UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNICAL EDUCATION, KUMASI

ASSESSING AXIAL VARIATION OF SOME PHYSICAL, ANATOMICAL AND MECHANICAL PROPERTIES OF 10, 15 AND 20-YEAR-OLD TEAK (*TECTONA GRANDIS)* WOOD.

INYONG STEPHEN

MARCH, 2019

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A Dissertation Submitted to the Department of WOOD SCIENCE AND CONSTRUCTION TECHNOLOGY, Faculty of TECHNICAL EDUCATION, Submitted to the School of Graduate Studies, in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Philosophy (Wood Science and Technology) in the University of Education, Winneba

MARCH, 2018

DECLARATION

STUDENT’S DECLARATION

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

Signature: ....

Date: ....

SUPERVISOR’S DECLARATION

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

Name: PROF. MARTIN AMOAH

Signature: ....

Date: ....

DEDICATION

I dedicate this dissertation to Almighty God for his protection throughout the programme, my dear wife Mrs. Yuose Anne and my children, Wisdom Saanumoh, Theophillous Naagmenkuma and Tiersu Micheal for their prayer support.

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ABSTRACT

The wood industries in Ghana have been using teak wood harvested from different rotation ages ranging from 10 to 50 years. The optimal age of teak used for various wood productions is not known. The aim of this research was to assess selected physical, anatomical and mechanical properties of plantation teak of different ages (10, 15 and 20-years) grown in the guinea savanna ecological zone in Ghana. Same samples species were used for determination basic density, air dry density, oven dry density and the mechanical properties. Mechanical strength test samples were prepared and tested in accordance with the British standard (BS373: 1957). The range of mean strength values were as follows: Modulus of Rupture; 73N/mm^2, 71N/mm^2 and 80N/mm^{2}for the 10, 15 and 20-year-old teak respectively. Modulus of Elasticity respectively values were 10404N/mm^2, 9433N/mm^2 and10017 N/mm^2 Compression parallel to grain were 49, 54 and 52N/mm^2 respectively and shear parallel to grain: 16, 15 and 14N/mm^2 respectively. The relationship between teak wood properties and age of trees was not apparent. This suggests that other factors may influence the wood properties of teak trees. In general wood properties of young teak 10 and 15-years were not inferior to the ones from older plantation 20-years. Based on their physical wood properties, 10 and 15-year-old teak can be acceptable for wood production. The fibre length varies between the ages of the teakwood, ranging between 0.77µm for the 20-year-old and 0.913 µm for the 15-year-old. . MoE correlated positively and significantly with fibre width ($r = 0.48$, $p< 0.05$ and double wall thickness ($r = 0.50$, $p< 0.05$). Unexpectedly, both air dry density and basic density correlated positive with MoE and MoR.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Teak *(Tectona grandis)* grows naturally in Southeast Asia and is an important timber species due to its highly durable wood that is appreciable to a wide range of noble end-uses, e.g., carpentry, boat construction and outdoor equipment (Keogh 2013). For these reasons, teak was introduced into Latin America, Australia and Africa and is now one of the main tropical plantation species in the world (Bhat & Indira. 2005). *T. grandis* plantations occur naturally in parts of India, Myanmar, Lao PDR, Thailand, and it is naturalized in Java, where it was probably introduced some 400-600 years ago (Troup 1921, Kadambi 1972, White 1991).

The tree (teak) has been widely established in plantations as an exotic species for producing high quality poles and timber outside the countries of its natural existence. The earliest plantation of teak, apart from Java, has been traced back to the 1680s when a Dutchman, Van Rhede successfully introduced the tree to Sri Lanka. Teak planting in India began in the1840s but major planting took off from 1865 onwards. In Myanmar and Indonesia, teak plantations using the "taungya" method were initiated in 1856 and around 1880 respectively. Early introduction of teak outside Asia was first made in Nigeria, from Indian origin in 1902 and Burmese origin. As the demand for teakwood continues to increase, there is a tendency to increase the utilization of plantation-grown timber of relatively short rotations of 20-30 years (Pandey and Brown 2001). Teak has been successfully established as an exotic species in many countries, e.g. Sri Lanka, Bangladesh and China in Asia;

Ghana, Nigeria, Ivory Coast, Senegal, Togo and Benin in West Africa; Sudan and Tanzania in East Africa; Trinidad, Puerto Rico and Panama in Central America; Brazil and Ecuador in South America Keogh R (2009); Hougs, unpublished data). Perhaps the first pure teak plantation in Tropical America was established in Trinidad in 1913 (Keogh 1979) with seed from Burma. Planting of teak in Honduras, Panama and Costa Rica started between 1927-29.

Reliable area statistics on the historical progress made in Teak plantation are incomplete, but it appears that the major area under teak plantation of about 0.31 million ha, was in Java (Indonesia). The estimated planted area for this species is 4.35 million ha in 52 different countries (Kollert and Cherubini, 2012). The highest proportion area planted in Asia with 83% followed by Africa with 11%, and 6% in tropical America.

Teak wood represents a small proportion of the timber and contributes to less than 2% to the total global log market (FAO, 2005). To even meet this, contribution plantation teak has been harvested in cycles varying from 15 to 30 years, contrary to the conventional long rotation concept of over 70 years. The result is a wood with a large proportion of juvenile wood, which may be undesirable for some applications, because it may be less durable when compared to natural forest teak trees (Moya and Marın 2011). The wood also is prized mostly for its natural durability and high dimensional stability in association with pleasant aesthetics. Some end-user requirements include high heartwood content (at least 85%) wood density (> 675 kg/m3) and sufficient strength [modulus of rupture (MoR> 135N/mm^2) (Bhat 1998). Historical review of teak in Ghana indicates that Teak plantation was established in the period 1940–1950 and then left without forest management and thus were prone to bush fires, felling for fuel wood by local communities and illegal timber logging. Forest including teak ones is considered one of the strong drivers of economic developments on account of the accruals from source of the wood for them.

Age is a major factor that can affect the strength of teak wood. This appears to have been proven by researchers using teak form different origins. e.g., India, Togo, Costa Rica, Ivory Coast, and Panama. The chemical composition and the general wood properties are recommending for the wood high quality construction/ structural works. Industrial plantations of teak have been projected to cover about 45,000 ha in order to supplement wood supply in the world, as well as to safeguard the depletion of biodiversity resources of the natural forest (Dreschel and Zech, 1994).

1.2 The Statement of the Problem

Teak (*tectona grandis*) was introduced in Ghana in the early 1930s and has since been acclimatized well now and adapted for industrial plantations and small woodlots. Large plantations development of teak in Ghana started in the late 1960s under the plantation development programme which was initiated by the United Nations Reforestation Programme (Prah, 1994). These industrial plantations of teak were projected to cover about 45,000 ha and were to supplement wood supply as well as to safeguard the depletion of biodiversity resources of the natural forest (Dreschel and Zech, 1994).

Teak was chosen over other timber species probably because it gives good and durable hardwood, hence used for wide range of furniture and construction works. The poles are extensively used as cable support for the transmission of electricity and telegraphic waves. The tree is also valued by small-scale farmers and local communities as good poles for fencing and making of rafters. It is often used as fuel wood, and stakes on yam farms. Its leaves are also believed to have medicinal value, hence planted around villages and several communities (FAO and UNEP, 1981).

In the Savannah Zone (SZ) and Dry Semi-Deciduous Forest Zone (DFSZ) however, a large number of exotic species were tried from 1951 to supply timber, poles and fuel wood. Species that showed promise included *Azadirachtaindica, Senna siamea, Cedrelamexicana, Dalbergia sissoo, Gmelina arborea,* and *T. grandis*. Foli et al, 1997) between 1927 and 1990, over 150 tree species were assessed in research trials in various ecological zones in the country. Out of these, about 30 species (20%) were indigenous (Foli et al., 1997). These were undertaken mainly through the Taungya system. Existing government forest plantations established prior to the implementation of the National Forest Plantations Development Programme in 2002 cover an area of 19,378.26 ha in the High Forest Zone. Over 70% of these plantations consist of *T. grandis* (Teak). Forest plantations in Northern Ghana (Upper East, Upper West and Northern Regions) are estimated to cover 2,553 ha and were primarily established for fuel wood production, environmental protection and furniture production. Tree species planted include Teak, *Gmelina, Anogeissusand Eucalyptus*. It is projected that 75% of the cropland area (i.e. approximately 4 million ha) across the high forest, transition and Savannah zones will be targeted for trees-on-farms/farm boundary planting/climate smart agriculture by 2040, (Ghana Forest Plantation Strategy; 2016).

In India, Jha (1999) it was reported that teak rotation at 20 years gave the highest return if investment as well as acceptable wood quality. (Perez 2008) Bhat and Priya (2004) reported that teak rotation age was prevalent at 35 years, while the traditional teak plantation rotation was previously 50 years or more. They reported that wood density, dimensional stability and strength properties of 35 and 50-year-old teak were not significantly different. However, there were no scientific figures supporting their statement. Due to the limited number of studies on the properties of teak relative to age, the present study aim to assess some selected physical, anatomical and mechanical properties of plantation teak of different ages (10, 15 and 20 years) grown in guinea savanna ecological zone (Sawla- Tuna- Kalba District)of Ghana.

1.3 Objectives

1.3.1 General objective

The main purpose of the study was to evaluate the axial variation of some physical, anatomical and mechanical properties of *T. grandis* trees of different ages in order to ascertain a specific age teak tree can be harvested and best utilize.

1.3.2 Specific objectives

1. To compare the axial variation in physical properties (MC, basic density green density, air dry density and oven dry density) of *T. grandis* trees of ages 10, 15 and 20 years.
2. To investigate the axial variation of mechanical properties (static bending, compressive strength parallel to grain and shear strength parallel to grain) of *T. grandis* of different ages.

3. To evaluate the influence of anatomical properties on the physical and mechanical properties (fibre biometry and wood tissues proportion) of *T. grandis*.

1.4 Significance of the Study

The significance of the research includes the following:

i. Findings of the study will draw the attention of the users of the *T. grandis*, to the most appropriate ages that this tree can be converted for use with respect to its physical and mechanical properties.

ii. Will aid the use of *T. grandis* practically, by showing which section of the tree, axial or radial, is appropriate for what specific use.

iii. The wood users to know the optimum density with respect to age.

CHAPTER TWO

LITERATURE REVIEW

2.1 Brief Description of Teak (*Tectona grandis*)

Teak (*Tectona grandis*) is one of the tropical hardwood species from the family verbenaceae. It is an important timber species with worldwide reputation (Banik, 1993). *T. grandis* grows naturally in Southeast Asia and is an important timber species due to its highly durable wood that is appreciated for a wide range of noble end-uses, e.g., carpentry, boat construction and outdoor equipment (Keogh 2013). For these reasons, teak was introduced into Latin America, Australia and is no Central America, the Pacific, Africa and the Caribbean Islands and thus has become one of the main tropical plantation species in the world (Bhat, 2005). Teak tree can grow to a height of 30 – 40m. It has fluted bole and sometimes possess slight buttress (Keay, 1989). Teak is the one of the fast-grown tree species. Though fast growth is associated with the products of less quality wood Bhat and Indira (1997) concluded that fast growth is not always associated with inferior quality, and that some juvenile and mature wood have similar dimensional stability (Bhat et al.2001). It is known that the technological qualities of teak are mostly obtain from its heartwood due to its esthetic characteristics and durability due to high content of extractives. (Miranda et al. 2011). The color in heartwood however depends on the environmental conditions (Moya & Calvo-Alvarado 2012).

Teak can grow up to an age of 100 years and above. It sheds its leaves annually as part of its life cycle. Its high world-wide demand is attributed to its high-quality timber on account of the attractiveness and sturdiness of the wood it produces (Sarre and Ok-ma, 2004). The tree has a straight trunk, thick base, a spreading crown, and four-sided branches. The leaves are rough in texture, are opposite or whorled, and every branch ends in many small white flowers. The heartwood is golden – yellow in colour, has a pleasant and strong aromatic fragrance. Its beautiful dark brown colour is molted with darker streaks when seasoned and this makes it more beautiful.

2.2 Teak wood as a structural Material

Wood is heterogeneous conglomeration of large numbers of very small elements of cells (Brown, 1988). The cavities of these cells in a dry condition are at least, largely occupied by air (Jane, 1956). According to Brown (1998), wood is basically a porous mass of tube-like material held together by amorphous molecules of lignin and depending upon species and types, containing various chemicals, minerals, gum and silica. It is extremely complex substance whose versatility is unparalleled by any other material (Panshin et al; 1964).

The durability of Teak products is sometime attributed to 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 is not brittle due to its anti-bacterial characteristics. General Machining of teak wood is relatively straight forward. Boring, gluing, moulding, nailing, planning, sawing, veneering, and turning do not posed major problems (Keogh et al., 2001). These working properties with *T. grandis* has be numerous end uses in structures including furniture making ship building, and marine construction. Its high resistance to chemicals also makes it ideal for laboratory benches.

The wood is also ideal for constructional works that are likely to be exposed to the weather e.g. Doors frames, window frames, garden furniture etc. (Keogh et al., 2001).

T. grandis wood, is usually certified on the basis of social and environmental practices throughout its entire forest and wood chain, and 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 the tropics from now and into the foreseeable future. However adequate information on their strength properties is required for maximum utilization especially those from off reserve areas (Keogh et al., 2001).

2.3 Wood as a Structural Material

Eaton and Hale (1993) have said that throughout the course of history wood has remained one of the most important natural resources available to man and is found in every area of modern existence. Wood is a structurally sound material and compares favorably with concrete, steel, stone, and a variety of other products or materials. Wood in its natural state can be used for many forms of construction (Jayanetti, 1999). As a construction material, wood is strong, light, durable, and flexible and easy to work with. In contrast to some of the substitutes for wood such as brick, metal, concrete and plastics, for structural purposes wood is renewable and can be produced and transported with little energy consumed and the products are renewed (Madson, 2004).

According to Eaton & Hale (1993), the properties of solid wood and the structural durability of certain species of timber have provided man with a material, which has performed many functions including its use as a building material for shelter et al,(1982).

also noted that in the North America during the 1970s, more wood products were used for construction than all other materials combined. Furthermore, the world consumption of timber alone is equal to the world's annual production of steel and iron.

2.4 The Physical Properties of Wood

There are a number of physical properties of wood that also affect the strength of timber and, can lead to different results being obtained from different specimens of the same species (Taylor, 1991).

2.4.1 Moisture Content

Dinwoodie and Desch (1996) defined moisture content (mc) of wood as the amount of water present in the wood which can be expressed as the percentage of the oven-dry mass of the piece of wood. Moisture content has influence on all other properties of wood. Panshin and de Zeeuw (1980) asserted that below the fiber saturation point, most of the strength properties wood varies inversely with its moisture content.

The water distribution in trees depends on both the wood species and the environmental conditions. The moisture content is either distributed equally in the whole log or significant moisture gradients can exist in radial or longitudinal direction. Besides the moister differences in a single log, there can also be significant differences of moister content and distribution in different logs of the same wood species at the growing conditions (Reed et al, 1995). Water is needed primarily in trees for the transportation of nutrients and minerals. Water in wood is contained in the cell walls and cavities of the various wood cells. The water in the cavities is called bound water due to the strong bonds caused by chemical and physical binding forces (Reed, 1995) at the moisture content between 0 and 6%, water is bounded by chemical-sportive manner, between 6 and 15% the bound is by different types of adsorption forces, and between 15 and 30% the bound is by capillary condensation. The range in which the cell walls of wood fibers are saturated and free water is removed is termed the fiber saturation point (FSP). The numerical value of fiber saturation point depends not only on the wood species but also on the wood temperature and can therefore range between 22 to 36%. Blow fiber saturation point, shrinkage or swelling occurs and leading to the increasing or reduction in cohesion and stiffness (Kollman and Cote, 1984).

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 environment and depends on the relative humidity and temperature of the surrounding air (Arntzen& Charles, 1994). Under this condition, the wood neither gains or losses moisture to the environment. EMC wood is in symmetry with its environment in terms of moisture level.

(Arntzen& Charles, 1994). In structural applications, moisture content of wood undergoes gradual and short-term changes with varying temperature and humidity 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) permeability, (b) temperature and the moisture differences and (c) EMC potential of the members. According to Arntzen and Charles (1994), disparities in wood moisture content cannot be stopped entirely but can be minimized by the application of treatments or surface coatings of the wood.

2.4.2 Fibre Saturation Point

In drying of wood, the 'free' water evaporates first, followed by the bound water. The condition existing when all the free water has been evaporated and the cell walls are still completely saturated is termed the fibre saturated point (FSP). It usually occurs at moisture contents between 25 – 30 %. It varies with different wood species and within individual wood pieces. The variation is caused by differences in the chemical composition, crystallinity of the cellulose, compactness of the cell wall, specific gravity and extractive content. The moisture content corresponding to the FSP varies with temperature also, decreasing as temperature increases. It is also affected by prolonged exposure of wood to high temperatures which results in a permanently reduced FSP.

The condition of wood at FSP is associated with maximum swollen volume of the cell wall and with major changes in the physical behavior of wood, and hence is of primary importance. Shrinkage is normally defined as the reduction in size which occurs when wood dries from the condition down below the fiber saturation point. Below the FSP most properties are negatively correlated with moisture content. Below the FSP wood exhibits improved electrical resistance, resistance to decay, better gluing characteristics, nail-holding power, and a continued reduction in density. Values of FSP are determined by procedures that include:

i. Extrapolation to 100% relative humidity of sorption data on equilibrium moisture content,

ii. Observation of shrinkage initiation with loss of moisture, and

iii. Analysis by the polymer exclusion technique (Stamm, 1971).

2.4.2.1 Shrinkage and Swelling

Wood changes in dimension, (shrinkage and swelling,) take place below the FSP where all 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 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 the radial shrinkage. Generally, shrinkage and swelling is expressed as percentage and can be calculated using the formula: $hrinkageorSwelling$, % = $Change\ in\ dimension\ or\ volume\ Initial\ dimension\ or\ volume$ ×100.

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 lignocellulose 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. (1994) 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.

2.4.2.2 Effect of Grain Direction on Shrinkage

Wood is not homogenous material with equal shrinkage in all directions. Its anatomical structure results in shrinkage behavior which varies between the different structural axes of the wood. The bound water responsible for the shrinking and swelling is attached to sites of cellulose chains, since most of the cellulose chains are inclined at 10^0 to15^0 from the vertical axis, any dimensional change due to loss of moisture will primarily be across the grain (i.e. Transverse shrinkage/swelling is much higher) with only a very small component in the longitudinal direction. In normal wood, longitudinal shrinkage SL is only 0.1 to 0.3%, and is therefore negligible for practical purposes. Shrinkage in tangential plane (aligned with the growth rings) is about 1.4 to 2.0 times that in the radial plane (on a radius). Total radial shrinkage SR ranges from about 3 to 6% and tangential shrinkage ST from 6 to 12% for some Ghanaian species (Ofori et al 2009).

2.5 Basic Density of Wood

Wood density is an important property for both solid wood and fibre products in both conifers and hardwood Panshin and de Zeeuw (1980) reported that density is the general indicator of cell size and is good predictor of strength, stiffness, ease of drying, machining, hardness and various paper making properties. Brazier and Howell (1979) also expressed their opinion that density is the most important property that influences the use of timber. They emphasized that it affects the technical performance of the wood in particular the strength and processing behavior of the sawn wood, veneer and fibre in pulp production. Crown (1992) reported that density of wood is recognized as the key factor influencing wood strength. Indeed, according to Schniewind (1989) much of the variation in wood strength, both between and within species, can be attributed to differences in wood density. Research has shown that higher density species tend to have stronger timber than lower density species (Tsehaye et al., 1995b)

2. 5.1 Density variations within a tree.

Density within a tree varies from pith to the bark and with height in the stem. Wood density varies from early wood to latewood tissue within each annual ring. Latewood tissue is composed of cells of relatively small radial diameter with a thick wall and a small lumen and therefore, has a higher density than thin walled early wood cells with a larger cell lumen (Haygreen and Bowyer, 1996). In many conifer trees, the basic density of the latewood is more than twice the early wood, thus increase in the proportion of latewood leads to an increase in whole ring basic density (Ward, 1975; Elliot 1970). The relative densities of the early wood and latewood within a tree are strongly correlated (Gladstone et al., 1970). Usually a tree with high density early wood will also have high density latewood (Zohel and Jett, 1995).

2.5.2 Density variation between species.

Each tree has its own characteristic of wood density (O, Sullivan, 1976). Density variation between species is basically due to differences in anatomical structure. Species differ with regard to cell types and distribution of the cells within the wood. Also, the differences in the concentration of extractives and the chemical composition of cell walls may influence density. It should be noted, however, that wood of different species does not always differ in density (Tsoumis, 19992).

2.5.3 Density on strength

Wood is highly anisotropic in its strength; it has different properties in longitudinal and tangential directions. This is due to its cellular structure and the physical organization of the cellulose chain molecules within the cell walls (Schniewind, 1989). The existence of a linear relationship between wood density and strength has been demonstrated by several investigators (Sullivan, 19976). Similarly, it has been found that within the range of specific gravity found in most species, an approximately linear relationship exists between the strength and specific gravity.

2.5.4 Environmental impact on density

Wood density is influence by the environment, which determines the rate of growth. The density of wood is known to decrease in response to increased growth rate (savill and Sandels, 1983). This decrease in density has been recorded in the juvenile wood of fast grown species. Mitchell and Denne (1997) found that on site where Sitka spruce stands were fast growing, wood density decreased more rapidly across the juvenile wood, down to a lower minimum value, than on sites where Sitka spruce stands were slower growing. The growing rate also influence the extend of juvenile core and the proportion of the stem it comprises. In fast grown trees cultivated on a short rotation, a larger proportion of stem it comprises juvenile wood. Tree from shorter rotations have lower density, because the proportion of low-density juvenile wood is higher (Zobel and Jett, 1995)

2.5.5 Measurements of Wood Density

Radiation densitometry is a commonly used technique for assessing density characteristic of wood samples. Direct measurement of the intensity of the radiation passing though the sample enables wood density variations to be recorded automatically (Crown and Clement, 1983). X-ray densitometry is also used to give an optical radiographic reading of wood density but does not give and actual reading value.

Other methods of measuring wood density include the water immersion method. This method determines the volume of the wood sample by measuring its buoyancy i.e. the difference between the absolute weight of the specimen and its weight when submerged in water. This method is also known as the direct method. Another water- based method involves soaking the wood samples before immersion in water. This method determines the volume of the wood sample by measuring the increase in weight of a container of water when the wood sample is submerged in it. A variation of this method involves using mercury instead of water as the displacement medium (O, Sulivan, 1976). There is also an oven-dry method. In using, this method a 25 mm cross section is cut and oven-dried at 103 ±2^{o}c until weight equilibrium is achieved. The volume of the cross section is determined from physical dimension measurements (Evertsen, 1988). Formula for determine Oven dried, Oven dry weight = Amount of moisture/ oven dry weight x 100.

2.5.6 Studies on basic density of *T. grandis*

The density is expressed either in; (a) kilograms per cubic meter (kg/m^3), (b) pounds per cubic foot (lb/ft3), or (c) grams per cubic centimeter (g/cm^3) (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 provision that clear, straight grained, and free from defects are prerequisite to its application.

According to Forest Product Laboratory (FPL) (2010). Reported 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 (1984), wood density is strongly related to its 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 such rays and axial parenchyma (Zhang and Zhong, 1992).

2.6 Wood cells and microfibreils

The wallsof wood cells are made up of the primary wall and the secondary wall. The secondary wall is composed of three layers, S1, S2 and S3. The S1 layer is closer to the middle lamella, while the S3 layer is the layer closer to the cell lumen. The walls of wood cells are made up of three main substances. These are cellulose, hemicellulose and lignin (Buttrefield and Meylan, 1980). Cellulose is laid down in the cell walls in the form of microfibrils (Haygreen and Bowyer, 1996).

Among the three layers in the secondary cell wall, the S2 layer is the thickest and therefore, the most important (Tsoumis, 1992). Haygreen and Bowyer (1996) also reported that because the S2layer is much thicker than the S1 or S3 layer, it has the greatest effect on how the cell behaves. Microfibrils are the structural units of plant cell walls. Each microfibril contains a number of cellulose chain molecules bundled together, and is surrounded by low molecular weight hemicelluloses (Tsoumis, 1992). The hemicellulose act as connecting agent that link or bond the microfibrils together (Haygreen and Bowyer, 1996). The cellulose chain molecules are generally arranged lengthwise with regard to the microfibril axis, but run parallel to each other in positions. These sections are called crystalline regions. The molecules in these regions are strongly connected to each other by hydrogen bonding. The crystalline regions are followed by amorphous regions in which the cellulose molecules have no definite arrangement. The transition from crystalline to amorphous region is gradual.

Approximately two thirds of the cellulose in the cell wall is crystalline in form while one third is amorphous (Tsoumis, 1992). Microfibrils vary in width from 1µm in primary walls to 10µm in the secondary walls (Zobel and Jett, 1995). The angle that the cellulose microfibrils make to the axis of the cell wall is known as microfibril angle. Microfibrils are present in each of the cell wall layers (Butterfield and Meylan, 1980).

2.6.1 Impact of microfibril angle on wood quality

The microfibril angle (MFA) of the S2 layer in the cell wall is known to be one of the main determinants of the mechanical properties of the wood including the modulus of elasticity (MoE) and shrinkage anisotropy (longitudinal and tangential shrinkage) (Donaldson, 1996). Watson and Dadswall (1964) reported that the microfibril angle also had a significant impact on paper properties. Small micrifibril angles were associated with high tensile strength in paper, while large microfibril angle were associated with larger stretch and tear indices. The microfibril angle is known to be inversely related to fibres length, with longer fibres having smaller angles (Donaldson, 1993).

2.6.2 Microfibril angle and wood stiffness

The stiffness of wood arises from its cellulose content and the way this cellulose is distributed within the cell wall (Cave and Walker, 1994). Cave and Walker (1994) reported that the only known physical characteristic of wood capable of effecting large changes in the stiffness of wood is the cellulose microfibril angle in the S2 layer of the fibre cell wall. Meyline and Probine (1969) also reported that the microfibril angle in the S2 layer of the fibres cell wall is a principal predictor of timber quality, with density behaving as an additional variable. In an experiment carried out by Cowdrey and Preston (1966) a six-fold increase in stiffness in the early wood of Sitka spruce was observed as the microfibril angle decreased from 40^0 to 10^0.

2.6.3 Microfibril angle, density and strength

Harris and Meylan (1965) found that wood density and fibre length varied independently between trees. As a result, a strong correlation between wood density and microfibril angle, or wood density and strength should not be expected. At the same time, microfibril angle is known to interact with density and may also interact with spiral grain, to influence the strength and stiffness of clear wood (Donaldson and Burdon, 1995). The shorter cell lengths observed in fast grown conifers imply lower tensile strength (Senft et al, 1985).

2.7 Strength Properties

Wood may be described as an orthotropic material and for that matter, has unique and independent mechanical properties in the direction of three mutually perpendicular axes, longitudinal, tangential and radial. Mechanical properties must commonly be measured and represented as strength properties for the design including modulus of rupture in bending, modulus of elasticity parallel to grain, compressive stress parallel and perpendicular to grain, and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain and hardness. Strength properties commonly measured in clear wood include torsion, toughness, rolling shear and fracture toughness. Other properties involving time under load include creep, creep rupture or duration of load and fatigue.

The size of the test sample to be used is normally determined by the type of information required and the test protocol or standard to be used. In the early days the use of small clear test specimens was used for the derivation of working stresses for timber. However, since the mid-1970s this size of test pieces had been superseded by structural –size timber. However, the small clear test piece still remains valid for characterizing new timber and for the strict academic comparison of wood from different trees or from different species. The use of structural- size test pieces reproduce actual service loading condition and they are of particular value because they allow for defects such as knots, splits and distorted grain, which affect the strength of wood. However, the use of large pieces is more costly (Dinwoodie, 2000).

To design with any material, mechanical strength properties estimates need to be determined. America Standard for Testing Materials (ASTM) and European standards test methods has procedures that require the determination of mechanical properties via stress-strain relationships. Flexural (bending) properties are important in wood design. Many structural designs recognize either bending strength or some function of bending, such as deflection, as the limiting design criterion. Structural examples in which bending-type stresses are often the limiting consideration are bridges or bookshelves.

Under service conditions timber often has to with stand-imposed load for many years, perhaps even centuries. Timber does not behave in a truly elastic mode; rather its behavior is time dependent. The magnitude of the strain is influenced by a wide range of factors. Some of this are property dependent, such as density of the timber, angle of grain relative to direction of load application and angle of the microfibrils within the cell wall. Others are environmentally dependent, such as temperature and relative humidity (Dinwoodis, 2000).

2.7.1 Methods of determining strength properties

The determination of strength properties of wood predicting the performance of materials in service. Two distinctly different methods are in use to characterize the properties of wood. These are small, clear defect-free specimens and test on timber and structural sizes (Bodig and Janyne, 1982). Only the former method is considered.

2.7.2 Test of small specimens of wood

This method is valid for characterizing new timber and for strict academic comparison of wood from different species. The method utilizes in a standardized procedure small, clear, straight-grained species of wood, which represent maximum quality that can be obtained. As such, the test specimens are not representative of timber actually being used without the application of a number of reducing factors. However, the method does afford the directional comparison of wood from different species (Dinwoodie and Desch, 1996)

2.7.3 Variability of strength properties of wood

The strength properties of wood species are known to vary widely. Some indication of the spread of property value is therefore desirable (Green et al; 1999).Ideally, the weakest strength value for the species should be used, but in practice the characteristic strength is given. The European standard EN 12511 (CEN, 2002) for determining the characteristics value uses 5% point of exclusion for the mean bending strength of the test specimens. For the mechanical strength property of small clear specimen, statistically, this reduced characteristic strength value at the 5% point of exclusion. Some mechanical strength properties of wood include; modulus of elasticity (MoE) modulus of rupture (MoR) shear strength, and hardness etc.

2.7.4 Modulus of Elasticity

Elasticity referred to the deformations produced by low stress below the proportional limit is completely recoverable after loads are removed. When loaded to stress levels above the proportional limit, plastic deformation or failure occurs. Hook's Law state, that the ratio of stress to strain for a given piece of wood within the elastic range is constant MoE = $L^3 X (P_2 – P_1) /48I(d_2 - d_1)$ where (P2- P1) is the load increment (N) in the linear part of the stress-strain curve, L is the sample length between the two supports (mm), $(d_2 - d_1)$ is the deflection (mm) corresponding to the load increment $(P_2 - P_1)$, Iis the moment of inertia (mm). The ratio is called the modulus of elasticity. Sometimes also called Young's Modulus usually abbreviated as MOE or simply E, this ratio equals to the stress divided by the resulting strain.

It can be calculated by choosing any set of values of stress and resulting strain, although the stress and strain values at the proportional limit are conventionally used (Hoadley, 2000). The slope of the linear curve is the modulus of elasticity, E, gives a measure of a relative stiffness; the steeper the slope, the higher the E value and stiffer the wood. The higher the Elastic value, the lower the deformation under a given load,Hoadley, (1990). The procedure to determine MOE is fully described in ASTM D 1037 and ASTM D 5456 for structural composite lumber products.

2.7.5 Modulus of rupture.

Reflects the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted measure of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit (McNatt 1973). MoR= $3PL/2bd^{106}$where P is the maximum load (N), L is the length of sample between the two supports (mm), b is the sample width (mm), and d is the sample thickness (mm).

2.7.6 Shear Modulus

Shear modulus, also called modulus of rigidity, indicates the resistance to deflection of a member caused by shear stresses. Shear stress is different from tension or compression stresses in that it tends to make one side of a member slip past the other side of a member adjacent to it. There are two main types of shear in different planes of wood: interlinear shear and edgewise shear or shear through-the-thickness. Interlinear shear is also commonly called planar shear (or rolling shear, or horizontal shear) in plywood panels it is used to describe stress that acts between the veneers that are glued with grain direction in adjacent pieces perpendicular to one another. Edgewise shear is also commonly called racking shear. The modulus of rigidity varies within and between species, resin application, moisture content, and specific gravity.

2.7.7 Compression strength parallel-to-surface

This is the maximum stress sustained by a specimen from a test with compression forces applied parallel to the surface. Tests are made with the long dimension of the specimen cut both parallel and perpendicular to the long dimension of the board to determine the material's resistance to crushing in each of the primary panel directions.

2.7.8 Hardness

Hardness refers mainly to the resistance of the surface of the wood to bruising and indentation. The hardness test is a measure of the load required to force a small steel ball into the wood to half its diameter which; the load applied gradually. Many hard timbers have good wearing properties i.e., resisting abrasion or wearing away. Hard timbers are usually dense, having relatively thick-walled cell, and are often difficult to saw, plane, nail and others. Walton (1968). Lignin is found between individual cells and within the cell walls and serves as a binding agent between the individual cells whilst within the cell walls lignin is very closely related to cellulose and the hemicelluloses to give rigidity to the cell (Peng *et al.,* 2002).

2.8.0 Anatomical Properties of Wood.

2.8.1 Vessels or Pores

These are the transverse openings of vessel elements. In hardwood these are the largest diameter opening one sees on the transverse plane of wood and the smallest pores are barely visible with a 10x hand lens, but nonetheless remain recognizable as individual cells.

2.8.2 Fibres

Fibres are among the smallest diameter cells and have the thickest walls. On a transverse surface, masses of fibers take on a dense appearance after forming a dark background or ground mass against which pores and lighter colored masses of parenchayma and ray cells contrast.

2.8.3 Ray Cells

Some rays are barely visible with a hand lens; others are clear to the unaided eye. They appear as fairly straight radial lines across a transverse surface and are usually a lighter shade than the ground mass. In wood that luck obvious growth rings, locating rays can be an important aid in establishing a radial surface and the tangential surface perpendicular to it.

2.8.4 Parenchyma Cells

Parenchyma cells are found in every hardwood. In many woods, however, they are visible on masse in transvers section as lighter- colored lines or areas.

2.8.5Tracheids

Tracheids are less frequent among hard wood but they are usually abundant in softwood. In cross section they are virtually indistinguishable from parenchyma because both are thin- walled and about the same diameter. Moreover, the two are usually intermixed in the vicinity of pores. As seen with the hand lens, such combined masses of tracheids and parenchyma are described as lighter- colored tissue or simple as parenchyma.

CHAPTER THREE

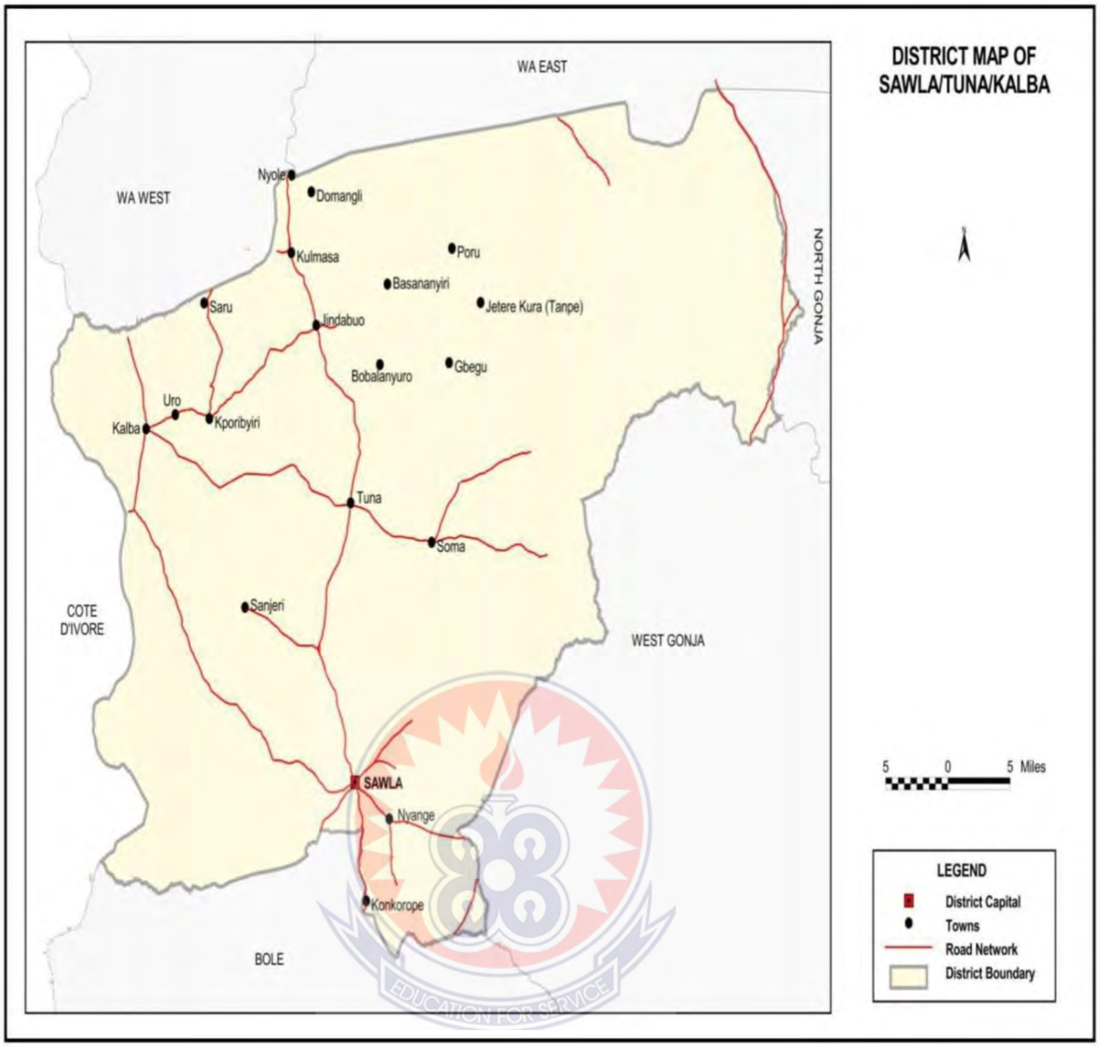
MATERIALS AND METHODS

3.1 Introduction

This chapter seeks to provide the outline, the parameters used in selecting samples and the methods used to gather data for the study. They include the following: facilities, wood species for sample and sampling procedures, experimental methods and data analysis. The properties investigated in this study were the density, moisture content, shrinkage and swelling, compression parallel to grain, shear parallel to grain, modulus of rupture and modulus of elasticity of the selected species, the chemical composition and anatomical properties of plantation teak wood.

3.2 Background of the Study Area

Sawla-Tuna-Kalba District was carved out of the then Bole District in 2004. The District was one of the 28 districts created in that year by an LI 1768 in the Northern Region. The district is located in the western part of the Region, between latitude 8o40’ and 9O40’ Northern and longitudes 1o 50’ and 2o 45’ West. It shares common boundaries with Wa West District and Wa East District to the North, Bole District to the South, West Gonja District to the East and La Cote d’Ivoire and Burkina Faso to the West. It has a total land area of about 4,601 square kilometers out of the total area of 74,984 kilometers of the total land mass of the Northern Region. Sawla-Tuna-Kalba District capital, Sawla is about 210 kilometers North West of Tamale, the Regional Capital in the Republic of Ghana.



The District map of Sawla – Tuna - Kalba

Table 3.1: Site characteristics of teakwood sample

Site	Sawla-Tuna-Kalba District (dry site)
Coordinates	Longitude (1°50ˈ and 2°45ˈW) Latitude (8°40ˈ and 9°40ˈN)
Soil type	Light textured and horizons; sandy loams and loams.
Vegetation	Guinea savanna woodland
Climate type	Tropical continental. Unimodal rainfall starting from early May and ending late October. Highest rainfall occurs between July and September. Dry season spans November-April.
Average temperature	Daily temperature between 28°C and 40°C.
Average precipitation	Monthly rainfall between 200 and 300mm
Tree age (years)	10-20
DBH (cm)	16-25
Total height (m)	11.3 – 29.9
Number of rings at DBD	11-23

3.2.1 Other descriptions of the District are as follows:

Climate/ Temperature

The climate of the District is the tropical continental type. There is only one rainy season in a year, which occurs between early May and late October. The highest rainfall is experienced between July and September. The monthly main rainfall ranges between 200mm and 300mm. The period between November and April is the dry season. This season is characterized by the cold harmattan winds associated with varied airborne diseases. In terms of temperature, the district experiences extremes of it. The coldest nights in the year are experienced in the months of December, January and February. During this period the air becomes dry and the atmosphere becomes hazy and one cannot see clearly due to the fine dust in the air.

The day temperature within the same period is between 28ºC and 40ºC but under cloudiness skies, the night can be very cold with temperature under 28^0C. The temperatures suddenly rise in the months of March, April and May when temperature exceed 30^0C. The nights are usually hot and people prefer to cook, eat and sleep outside. But when the rain start the mean temperature begins to fall again.

3.2.2 Soil/Vegetation

The predominant vegetation found in the District is mainly Guinea savanna woodland with wide spread of the trees, just like any other part of the Northern region. Some of the common trees found in the District include Shea (Parkia *Biglobosa*) cashew, dawadawa, (*African Locust beans*) teak, (*Tectona grandis*) kapok and mango.

In recent time, the natural vegetation of Sawla-Tuna-Kalba district has disappeared, especially around the settlement. This had been due to the interference by man and animals through cultivation, grazing and exploitation for fire wood. In the dry season, the grasses in most part of the district are periodically burnt down to either clear the land for crops cultivation or hunting of animals. These activities have deprived the land of much vegetation cover and nutrients over the years. These have therefore affected food production in the district.

The District is composed of soils in varied nature, occurring in complex associations. The predominant soil types found in the district are light textured surface horizons in which sandy loamy and loamy are common. Many soils contain abundant coarse material in the form of either gravel or stone which adversely affect their physical properties particularly their water holding capacity. The soil is generally very fertile for agricultural cultivation.

3.3 Sample Collection and Preparation

The material was collected from a 10-, 15- and 20- year-old *Tectona grandis* plantation from St, Johns Primary School plantation farm in Tuna, in Sawla –Tuna –Klaba District. A total of 9 teak trees comprising three each of the year groups were sampled and harvested June 2017. In order to minimize tree-to-tree variation, the selection of the trees was done following the recommendation by Lei et al. (1996). The diameter at breast height (DBH) of the trees ranged between 16- 25 cm while the total heights from the stump level to the top of the crown were in the range 11.3-29.9 m (Table 1). Each tree was cut at 15cm from the ground and further cut into three sections, namely, bottom, middle, and top of the tree stems, respectively. The boules were used for the determination of density and mechanical testing. The wood samples were prepared at the Wa Technical Institute Wood Technology Workshop. The tools and equipment used includes: Chain saw (Dolmar), Circular saw, Band saw, crosscut saw, surface plainer and thicknesser, were used for preparing the samples.

Figure 3.1: A, B, C and D. Timber stacks for air drying, and timber sawn to require sampling size using circular sawing machine.

Figure 3.2: A, B and C Samples prepared to size, labeled ready for testing.

3.4 Moisture Content

Moisture content was determined by the oven dry method where green samples collected from the bottom, middle and top were sawn into sizes of 20 × 20 × 20 mm in accordance with the British Standards, BS 373 (1957). The specimens were weighed using an electrical digital balance. The specimens were oven dried at 103 ± 2^0c for 24 hours, cooled in desiccators 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, % = weight with water – oven dry weight over dry weight x 100.

3.4.1 Density Determination

Determination of the density of *T. grandis* was done in accordance with the American Standards of Testing Materials, ASTM D 143-94 (2007). Specimens for Basic density, Green density, Air dry density and Oven dry determination were cut alternatively from each strip and their dimensions were in accordance with ASTMD 143-94 (2007) standard procedures (20 × 20 × 20 mm cubes. A total of fifteen (15) samples each were taken from each trees, making a total of one hundred and thirty- five (135) from nine trees. The same samples were used for all physical tests. Specimens were soaked in distilled water for 72 hour so that moisture content was above the fibre saturation point (FSP) before measurement. The saturated mass of the specimens were determined to the nearest 0.001g using an electronic balance while the radial, tangential and longitudinal dimensions were measured to the nearest 0.001mm with digital veneer calipers. Saturated volume of the specimen was calculated based on the saturated dimensions.

To determine the air-dry density (AD), specimens were air-dried and conditioned to 20℃ and 65% relative humidity for 120 days in order to reach a moisture content of approximately 12%. Masses and dimensions of the specimens at 12% MC were used to calculate their air-dry density values. Finally, the specimens were oven-dried at 103 ± 2℃ until a constant mass was obtained. The specimens were subsequently cooled to room temperature after which masses and dimensions were taken. Basic density (BD) of the specimens was based on oven-dried mass divided by saturated volume whereas oven-dry density (OD) was estimated by dividing the oven-dried masses of the specimens by their respective oven-dry dimensions.

3.5 Determination of the Strength Properties

Two hundred and seventy (270) samples (made up of sap/heartwood from portions of billet division) of each tree were prepared for bending parallel to grain, modulus of elasticity (MOE) and the modulus of rupture (MOR) test, two hundred and eight (270) samples for compression parallel to the grain test and two hundred and eighteen (208) samples for shear parallel to grain. Four hundred and five (405) all for mechanical tests as depicted in the table 3.1

Table 3.2: Numbers of samples taken from billet 1, 2 and 3 of each tree for the determination of MOE, MOR, compression and shear parallel to grain.

Buttress	**Compression Heart/sap**	**MOR Heart/sap**	**MOE Heart/sap**	**SHEAR Heart/sap**
10 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
15 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
20 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
Total	**90**	**90**	**90**	**90**

Grand total = 360

Table 3.3: Numbers of samples taken from billet 1, 2 and 3 of each tree for the determination of MOE, MOR, compression and shear parallel to grain.

Middle	**Compression Heart/sap**	**MOR Heart/sap**	**MOE Heart/sap**	**SHEAR Heart/sap**
10 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
15 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
20 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
Total	**90**	**90**	**90**	**90**

Grand total= 360

Table 3.4: Numbers of samples taken from billet 1, 2 and 3 of each tree for the determination of MOE, MOR, compression and shear parallel to grain.

Top	Compression Heart/sap	MOR Heart/sap	MOE Heart/sap	SHEAR Heart/sap
10 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
15 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
20 years				
Tree 1	10	10	10	10
Tree 2	10	10	10	10
Tree 3	10	10	10	10
Total	**90**	**90**	**90**	**90**
Grand total=360				

In all, 405 samples were used for testing mechanical and strength properties.

3.5 Modulus of Elasticity

The modulus of elasticity is an index of the stiffness of a piece of wood. In this study it was measured using the central loading method, using this method the end of the 20 mm x 20 mm x 300mm samples were supported at a load placed on the Centre of the sample. The test pieces were supported at the ends in such a way that they were quite free to follow the bending action and were not restrained by friction which would resist the bending and tend to introduce longitudinal stresses. The specification of the BS 373 (1957) the loading heads moved at a constant speed of 0.65cm min-1. The orientation of the annual rings in the 2cm standard test piece was parallel to the direction of loading. Deflection of the beam at mid-length was measured with reference to the outer points of loading in the loading method. The formula used for the calculation of MOE was:

$$\text{MOE} = \frac{L^3 x\ (P_2 - P_1)}{48I\ (d_2 - d_1)}$$

Where (P_2 - p_1) is the load increment (N) in the linear part of the stress – strain curve, L is the sample length between the two supports (mm), (d_2 – d_1) is the deflection (mm) corresponding to the load increment (p_2 – p_1), and *I* is the moment of inertia (mm)

3.5.1 Modulus of Rupture (MOR)

The modulus of rupture is the maximum load a wood sample can sustain prior to rupture. The MOR was determined using a similar test procedure as outline for MOE. However, for the MOE test, the maximum load prior to rupture was recorded and this was used to calculate the MOR as follows:

$$\mathrm{MOR} = \frac{3PL}{2bd^{10/6}}$$

Where P is the Maximum load (N), L is the Length of sample between two supports (mm), b is the sample width (mm), and d is the sample thickness (mm).

3.5.2 Compression parallel to Grain

The sample for compression parallel to grain test was perform according to BS: 373 (1957). The 60mm x (axial) 20mmx 20 mm specimens were employed and the test was performed on a universal machine. As in the case of the static bending test, the specimens were stored in a room for three weeks to allow the moisture content to equilibrate to about 12%. The actual moisture content of the specimens was determined by electrical moisture meter after testing. Specimen dimensions were measured to the nearest 0.001mm the dimensions before the testing. The compression strength parallel to the grain was calculated by the following equation:

$$\mathrm{MCS} = \frac{p}{bd}$$

Where*:* *MCS* = compression strength (MPa*) P* is the Maximum load at the break point (N), *bd* is the area of cross – section of a specimen on which force was applied.

3.5.3 Shear parallel to grain.

The shear parallel to grain test was carried out on Instron – 4487 machine with load cell capacity of 100kN. Sample size 50mm x 50mm x 50 were extended from both sapwood/ heartwood of each billet. The load that caused each wood sample to fail was recorded and immediately kept in polythene bag to prevent moisture content changes. The formula used for the calculation of shear parallel to grain was: p/ bh Where p = maximum load in Newton's b = breadth of the test piece in mm. h = height of the test piece in mm. Shear parallel to grain test was carried out at the Timber Mechanics and Engineering Laboratory at FORIG by an Instron -4482 machine with load cell capacity of 100kN.

Figure 3.3: Bending test using Inspekt universal machine.

Figure 3.4. Shear strength test using Instron 4482 machine

3.6 Sample Collection and Preparation for Anatomical Features

Six (6) 20mm cubes samples were prepared from each of the nine trees of ages 10, 15 and 20 year from the same location of the plantation, the total of 18 cubes for (Microtome) from nine trees of different ages considering the bottom, middle and the top of the tree section. The samples were softened before sectioning with a sliding microtome, by placing in water for 21 days followed by soaking in a mixture of ethanol and glycerol, at a ratio of 1:1 for 21-30 days. Thin sections of 25µm thickness were cut from transverse surface of the sample using a sliding microtome. The sections were first washed in distilled water and then stained in 1% safranin in 50% ethanol solution for about 10-15 min. afterwards, the sections were rewashed in distilled water and dehydrated in increasing concentration of ethanol from 30, 50, 70, 90, and 100% for 5-10 min. They were then immersed in xylene to remove little traces of water. The sections were then finally mounted permanently in Canadian balsam after which the slides were dried in an oven at 60^{o}c overnight.

Figure 3.4: A, B and C Shows the chemical, tools and equipment for microtome preparation for anatomical test.

Figure 3.5: A, B and C Shows an oven, other equipment and photomicrograph for wood maceration for the test.

The maceration process was for the separation of fibres. Two match stick sized specimens were plucked from each of the anatomical subsample. These match-stick sizes were placed in separate labeled containers and immersed in a mixture of glacial acetic acid and hydrogen peroxide (6%) prepared at ratio of 1:1. The specimens in the solution were incubated in an oven at 60^{o}c till complete maceration was attained. Macerated fibres were temporarily mounted in glycerol for measurement of fibre lengths. Photomicrographs were taken from the sections and macerated slides separately at 40x magnifications using light microscope with a digital camera.

All the measurements of anatomical tissues were done on the photomicrographs using Miplus (MSI) software. Fibre length and vessel diameters were manually measured from one end to the other. In determining the proportions of the three different year age group of *T grandis* wood tissues (vessel, fibres, parenchyma and ray cells), the micrographs were inclined at 45^{0} in Miphus (MSI) with reference to the ray parenchyma orientation.

3.7 Methods of Statistical Analysis

Estimation of tested physical and strength properties of the species (i.e. density, moisture content, modulus of elasticity, modulus of rupture, compression parallel to grain and shear parallel to grain) were conducted for each tree within each species. The variation in the tested physical and strength properties of the species were conducted for each tree within each species at the three axial locations (but, mid and top) and the overall variation between the tree axial locations within each species. The main statistical tools used were descriptive statistics and ANOVA to determine any significant variation in properties (all variations were tested at 97% p = 0.05, LC). The data was analyzed statistically to assess the significant difference within each division of each tree and the variability between strength properties of the nine trees of *T. grandis* using Excel analysis tool (tool for scientific data analysis) in finding the descriptive statistics and a single factor analysis of variance (ANOVA) to describe relationships.

CHAPTER FOUR

RESULTS

4.1 Introduction

The research set to determine some physical, anatomical and mechanical properties of (teak) *Tectona grandis*. This chapter outlines the results of descriptive statistics and summary of ANOVA mean of the parameters of investigated trees of *T. grandis.*

4.2 Wood Densities at Different Ages and Stem Position of Teakwood

Table 4.1 reports the variation in air dry density; oven dry density, basic density and green density with tree age and stem position of teak. Air dry density varies from 620kgm^{-3} for the 20-year-old teak to 689kgm^{3} for the 15 year- old. Differences were observed in the variation of air-dry density across stem position. For the 10 year- old teak air-dry density at the bottom and middle portions was stable at 649kgm^{-3} while the top portion recorded a marginally higher air-dry density. For the 15-year-old, the highest air-dry density was found in the bottom (743kgm^{-3}) and the lowest in the middle (630kgm^{-3}). The 20 year- old teak had the highest air-dry density in the top position, decreasing in the middle and increasing marginally in the bottom portion.

Oven-dry density decreases from the 10- year-old teak to the 20- year-old. Axial variation of oven dry density did not exhibit any regular pattern across the ages of the trees. For the 10- and 20 -year-old trees, the top portions had the highest oven dry density whereas the bottom part had the highest oven dry density in the 15- year old. Basic density increases from the 10-year- old to the 15- year old and drops in the 20-year-old. Similar pattern was observed for the species with respect to axial variation in basic density. The top portions of the 10- year and 20- year old trees of the species were highest in basic density, whereas in the 15- year-old, the highest basic density was found in the bottom part. Between tree variation was significant for only the basic density (F- value =50.654, p =0.019). Tree age and stem position were significant sources of variation for air dry density, oven-dry density, basic density and green density (Table 4.2).The interaction between tree age and stem position was an important source of variation for only air-dry density at (F-value =7.956, p= 0.001) and oven- dry density (F- value= 2.056, p = 0.001)

Table 4.1: Effect of tree age and stem position on wood densities of *T. grandis* sampled from the northern savanna ecological zone

Property	**Height position**	**Age of tree**		
		10	**15**	**20**
Air dry density (kg/m^3)	Bottom	649 (46.3)	743 (48.8)	620 (61.5)
	Middle	649 (28.6)	630 (43.4)	584 (49.2)
	Top	689 (36.1)	691 (46.5)	630(59.8)
	Mean	**663 (46.3)**	**689 (64.8)**	**620 (48.9)**
Oven dry density (kg/m^3)	Bottom	613 (50.9)	630 (55.8)	542 (55.9)
	Middle	598 (28.2)	567 (37.3)	515 (30.6)
	Top	623 (49.7)	607 (37.7)	563 (53.9)
	Mean	**612 (44.9)**	**602 (50.5)**	**540 (51.1)**
Basic density (kg/m^3)	Bottom	503 (53.3)	528 (78.9)	458 (34.3)
	Middle	489 (31.5)	474 (24.4)	461 (30.0)
	Top	516 (36.2)	550 (45.8)	474 (48.3)
	Mean	**503 (42.1)**	**518 (62.5)**	**465 (38.2)**
Green density (kg/m^3)	Bottom	809 (88.5)	849 (65.3)	741 (76.4)
	Middle	762 (56.1)	803 (72.1)	763 (33.5)
	Top	816 (44.7)	903 (78.5)	758 (57.8)
	Mean	**796 (68.6)**	**853 (98.9)**	**754 (57.4)**

Table 4.2: Summary ANOVA various components for density at 12%mc, oven-dry density, basic density and green density of *T. grandis*

Factor	df	Density at 12%MC (kgm^{-3})		Oven dry density (kgm^{-3})		Basic density (kgm^{-3})		Green density (kgm^{-3})	
		p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value
BT	1	0.316	1.014	0.399	0.717	0.019	50654	0.052	3.854
TA	2	0.001	26.041	0.001	22.154	0.001	10.223	0.001	10.062
SP	2	0.001	17.653	0.001	12.242	0.001	11.333	0.044	3.210
TA* SP	4	0.001	7.956	0.001	2.057	0.073	2.201	0.081	2.132

BT= between trees; TA= Tree age (years); SP= Stem position;

4.3 Static bending tests (modulus of rapture (MOE) and modulus elasticity (OR), compression strength and shear strength.

Variation of mechanical properties with age and stem position of *T. grandis* are reported in Table 4.3. Average MoE was 10404Nmm-^{2,} 9433Nmm^{-2} and 10017Nmm-^{2} for the 10, 15 and 20 -year -old teak, respectively. Axial variation in the parameter showed that MoE of the 10- year- old increased from the bottom end to the middle section followed by a small decrease in the top. The 15- year-old tree exhibited increases in MoE from the butt and to the top portion whereas reverse trend was observed in the 20- year- old a reduction in MoE from the butt end to the top end.

Average bending strength MoR varied from 73 Nmm-^{2} for the 10- year-old teak to 80 Nmm-^{2} for 20-year- old. A marginal reduction in MoR from the bottom end to the top end was observed for the 10-year-old. For 15-year-old, the parameters from the bottom end to middle portion and then increased again at the top portion. The 20-year-old teak had the highest while 15yr- teakwood lowest bending strength at the middle portion, respectively, with the bottom end having an intermediate value. The strength in compression of the species was highest in the 15-year-old (54 Nmm-^{2}), followed by the 20-year-old (52 Nmm-^{2}) and the 10-year-old (49 Nmm- ^{2}). Compressive strength was relatively stable across the height for all the age groups. Shear strength decreased marginally with tree age and also decreases across the tree height (Table 4.3). Bending strength and MoR of teak did not vary with between trees, however, between tree variation was a significant source of variation in the compression and shear strength (Table 4.4). Tree age was an important source of variation in all the mechanical properties investigated whereas tree height was a significant source of variation for bending strength, and shear strength. The interaction of tree age and tree height was a source of variation for mechanical properties investigated (Table 4.4)

Table 4.3 Mechanical properties along tree height of 10, 15 and 20 years of *Tectona grandis*

Property	**Height position**	**Age of tree**		
		10	**15**	**20**
Modulus of elasticity (Nmm^{-2})	Bottom	9657 (268)	8886 (1743)	10416 (1986)
	Middle	10851 (1853)	9513 (1733)	10203 (1903)
	Top	10830 (2201)	9807 (1805)	9451 (1471)
	Mean	**10404 (2340)**	**9433 (1787)**	**10017 (1826)**
Bending strength (Nmm^{-2})	Bottom	75 (25)	78 (18.67)	85 (25)
	Middle	73 (21)	63 (21)	89 (18)
	Top	71 (20)	72 (24)	67 (18)
	Mean	**73 (22)**	**71 (22)**	**80 (23)**
Compressive strength (Nmm^{-2})	Bottom	48 (6)	55 (3)	51 (11)
	Middle	50 (4)	52 (2)	53 (6)
	Top	49 (6)	54 (3)	52 (4)
	Mean	**49 (5)**	**54 (3)**	**52(8)**
Shear strength (Nmm^{-2})	Bottom	16 (1)	17 (1)	16 (0.9)
	Middle	14 (.0)	15 (0.4)	14 (0.7)
	Top	16 (0.5)	14 (0.4)	13 (1)
	Mean	**16 (1)**	**15 (0.2)**	**14 (2)**

Table 4.4: Summaries ANOVA for bending strength, MOE, compression strength and shear strength at 12% MC of *T. grandis*.

Factor	df	MoE		MoR		Compressive strength		Shear strength	
		(MPa)		(MPa)		(MPa)		(MPa)	
		p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value
BT	1	0.217	1.534	0.272	1.211	0.001	3.331	.000	2.758
TA	2	0.021	6.679	0.010	4.730	0.001	18.737	.000	19.396
SP	2	0.169	1.792	0.012	4.510	0.581	.544	.000	68.249
TA* SP	4	0.023	2.874	0.002	4.171	0.01	3.369	.000	26.279

BT= between trees; TA= Tree age (years); SP= Stem position;

4.4 Anatomical Features of Teakwood

The anatomical features of the 10, 15, and 20- year-old teakwood are presented in Figures 1 - 9. Vessels are predominantly solitary with few multiples of 2-3 (in both early wood and latewood). (Fig 4. 2A). Across the age groups, vessels are occasionally partially filled with tyloses also in both the early wood and latewood. Most of the vessels are circular or oval in shape. Vessels occupied 8%, 12% and 8% of the ring area of the 10, 15 and 20-year-old teakwood, respectively (Table 4.5). The proportion of vessels per mm^2 tends to decrease from the bottom of the 10 and 15-year-old teakwood while a reverse trend was observed for the 20-year-old. Differences in vessels proportion across trees was a significant source of variation with respect to the parameter ($p < 0.001$) but tree age and tree height were not significant in the parameter (Table 4.6).

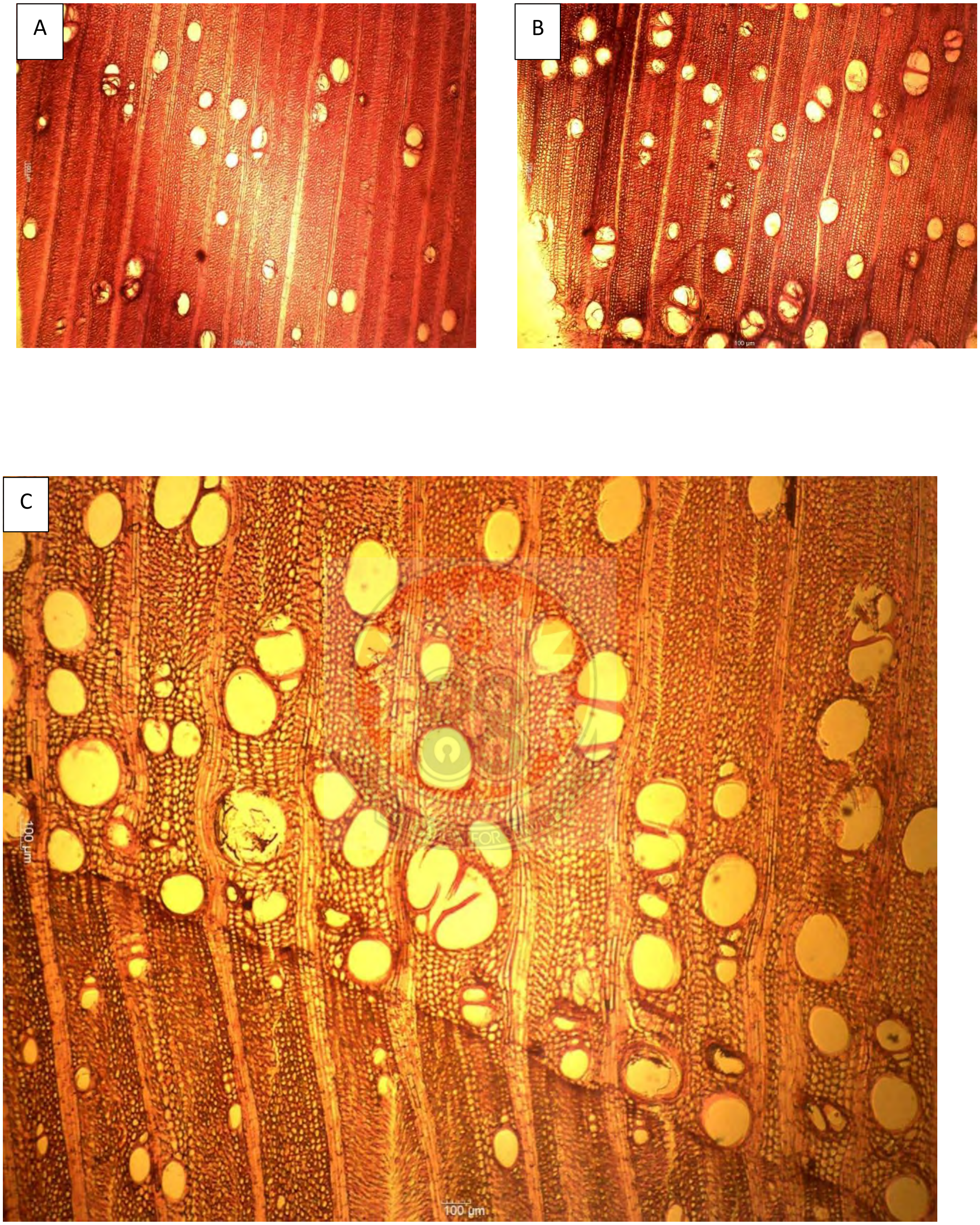


Figure 4.1: Transverse section of 10-year-old *Tectona grandis.* A, B, and C: bottom, middle and top sections

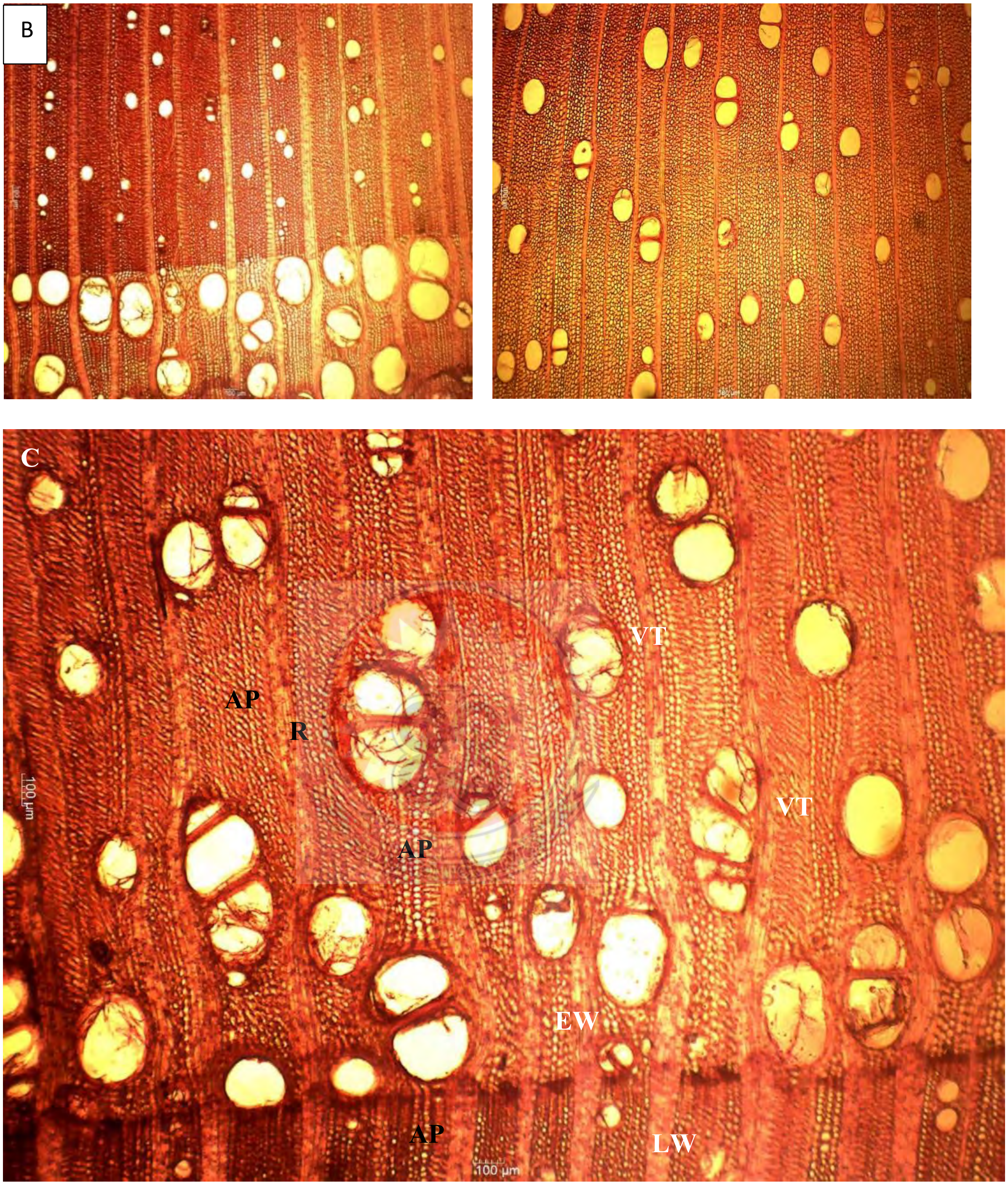


Figure 4.2: Transverse section of 15-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

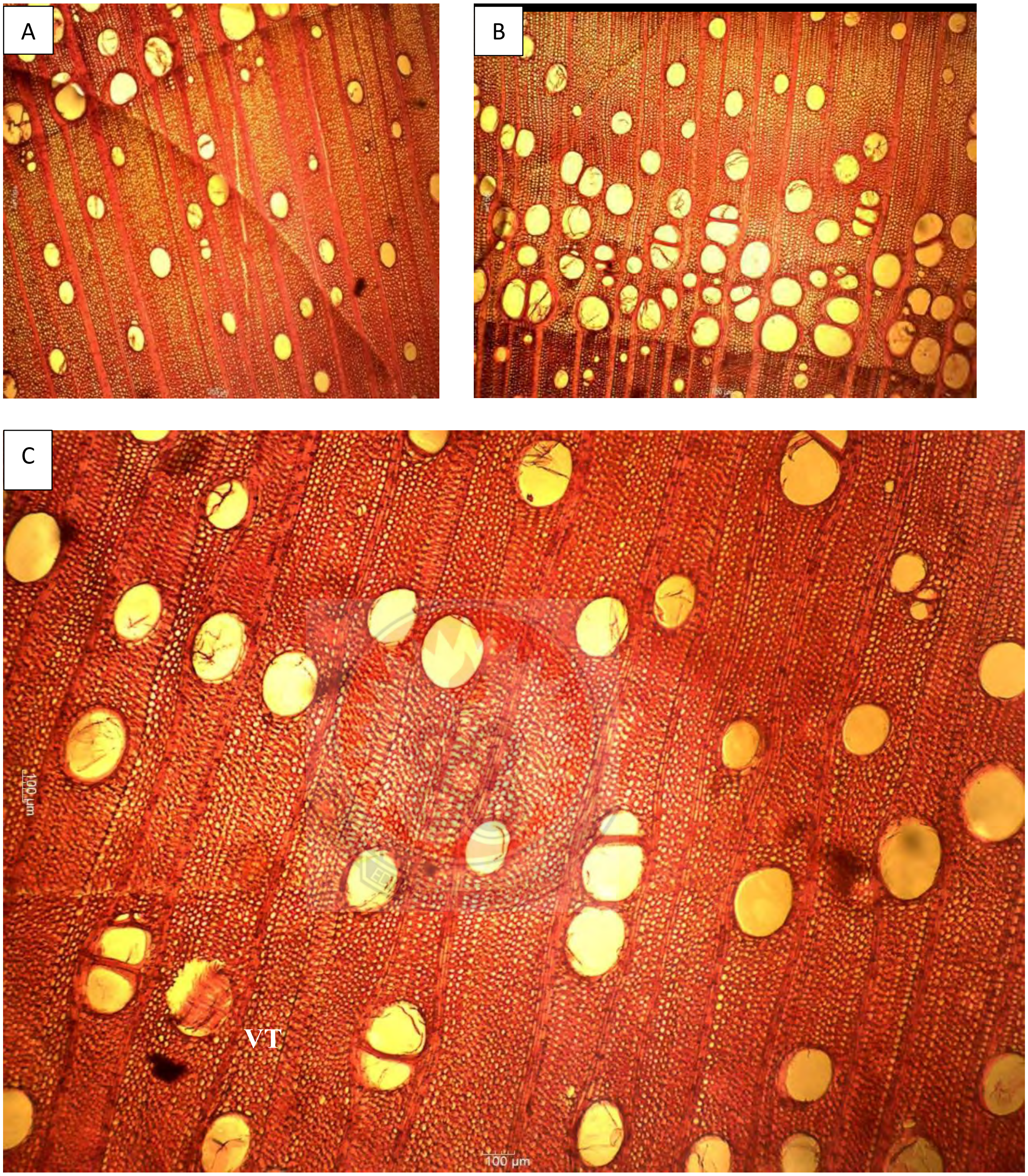


Figure 4.3: Transverse section of 20-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

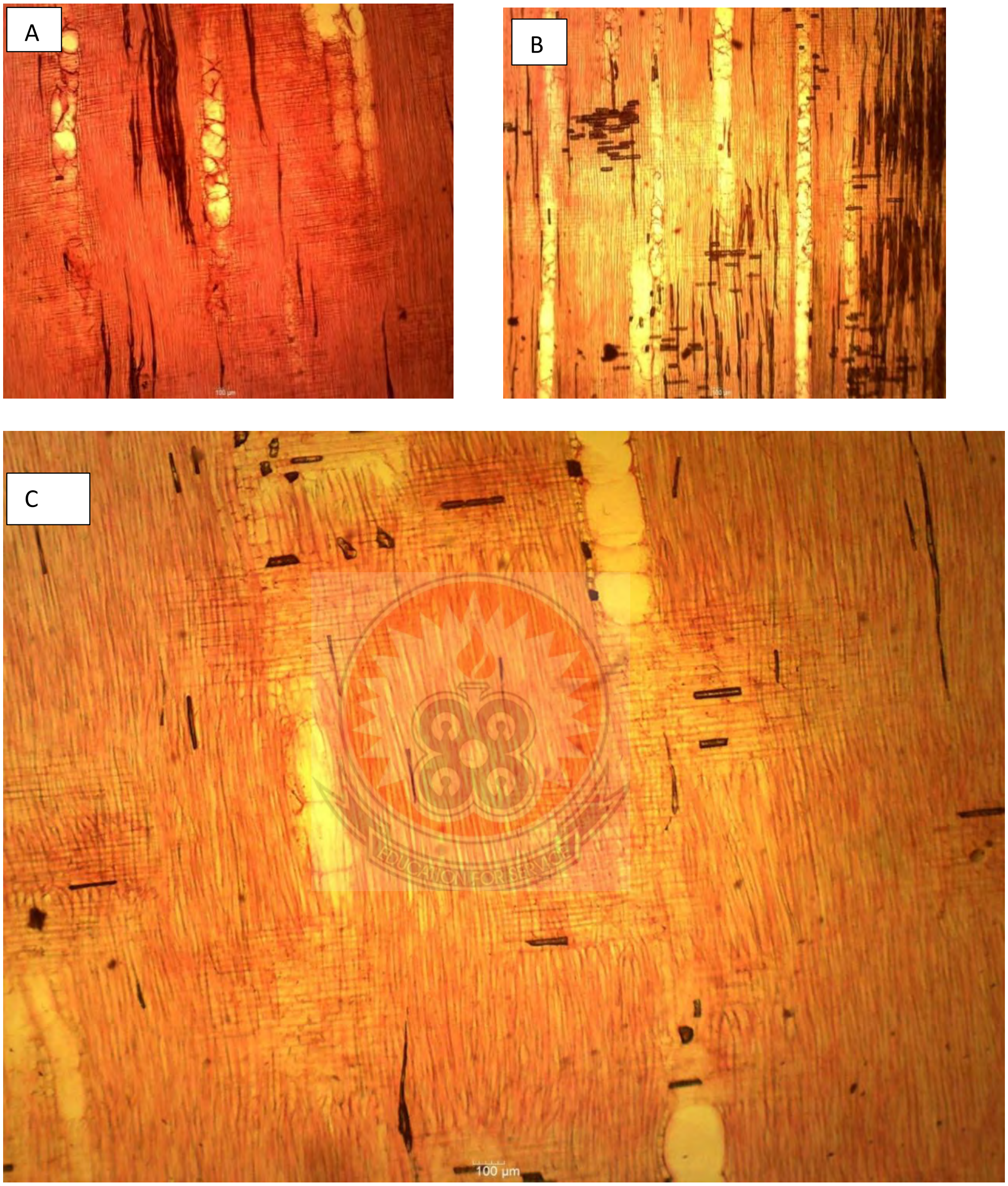


Figure 4.4: Radial sections of a 10-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

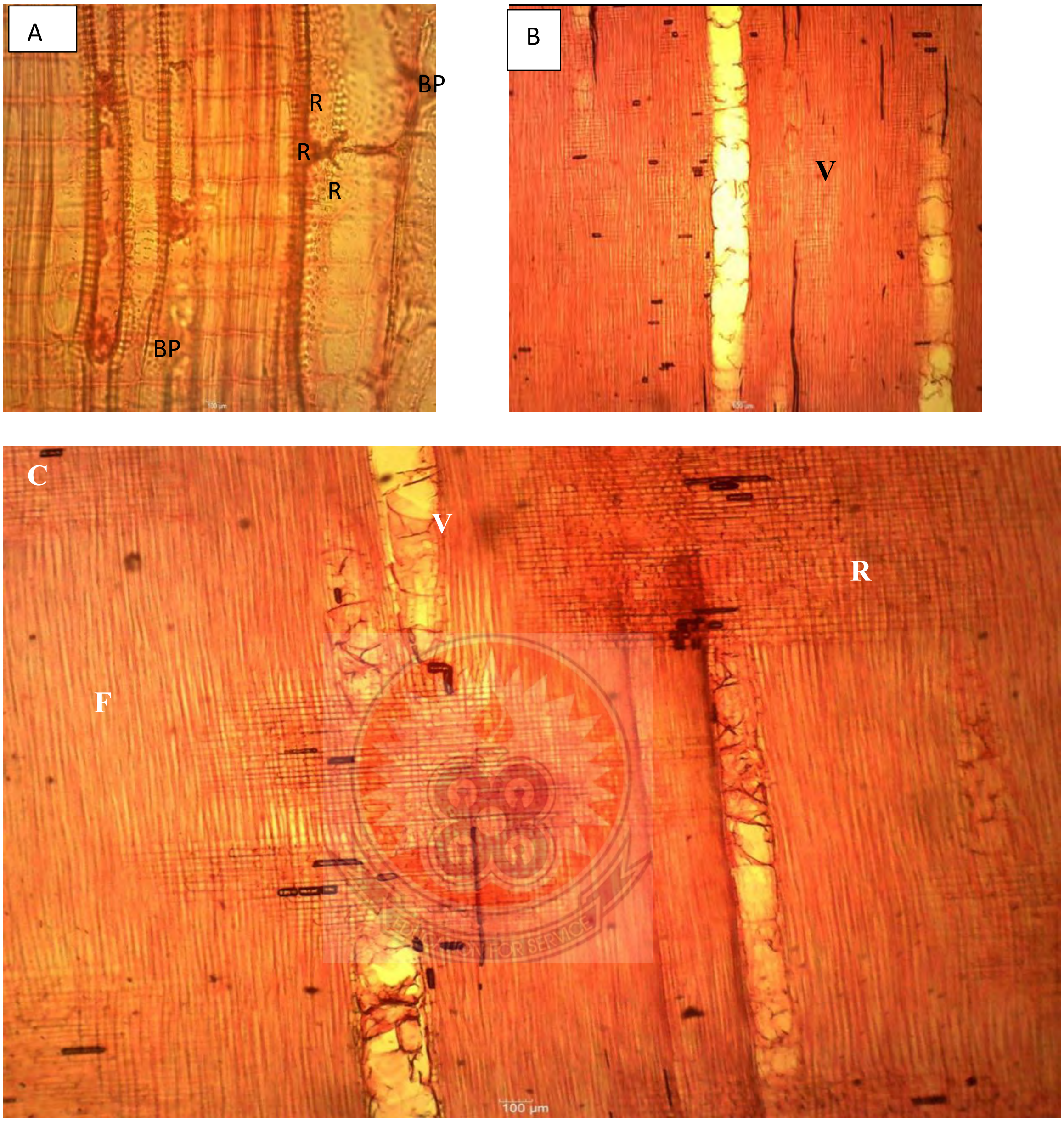


Figure 4.5: Radial sections of a 15-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

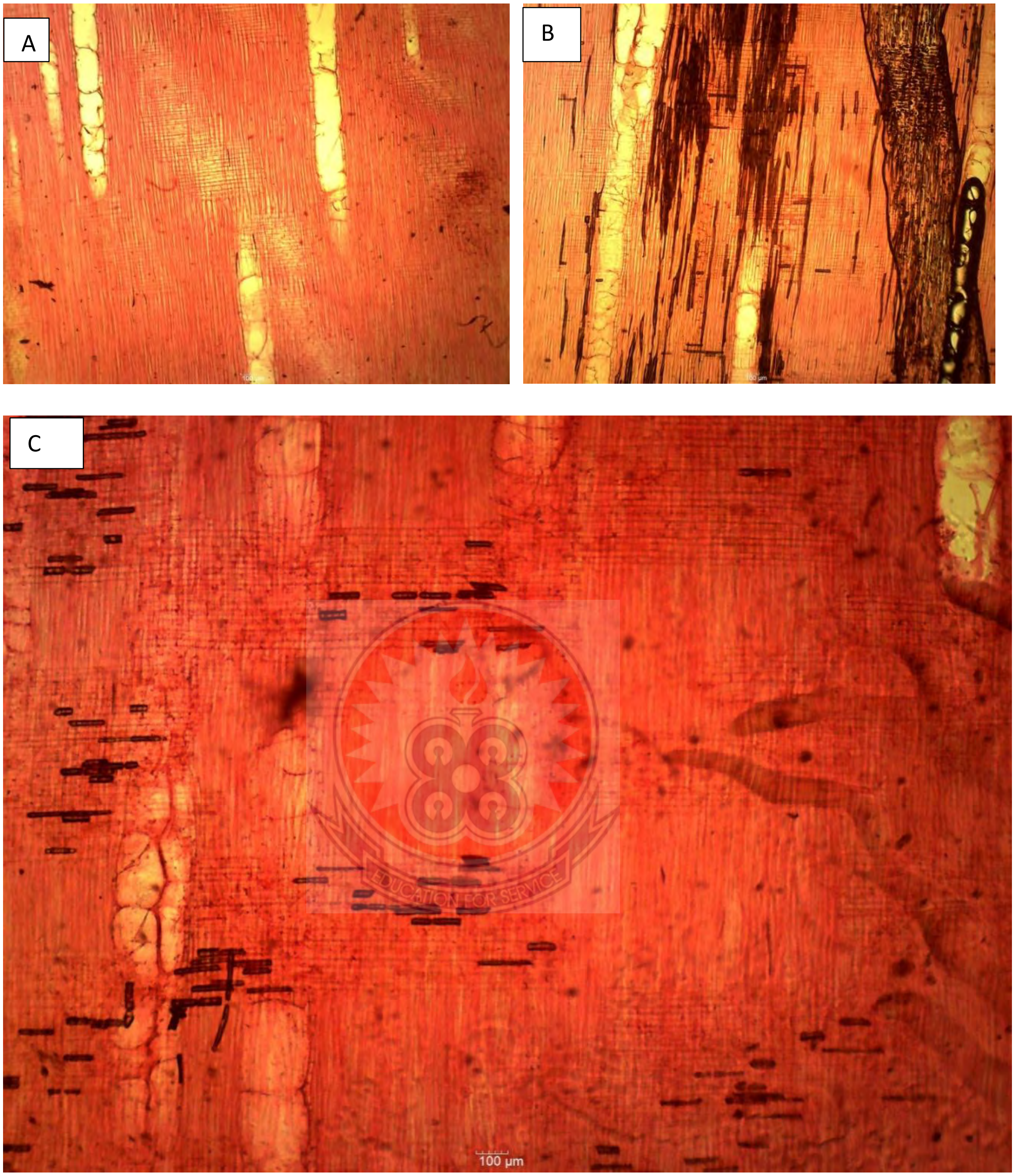


Figure 4.6: Radial sections of a 20-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

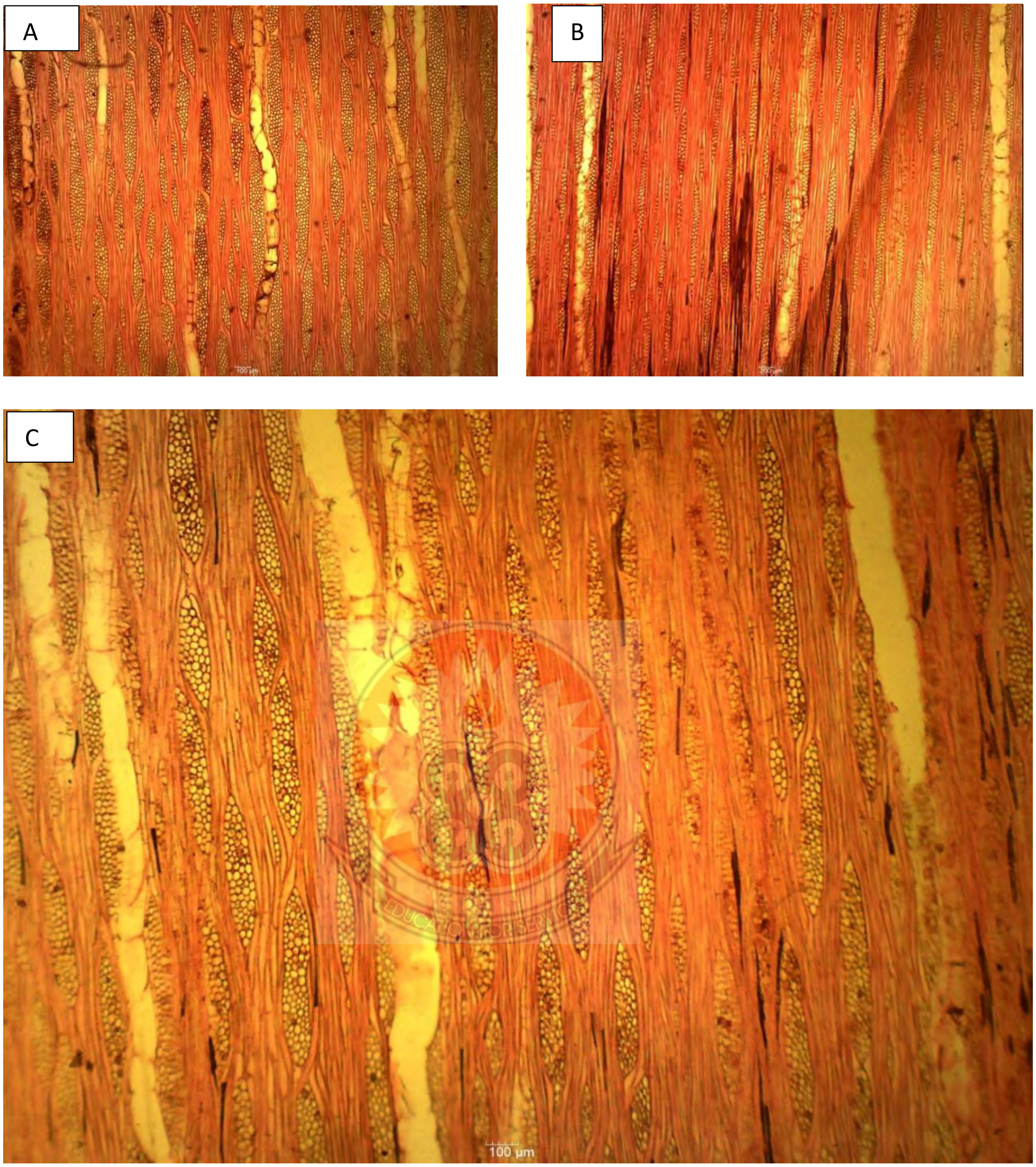


Figure 4.7: Tangential sections of a 10-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

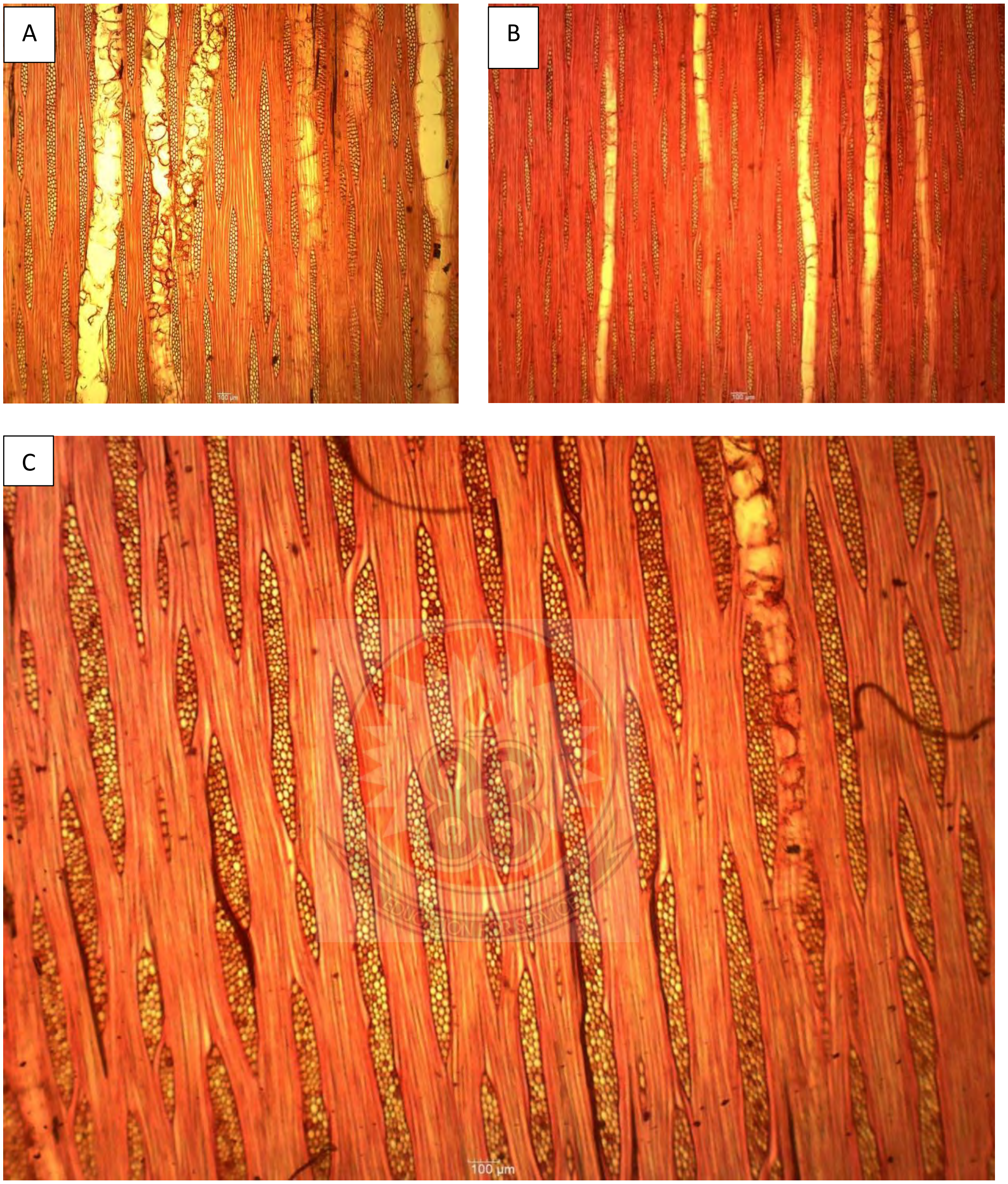


Figure 4.8: Tangential sections of a 15-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

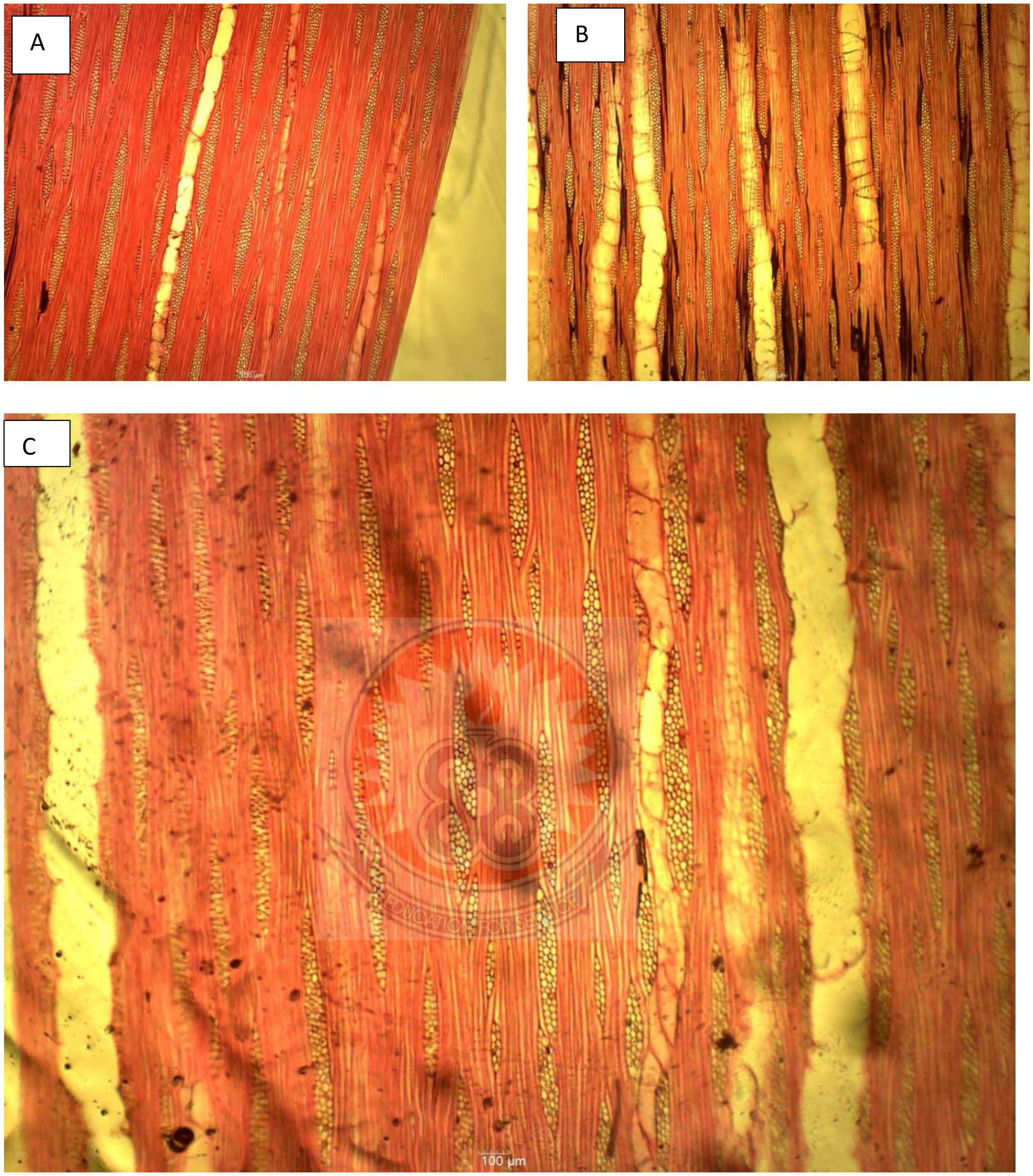


Figure 4.9: Tangential sections of a 20-year-old *Tectonagrandis.* A, B, and C: bottom, middle and top sections

Fibres constituted about 63%, 72% and 53% of the cross-sectional area of the 10, 15 and 20-year-old teakwood, respectively. Across the age groups of the teakwood, the bottom section represented the lowest fibre proportion, increasing in the middle section across the trees and dropping marginally in the 10, and 20-year-old, where the fibre proportion in the top section were somewhat low.

The fibre length varies between the ages of the teakwood, ranging between 0.77µm for the 20-year-old and 0.913 µm for the 15-year-old. Axial variation of the fibre length also existed across the ages of the teakwood, the bottom section was found to exhibit the longest fibre length (1.26 µm 7and 1.040 µm respectively). The width of the fibre was found to be highest in the 10-year-old (26) µm with the 20-year-old, here the intermediate value (22). A µm axial variation of the fibre width was found among the age group of the teakwood, for 10-and 15-year-old, fibre width increased from the bottom to the top sections while a reverse trend was observed for the 20-year-old teakwood. Fibre lumen and double wall thickness of the teakwood appeared to a similar trend as in the case of fibre width, the highest in the 10-year-old (Table4.7).

ANOVA results showed that both between trees and trees age were significant sources of variation in the fibre proportion (Table 4.6). Axial parenchyma is somewhat scanty, constituting 12%, 8% and 7% of the total tissue in the 10- , 15- and 20-year-old teakwood, respectively. Axial parenchyma is mostly made up of 3- 4 cells wide and are predominantly para-tracheal, confluent with a few deform and vasicentric.

Ray paranchyma occupied about 15%, 10% and 14% of the total tissue in the 10, 15- and 20-year-old teakwood. Rays are homocellular with 2- 4 cells wide.

Table 4.5: Anatomical characteristics of 10, 15 and 20-year-old teakwood

	Stem position	Tree age (years)		
		10	**15**	**20**
Vessel proportion (%)	Bottom	9 (9)	18 (9)	3 (3)
	Middle	6 (4)	10 (6)	4 (4)
	Top	5	8 (3)	17 (8)
	Mean	**8 (8)**	**12 (8)**	**8 (8)**
Fibre proportion (%)	Bottom	59 (13)	65 (12)	49 (31)
	Middle	70 (4)	74 (7)	59 (30)
	Top	60	76 (7)	50 (25)
	Mean	**63 (11)**	**72 (2)**	**53 (27)**
Axial parenchyma proportion (%)	Bottom	12 (9)	11 (11)	6 (5)
	Middle	14 (9)	5 (6)	5
	Top	.000	9 (8)	10 (5)
	Mean	**12 (9)**	**8 (9)**	**7 (6)**
Ray parenchyma proportion (%)	Bottom	19 (7)	12 (7)	22(6)
	Middle	8 (4)	11 (5)	22 (6)
	Top	20	7 (7)	13 (3)
	Mean	**15 (8)**	**10 (6)**	**14 (6)**

Table 4.6: Summary ANOVA for selected anatomical properties of 10, 15 and 20 year- old *T. grandis*

Factor	df	Vessel proportion (%)		Fibre proportion (%)		Axial parenchyma (%)		Ray parenchyma (%)	
		p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value
BT	1	.001	58.839	.001	373.199	.001	35.400	.001	207.440
TA	2	.157	1.948	.027	4.018	.858	.154	.001	8.930
SP	2	.311	1.208	.323	1.165	.634	.462	.112	2.326
TA* SP	4	.006	4.241	.957	.160	.283	1.315	.046	2.701

BT=between trees; TA= tree age; SP=stem position;

Table 4.7 shows the variation of fibre length, fibre width, lumen and double wall thickness of *T. grandis* across tree height for three different ages. Fibre length averaged 821µm, 913 µm and 770 µm for the 10, 15- and 20-year-old teak. Across the tree age, fibre length was higher in the bottom than the top sections. Fibre width was highest in the 10-year-old teakwood, decreasing marginally in the 15 and 20-year old. The axial variation of fibre width showed higher values in the top than in the bottom for the 10 and 15-year-old teakwood whereas a reverse trend was observed for the 20-year-old teakwood. The same tend was found for the fibre lumen and double wall thickness (Table 4.7).

Table 4.7 Fibre length, fibre width, lumen and double wall thickness for different tree ages of *T. grandis*

	Stem position	Tree age (years)		
		10	**15**	**20**
Fibre length (µm)	Bottom	904(142)	1267 (166)	1040 (180)
	Middle	972(109)	635 (.000)	635 (.000)
	Top	635(.000)	838 (226)	635 (.000)
	Mean	**841 (178)**	**913 (309)**	**770 (218)**
Fibre width (µm)	Bottom	17 (6)	20 (6)	23 (5)
	Middle	18 (5)	20 (5)	21 (4)
	Top	71 (26)	22 (4)	21 (5)
	Mean	**35 (71)**	**21 (5)**	**22 (5)**
Lumen (µm)	Bottom	9 (5)	11(6)	15 (5)
	Middle	9 (4)	10 (4)	12 (3)
	Top	71 (128)	13 (3)	15 (5)
	Mean	**30 (73)**	**11 (5)**	**14 (5)**
Double wall thickness (µm)	Bottom	8 (4)	9 (3)	9 (2)
	Middle	9 (2)	9 (2)	9 (2)
	Top	71 (128)	9 (2)	9 (2)
	Mean	**21 (73)**	**9 (2)**	**9 (3)**

Table 4.8: Summaries ANOVA for fibre length, fibre width, lumen and double wall thickness for different tree ages of *T. grandis*

Factor	df	Fibre length (µm)		Fibre width (µm)		Lumen (µm)		Double wall thickness (µm)	
		p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value
BT	1	.000	9874	.000	68.546	.000	27.082	.000	16.286
TA	2	.000	24.108	.643	.443	.585	.537	.349	1.058
SP	2	.000	188.330	.304	1.198	.215	1.550	.456	.788
TA* SP	4	.000	54.521	.346	1.124	.390	1.035	.337	1.143

4.5 Correlation of Anatomical Properties with Density and Mechanical Properties.

The air dry and basic density correlated moderately with fibre proportion (FP) ($r = 0.37$, $p > 0.05$; $r=0.55$, $p<0.05$, respectively) and fibre length (FL) ($r = 0.55$, $p < 0.05$; $r = 0.31$, $p > 0.05$) respectively.(Table4.9). The correlating of double wall thickness with air dry density ($r = 0.28$, $p > 0.05$) were positive but not significant. MoE correlated positively and significantly with fibre width ($r = 0.48$, $p < 0.05$ and double wall thickness ($r = 0.50$, $p < 0.05$). Unexpectedly, both air dry density and basic density correlated negatively with MoE and MoR. The correlation of the fibre length with shear strength was positive and significant ($r = 0.58$, $p < 0.05$) whereas air dry density and basic density correlated positively with shear strength and compressive strength (Table4.9).

Table 4.9: Correlations of anatomical characteristics and the mechanical properties of teakwood from guinea savanna, Ghana

	VP	AP	FP	RP	FL	FW	L	DWT	AD	BD	MoE	MoR	CMS	SS
VP	1													
AP	.43	1												
FP	.02	.15	1											
RP	-.45	-53*	.7*	1										
FL	.23	.55	.03	-.16	1									
FW	-.30	77**	-.15	.35	-.35	1								
L	-.25	74**	-.24	.37	-.36	.99**	1							
DWT	-.27	70**	-.09	.31	-.34	.98	.97*	1						
AD	.48*	.17	.37	-.43	.55*	.24	.22	.28	1					
B D	.28	.16	.5*	-.4*	.31	.21	.19	.25	.86	1				
MoE	-84**	-.32	-.10	.29	-.25	.48*	.47	.50*	-.33	-.23	1			
MoR	-.43	-.06	-.41	.6*	.34	-.11	-.11	-.17	-.26	-.27	.21	1		
CMS	0.44	.08	.29	-.39	.23	-.28	-.32	-.39	.27	.22	.57*	.15	1	
Shear	.018	-.17	-.07	.35	.58*	.24	.21	.27	.52*	.25	-.15	.22	-.12	1

VP= vessel proportion; AP= axial parenchyma; FP= fibre proportion; RP= radial parenchyma proportion; FL= fibre length; FW= fibre width; L= lumen; DWT= double wall thickness; AD= air dry density; BD= basic density; MoE= modulus of elasticity; MoR = modulus of rupture; CS= compressive strength; SS= Shear strength.

CHAPTER FIVE

DISCUSSIONS

5.0 Introduction

This chapter analyzed and discusses the findings and opinions about the results. The analysis covers the basic density of fresh wood samples, oven drying, the strength properties of *T. grandis* at 12% mc for strength test conducted and some anatomical properties of *T. grandis*.

5.1 Wood Density of Teakwood

The comparison with wood density values reported in the literature for *T. grandis* showed similar mean values and variation. In general, older trees are expected to exhibit higher density values then young ones. A reverse trend was reported by Wanneng et al, (2014) where younger teak trees exhibited relatively higher density values then the older ones. The authors reported that mean air-dry density of 10-year-old was 714kgm^{-3}while 15-year-old 696kgm^{-3}, 20-year-old 708kgm^{-3} and 25-year-old 663kgm^{-3}. The results of this study confirmed this trend in density with respect to tree age. Air dry increased from 10-years –old to 15-year-old and decreased in the 20-year-old. The same trend was found for the basic density where is oven dry density showed a decreasing trend with respect to age. The range of 465 to 518kgm-3 for density was lower than the range (579 to 633kgm-3) for 50- 70-year-old teak trees sampled from East Timor (Miranda et al, 2011). However, the range found in this study was comparable to that reported for basic density by Wanneng et al. (2003).

The mean air-dry density found in the present study was slightly lower than the mean values (664 to 714 kgm-3) reported by Wanneng PX et al. (2014) reported for 10 to 34-year- old plantation teak from Panama (Posch et al. 2004). Bhat and Priya (2004) reported lower values of air- dry density for 21- and 60-year-old teak plantations in India. Factors that might have had influence on the density values include the growth rate (tree age), plantation site (soil), geographical location and climate (wind and annual rainfall) (Wanneng PX et al. 2014). The lower wood density values observed for teakwood could be attributed to a lower rainfall. This site experiences only three months of rainfall (July to September) and the monthly precipitation ranges from 200mm to300mm. Regarding the longitudinal variation of teakwood density, it was fond that in general, the bottom potion was lower in wood density than the top portion. This trend has been reported by other authors, including Perez and Wanneng (2003) and Moya and Ledezma (2003).

5.2 Mechanical Properties

The mechanical properties of teak wood from the guinea savanna of Ghana are similar to values reported for teakwood from origins. The average MoE values (9433 to 10404Nmm^{-2}) were similar to those published by Mivanda et al. (2014) for teak in East Timo (10684Nmm^{-2}), by Bialleres & Durand (2000) for teak wood of different origins (7848Nmm^{-2}), and by Bhat & Priya (2004) for 21 and 65- year-old teakwood from India (8436 – 17580Nmm^{-2}).

Teakwood MoE did not vary with tree stem position and between trees but varied with tree age (Table 4.4). The relative stability of MoE across tree height indicates that stiffness of teakwood would be constant across the height and would not pose any engineering problem during utilization. The mean bending strength (MoR) of 71- 80Nmm^{-2} was somewhat lower than the values reported for teakwood from Panama (105Nmm^{-2}, Posch et al, 2004), Bhat and Priya, (2004) reported values of 133.2 and 91.8Nmm^{-2} for 21-year-old plantation. The lower MoR values fond for teakwood from the guinea savanna, Ghana, suggests that they could be used for high construction. The significant variability of MoR along the height of the teak trees indicates quality problem in respect of bending strength.

The mean compressive strength (MCS) found in this study (49- 54Nmm^{-2}) was comparable to the values reported for 50- 70-year-old teak trees from East Timo (50Nmm^{-2}, Miranda et al, 2011), 50Nmm-2 reported by Posch et al, (2004), 44.4- 65.9Nmm^{-2} by Bailleres and Durand (2000) and 44.6- 53.9Nmm-2 for slow- and fast growth 21-year-old plantation teak trees (Bhat & Priya, (2004). Mean compressive strength of teakwood from guinea savanna did not vary significantly with tree height and thus no technological problems would be posed in the utilization of such teakwood.

5.3 The Anatomical Characteristics of Teakwood

Figures 4.1 to 4.9 the anatomical structure of teakwood, and Table 4.5 to Table 4.7 summarizes the dimensions and proportion of tissues in the studied trees. The fiber proportion and dimensions (length and diameter) decreased with tree height and fiber wall thickness remained constant across the height (Table 4.5), but the differences were only statistically significant for fiber length and diameter ($p < 0.05$). The same trend of variation was found in 15-, 20- and 25-year-old teakwood from Nigeria (Izekor & Fuwape (2011) and in 15-year-old trees from Malaysia (Josue & Imiyabir, (2011). The number of vessels per mm^2 varied axially with an increasing frequency of vessels towards the top, while the proportion of vessels tended to increase from base to middle and then decreases to the top (Table 4.5). The height level was a statistically significant ($p<.000$) source of variation for the frequency of vessels but was not significant for the proportion of vessels. The proportion of ray parenchyma increased from the base to the tree top, although not linearly i.e., rays proportion increased from base to middle and then decreased for the top. (Table4.5) also indicated that, length of the vessel elements is similar to the few reported values: 279 µm (Ahmed and Chun 2011), 250 µm (Freitas 1958) and 244 µm (Freitas 1963). The vessels were more abundant compared to other reported values of 4–9 vessels/mm^2 (Richter and Dallwitz 2000), 6 vessels/mm^2 (Ahmed 2011), 2–6 vessels/mm^2 (Freitas 1958) and 4–8 vessels/mm^2 (Freitas 1968).

Table 4.7 reports the average vessel area and tangential diameter of vessels decreased from base to the top, while vessel length increased from base to top. The decrease of vessel area and proportion with the concomitant increase of vessel frequency from base to the top of the tree has been reported by Fichtler (2012) for tropical trees, although the vessel proportion was quite variable and influenced by ring width differences. This was not the case in the studied trees for which (Sousa et al. 2012) showed a small and insignificant axial variation of ring width. the average fiber width of 20 µm is similar to the values reported by (Josue 2011, Moya et al, 2009 and Freitas 1958) respectively, 35 µm (27–46 µm), 21–29 and 25 µm, and larger than the 15 µm (17–20 µm) reported by (Tewari 1999). The fiber wall thickness and lumen diameter were on average 14 µm and18.11, respectively, which were higher than the values of 3.6 and 4.0 µm, 4.0 and 3.2–5.7 µm reported by Freitas (1958), Tewari (1999) and Moya et al. (2009), respectively. The diameter of fiber lumen was in the range of the 11–20 µm reported by (Moya et al. 2009).

Table 4.7. Reports the correlations of anatomical properties with air-dry density and Compressive strength. The relationships between anatomical properties and air-dry density deserve considerable attention, because air-dry density is the most important determinant of compressive strength and bending strength in teakwood species. Double wall thickness and fibre length, fibre width and lumen are major factors in the variation of wood density (Panshin and de Zeeuw 1980). In the present study, fibre length was correlated with air-dry density, while fibre wall thickness was positively correlated. The MoE increases positive to fibre width and double wall thickness, while the compressive strength is correlates positively with fibre length.

In addition, the average vessel diameter showed a significant positive correlation with air-dry density (Table 4.7). In contrast, increased fibre diameter significantly decreased air-dry density and compressive strength. There was a strong positive correlation between the proportion of cell wall and both air-dry density and compressive strength.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This study was conducted to evaluate the axial variation of the physical, anatomical and mechanical properties of *T. grandis* trees at different ages. The measured physical properties, which included basic density, green density, air dry density and oven dry density). The mechanical properties investigated were static bending, compressive strength parallel to grain and shear strength parallel to grain. The overall objective was to evaluate the influence of anatomical properties of *T. grandis* on physical and mechanical properties.

6.2 Summary of Findings

A summary of findings is presented under the following objectives:

1. To compare the axial variation in physical properties (basic density, green density, air dried density and oven dried density) of *T. grandis* trees of ages 10, 15 and 20 years.
2. To investigate the axial variation of mechanical properties (static bending, compressive strength parallel to grain and shear strength parallel to grain) of *T. grandis* of different ages.
3. To evaluate the influence of anatomical properties of *T. grandis* on its physical and mechanical properties (fibre biometry and wood tissues proportion) of *T. grandis*.

Objective one: the objective one of the study was to compare the axial variation in physical properties (basic density, green density, air dried density and oven dried density) of *T. grandis* trees of ages 10, 15 and 20 years.

The main finding s of the study in relation to objective one was as follows:

1. The mean basic density values of *T. grandis* were 503kg/m^3, 518kg/m^3 and 465kg/m^3 for 10, 15 and 20-year-old teak, respectively.
2. The mean green density values of the species were 796kg/m^3, 853kg/m^3 and 754kg/m^3 for 10, 15 and 20-year-old teak, respectively.
3. The mean air-dry density values were 663kg/m^3, 689kg/m^3 and620kg/m^3 for 10, 15 and 20-year-old teakwood, respectively.
4. The mean oven dry density values were 612kg/m^3, 602kg/m^3 and 540kg/m^3 for 10, 15 and 20-year-old teakwood, respectively.
5. In general, wood density of teak was found to increase from 10-year-old to 15-year-old teak and drops in the 20-year-old.

Objective two: the second objective of the study; ought to compare the axial variation of mechanical properties (static bending, compressive strength parallel to grain and shear strength parallel to grain) of *T. grandis* of different ages.

The main findings of the study in relation to mechanical properties of teakwood samples used were as follows:

1. The mean bending strength (MOR) of 73 N/mm^2, 71N/mm^2 and 80Nmm^2 reported for 10, 15 and 20-year-old teak are somewhat lower than the values found for teak wood of other origins

2. The mean compressive strength (MCS) values were 49 N/mm^2, 54N/mm^2 and 52N/mm^2. These values were similar to what was reported in the literature.
3. The mean Modulus of Elasticity (MoE) values of 10404N/mm^2, 9433N/mm^2 and10047N/mm^{2}found for 10, 15 and 20-year teakwood were similar to the reported values in the literature.
4. The Shear strength mean value reported with marginal different of 16N/mm^2, 15Nmm^2 and 14Nmm^2 respectively.

1. **Objective three: the objective three aimed at evaluating the influence of anatomical properties (fibre length, the double wall thickness, fibre lumen, fibre proportion, vessel proportion, axial and ray parenchyma proportion) on its physical and mechanical properties of *T. grandis*.**

The main findings of the study regarding the influence of anatomical properties on the physical and mechanical properties of *T. grandis* were:

1. The proportion of vessels per mm^2 tends to decrease from the bottom to the top of 10, 15-year-old teakwood while a reverse trend was observed for 20-year-old.
2. Fibres were the most abundant tissue in the teakwood account 52 % of the cross-sectional area. The fibre proportion and dimensions (length and diameter) decreased with tree height and fibre wall thickness remained constant across the height
3. The mean proportion of axial parenchyma of 14 % was lower compared with the values reported in the literature i.e., 24–31 and 26–27 % in 21- and 65-year-old plantation, respectively.

4. The proportion of ray parenchyma increased from the bottom to the top, although not linearly i.e., ray proportion increased from bottom to middle and then decreased in the top.
5. This variation in the vessel biometry is indicative of the adaptation of teak to local growth conditions, mainly rainfall and water availability, or by inheritance as suggested by (Nocetti et al. 2011) and is certainly of factor contributing to the high adaptability of teak to several environments.
6. Air dry density and basic density were found to correlate positively with fibre length, double wall thickness and fibre proportion even though the correlating to coefficient was low.

6.3 Conclusion

From the finding of the study, the following conclusion can be drawn.

1. The density values of 10, 15 and 20-year-old teakwood found in this study were within the range of reported values in the literature. Teak trees of 10-20-years investigated in this study have density values comparable to older trees and therefore can be utilized for construction purposes.
2. The bending strength values of the teakwood were also similar to the reported values for older teak trees. The bending strength of the teak trees investigated is there not inferior to the reported values of the teak trees elsewhere.
3. The anatomical properties of the teakwood investigated predicted the density and bending strength fairly well.

6.4 Recommendation

The study recommends that,

The 10 and 15-year-old teak wood would be acceptable for verities of wood products for both outdoor and indoor service conditions for domestic and international markets. However, it is critical that proper processing and manufacturing procedures are applied to allow the products meet international quality requirements, product standards and specifications. Base on the teakwood property results, rotation age between 10 and 15-years would be suitable for harvesting.

6.5 Suggestion for Further Research

1. This suggests that other factors may influence the properties of plantation –growth teak. Therefore, it is highly recommended that future research should determine not only the relationship between wood properties and growth rate of trees but also external factors such as site (soil, altitude), tree genetics, wind and methods of management.
2. To compare coloure variation of teakwood between trees and other geographical location.
3. To compare the strength properties of unmanaged, that is natural and plantation teakwood.

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