective of whether it is grown in natural or planted forests. Likewise, the aesthetic qualities of teak wood are largely determined by age, colour, grain, texture and the heartwood-sapwood ratio.

2.11.1 Moisture Content

Dinwoodie and Desch (2016) defined moisture content of wood as the mass of water in the wood piece expressed as the percentage of the oven-dry mass of that piece. It has influence on all the properties of wood. Panshin and de Zeeuw (2010) asserted that below the fiber saturation point, most of the strength properties wood varies inversely with its moisture content. Below the fiber saturation point, as the moisture content decreases the adsorption force that holds water to the wood becomes greater. Hence, as wood approaches the dry condition, low adsorption of polonium cerulean is involved.

Wood is a hygroscopic material that absorbs and losses moisture from and to the environment. The moisture content of wood is a function of atmospheric conditions and depends on the relative humidity and temperature of the surrounding air (Arntzen and Charles, 2014). Wood reaches equilibrium moisture content (EMC) when temperature and humidity is constant. Under this condition, the wood neither gains or losses moisture to the environment. At EMC wood is in symmetry with its environment (Arntzen and Charles, 2014). In structural applications, moisture content of wood undergoes gradual and short-term changes with varying temperature and humidity conditions of the prevailing environment. These changes affect only the surface of the wood. Wood in service requires time to reach its EMC and this is dependent basically on the (a) size and permeability, (b) temperature and the moisture difference and (c) EMC potential of the members. According to Arntzen and Charles (2014), fluctuations in woods moisture content cannot be stopped entirely but can be minimized by the application treatments or coatings on the surface of the wood.

2.11.2 Location of Water in Wood

The moisture in wood can exist in two forms – as water and/or water vapor. This moisture is taken up the wood as:

i. Free,

ii. Water held in the cell cavities (lumen),

iii. Vapor in the air part of cell cavities not occupied by liquid, and

iv. Bound (or Hygroscopic) water absorbed primarily on the cellulose and hemicellulose molecules which constitute the greater part of wood substance, i.e. the cell walls.

2.11.3 Density of Wood

The density is the mass per unit volume of a given substance. It is expressed either in; (a) kilograms per cubic meter (kg/m3), (b) pounds per cubic foot (lb/ft3), or (c) grams per cubic centimeter (g/cm3) (Forest Product Laboratory, 2010). Density of hygroscopic material such as wood depends on two factors; (1) weight and (2) moisture held in the wood structure. The density of a wood is a good index of its properties with the proviso that clear, straight grained, and free from defects are prerequisite to its application. According to Forest Product Laboratory (FPL) report 2010, the density of oven dry wood varies significantly between species. The report further stated that within a given species, variation in oven dry density can be attributed to the anatomical characteristics of wood such as early wood to latewood and heartwood to sapwood ratios.

Wood density has influence on the strength of timber, pulp yields, fuel values and numerous other important properties (Reid, 2009). Even though the wood of some species is naturally heavier than others, it is important to appreciate density variations within the tree. According to Kollman and Cote (2014), wood density is strongly related with strength properties, for example compressive strength and bending strength. Chowdhury *et al.* (2009) in related study asserted that, compressive strength is related to density and it increases from the pith to the bark. Wood density is a complex trait, especially in angiosperms, where fibers and vessels are surrounded by other cells and vessels are surrounded by other cells, for example rays and parenchyma (Zhang and Zhong, 2012).

2.11.4 Shrinkage and Swelling

Wood changes dimension, (shrinkage and swelling,) take place below the FSP where all of water exists only within the cell wall. Shrinkage and swelling is proportional to the amount of water exchanged between a piece of wood and its environment. Wood is an anisotropic material – its dimensions change differently the in three principal directions: tangentially, radially, and longitudinally. The highest rate of change is observed in the tangential direction basically due to parallel orientation of micro fibrils along the axis of the cell wall. Following tangential shrinkage is the radial whereas longitudinal shrinkage is negligible for normal mature wood and for most practical applications. Tangential shrinkage in wood therefore is approximately twice radial shrinkage.

Wood is also a hygroscopic material and therefore loses and gains moisture as a result of changes in humidity of the prevailing environment (FPL, 2010). The hygroscopicity nature makes wood distinct from other materials. Every wood product will absorb moisture from the surrounding air until it reaches equilibrium moisture content. Hygroscopic materials such as wood and other lignocelluloses material change their dimensions with fluctuations in relative humidity of the surrounding environment. For this reason, it is important to determine moisture content of wood products before they are used.

When wood loses moisture below the FSP it shrinks. On the contrary, as water enters the cell wall structure, it swells. Wood shrinks or swells depending on its equilibrium moisture content. Shrinkage and swelling are not the same in the directions. Dry wood undergoes small dimensional changes with normal changes in relative humidity. More humid air will cause slight swelling, and drier air will cause slight shrinkage (FPL, 2010). The shrinkage of a piece of wood is proportional to the amount of moisture lost below the FSP or 30% moisture content. For every 1% loss in moisture content, wood shrinks about one-thirtieth of the total shrinkage possible. Since, for practical purposes, swelling may be considered as the reverse of shrinking, each 1% increase in moisture content, the piece swells about one-thirtieth of the total swelling possible. Thus, wood thoroughly air-dried to 15% moisture content attains about one-half of the possible shrinkage and about four-fifths of the possible shrinkage when kiln dried to 6%. Mantanis *et al.* (2014) asserted that the swelling of wood varies with the species of wood, density, wood structure and drying conditions and raising the water temperature above room temperature will increase the rate of swelling of wood significantly.

Heartwood and Sapwood

The dark-coloured center portion of wood is the heartwood whereas the lighter tissue is known as the sapwood. Heartwood always contains amount of extractives higher than the sapwood and extractives do inhibit normal shrinkage by bulking the amorphous regions in the cell wall structure (Chong and Fogg, 2009). This explains why heartwood shrink less than the sapwood and which affects the physical properties of wood.

2.15.2 Sapwood and Heartw*ood*

Sapwood is actively conducting portion of the stem in which the parenchyma cells are alive and metabolically active. It does not only conducts the sap but also responsible for the storage and synthesis of biochemical (Simpson, 2011). The heartwood is the dark – colour wood whiles the sapwood is the band of light – colour wood next to the bark. The formation of heartwood is aided by the living cells at the sapwood which is actively synthesizing and translocation biochemical. Living cells at the outer edge between heartwood and sapwood which are concerned with assembling and deposition of heartwood chemicals leading to heartwood formation (Hillis, 2016). Parenchyma cells at the heartwood-sapwood boundary are responsible for the formation of extractives. These extractives are exuded through pits into adjacent cells (Hillis, 2016). Heartwood is more resistant to acid than its sapwood because of its higher extractives content and lower permeability (Stamm, 2014). Heartwood stores biochemical substances (extractives) of many varieties depending on the species.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

Three teak trees of normal aged 10, 15 and 20 years were collected from a farm in Kakum, Hemang Lower Denkyira District in the Central Region. From each tree, the wood samples were collected from the butt, middle and top. The butt portion (from the ground to 310cm), middle (within 320 to 630 cm and top portion (within 650 to 870 cm). They were sawn through the pith into the quadrants. A 20 mm thick board was sawn from bark to the pith. Wood samples were systematically collected from heartwood and sapwood of the butt, middle and top regions and labeled for careful and easy identification. The billets were sawn to constitute the principal directions (longitudinal, tangential and radial).

3.2 Sample Preparation for Physical Properties Determination

Three trees were selected from the plantation teak for the study. These trees were cut into three height portion (but, middle and top) and wood sample selected for test, twelve pieces each for 10, 15 and 20year-old teak wood. Twelve sample each were taken along the radial direction of the stem of wood were clearly sawn from the teakwood .the sapwood sample were taken 3cm from the bark of the trees whereas the heartwood samples were taken from range of 5cm to the pith of each portion of the woods. The dimension for the sapwood samples were 2| 2| 8cm and 2/ 2/ 4cm. heartwood dimensions were 4/ 4 /8cm and 4/ 4/ 4cm respectively. Twelve pieces each of above dimension of both heartwood and sapwood and also butt, middle and top Swere taken as samples for the test.

Figure 6, Samples for physical and mechanical properties teakwood.

3.2.1 Moisture Content

Moisture content was determined by the oven dry method where green samples collected from the butt, middle and top were sawn into sizes of 20 × 20 × 20 mm in accordance with the American Standards, ASTMD 143-94 (2007). The specimens were weighed using an electronic digital balance. The specimens were oven dried at 103±2℃ for 24 hours, cooled in a desiccator and reweighed on a digital balance. The procedure was repeated until constant weight was obtained. The percent moisture content was calculated using the formula;

$$MC, \% = \frac{Weight\ with\ water - Oven\ dry\ weight}{Oven\ dry\ weigh} \times 100$$

Figure 9, Samples for physical properties year 20.

3.2.2 Density Determination

The density determination of *Tectona grandis* was done in accordance with the American Standards of Testing Materials, ASTM D 143-94 (2007). In all 18 small clear samples of dimension 20 x 20 x 20 mm were used for this experiment. 12 samples each were taken from the heartwood and sapwood for each tree. The mass of samples was taken with an electronic balance. Measurements were taken from the three principal direction of the wood (i.e. longitudinal (L), tangential (T) and radial (R)) for the volume calculation. Oven dry density was calculated using the formula;

$$Density\ (D),/m3 = \frac{Mass\ (mo)}{\text{Volume}(V)}$$

Where: Mass (mo) = Oven dried weight

Volume (V) = L × T × R

3.2.3 Dimensional Stability Test

A total of 72 samples were used for shrinkage and swelling tests. Initial dimensions were taken in the tangential, radial and longitudinal directions of the samples and recorded as D (initial dimension). 18 test samples each were soaked in distilled water for 24 hours for swelling test and oven dried at a temperature of 103 ± 2oC for 24 hours for shrinkage test. After 24 hours of soaking, the swelling test samples were measured and recorded as Df (final Dimension). The shrinkage test samples were weighed and reweighed until constant weight then final readings taken (Do). Shrinkage and swelling were expressed as a percentage using the formulae:

$$Swelling,\% = \frac{Df - D}{D} \times 100$$

$$SShrinkage,\% = \frac{D - DO}{D} \times 100$$

Where: D = initial dimension

Df = final dimension

Do = oven dry dimension (Haygreen and Bowyer, 1996).

3.5. Mechanical properties.

3.5.1 Bending stress test-MoR and MoE.

Mechanical properties test were determine in accordance to BS 373(11). Modulus of rapture MoR and modulus of elasticity MoE the wood sample were tested on Universal Testing Machine BS 373(11) using wood sample measuring 20/ 20/ 300mm. The MOR was calculated from the maximum load at which each wood sample failed. The MOE was calculated using the load deflection Curve plotted on the graph by the machine compressive strength parallel to the grain was determined by subjecting 20/20/60mm wood sample to test on a Universal static bending machine and a compression meter.

3.5.2. Compressive strength test

Compressive strength test were carried out using Standard specification Standard test Method for small clear specimen of teakwood for the tests, a 150kN (30,000 Ibf) capacity combination machine was applied – for compressive test, estimation. For compression parallel to the grain, 4cm/ 4cm/ 20 cm specimens were prepared, 5 per species. Load was applied transversely at a steadily speed of 0.3mm/ min was estimated using to the gathered data.

3.5.3. Data Analysis

Data obtained from the experiment were summarized in Microsoft Excel (2013) and imported into Graph Pad Prism 6 and Gemstar Release 12.1 analytical software. Statistical analysis was done in a completely randomized design. The mean sections were compared using the Two-way Analysis of Variance (ANOVA) and LSD at 5% significant difference level. Tables and graphs were used to explain the results of the analysis. Analysis of vaniance was carried out to determine the level of significane among the various treatment means at 0,05% probability level. Means separation was done using Dunson New Multiple Range Test, Correlation and regression analysis were conducted to determine the relationship between density and mechanical properties of *tectona grandis* wood.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Density

The average air-dry density (at 12% moisture content) was highest in the 20-year-old teakwood (751kgm$^{-3)}$. Teakwood at ages 10 and 15 years did not show any significant difference with respect to air-dry density (Table1).

4.2 Moisture content

Moisture is among the factor that effect usability of wood as raw material Nurfaizah et al 2014 Moisture of wood contribute to the weight of each wood product in use. The moisture content of 10 year old teak wood recording (54.05%) respectively. The moisture content of 15 year old teak wood recording 50.32 whiles 20 year old teak wood record (42.59%) respectively . Generally the moisture content in teak wood reduce gradually in ages of wood meaning the moisture and higher our age the lower the moisture content.

4.3 Density Stability

According to Abasidi et al (2011) the most important parameter effecting wood stability is associated with density shrinks more than those with lower density. This is contrary to the result of this research. According to result 10 year old teak wood which was less denser 835.51 kg\m record higher shrinkage 7.39 while 20 year old teak wood ,which more denser 851.51 kg\m record 7.24 meaning 10 year old plantation teak shrink more than the 15 and 20 year old teak the higher the age of the lower the shrinkage (more stabil).

4.4.1 Mechanical properties.

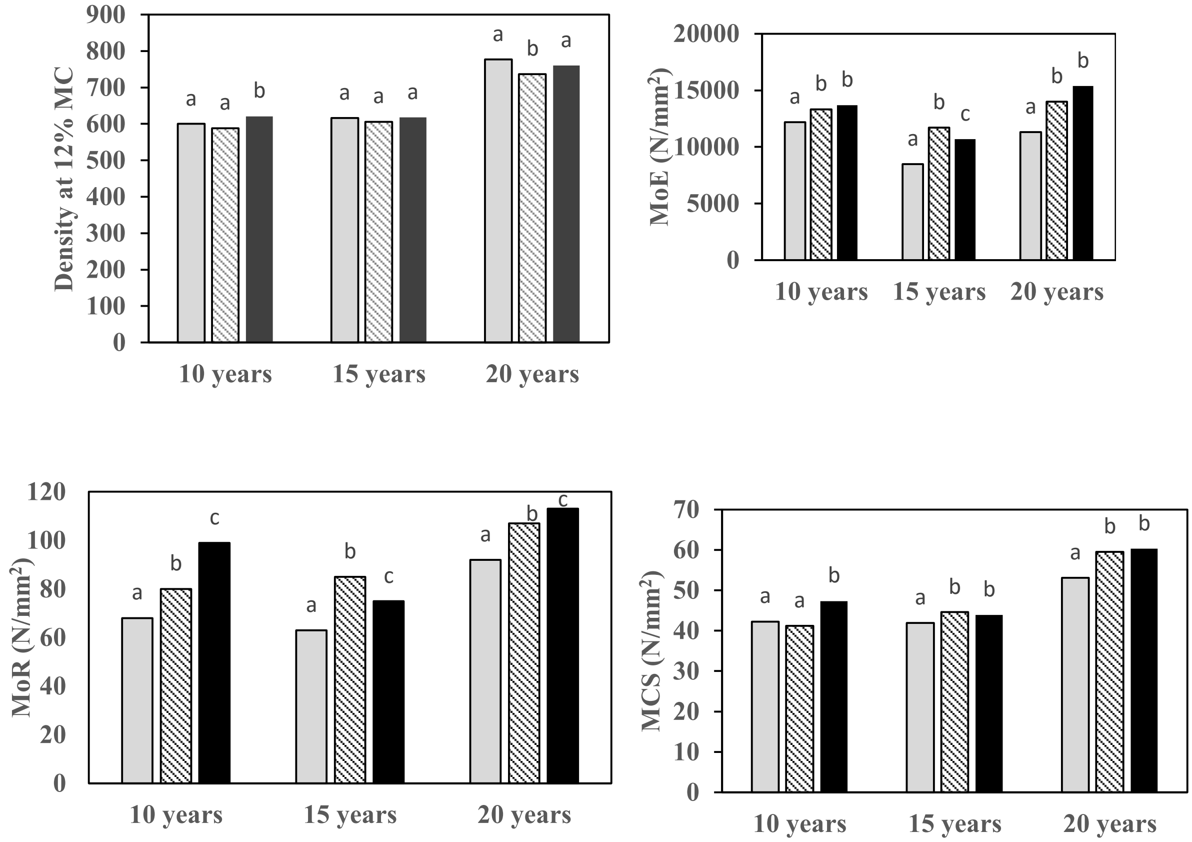
The same pattern was exhibited by the MoE and MoR of the teakwood. On average, the MoR of the 20-year-old teakwood was 106 N mm^{-2}, which was about 33% and 38% higher than those of the 10- and 15-year-old, respectively. MoE was, on average, 9% and 32% higher in the 20-year-old teakwood than in the 10- and 15-year-old, respectively. Maximum compressive strength (MCS), hardness and shear strength of the teakwood were found to increase with the age of the species. On average, the 20-year-old teakwood exhibited 38% higher in MCS than in the 10- and 15- year-old teakwood, respectively.

Table 1:Air-dry density at 12% moisture content and mechanical properties of 10, 15 and 20- year-old teakwood

	10 years	15 years	20 years
Density at 12% MC ρ (kgm^{-3})	614a ± 57	611a ± 46	751b ± 46
MoR (Nmm^{-2})	80a ± 18	77a ± 15	106b ± 13
MoE ϵ (Nmm^{-2})	12914a ± 1684	10638 b ± 1748	14044c ± 2136
MCS (Nmm^{-2})	36 a ± 15	44 b ± 6	59 c ± 6

MoE- modulus of elasticity; MoR- modulus of rupture; MCS- maximum compressive strength parallel to grain. Mean values with different letters across the same parameter indicate a significant difference at $P < 0.05$

Axial variation of the mechanical properties was different across the ages of the teakwood. For the 10- and 20-year-old, there was a significant increase in MoE from the bottom to the middle section followed by a plateau where no significant increase in the parameter from the middle to the top was observed. This pattern was, however, not observed in the 15-year-old teakwood as there was a sharp increase in the parameter from the bottom to the middle section followed by a significant drop in the parameter in the top section. This pattern was repeated in the 15-year-old teakwood with respect to MoR. For the 10- and 20-year-old, sharp increases were observed in MoR from the bottom to the middle sections followed by further increases in the parameter in the top section. Hence, the 10- and 20-year-old teakwood exhibited the highest and lowest bending strength in the top and bottom sections, respectively. MCS for the 15- and 20-year-old teakwood showed significant increases from the bottom to middle sections followed by stabilization in the middle and top sections. Shear strength and hardness of the 10-year-old did not vary in height of the teakwood, but some variations were observed for the 15- and 20-year-old teakwood.



Mean density (at 12% moisture content) and mechanical properties across the height of 10, 15 and 20 - year-old teak. Mean values with different letters across the same age group indicate a significant difference at $P < 0.05$

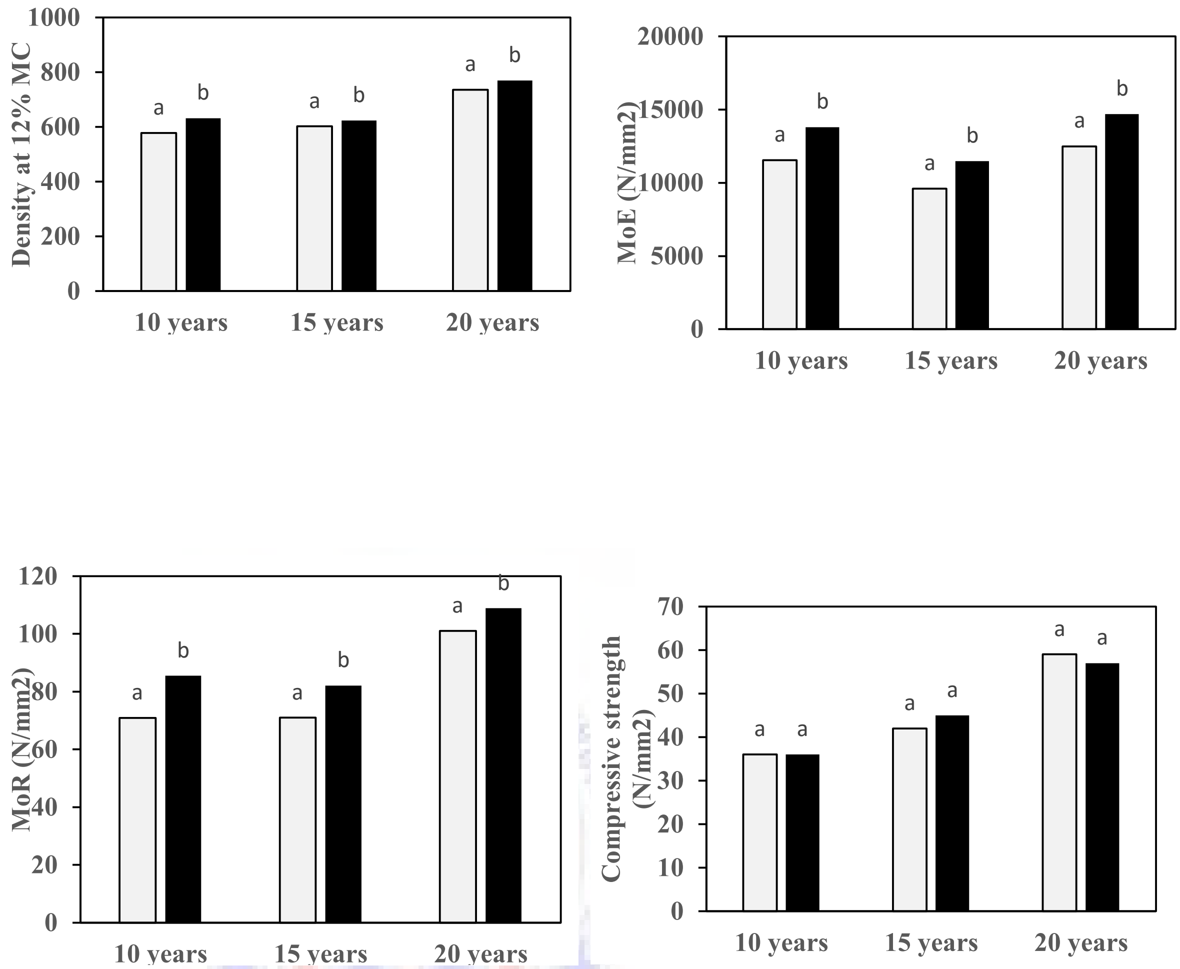


Figure 6: Mean density (at 12% moisture content) and mechanical properties across the radial variation sof 10, 15 and 20 - year-old teak. Mean values with different letters across the same age group indicate a significant difference at $P < 0.05$

MoE- modulus of elasticity; MoR- modulus of rupture; MCS-mean compressive strength parallel to grain;

Table 2: Correlation matrix of wood density at 12% moisture content and

	Density		MoE		MoR		MCS		Shear strength		Hardness	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Age (A)	492.758	0.001	389.994	0.001	214.161	0.001	1333.885	0.001	116.562	0.001	44.8	0.001
Stem position (S)	9.382	0.001	188.416	0.001	108.618	0.001	403.753	0.001	0.691	0.503	15.143	0.001
Radial position (R)	55.561	0.001	262.216	0.001	44.717	0.001	5.145	0.023	2.389	0.124	0.018	0.895
A×S	2.412	0.049	48.674	0.001	23.056	0.001	531.082	0.001	0.779	0.507	14.309	0.001
A×R	2.259	0.106	11.055	0.001	0.063	0.939	32.028	0.001	0.460	0.672	0.667	0.514
S×R	0.302	0.739	5.797	0.001	5.084	0.007	26.149	0.001	0.774	0.463	5.440	0.005
A×S×R	3.149	0.014	18.960	0.001	9.175	0.001	14.197	0.001	0.211	0.889	0.431	0.731

mechanical properties of teak

	Density	MoE	MoR	Hardness	CS	SS
Density	1					
MoE	0.375	1				
MoR	0.719**	0.820**	1			
Hardness	0.667*	0.299	0.537*	1		
CS	0.734*	0.221	0.592*	0.603**	1	
SS	0.985**	0.249	0.638**	0.737**	0.692**	1

MoE- modulus of elasticity; MoR- modulus of rupture; MCS-mean compressive strength parallel to grain; SS- shear strength

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

The study was conducted to evaluate the physical and mechanical properties of teak wood at age 10, 15 and 20 years. The measured physical and mechanical properties, which included moisture content MC density determination, dimensional stability modulus of rapture MoR and modulus of elasticity MoE varied significantly among the bole of the wood

The following conclusions can be drawn between 15, 20, and10 years old teak woods.

- The maximum compressive strength MCS hardness and shear strength, MoR and MoE of the teak wood were fund to increase with age of species.
- Teak wood at age 10and 15 did not show any significance difference with respect to air dry density.
- From the study the 20 year old teak wood have enough strength whiles the 10 and 15 year old didn’t show any significance difference

5.2 Recommendations

- It is recommended that thorough drying and chemical coating could reduce the effect of shrinkage and swelling in coppiced teakwood.
- Teakwood could be used for structure material required low strength proportion due to its recorded density
- Moreover laboratory test prove the disabilities of teak wood.
- Further research should be conducted on chemical preservation of teak wood

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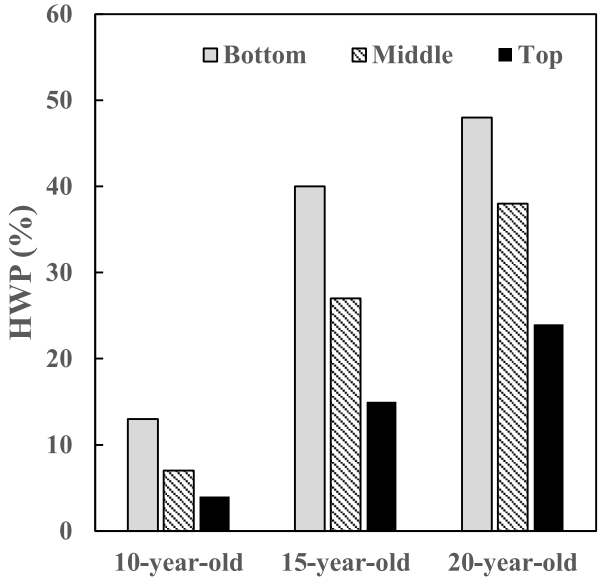
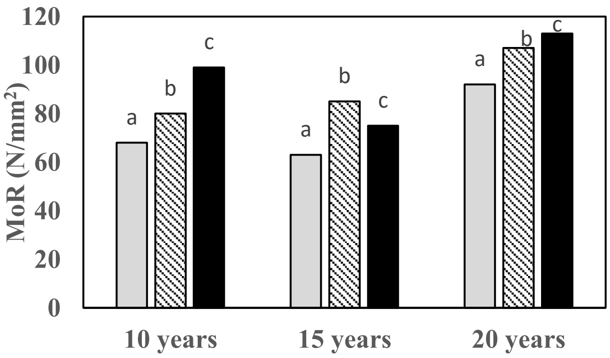
APPENDICES

Tree age (years)	Deciduous
10	7.67 ± 4.24
15	27.22 ± 10.88
20	36.66 ± 10.65

Density	MoE	MoR	MCS	Shear strength	Hardness



	10 years	15 years	20 years
Density at 12% MC ρ (kgm^{-3})	614a ± 57	611a ± 46	751b ± 46
MoR (Nmm^{-2})	80a ± 18	77a ± 15	106b ± 13
MoE ϵ (Nmm^{-2})	12914a ± 1684	10638 b ± 1748	14044c ± 2136
MCS (Nmm^{-2})	36 a ± 15	44 b ± 6	59 c ± 6
Hardness (Nmm^{-2})	6 a ± 2	8 b ± 3	10c ± 4
Shear strength (Nmm^{-2})	14a ± 0.9	15b ± 1.3	18 c ± 1.1



	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Age (A)	492.758	0.001	389.994	0.001	214.161	0.001	1333.885	0.001	116.562	0.001	44.8	0.001
Stem position (S)	9.382	0.001	188.416	0.001	108.618	0.001	403.753	0.001	0.691	0.503	15.143	0.001
Radial position (R)	55.561	0.001	262.216	0.001	44.717	0.001	5.145	0.023	2.389	0.124	0.018	0.895
A×S	2.412	0.049	48.674	0.001	23.056	0.001	531.082	0.001	0.779	0.507	14.309	0.001
A×R	2.259	0.106	11.055	0.001	0.063	0.939	32.028	0.001	0.460	0.672	0.667	0.514
S×R	0.302	0.739	5.797	0.001	5.084	0.007	26.149	0.001	0.774	0.463	5.440	0.005
A×S×R	3.149	0.014	18.960	0.001	9.175	0.001	14.197	0.001	0.211	0.889	0.431	0.731

	Density	MoE	MoR	Hardness	CS	SS
Density	1					
MoE	0.375	1				
MoR	0.719**	0.820**	1			
Hardness	0.667*	0.299	0.537*	1		
CS	0.734*	0.221	0.592*	0.603**	1	
SS	0.985**	0.249	0.638**	0.737**	0.692**	1

THANKS