KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

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DEPARTMENT OF WOOD SCIENCE TECHNOLOGY

ASSESSING THE PHYSICAL AND CHEMICAL PROPERTIES OF 15 YEAR OLD NORMAL AND COPPICED TEAK (*Tectona grandis*) WOODS FOR THEIR EFFECTIVE UTILIZATION

By

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15YEAR OLD NORMAL AND COPPICED TEAK (*Tectona grandis)*

WOODS FOR THEIR EFFECTIVE UTILIZATION

By

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DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

The increasing demand for timber in Ghana has placed much pressure on some of the timber species whose technical information is known. The incumbent trend of deforestation has posed a threat on the sustainability of the country's timber resources in the near future if adequate measures are not put in place to curb this problem. To this effort many exotic species have been introduced into the country and raised in plantations both on and off reserves to supplement the timber in the natural forest. Among these exotic species is the *Tectona grandis*. Despite the establishment of these hardwood species in plantations, wood users do not have adequate information which will encourage the maximum utilization of these species. The study was aimed at evaluating the physical which were moisture content, density the shrinkage and swelling while chemical properties were cellulose, lignin, extractives and holocellulose of coppiced teak wood and comparing to normal teak wood at the age of 15 years for its utilization. Three trees each were selected from plantations of the normal teak and the coppiced teak for the study. These trees were cut into three height portion (butt, middle and top) and wood samples selected for the test. For physical properties, 36 samples were taken from each height portion of which 18 samples each were taken along the radial direction of the stem (heartwood and sapwood). Samples for chemical analyses were taken from these samples tests of both heartwood and sapwood. These samples were replicated three times for each of the test samples. The mean values for moisture content were 49.07% and 48.73% for the normal and coppiced teak woods respectively. Density values were 842.95 kg/m^3 and 835.51 kg/m^3 respectively for normal teak wood and coppiced teak wood. Shrinkage values were 7.39% and 7.38% for coppiced and normal teak wood respectively. Coppiced teak wood swells (1.04%) more than that of the normal teak wood (0.98%). The highest density of *Tectona grandis* was

found at the butt portion, followed by middle and top portion. Along the radial direction, it showed that the density was highest at sapwood followed by the heartwood. Percentage of moisture content increased from butt to top portion. Tree portion did not affect the lignin content, cellulose content, holocellulose and hemicellulose contents. From the study, the normal teak wood was proven to be better than coppiced teak wood in terms of both physical and chemical properties, but the coppiced teak wood can be utilized, in some respect, as a suitable substitute to the normal teak wood.

DEDICATION

I dedicate this thesis to my husband, Mr.Alexander Oppong, and children, Marina Oppong Abina, Krista Oppong Badu and Gideon Oppong Fernando.

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I thank the Ebenezer God for His protection throughout this period of my education. I extend my sincere gratitude to my supervisors Dr. N.A. Darkwa and Dr. Kojo Agyapong Afrifah and my HOD Prof. Antwi Boasiako Charles for their immeasurable assistance. I again acknowledge the contribution of the Teaching and Research Assistants of Wood Science and Technology especially Mr. Kwadwo Boadu Boakye and Mr. Enoch Adjei Mensah.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Wood is the hard fibrous material which forms the main substance of the trunk and branches of a tree or shrub. Wood has many desirable features that make it a material of choice for many projects especially in construction and furniture making. Contained in wood are many chemically derived products including charcoal, dyestuffs, explosives, cellophane, lacquers, yeast and turpentine. The main constituents of all woods are the cellulose and lignin. The quality of wood for a particular purpose is not only influenced by these constituents but also its properties such as density, natural durability, ease of working (Reid, 2009).

Ghana is endowed with forest resources which are essential for the country's development and contribute to the welfare of most Ghanaians and future economic prosperity of the nation. About 680 different tree species are found in the forest reserves of Ghana. Approximately 420 of these species attain timber size whereas 126 of them occur in sufficient volume to be considered utilisable as a raw material base for the timber industry of the country (Ghartey, 1989). Nonetheless, just about 10 species contribute 90% to the wood product export earnings (Jayanetti *et al.*, 1999), with 4 species contributing about 60% of the total production.

The dependence of the timber export trade on few species represent an inefficient utilization of the timber resources. Improved utilization of these wood species can help increase economic value of the country and thus improve the chances of sustainable management (Ofori and Brentuo, 2005). The over reliance on the few timber species is a major problem confronting Ghana's timber industry and sustainable management.

Amelia and co-workers (2007) asserted that, wood has dropped from 8,000,000 hectares to 1,600,000 hectares over the last century. Tamakloe (2011) estimated logging of Ghana's high forest to over 90% since the late 1940s and the rate of deforestation to be 5% in the offreserves and 2% in the reserves. According to the Forestry Commission of Ghana, the rate of deforestation in Ghana is estimated at 65,000 hectares per annum. This estimate establishes a severe deforestation pattern and devastation repercussions for the forest resources in the near future (Tropenbos, 2005).

Notwithstanding these consequences, the demand for wood produce will continue to increase due to the growing numbers of the Ghanaian population and rising standards of living of the people. In order to meet the demand for wood on sustainable yield basis, the wood supplied from the natural forest need to be supplemented. Consequently, certain hardwood tree species such as *Tectona grandis* (teak), *Nauclea diderichii, Mansonia altisima* have been raised in plantation on and off reserves to supplement wood supplied from the forest.

One species that has been widely established in plantations throughout the tropics because of its good growth and stem form and its ability to produce high quality timber is the *Tectona grandis* (teak). Teak grows very fast and survives a wide range of climatic conditions. It thrives best in fairly moist regions (Thaiusta, 1999). Many factors including site, seed supply and seed quality affect the success of teak planting.

There are three main practices that can be observed in order to regenerate harvested *T. grandis* plantations (Kadambi, 1972; Street, 1962). These practices are by seeding, coppicing and root-shoot cutting. Coppiced teak trees tend to grow faster than seeded teak trees so Ghanaians are now tending to use coppice teak trees for regeneration instead.

1.2 Statement of the Problem

Fast grown woods appear to have properties different from normal wood. Coppiced woods turn to grow faster. Therefore, it is anticipated that coppiced teak wood would have properties different from their normal wood. However, it is the availability of substantial scientific knowledge on the physical and chemical behaviour of plantation grown coppiced wood that will make it possible to develop more efficient methods of using it as a structural material (Izekor and Fuwape, 2010).

1.3 Aim

This study was aimed at evaluating the physical and chemical properties of coppice teak wood in order to ascertain how it compares to the normal teak wood and gain knowledge on how best to utilize it.

1.4 Activities

1.0 Physical properties (the moisture content, density, shrinkage and swelling) of coppice and normal teak woods.

2. Chemical properties (cellulose, lignin and hemicellulose) of coppice and normal teak woods.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Classification and Distribution of Teak

Teak (*Tectona grandis* Linn. f.) is one of the tropical hardwood species from the family verbenaceae. It is an important timber species with worldwide reputation (Banik, 1993). It is naturally endemic to Thailand, Peninsular India, Myanmar and Laos. Teak was first introduced in plantations in Java (White, 1991) and also cultivated in the South and SouthEast Asia, South and Central America, the Pacific, Africa and the Caribbean Islands (Tewari, 1992).

This tree can grow to a height of 30 – 40 cm. It has fluted bole and sometimes possess slight buttress (Keay, 1989). Teak has been successfully established and rated as one of the fastest growing timber species in many other countries of the world including Ghana. Teak can grow up to an age of 100 years. It sheds its leaves annually at dry season as part of its cycle of life. Its world-wide demand is attributed to its high quality timber on account of the attractiveness and sturdiness of the wood it produces (Goh *et al*., 1997; Sarre and Ok-ma, 2004). The tree has a straight trunk, thick base, a spreading crown, and four-sided branchlets. The leaves, rough in texture, are opposite or whorled, and every branch ends in many small white flowers. The heartwood is golden – yellow colour, has a pleasant and strong aromatic fragrance. Its beautiful colour darkens into brown and moulted with darker streaks when seasoned.

2.2 Teak as a Building Material

Wood properties of *T. grandis* include its resistance to all kinds of weather or non-corroding properties, its solid fiber and elasticity, facilitate eases of working. The durability of Teak products is the oil in its heartwood. This special oil content makes the wood always seen gleam and maintains this glow when left outside for a long period of time. In addition, Teak wood will not be brittle due to its anti-bacterial characteristics. Machining is relatively straight forward. Boring, gluing, moulding, nailing, planning, sawing, veneering, and turning do not present major problems (Keogh *et al*., 2001). *T. grandis* has numerous end uses including ship building, marine construction and furniture making. It is suitable for carving and lasts long in contact with the ground. Its high resistance to chemicals makes it ideal for laboratory benches. The wood is ideally for constructional works where exposed to the weather e.g. Doors, windows, frames, trellis work, garden furniture etc. (Keogh *et al*., 2001). *T. grandis* wood, which is certified on the basis of social and environmental practices throughout its entire forest and wood chain, has a bright future as an industrial raw material .For this reason, the species is likely to retain its importance as the major high grade plantation species for tropics into the foreseeable future and adequate information on their strength properties is required for maximum utilization especially those from off reserve areas (Keogh *et al*., 2001).

2.3 Factors Affecting the Physical Properties of Wood

There are several factors affecting the strength of timbers and the nature of the material is such that widely differing results can be obtained from differing specimens of the same species (Taylor, 1991).

2.3.1 Moisture Content

Dinwoodie and Desch (1996) defined moisture content of wood as the mass of water in the wood piece expressed as the percentage of the oven-dry mass of that piece. It has influence on all the properties of wood.

Panshin and de Zeeuw (1980) asserted that below the fiber saturation point, most of the strength properties wood vary inversely with its moisture content. Below the fiber saturation point, as the moisture content decreases the adsorption force that holds water to the wood becomes greater. Hence, as wood approaches the dry condition, low adsorption of polymonomolecular is involved.

Wood is a hygroscopic material that absorbs and losses moisture from and to the environment. The moisture content of wood is a function of atmospheric conditions and depends on the relative humidity and temperature of the surrounding air (Arntzen and Charles, 1994). Wood reaches equilibrium moisture content (EMC) when temperature and humidity is constant. Under this condition, the wood neither gains or losses moisture to the environment. At EMC wood is in symmetry with its environment (Arntzen and Charles, 1994).

In structural applications, moisture content of wood undergoes gradual and short-term changes with varying temperature and humidity conditions of the prevailing environment.
These changes affect only the surface of the wood. Wood in service requires time to reach its EMC and this is dependant basically on the (a) size and permeability, (b) temperature and the moisture difference and (c) EMC potential of the members. According to Arntzen and Charles (1994), fluctuations in woods moisture content cannot be stopped entirely but can be minimized by the application treatments or coatings on the surface of the wood.

2.3.2 Location of Water in Wood

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

i. Free,

ii. Water held in the cell cavities (lumen), iii. Vapour in the air part of cell cavities not occupied by liquid, and iv. Bound (or Hygroscopic) water absorbed primarily on the cellulose and hemicellulose molecules which constitute the greater part of wood substance, i.e. the cell walls.

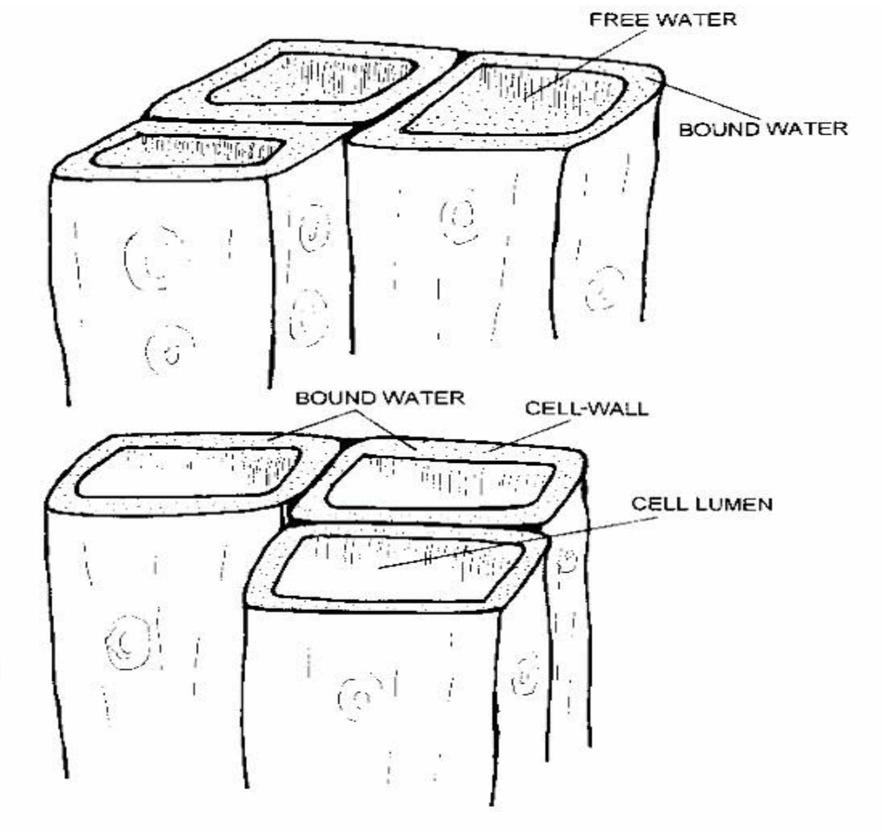

Figure 2.1 Location of water in wood cell

2.3.2.1 Free Water

Free water (or polymolecularly adsorbed water) is contained in the cell lumen (the primary pore space) or less mechanically by surface tension forces rather than molecular attraction (Figure 2.1). The water in general does not fill the lumen entirely, and in such case the lumen contains water, water vapour, and air or gases such as CO_2. When water does fill the lumen completely (as in some Australian eucalypts), the condition tends to retard moisture movement during drying and contributes to a seasoning defect called “collapse”. The quantity of free water present is limited by the porosity or fractional void volume of the wood (Ofori, 2004).

2.3.2.2 Bound Water

Bound water (monomolecularly adsorbed water, hygroscopic water, or imbibed water) is contained in the cell walls (the secondary pore space) i.e. transient cell wall capillaries and the amorphous regions of the cellulose micro fibrils. The hydroxyl groups of cellulose molecules in the amorphous regions attract molecules of water and are linked to them by hydrogen bonding (Ofori, 2004b).

2.3.3 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 24 – 30%. It varies with different wood species and somewhat within individual pieces of wood. 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 behaviour of wood, and hence is of primary importance. Shrinkage is normally defined as the reduction in size which occurs 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, and better gluing characteristics and nailholding 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, iii. Analysis by the polymer exclusion technique (Stamm, 1971).

2.3.4 Moisture Content Determination

There are several ways of determining the moisture content of wood, but by far the most satisfactory for most purposes is the gravimetric or oven dry method.

2.3.4.1 Gravimetric or Oven-Drying Method

The standard gravimetric or oven-drying method of moisture content determination is to dry the wood in an oven to constant mass at 103±2˚C. This procedure reduces the sample moisture content to a low value at equilibrium with a relative vapour pressure sufficiently close to zero that the sample is assumed to have attained its dry weight, W_o. The method is accurate throughout the whole range of moisture content, but it is destructive (i.e. cutting), time consuming and inadvertently causes the evaporation of volatile constituents other than water from the wood during drying in the oven (Ofori, 2004).

2.3.4.2 Hygroscopic Method

In a hole (6 mm diameter, 95 mm length) freshly drilled into a piece of wood, the relative humidity corresponds to moisture content of the surrounding wood. Thus it is possible to measure the MC of the wood by hygrometer. Measurements are restricted to the range between 3 and 25% moisture content. The instrument consists of a perforated tube containing a string of hair which changes its length in response to changes in humidity. Samples are first conditioned to intermediate moisture content in the hygroscopic range (Ofori, 2004).

2.3.4.3 Distillation Method

The evaporation of volatile components other than water during drying may cause substantial errors in the gravimetric method of measuring moisture in wood. If the wood contains volatile substances, such as resins, solvent extraction is employed. Boiling the wood sample in a water-immiscible liquid which is a solvent for volatile extractive compounds, [such as toluene, xylene, and trichloroethylene] to dissolve the volatile substance, water is distilled from the wood, at the same time and is collected in a reflux condenser system and separated from solvent by means of a calibrated trap. By taking the weight of the water collected, and the weight of the dry wood sample, the moisture content of the extractive-free wood can be calculated (Ofori, 2004).

2.3.4.4 Kari Fischer Titration Method (KFTM)

The KFTM for determining the moisture content of wood is another technique which is particularly useful for material containing volatile extractives. This technique has been found to give low moisture content values as compared to the oven-drying method for some species believed to contain volatile oils. In this method the water content is measured by titration using a methanol solution of sulphur dioxide, iodine, and pyridine. At the end point of titration free iodine appears which can be detected either visually or potentionmetrically, the latter method giving precise results (Ofori, 2004).

2.3.4.5 Electric Moisture Meters

Electric moisture meters permit the determination of moisture content without cutting or mutilating the board. They are very rapid and simple to use. Electric moisture meters rely on the increase in direct current [dc] resistivity and the decrease in the alternating current [ac] dielectric constant as timber dries below the fibre saturation point (FSP).

2.3.4.6 Electric Resistance Moisture Meter

The electric resistance moisture meter expresses moisture content in wood as a function of dc resistivity. The meters are generally supplied with pin-type electrodes [e.g. 2 or 4 phonograph needles] that are driven into the wood being tested. The dc resistivity decreases strongly with increasing temperature and is affected by the presence of electrolytes like extractives and moisture gradients over the depths penetrated by the electrodes of the instrument. The instrument must therefore be calibrated for a given temperature range and the kind of wood. The instruments are useful only over a total range from 7 to 25% moisture content in the wood (Ofori, 2004).

2.3.4.7 Capacitance Type Moisture Meter

The Capacitance type moisture meter relies on the increase of dielectric constant of dry wood [of about 2] with increase in moisture content which approaches 81 of a fully saturated wood above FSP. The Instrument uses integral surface-contact-type electrodes [usually 4 or more metal segments] which are pressed against the timber under test. The electric field radiating from the electrode penetrates about 20 mm into the wood so that timber thickness to about 40mm may be tested. This has an advantage over dc resistivity meters since the readings are not affected by ash or mineral content. It can also be used to measure relatively accurately moisture contents below 8%. However, readings must be corrected for density variations within the timber (Ofori, 2004b).

2.3.5 Density of Wood

The density is the mass per unit volume of a given substance. It is expressed either in; (a) kilograms per cubic meter (kg/m^3), (b) pounds per cubic foot (lb/ft^3), 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 proviso that clear, straight grained, and free from defects are prerequisite to its application.

According to Forest Product Laboratory (FPL) report 2010, the density of oven dry wood varies significantly between species. The report further stated that within a given species, variation in oven dry density can be attributed to the anatomical characteristics of wood such as early wood to latewood and heartwood to sapwood ratios.

Wood density has influence on the strength of timber, pulp yields, fuel values and numerous other important properties (Reid, 2009). Even though the wood of some species is naturally heavier than others, it is important to appreciate density variations within the tree. According to Kollman and Cote (1984), wood density is strongly related with strength properties, for example compressive strength and bending strength. Chowdhury *et al.* (2009) in related study asserted that, compressive strength is related to density and it increases from the pith to the bark. Wood density is a complex trait, especially in angiosperms, where fibers and vessels are surrounded by other cells and vessels are surrounded by other cells, for example rays and parenchyma (Zhang and Zhong, 1992).

2.3.6 Shrinkage and Swelling

Wood changes dimension, (shrinkage and swelling,) take place below the FSP where all of water exists only within the cell wall. Shrinkage and swelling is proportional to the amount of water exchanged between a piece of wood and its environment. Wood is an anisotropic material – its dimensions change differently the in three principal directions: tangentially, radially, and longitudinally. The highest rate of change is observed in the tangential direction basically due to parallel orientation of microfibrils along the axis of the cell wall. Following tangential shrinkage is the radial whereas longitudinal shrinkage is negligible for normal mature wood and for most practical applications. Tangential shrinkage in wood therefore is approximately twice radial shrinkage. Figure 2.2 shows the swelling of blocks in the three principal directions.

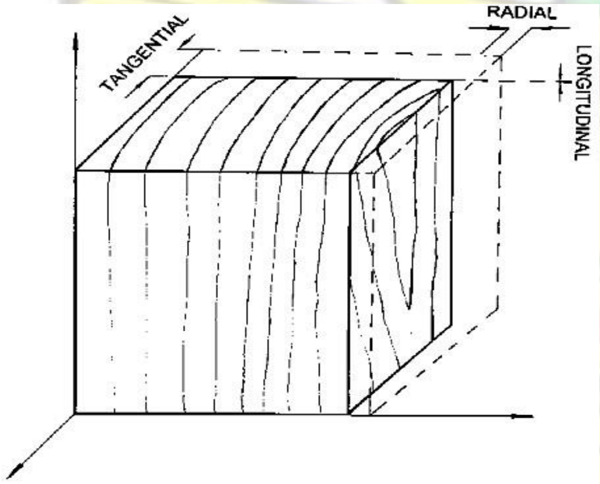

Figure 2.2, Swelling of block of wood in three directions (dotted lines)

Generally, shrinkage and swelling is expressed as percentage and can be calculated using the formula:

$$Shrinkage\ or\ Swelling, \%\ = \frac{Change\ in\ dimension\ or\ volume}{Initial\ dimension\ or\ volume} \times 100$$

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 lignocellulosic 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.

2.3.7 Heartwood and Sapwood

The dark-coloured centre portion of wood is the heartwood whereas the lighter tissue is known as the sapwood. Heartwood always contains amount of extractives higher than the sapwood and extractives do inhibit normal shrinkage by bulking the amorphous regions in the cell wall structure (Chong and Fogg, 1989).This explains why heartwood shrink less than the sapwood and which affects the physical properties of wood.

2.3.8 Rays

Rays provide pathways where sap can travel horizontally to and from the phloem. Virtually all woods contain rays (Wheeler *et al.,* 1986). They have an effect on wood properties, for instance, rays restrain dimensional change in the radial direction. Their presence is somewhat responsible for the fact that upon drying, wood shrinks less radially than it does tangentially (Frey-Wyssling, 1963).

2.3.9 Effect of Grain Direction on Shrinkage

Wood is not homogenous material with equal shrinkage in all directions. Its anatomical structure results in shrinkage behaviour 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^{o} C to15^{o}C 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 S_L 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 S_R ranges from about 3 to 6% and tangential shrinkage S_T from 6 to 12% for some Ghanaian species (Ofori *et al*., 2009).

2.3.10 Effect of Moisture Content on Shrinkage

The most important factor affecting shrinkage is the change in moisture content below FSP. Shrinkage is found to be directly proportional to the amount of water removed from the cell walls. Shrinkage is expressed as a percentage of the green dimension stable at all moisture contents above FSP. At zero moisture content, maximum shrinkage is attained. As wood dries, the surface of the wood normally dries first, and its moisture content may be considerably below the FSP while the core remains wet, at this stage the moisture content of the wood is comparatively high.

2.4 Chemical Properties of Wood

Wood is primarily composed of lignin, cellulose, hemicelluloses, and extractives. Each of these components accounts for the wood's properties, which ultimately impact properties of the product made from the wood (Sjostrom, 1993). Wood is a three dimensional biopolymer composite composed principally of carbon, hydrogen and oxygen. Wood also contains inorganic compounds that remain after combustion in the presence of oxygen. Wood is connected with chains of cellulose, hemicellulose and lignin with little amounts of inorganic compounds and extractives (Brown, 1997). In addition to these major constituents, the cell wall also contains pectins and extractives.

2.4.1 Holocellulose in Wood

Holocellulose is the combination of 40 – 45% of cellulose and 15 – 25% of hemicelluloses which accounts 65 – 70% of the weight of dry woods. The cellulose and hemicelluloses form the major carbohydrate content of the wood. There are also little amounts of other sugar polymers such as starch and pectin (Stamm, 1964).

2.4.2 Cellulose

Cellulose is produced from a glucose-based sugar nucleotide. A nucleotide is a compound derived from combining a sugar with a phosphate group and a base that is a component of RNA or DNA (Kozlowski and Pallardy, 1997). Cellulose is a linear polymer of (β-1→4) D – glucopyranose. It occurs primarily in the S_2 layer of the cell wall of wood and is present in only smaller quantities in the compound middle lamella. It increases as a proportion of dry weight of the cell wall through the center of the S_2 layer. Wood cellulose is about 60 to 70% crystalline and 30% amorphous (Kollman and Cote, 1968).

Cellulose chains are grouped together into microfibrils arranged in a helical structure in each layer of the wood cell wall. Cellulose is the strongest polymer in wood accounting for strength in the wood fiber because of its linear orientation and high degree of polymerization. Cellulose dissolves in strong acids and insoluble in alkali. The structure of cellulose can resist failure in tension (Sjostrom, 1993).

2.4.3 Holocellulose

The carbohydrate portion of wood is composed of cellulose and hemicellulose with minor amounts of other sugar polymers such as starch and pectin (Stamm, 1964). Holocellulose is the combination of cellulose (40 – 45%) and the hemicelluloses (15-25%). The number of glucose molecules is referred to as the degree of polymerisation

2.4.4 Lignin

Lignin is a three dimensional polymer composed of phenyl propane units. It has irregular structure and cannot be isolated from wood without degrading the wood (Kollman and Cote, 1968). Lignin is found between individual cells and within the cell walls. It serves as a binding agent between the individual cells whilst within the cell walls, lignin is very closely related with cellulose and the hemicelluloses to give rigidity to the cell (Peng *et al.,* 2002). The compound middle lamella has higher lignin content and is highly concentrated throughout the secondary wall.

2.5 Factors Affecting the Chemical Properties of Wood

2.5.1 Juvenile wood

Juvenile woods have high compression wood than matured wood and hence have smaller cell diameter and larger micro fibril angle. For density, mature wood is higher as compared to juvenile wood. For its chemical composition, juvenile wood have less of cellulose and more of the hemicelluloses and lignin as compared to mature wood. Nonetheless as the cell matures, there is a progressive increase in cellulose content and a progressive decrease in the hemicellulose content. As their cell matures their lignin content decreases more rapidly (Pashin and de Zeeuw 1980).

2.5.2 Sapwood and Heartwood

Sapwood is actively conducting portion of the stem in which the parenchyma cells are alive and metabolically active. It does not only conducts the sap but also responsible for the storage and synthesis of biochemical (Simpson, 1991). The heartwood is the dark – coloured wood whiles the sapwood is the band of light – coloured wood next to the bark. The formation of heartwood is aided by the living cells at the sapwood which is actively synthesizing and translocating biochemicals. Living cells at the outer edge between heartwood and sapwood which are concerned with assembling and deposition of heartwood chemicals leading to heartwood formation (Hillis, 1996). Parenchyma cells at the heartwood-sapwood boundary are responsible for the formation of extractives. These extractives are exuded through pits into adjacent cells (Hillis, 1996). Heartwood is more resistant to acid than its sapwood because of its higher extractives content and lower permeability (Stamm, 1964). Heartwood stores biochemical substances (extractives) of many varieties depending on the species.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

3.1.1 Species

Three trees each of normal and coppice teak wood aged 15 years were collected from a farm in Mpatapo in the Brong Ahafo Region. From each tree, the wood samples were collected from the butt, middle and top. The butt portion (from the ground to 310cm), middle (within320 to 630 cm and top portion (within 650 to 870 cm). They were sawn through the pith into the quadrants. A 20 mm thick board was sawn from bark to the pith. Wood samples were systematically collected from heartwood and sapwood of the butt, middle and top regions and labelled for careful and easy identification. The billets were sawn to constitute the principal directions (longitudinal, tangential and radial).

3.2 Sample Preparation for Physical Properties Determination

Six each of radial and tangential samples of the three 15 year old teak lumber of length 8.9 m and thickness of 2.5 m and 5 m were sawn and planed into lengths, widths and thicknesses of 2 x 2 x 2 cm using circular saws and planner respectively. The heartwood and sapwood were clearly sawn from the coppiced and normal teak. The sapwood samples were taken from 3 cm from the bark of the trees whereas the heartwood samples were taken from the range of 5 cm to the pith of each portion of the woods (coppiced and normal teaks).

3.2.1 Moisture Content

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

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

3.2.2 Density Determination

Determination of the density of *Tectona grandis* was done in accordance with the American Standards of Testing Materials, ASTM D 143-94 (2007). In all 36 small clear samples of dimension 20 x 20 x 20 mm were used for this experiment. 18 samples each were taken from the heartwood and sapwood. The mass of samples was taken with an electronic balance.

Measurements were taken from the three principal direction of the wood (i.e. longitudinal (L), tangential (T) and radial (R)) for the volume calculation. Oven dry density was calculated using the formula;

$$Density\ (D), kg/m^3 = \frac{Mass\ (m_o)}{Volume\ (V)}$$

Where: Mass (m_o) = Oven dried weight

Volume (V) = L × T × R

3.2.3 Dimensional Stability Test

A total of 72 samples were used for shrinkage and swelling tests. Initial dimensions were taken in the tangential, radial and longitudinal directions of the samples and recorded as D (initial dimension). 36 test samples each were soaked in distilled water for 24 hours for swelling test and oven dried at a temperature of 103 ± 2^{o}C for 24 hours for shrinkage test.

After 24 hours of soaking, the swelling test samples were measured and recorded as D_f (final Dimension). The shrinkage test samples were weighed and reweighed until constant weight then final readings taken (D_o). Shrinkage and swelling were expressed as a percentage using the formulae:

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

$$Shrinkage, \% = \frac{D - D_o}{D} \times 100$$

Where: D = initial dimension

D_f = final dimension

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

3.4 Chemical Properties

3.4.1 Preparation of Extractive Free Wood

Samples of coppice and normal teak (*T. grandis*) were collected from heartwood and sapwood regions of the butt, middle and top, ground and sieved for the chemical analysis. The specimens that passed through a sieve of No. 40 (425 μm) but retained on a No.60 (250 μm) sieve were collected.

Using the Soxhlet extraction apparatus three solvents, alcohol-acetone, alcohol and distilled water, were used for the preparation of extractives free wood in that sequence. In preparing the alcohol-acetone, four parts of acetone and two parts of ethyl alcohol were measured using 260 and 160 beakers respectively. Alcohol-acetone was first used for the extraction. Samples were loaded into the thimble ensuring that the samples did not extend above the top of the siphon tube, extracted until the extractives in the specimen were removed. This was done by monitoring until each solvent siphoned was colourless. The specimens were then removed from the thimble and air-dried. The same was repeated for the alcohol extraction. Specimens were finally extracted with distilled water of 150 ml for 4 hours. This material was air-dried and constituted the material for the other analysis (ASTM D 1105- 96, 2007).

3.4.2 Holocellulose

Two gms of extractive-free material was placed in a flask and 180 mls of buffered chlorite solution was added to 180 mls of water, 6.0 gm of glacial acetic acid, 6.8 gm of sodium acetate and 6.64 gm of sodium chlorite. The mixture was heated for four hours at 70 ^{o}C. Thereafter the mixture was filtered and washed with distilled water. The filtrate was air-dried and its weight and moisture content was taken. Holocellulose content of samples was expressed using the formula;

$$Holocellulose(\%) = \frac{oven\ dry\ weight\ of\ residue}{oven\ dry\ weight\ of\ extractive\ free\ sample} \times 100$$

3.4.3 Cellulose Test

The air-dried holocellulose was mixed with 17.5% NaOH and allowed to stand for 2 hours. This was washed with distilled water then washed with 15 mls of 10% acetic acid and then with 250 mls of distilled water and oven -dried. Percent alpha cellulose was calculated on the basis of the oven-dry wood in accordance with ASTM D 1103 as follows;

$$Alpha\ cellulose\ (\%) = \frac{W_2}{W_1} \times 100$$

Where**;**

W_2 = weight of oven-dry alpha cellulose residue

W_1 = weight of the original oven-dry wood sample**.**

3.4.4 Hemicellulose

The hemicellulose content of the teak wood were calculated with the equation that follows;

$$Hemicellulose(\%) = Holocellulose(\%) - Cellulose(\%)$$

3.4.5 Lignin Test

Lignin percent test of wood samples was done according to ASTM D 1106-96 (2007). 1 g of extractive free sample was weighed and mixed well with 72% sulphuric acid (H_2SO_4) and stirred thoroughly for 10, 15 and 25 minutes. A water bath was used to keep temperature at 15 ^oC of the mixture for 2 hours to 3% H_2SO_4. The mixture was diluted with distilled water of 560ml. The set up was boiled under reflux for 4 hrs. The specimen was allowed to settle and filtered on a filter paper. Residue free of acid was washed with 500 ml of hot water and dried in an oven for 2 hours. The specimen were cooled in a desiccator, and the content of filter paper as lignin weighed. Test specimens were oven dried at 105 ^{o}C for 2 hours, weighed and continued drying for 1 hour periods until constant weights for percent moisture-free wood. The percent lignin content of the wood samples were calculated using the formula;

$$Lignin\ (\%) = \frac{A}{W} \times 100$$

Where, A = Oven-dried weight of lignin

W = Oven-dried weight of test specimen

3.5 Data Analysis

Data obtained from the experiment were summarized in Microsoft Excel (97-2003) and imported into GraphPad Prism 6 and GenStat Release 12.1 analytical software. Statistical analysis was done in a completely randomized design. The mean sections were compared using the Two-way Analysis of Variance (ANOVA) and LSD at 5% significant difference level. Tables and graphs were used to explain the results of the analysis.

CHAPTER FOUR

4.0 RESULTS

4.1. Introduction

This chapter presents the results and analysis of this research in tables and figures. The detailed analysis is presented in tables at the appendix section.

4.2 Physical Properties of 15 Year Old Normal and Coppiced Teak Woods

4.2.1 Moisture Content

Table 4.1 shows percent age moisture content of the sapwood and heartwood of the top, middle and butt portions of coppiced and normal teak woods. The moisture content ranged from 41.08 ± 0.100 to 54.05 ± 0.066% for the heartwood and 45.53 ± 0.094 to 60.51 ± 0.067% for the sapwood of the normal teak wood. It was greater at the top section of both heartwood and sapwood (54.05 ± 0.066% and 60.51 ± 0.067% respectively) and least for the butt sections (41.08 ± 0.100% and 45.53 ± 0.094% respectively). For coppice teak wood, the moisture content (%) ranged from 41.27 ± 0.068 to 50.32 ± 0.060% for the heartwood and 44.37 ± 0.054 to 63.85 ± 0.213% for the sapwood. Similarly, it was higher for the top sections of both the heartwood and sapwood (50.32 ± 0.060% and 63.85 ± 0.213% respectively) followed by the middle section and the least was the butt section (41.27 ± 0.068% and 44.37 ± 0.054% respectively) (Table 4.1).

Table 4.1: Moisture content (%) of 15 year old normal and coppiced teak wood.

Portions	Moisture Content (%)			
	Normal Wood		Coppice Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	54.05 ± 0.066 [a]	60.51 ± 0.067 [a]	50.32 ± 0.060 [a]	63.85 ± 0.213 [a]
Middle	42.59 ± 0.100 [b]	50.68 ± 0.159 [b]	42.33 ± 0.045 [b]	50.26 ± 0.041 [b]
Butt	41.08 ± 0.100 [c]	45.53 ± 0.094 [c]	41.27 ± 0.068 [c]	44.37 ± 0.054 [c]
Mean	45.91	52..24	44.64	52.83

Means with different alphabets implies there is significant difference at 5% of level significance.

Generally, the moisture content (%) was higher for both sapwood of coppiced and normal teak wood (44.37 ± 0.054 - 63.85 ± 0.213% and 45.53 ± 0.094 - 60.51 ± 0.067% respectively) than that of the heartwood of both coppiced and normal teak wood (41.27 ± 0.068 - 50.32 ± 0.060 % and 41.08 ± 0.100 - 54.05 ± 0.066% respectively) (Table 4.1).

The results also shows increase in moisture content along the stem and outwards from the pith of both normal and coppiced teak woods. Table 4.1 shows the top section of the sapwood of the coppice teak wood recorded the highest moisture content whereas the butt section of the normal teak heartwood recorded the least.

Table 4.2, presents the results on the analysis of variance of the moisture content between the various portions and tree types. The results indicate significant differences in moisture contents between the different tree types and the portions of the trunk (i.e. top, middle and butt portions).

Table 4.2: Analysis of variance for the Moisture Content of normal and coppiced teak woods

Source of Variation	% of total variation	P value	P value summary	Significant?
Interaction	4.876	< 0.0001	****	Yes
Tree type	25.63	< 0.0001	****	Yes
Portion	69.16	< 0.0001	****	Yes

ANOVA table	SS	DF	MS	F	P value
Interaction	551.2	6	91.86	497.1	< 0.0001
Tree type	2897	3	965.7	5225	< 0.0001
Portion	7818	2	3909	21153	< 0.0001
Residual	37.70	204	0.1848		

$p<0.05$, indicate significant difference between means.

4.2.2 Density of *Tectona grandis*

Density results for normal and coppiced teak woods are presented in Table 4.3. The density of normal teak wood ranged from 830.20 ± 0.147 to 837.79 ± 0.150 kg/m^3 for the heartwood and 840.19 ± 0.127 to 859.96 ± 0.108 kg/m^3 for the sapwood (Table 4.3). Density was high at the butt both the of heartwood and sapwood (837.79 ± 0.150 kg/m^3 and 859.96 ± 0.108 kg/m^3 respectively) and least at the top sections (830.20 ± 0.147 kg/m^3 and 840.19 ± 0.127 kg/m^3 respectively) (Table 4.3). For coppice teak wood, density ranged from 820.08±0.094 to 834.48±0.168 kg/m^3 for the heartwood and 44.37 ± 0.054 to 63.85 ± 0.213 kg/m^3 for the sapwood. The density was also high at the butt of both the heartwood and sapwood (834.48 ± 0.168 kg/m^3 and 856.22 ± 0.251 kg/m^3 respectively) and least at the top sections (820.08 ± 0.094 kg/m^3 and 833.78 ± 0.107 kg/m^3 respectively).

Table 4.3: Density (kg/m^3) of 15 year old normal and coppiced teak wood.

Portions	Density (kg/m^3) Normal Wood		Coppiced Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	830.20 ± 0.147 [a]	840.19 ± 0.127 [a]	820.08 ± 0.094 [a]	833.78 ± 0.107 [a]
Middle	835.21 ± 0.152 [b]	848.33 ± 0.253 [b]	827.81 ± 0.193 [b]	840.68 ± 0.189 [b]
Butt	837.79 ± 0.150 [c]	859.96 ± 0.108 [c]	834.48 ± 0.168 [c]	856.22 ± 0.251 [c]
mean	834.4	849.49	827.46	843.56

Means with different alphabets implies there is significant difference at $p<0.05$. Otherwise, there is no significant difference between means.

Generally, density was higher for the sapwood and heartwood of normal teak wood (840.19 ± 0.127 - 859.96 ± 0.108 kg/m^3 and 830.20 ± 0.147 - 837.79 ± 0.150 kg/m^3 respectively) than that of coppice teak wood (833.78 ± 0.107 - 856.22 ± 0.251 kg/m^3 and 820.08 ± 0.094 - 834.48 ± 0.168 kg/m^3 respectively) (Table 4.3). Density also indicated a decreases along the bole of the woods from the butt to the top sections of the 15 year old normal and coppice teak woods (Table 4.3).

Analysis of variance on the difference between the densities of the various portions of the trees and between the trees is presented in Table 4.4. Significant differences was observed between the densities of the 15 years old normal and coppiced teak woods. The top, middle and butt sections also recorded significant differences between their densities (Table 4.4).

Table 4.4: Analysis of variance for the Density of 15 year old normal and coppiced teak woods

Source of Variation	% of total variation	P- value	P- value summary	Significant?
Interaction	5.285	< 0.0001	****	Yes

Tree type	58.69	< 0.0001	****	Yes	
Portion	35.56	< 0.0001	****	Yes	

ANOVA table	SS	DF	MS	F	P- value
Interaction	1386	6	231.0	393.3	< 0.0001
Tree type	15396	3	5132	8737	< 0.0001
Portion	9328	2	4664	7941	< 0.0001
Residual	119.8	204	0.5873		

p<0.05 indicate significant difference between means

4.2.3 Dimensional Stability of *T. grandis*

The results for the dimensional stability (shrinkage and swelling) determination of 15 year old *T. grandis* are presented in Tables 4.5 and 4.7.

4.2.3.1 Effects of Tree Types and Section of Bole on Shrinkage of Wood

Table 4.5 shows the percentage shrinkage for the top, middle and butt sections of 15 year old normal and coppiced teak woods. Shrinkage percent for normal teak heartwood and sapwood ranged from 7.32 ± 0.008 to 7.39 ± 0.007% and 7.35 ± 0.009 to 7.46 ± 0.004% for the sapwood of normal teak wood. Shrinkage was higher at both the top section of the heartwood and sapwood (7.39 ± 0.007% and 7.46 ± 0.004%) respectively and lower at the butt sections (7.32 ± 0.008% and 7.35 ± 0.009%) for the heartwood and sapwood of normal teak wood. For coppice teak wood, shrinkage (%) was greater in the sapwood (7.35 ± 0.005 - 7.47 ± 0.004%) than the heartwood (7.42 ± 0.007 - 7.29 ± 0.005%). The highest shrinkage was also recorded in the sapwood and heartwood of the top (7.47 ± 0.004% and 7.42 ± 0.007%

respectively) whereas the butt sapwood and heartwood recorded the least (thus, 7.35±0.005% and 7.29±0.005% respectively).

Table 4.5: Summary of mean and standard error for shrinkage of the 15year old teak woods

Portions	Percentage Shrinkage			
	Normal Wood		Coppiced Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	7.39±0.007^{a}	7.46±0.004^{a}	7.42±0.007^{a}	7.47±0.004^{a}
Middle	7.35±0.030^{b}	7.43±0.007^{a}	7.39±0.004^{b}	7.43±0.010^{b}
Butt	7.32±0.008^{b}	7.35±0.009^{b}	7.29±0.005^{c}	7.35±0.005^{c}

Means with different alphabets implies there is significant difference at p<0.05.

The shrinkage was generally higher in the sapwood and heartwood of the coppice teak wood (7.47 ± 0.004% and 7.42 ± 0.007% respectively) than that of normal teak wood (7.46 ± 0.004% and 7.39 ± 0.007%). There is also an increasing trend in shrinkage from butt to the top of the teak woods (Table 4.5).

Analysis of variance results shown in Table 4.6 indicates strong significant differences in the percentage shrinkage of the various portions of the 15 year old coppice and normal teak woods.

Table 4.6: Analysis of variance for the shrinkage of the 15 year old coppiced and normal teak woods

Source of Variation	% of total variation	P- value	P- value summary	Significant?
Interaction	2.775	0.0267	*	Yes
Tree type	17.21	< 0.0001	****	Yes
Portions	41.37	< 0.0001	****	Yes

ANOVA table	SS	DF	MS	F	P- value
Interaction	0.03048	6	0.005080	2.441	= 0.0267
Tree type	0.1890	3	0.06301	30.27	< 0.0001
Portions	0.4544	2	0.2272	109.2	< 0.0001
Residual	0.4246	204	0.002081		

p<0.05 indicate significant difference between the means

4.1.3.2 Effects of Tree Types and Section of Bole on Swelling of Wood

The influence of tree type and portion of the bole on the proportion of swelling is presented in Table 4.7. Swelling (%) was higher in the coppice teak wood than normal teak wood with mean values ranging from 0.79 ± 0.002 to 1.13 ± 0.002% and 0.94 ± 0.003 to 1.27 ± 0.003% for the heartwood and sapwood of coppice teak respectively and from 0.62 ± 0.006 to 1.20 ± 0.007% and 0.76 ± 0.004 to 1.33 ± 0.003% also for the heartwood and sapwood of normal teak wood (Table 4.7). Normal wood showed higher swelling at the top portion and lower at the butt portion for the heartwood and sapwood section (Table4.7). For coppice teak wood, swelling (%) was higher in the sapwood (0.94 ± 0.003 - 1.27 ± 0.003%) than the heartwood (0.79 ± 0.002 - 1.13 ± 0.002%). The highest swelling was recorded in the sapwoods of the top portion of normal and coppice teak woods (1.33 ± 0.003% and 1.27 ± 0.003% respectively) whereas the butt sections of both normal and coppice heartwoods recorded the least (thus, 0.62 ± 0.006% and 0.79 ± 0.002% respectively) (Table 4.7).

Table 4.7: Summary of mean and standard error for swelling of 15 year old teak woods

Portions	Percentage Swelling			
	Normal Wood		Coppiced Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	1.20±0.007^{a}	1.33±0.003^{a}	1.13±0.002^{a}	1.27±0.003^{a}
Middle	0.89±0.005^{b}	1.05±0.002^{b}	0.99±0.004^{b}	1.11±0.004^{b}

Butt	0.62±0.006^{c}	0.76±0.004^{c}	0.79±0.002^{c}	0.94±0.003^{c}
Mean	0.64	1.05	0.97	1.11

Means with different alphabets implies there is significant difference at p<0.05.

Observation reveal that swelling (%) increases from the butt to the top of the heartwoods and sapwoods of both normal and coppice teak woods (Table 4.7).

Table 4.8 presents the analysis of variance for the swelling of the various portions of the coppiced and normal teak woods. It shows that there is significant difference between the tree types, portions and their interactions at *p<0.05.* The detailed test is tabulated in Appendix B.

Table 4.8 Analysis of variance for swelling of 15 year old coppice and normal teak woods

Source of Variation	% of total variation	P value	P value summary	Significant?	
Interaction	5.546	< 0.0001	****	Yes	
Tree type	13.99	< 0.0001	****	Yes	
Portions	79.76	< 0.0001	****	Yes	
ANOVA table	SS	DF	MS	F (DFn, DFd)	P value
Interaction	0.5241	6	0.08734	267.9	< 0.0001
Tree Type	1.322	3	0.4407	1352	< 0.0001
Portion	7.536	2	3.768	11557	< 0.0001
Residual	0.06651	204	0.0003260		

There is significant difference between the means at p<0.05

4.2 Chemical Properties of Teak Wood 4.3.1 Lignin Content in the Various Portions and sections of the Normal and Coppiced

Teak Woods

Table 4.9 shows the lignin contents in the various portions of the 15 year old normal and coppiced teak woods. Lignin content was higher in the normal teak wood than coppice teak wood with mean values ranging from 22.61 ± 0.857 to 24.80 ± 0.337% and 23.73 ± 0.544 to 25.09 ± 0.246% for the heartwood and sapwood of normal teak wood respectively and from 22.20 ± 0.395 to 25.01 ± 0.165% and 21.95 ± 0.282 to 25.08 ± 0.341% also for the heartwood and sapwood of coppice teak wood (Table 4.9). For the normal teak wood, lignin content was higher at the heartwood and sapwood of the butt portion (24.80 ± 0.337% and 25.09 ± 0.246% respectively) and least at the top sections (22.61 ± 0.857% and 23.73 ± 0.544%) for the heartwood and sapwood respectively. Coppice teak wood showed higher lignin content in the heartwood (22.20 ± 0.395 - 25.01 ± 0.165%) than the sapwood (21.95 ± 0.282 - 25.08 ± 0.341%).

Table 4.9: Summary of mean and standard error for lignin content of 15-year old normal and coppiced teak woods

Portions	Lignin Content (%)			
	Normal Wood		Coppice Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	22.61 ± 0.857^{a}	23.73 ± 0.544^{a}	22.20 ± 0.395^{a}	21.95 ± 0.282^{a}
Middle	23.42 ± 0.699^{ab}	24.25 ± 0.425^{a}	23.94 ± 0.297^{b}	23.43 ± 0.644^{ab}
Butt	24.80 ± 0.337^{b}	25.09 ± 0.246^{a}	25.01 ± 0.165^{b}	25.08 ± 0.341^{b}
Mean	23.61	24.36	23.72	23.49

Means with different alphabets implies there is significant difference at p<0.05. Otherwise, there is no significant difference between means.

From Table 4.9, the highest percent lignin was recorded in the sapwood of the normal teak wood (25.01 ± 0.165 – 21.95 ± 0.282 %) than coppiced (24.80 ± 0.337 – 23.73 ± 0.544 %) wood at all stem positions and it decreased from the butt to the top of both coppiced and normal teak wood.

Table 4.10: Analysis of variance for the lignin content of 15-year old coppiced and normal teak woods.

Source of Variation	% of total variation	P- value	P- value summary	Significant?	
Interaction	5.506	0.6038	ns	No	
Tree type	7.041	0.1471	ns	No	
Portions	58.70	< 0.0001	****	Yes	
ANOVA table	SS	DF	MS	F	P- value
Interaction	3.165	6	0.5275	0.7661	= 0.6038
Tree type	4.047	3	1.349	1.959	= 0.1471
Portions	33.74	2	16.87	24.50	< 0.0001
Residual	16.53	24	0.6886		

P-values less than 0.05 are statistically significant.

Table 4.10 shows the analysis of variance for the lignin content in the various portions of the coppiced and normal teak woods. Significant differences were observed for the lignin content between the various portions for the coppiced and normal teak woods and their interactions (Table 4.10).

4.3.2 Effect of Portion of Bole on Cellulose Content of 15 Year Old Teak Wood.

Table 4.11 shows the cellulose contents in the various portions of 15 year old normal and coppiced teak woods. Cellulose content ranged from 39.68 ± 0.283 to 41.75 ± 0.297% for heartwood and 39.68 ± 0.283 to 40.15 ± 0.100% for the sapwood of normal teak. It was higher for the heartwood of normal and sapwood of coppiced teak wood (41.75 ± 0.297 and 40.15 ± 0.100 respectively) of the middle portion of the bole and least in the top section (39.68 ± 0.283 and 39.68 ± 0.283 for the heartwood and sapwood respectively). The highest cellulose content was recorded in the sapwood and heartwood of the butt portion (41.14 ± 0.414% and 41.27 ± 0.322% respectively) whereas the heartwood of the middle portion recorded the lowest (thus, 37.59 ± 0.420) (Table 4.11).

Table 4.11: Summary of mean and standard error for percent cellulose content of 15 year old of normal and coppiced teak wood.

Portions	Cellulose Content			
	Normal Wood		Coppice Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	39.68±0.283[a]	39.68±0.283[a]	39.97±0.283[a]	39.42±0.361[a]
Middle	41.75±0.297[b]	40.15±0.100[a]	37.59±0.420[b]	39.71±0.250[a]
Butt	41.55±0.242[b]	40.13±0.623[a]	41.27±0.322[c]	41.14±0.414[b]
Mean	40.99	39.99	39.61	40.09

Means with different alphabets implies there is significant difference at p<0.05.

Table 4.12 presents the analysis of variance for the cellulose content of the various portions of the normal and coppice teak woods. Table 4.12, shows that there is significant difference between the portions ($p<0.0001$), coppice and normal teak woods ($p=0.0005$) and their interactions ($p<0.0001$) at $p<0.05$.

Table 4.12 Analysis of variance for the Cellulose Content of 15-year old normal and coppiced teak woods

Source of Variation	% of total variation	P- value	P- value summary	Significant?
Interaction	40.28	< 0.0001	****	Yes
Tree type	17.90	0.0005	***	Yes
Portions	25.18	< 0.0001	****	Yes

ANOVA table	SS	DF	MS	F	P- value
Interaction	21.10	6	3.517	9.682	< 0.0001
Tree type	9.377	3	3.126	8.604	= 0.0005
Portions	13.19	2	6.595	18.15	< 0.0001
Residual	8.718	24	0.3633		

4.2.3 Assessment of Holocellulose in the various portions of 15-Year Old Normal and Coppiced Teak Woods

Table 4.13 shows the holocellulose contents in the various portions of 15 year old normal and coppiced teak woods. Holocellulose content of normal teak wood ranged from 63.07 ± 0.449 to 65.56 ± 0.510% for the heartwood and 68.02 ± 0.591 to 72.72 ± 1.208% for the sapwood (Table 4.13). It was higher for the sapwood of the middle portion (72.72 ± 1.208%) and lower than the heartwood of the butt section (63.07 ± 0.449%) of normal teak wood. For coppice teak, holocellulose ranged from 62.87 ± 0.393 to 64.72 ± 0.066% for the heartwood and 60.23±0.288 to 69.19±0.445% for the sapwood. Holocellulose content was higher for the middle portion of the heartwood and sapwood (64.72 ± 0.066% and 69.19 ± 0.445% respectively) and lower in the top section of sapwood (60.23 ± 0.288%).

Table 4.13: Holocellulose content of 15-year old normal and coppiced teak woods

Portions	Holocellulose Content (%)			
	Normal Wood		Coppice Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	65.56 ± 0.510^{a}	72.00 ± 0.295^{a}	64.27 ± 0.450^{ab}	60.23 ± 0.288^{a}
Middle	65.31 ± 0.180^{a}	72.72 ± 1.208^{a}	64.72 ± 0.066^{a}	69.19 ± 0.445^{b}
Butt	63.07 ± 0.449^{b}	68.02 ± 0.591^{b}	62.87 ± 0.393^{b}	63.86 ± 0.295^{c}

Means with different alphabets implies there is significant difference at $p<0.05$.

Table 4.14 shows the analysis of variance for the holocellulose content in the various portion of the 15 year old normal and coppiced teak woods. From Table 4.14, there is significant difference in the holocellulose content between the portions and between coppice and normal teak woods and their interactions at $p<0.05$.

Table 4.14 Analysis of variance for the holocellulose content of normal and coppiced teak woods

Source of Variation	% of total variation	P- value	P- value summary	Significant?
Interaction	20.08	< 0.0001	****	Yes
Tree type	60.02	< 0.0001	****	Yes
Portions	16.08	< 0.0001	****	Yes

ANOVA table	SS	DF	MS	F	P- value
Interaction	98.37	6	16.40	21.02	< 0.0001

Tree type	294.1	3	98.02	125.7	< 0.0001
Portions	78.77	2	39.38	50.50	< 0.0001
Residual	18.72	24	0.7799		

Generally, holocellulose was higher for both sapwood and heartwood of normal teak than that of coppice teak (Table 4.13).

4.2.4 Assessment of Hemicellulose in the various portions of 15 Year Old Normal and Coppiced Teak Woods

Table 4.15 shows the hemicellulose contents in the various portions of 15 year old normal and coppiced teak woods. Hemicellulose of normal teak ranged from 21.42 ± 0.548 to 22.98 ± 0.977% for the heartwood and 27.13 ± 0.486 to 32.29 ± 0.497% for the sapwood (Table 4.15). It was higher for the top portion of heartwood and sapwood (25.87 ± 0.535% and 32.29 ± 0.497% respectively) and lower for the butt portion of the heartwood (21.42 ± 0.548%). For coppice teak, hemicellulose ranged from 21.60 ± 0.658 to 32.57 ± 1.158% for the heartwood and 21.60 ± 0.537 to 29.48 ± 0.439% for the sapwood. It was also higher for the middle portion of the heartwood and sapwood and lower in the top sapwood (Table 4.15).

Table 4.15: Summary of mean and standard error for percent hemicellulose of 15 year old teak normal and coppiced teak woods

Portions	Hemicellulose Content (%)			
	Normal Wood		Coppice Wood	
	Heartwood	Sapwood	Heartwood	Sapwood
Top	25.87 ± 0.535^a	32.29 ± 0.497^a	24.31 ± 0.742^a	21.60 ± 0.537^a
Middle	22.98 ± 0.977^b	27.13 ± 0.486^b	32.57 ± 1.158^b	29.48 ± 0.439^b
Butt	21.42 ± 0.548^b	27.23 ± 0.329^b	21.60 ± 0.658^c	22.71 ± 0.684^c

Means with different alphabets implies there is significant difference at p<0.05.

Generally, hemicellulose was highter for the sapwood and heartwood of coppice teak than that of normal teak (Table 4.15).

Table 4.16 Analysis of variance for the hemicellulose content of 15-year old normal and coppiced teak woods.

Source of Variation	% of total variation	P- value	P- value summary	Significant?
Interaction	43.79	< 0.0001	****	Yes
Tree type	26.35	< 0.0001	****	Yes
Portions	24.21	< 0.0001	****	Yes

ANOVA table	SS	DF	MS	F	P- value
Interaction	251.8	6	41.96	31.05	< 0.0001
Tree type	151.5	3	50.50	37.37	< 0.0001
Portions	139.2	2	69.59	51.50	< 0.0001
Residual	32.43	24	1.351		

From Table 4.16, there is significant difference between the portions, coppice and normal teak woods and their interactions at $p<0.05$.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Physical Properties of Teak Wood

5.1.1 Moisture Content

Moisture content is among the main factors that affect usability of wood as a raw material (Nurfaizah *et al.*, 2014). Moisture of wood contributes to the weight of each wood product in use. The moisture content of the 15 years old teak wood according to tree portion and distance to the pith are: for normal teak wood the top portion recording 60.5% and 54.05% for its sapwood and heartwood respectively whereas the coppiced teak recorded 63.85% and 50.32% for its sapwood and heartwood respectively; the middle portion also recorded 50.68% and 42.59% for the normal sapwood and heartwood respectively whilst the coppiced wood had 50.26% and 42.33% for its sapwood and heartwood respectively; but then, the butt portion of the normal teak wood were 45.53% and 41.08% for sapwood and heartwood respectively and 44.37% and 41.27% respectively for coppiced wood sapwood and heartwood. The highest moisture content of 63.85% was observed in the top portion of the coppiced wood sapwood while, the lowest recoding of 41.08% was at the butt portion of the normal wood heartwood.

Generally, the moisture content increased with the increasing height of tree portion and outward from the pith. The moisture content increased with tree portion and outward from the pith due to the fact that, the percentage of active cells in sapwood is greater than that of heartwood which compose of more cells (Nurfaizah *et al.*, 2014).

According to Dinwoodie and Desch (1996), moisture content has influence on all the properties of wood specifically the strength properties. Several researchers have related wood strength to the moisture content of wood (USDA 1999). Moisture content of the normal teak wood (49.07%) is greater than that of the coppiced teak wood (48.73%) as indicated in appendix (Table A5). From Table 4.1 in appendix, the moisture content of both the normal and coppice teak woods increase from butt (43.31% and 42.82% respectively) to top portion (57.28% and 57.09% respectively). The results show a small difference in moisture content. From Table 4.1 in appendix the normal wood of the 15 years old teak recorded the highest percent moisture content of 49.07% as compared to the coppiced teak wood which was 48.73%. Sapwoods of both the normal and coppiced teak woods (60.51% and 63.85% respectively) recorded the highest moisture content (Table 4.1); this is because the sapwood is the zone of active cell division and active transport of sap. Comparatively, the sapwood of the coppiced teak wood (63.85%) contained much moisture than that of the normal teak wood (60.51%). Moisture content influences the strength and stiffness of small clear wood specimens subjected to bending and strength properties increase with a decrease in moisture content (Barrett, 1975). There was a slight variation in the moisture content of both the heartwood and sapwood of both normal and coppiced teak woods. This is similar to the findings of Hogan (2005), in his research he concluded that similar hardwoods have only slight differences in moisture content between their sapwood and heartwood.

5.1.2 Density

The average values of density according to tree portion and distance are presented in Table A2 and A5 respectively. The density of the 15 years old teak wood decreased along the bole from the butt to top. The grand mean values were as follows; the butt portion recorded 847.11 kg/m^3, 838.01kg/m^3 for the middle portion and the top portion which recorded the least was 831.06 kg/m^3 (Table A2). From Table A5, the highest density was found in the normal teak wood (841.95 kg/m^3) whereas the least values was recorded in the coppiced teak wood (835.51 kg/m^3). The results indicate that the mean density was significantly affected by the tree portion. However, density increased significantly from the heartwood to the sapwood.

This is due to the formation of heartwood which generally somehow heavier than sapwood caused by the accumulation of air in the closed cell system (Panshin and Zeeuw, 1980). The density of both sapwood and heartwood of normal teak wood was greater than that of the coppiced teak wood (Table 4.3). From Table 4.3, the highest density was recorded in the butt of the normal teak sapwood (859.96 kg/m^3) and heartwood (837.79 kg/m^3) whilst the least was observed in the top of the coppiced teak wood heartwood (820.08 kg/m^3). This trend of variation in density from base to top is in an agreement with the trend reported by Espinoza

(2004). The highest mean value density at the base along the bole could be as a result of the aggregation of matured wood cells while highest mean value across could be attributted to the mixture combination of heartwood and sapwood cells that usually characterised the traditional zone in the course of heartwood formation.

5.1.3 Dimensional Stability

Wood changes in dimension with variation in moisture content. During the seasoning of green or freshly sawn lumber, there is a decrease in dimension. When seasoned wood is put in service its dimensions wood decrease or increase, depending on whether it loses or gains moisture. The dimensional changes in wood are brought about by the shrinking or swelling of the cells, or fibers, of which the wood is composed. Shrinking and swelling play important roles in the utilization of wood.

5.1.3.1 Shrinkage

According to Abasali *et al*. (2011), the most important parameter affecting wood shrinkage is associated with density. Species with higher density shrinks more than those with lower density. This is contrary to the results of this research; from Table A5, the coppiced teak wood which was less denser (835.51 kg/m^3) than the normal teak wood (841.95 kg/m^3) recorded percent shrinkage (7.39%) higher than that of the normal teak wood (7.38%). The pronounced differential shrinkage of normal and coppice teak wood is liable to cause wild splits and checks as well as distortions if not attended to during the kiln drying of these species.

From Table 4.5, the percent shrinkage increases from the butt to the top of both normal and coppiced teak woods. The results showed that the top portion of the coppiced teak wood shrinks higher (7.45%) than the normal teak wood (7.40%). Table 4.5 also shows that, the top sapwood of both the normal and coppiced teak woods (7.46% and 7.47% respectively) shrinks higher than the heartwoods (7.39% and 7.42% respectively for normal and coppiced teak woods).

Generally, shrinkage increased along the bole of the tree from butt to top and across from the heartwood to the sapwood. These observations appear to be similar to the report of Choong *et.al* (1989) on shortleaf pine trees. There is a greater amount of extractives in the heartwood and that the extractives inhibit normal shrinkage by bulking the armophous regions in the cell wall substance. This explains why the sapwood shrinks less than the sapwood of coppiced wood. Pattern of variations correlates the earlier findings of Mottonen and Luostarinen (2006) and Seralde (2006). These authors in their findings attributed the variability in dimensional changes of wood to decrease in density along the bole of the tree. The increase in shrinkage from the heartwood to the sapwood observed in this study is similar to the published work of Shupe and co-workers (1995a and 1995b) for yellow Poplar and cotton wood tree. Since the sapwood of both normal and coppiced teak recorded highest, they will be less dimensional stable for their end uses.

5.1.3.2 Swelling

The results indicate that the coppiced teak wood (1.04%) swells more than that of the normal teak wood (0.98%), (Table A4). Like the percentage shrinkage, percent swelling increased along the bole of the 15 years old coppiced and normal teak woods from the butt to the top and outward from the pith. From Table A4, the normal teak wood recorded 1.23%, 0.97 and

0.69% for the top, middle and butt portions respectively whereas the coppiced teak wood was 1.20%, 1.05% and 0.86% for the top, middle and butt portions respectively.

Table 4.7 also shows the increase of percent swelling outward from the pith. For instance, swelling percent of the top portion of the normal teak increased from 1.20% (for the heartwood) to 1.33% (for the sapwood) so did the top of the coppiced teak wood (1.13% to 1.27% for heartwood to sapwood respectively). The amount of swelling is proportional to the amount of water wood absorbs.

5.2 Chemical Composition of Teak Wood

Wood's chemical composition cannot be defined precisely for a given species of tree. Browning (1975) asserted that chemical composition varies with even tree parts, wood type, geographic location, soil conditions and climate. Nevertheless, Petterson (1984) after many years of research on chemical composition concluded that average values can be established.

Most of lignin, hemicellulose, and others were found to be higher in the normal teak wood as compared to the coppice wood. The Analysis of variance showed significant difference between the means of the chemical compositions of both the coppiced and normal teak (Appendix B5, B6, B7 and B8).

Chemical constituents, such as cellulose and lignin, of wood influence the rate of degradation (Shanbhag and Sundararaj, 2013). Cellulose is 30% armophlous and 70% crystalline which does not absorb water. Higher lignin content and total phenolic content, increase decay resistance of wood. Cellulose is one of the factors that drive insects, especially termites, towards wood species. This is because cellulose is a primary food source for termites (La Fage and Nutting, 1978). This explains the fact that there is a positive correlation between cellulose content of wood and wood degradation.

The highest extractives content inhibit swelling but lower rate and removal of extractives apparently result in increased swelling which is due to easier access of water to the wood (Hills, 2006). Hemicellulose is hydrophilic and therefore it presence result in increased swelling and also it helps in desorbing of water from the wood which result in shrinkage. Other phenolic compounds of wood impart higher resistance to insect attack. Most researchers including Syafii *et al.* (1988) asserted that wood species with lower amount of cellulose and higher lignin and total phenol are insect resistant, while the wood with higher amounts of cellulose and lower amounts of lignin and total phenol were susceptible to insect damage.

From Table A5, the normal teak wood was proven to possess the highest values of all the parameters researched under the physical properties. Based on the chemical properties, the normal wood would be more resistance to bio-degradation and increases its durability.

Coppiced teak wood on the hand can be chemically preserved to prevent insect attack.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This study was conducted to evaluate the physical and chemical properties of 15 year old normal and coppiced teak woods. The measured physical and chemical properties, which included moisture content, dimensional stability, density, lignin, cellulose, holocellulose and hemicellulose varied significantly among their means along the bole of the woods.

The following conclusions can be drawn between the 15 years old coppiced and normal teak woods;

- Moisture content, shrinkage and swelling were greater in coppiced than normal wood. Coppiced wood would be less dimensionally stable resulting in fracture, splitting and distortion of its products.
- Normal teak wood was more dense than the coppiced type; hence, the formal would be stronger than latter.
- Lignin, Holocellulose were greater in normal than coppiced teak wood. Coppiced wood had more hemicellulose than the normal type. Based on these chemical properties, normal wood would be more resistant to bio-degradation than coppiced wood.

From the study, the normal teak wood was proven to be better than coppiced teak wood in terms of both physical and chemical properties.

6.2 Recommendations

It is recommended that:

1. Thorough drying and chemical coatings could reduce the effect of shrinkage and swelling in coppiced teak wood.
2. Coppiced teak wood could be used for structures requiring low strength properties due to its recorded density.
3. Moreover, chemical preservation could improve the durability of coppiced teak wood.
4. Further research should be conducted on mechanical properties of both coppiced and normal teak woods.

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APPENDICES

APPENDIX A, Summary of Means of both Physical and Chemical Properties

Table A1 Summary of Percent Moisture Content of the Portions of the 15 Years Old Teak Wood

	Coppiced	Normal	Grand Mean
Butt	42.82	43.31	43.06
Middle	46.29	46.63	46.46
Top	57.09	57.28	57.18
Grand Mean	43.73	49.07	
p-value	<0.001		
LSD (5%)	1.337		
CV (%)	8.3		

Table A2 Summary of Density (kg/m^3) of the Portions of the 15 Years Old Teak Wood

	Coppiced	Normal	Grand Mean
Butt	845.35	848.88	847.11
Middle	834.24	841.77	838.01
Top	826.93	835.20	831.06
Grand Mean	835.51	841.95	
p-value	<0.001		
LSD (5%)	2.723		
CV (%)	1.0		

Table A3 Summary of Percent Shrinkage of the Portions of the 15 Years Old Teak Wood

	Coppiced	Normal	Grand Mean
Butt	7.32	7.33	7.33

Middle	7.41	7.41	7.41
Top	7.45	7.40	7.43
Grand Mean	7.39	7.38	
p-value	<0.001		
LSD (5%)	0.01831		
CV (%)	0.8		

Table A4 Summary of Percent Swelling of the Portions of the 15 Years Old Teak Wood

	Coppiced	**Normal**	**Grand Mean**
Butt	0.86	0.68	0.78
Middle	1.05	0.97	1.01
Top	1.20	1.26	1.23
Grand Mean	1.04	0.97	
p-value	<0.001		
LSD (5%)	0.02452		
CV (%)	7.4		

Table A5 Summary of Results in Two-way ANOVA

Physical properties of the 15 years old teak wood				
	Density (kgm^{-3})	**Moisture Content (%)**	**Swelling (%**	**Shrinkage (%)**
Coppiced	835.51	48.73	1.04	7.39
Normal	841.95	49.07	0.97	7.38
P value	<0.001	0.541	<0.001	0.205
LSD (5%)	2.224	1.092	0.020	0.015

CV (%)	1.0	8.3	7.4	0.8

Chemical properties of the 15 years old teak wood

	Lignin (%)	**Holocellulose (%)**	**Cellulose (%)**	**Hemicellulose (%)**
Coppiced	23.60	64.19	39.85	24.45
Normal	23.98	67.78	40.50	27.06
P value	0.174	<0.001	0.033	0.020
LSD (5%)	0.556	1.990	0.592	2.171
CV (%)	3.4	4.4	2.2	12.4

APPENDIX B, Detailed Tukey's Multiple Comparisons for Test Samples

Table B1 Tukey's Multiple Comparison for Moisture Content

Within each row, compare columns (simple effects within rows)

Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-1.507	-1.845 to -1.168	Yes	****
Butt vs. Top	-12.97	-13.30 to -12.63	Yes	****
Middle vs. Top	-11.46	-11.80 to -11.12	Yes	****
NS				
Butt vs. Middle	-5.150	-5.488 to -4.811	Yes	****
Butt vs. Top	-14.98	-15.32 to -14.64	Yes	****
Middle vs. Top	-9.827	-10.17 to -9.489	Yes	****

CH				
Butt vs. Middle	-1.055	-1.393 to -0.7169	Yes	****
Butt vs. Top	-9.050	-9.388 to -8.712	Yes	****
Middle vs. Top	-7.995	-8.333 to -7.656	Yes	****
CS				
Butt vs. Middle	-5.888	-6.226 to -5.550	Yes	****
Butt vs. Top	-19.48	-19.82 to -19.14	Yes	****
Middle vs. Top	-13.59	-13.93 to -13.25	Yes	****

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	41.08	42.59	-1.507	0.1433	18	18	14.87	204
Butt vs. Top	41.08	54.05	-12.97	0.1433	18	18	128.0	204
Middle vs. Top	42.59	54.05	-11.46	0.1433	18	18	113.1	204
NS								
Butt vs. Middle	45.53	50.68	-5.150	0.1433	18	18	50.82	204
Butt vs. Top	45.53	60.51	-14.98	0.1433	18	18	147.8	204
Middle vs. Top	50.68	60.51	-9.827	0.1433	18	18	96.98	204
CH								
Butt vs. Middle	41.27	42.33	-1.055	0.1433	18	18	10.41	204
Butt vs. Top	41.27	50.32	-9.050	0.1433	18	18	89.31	204
Middle vs. Top	42.33	50.32	-7.995	0.1433	18	18	78.90	204
CS								
Butt vs. Middle	44.37	50.26	-5.888	0.1433	18	18	58.11	204
Butt vs. Top	44.37	63.85	-19.48	0.1433	18	18	192.3	204
Middle vs. Top	50.26	63.85	-13.59	0.1433	18	18	134.1	204

B2	Density			
Within each row, compare columns (simple effects within rows)				
Number of families	4			
Number of comparisons per family	3			
Alpha	0.05			
Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	2.577	1.973 to 3.180	Yes	****
Butt vs. Top	7.591	6.988 to 8.194	Yes	****
Middle vs. Top	5.014	4.411 to 5.617	Yes	****
NS				
Butt vs. Middle	11.63	11.03 to 12.23	Yes	****
Butt vs. Top	19.77	19.16 to 20.37	Yes	****
Middle vs. Top	8.136	7.532 to 8.739	Yes	****
CH				
Butt vs. Middle	6.672	6.069 to 7.275	Yes	****
Butt vs. Top	14.40	13.80 to 15.00	Yes	****
Middle vs. Top	7.728	7.125 to 8.331	Yes	****
CS				
Butt vs. Middle	15.54	14.94 to 16.14	Yes	****
Butt vs. Top	22.44	21.84 to 23.04	Yes	****
Middle vs. Top	6.898	6.295 to 7.501	Yes	****

Table Multiple Comparison for

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	837.8	835.2	2.577	0.2555	18	18	14.26	204
Butt vs. Top	837.8	830.2	7.591	0.2555	18	18	42.02	204
Middle vs. Top	835.2	830.2	5.014	0.2555	18	18	27.76	204
NS								
Butt vs. Middle	860.0	848.3	11.63	0.2555	18	18	64.38	204
Butt vs. Top	860.0	840.2	19.77	0.2555	18	18	109.4	204
Middle vs. Top	848.3	840.2	8.136	0.2555	18	18	45.04	204
CH								
Butt vs. Middle	834.5	827.8	6.672	0.2555	18	18	36.93	204
Butt vs. Top	834.5	820.1	14.40	0.2555	18	18	79.71	204
Middle vs. Top	827.8	820.1	7.728	0.2555	18	18	42.78	204
CS								
Butt vs. Middle	856.2	840.7	15.54	0.2555	18	18	86.04	204
Butt vs. Top	856.2	833.8	22.44	0.2555	18	18	124.2	204
Middle vs. Top	840.7	833.8	6.898	0.2555	18	18	38.19	204

B3 Percent Shrinkage

Within each row, compare columns (simple effects within rows)

Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-0.02899	-0.06490 to 0.006911	No	ns
Butt vs. Top	-0.07241	-0.1083 to -0.03651	Yes	****
Middle vs. Top	-0.04342	-0.07932 to -0.007515	Yes	*
NS				
Butt vs. Middle	-0.07896	-0.1149 to -0.04306	Yes	****
Butt vs. Top	-0.1141	-0.1500 to -0.07817	Yes	****
Middle vs. Top	-0.03511	-0.07102 to 0.0007907	No	ns
CH				
Butt vs. Middle	-0.1009	-0.1368 to -0.06495	Yes	****
Butt vs. Top	-0.1374	-0.1733 to -0.1015	Yes	****
Middle vs. Top	-0.03652	-0.07242 to -0.0006143	Yes	*
CS				
Butt vs. Middle	-0.07471	-0.1106 to -0.03881	Yes	****
Butt vs. Top	-0.1199	-0.1558 to -0.08396	Yes	****
Middle vs. Top	-0.04515	-0.08106 to -0.009251	Yes	**

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF

Table Multiple Comparison for

NH								
Butt vs. Middle	7.316	7.345	-0.02899	0.01521	18	18	2.696	204
Butt vs. Top	7.316	7.388	-0.07241	0.01521	18	18	6.734	204
Middle vs. Top	7.345	7.388	-0.04342	0.01521	18	18	4.038	204
NS								
Butt vs. Middle	7.349	7.428	-0.07896	0.01521	18	18	7.343	204
Butt vs. Top	7.349	7.463	-0.1141	0.01521	18	18	10.61	204
Middle vs. Top	7.428	7.463	-0.03511	0.01521	18	18	3.265	204
CH								
Butt vs. Middle	7.285	7.386	-0.1009	0.01521	18	18	9.379	204
Butt vs. Top	7.285	7.423	-0.1374	0.01521	18	18	12.78	204
Middle vs. Top	7.386	7.423	-0.03652	0.01521	18	18	3.396	204
CS								
Butt vs. Middle	7.353	7.427	-0.07471	0.01521	18	18	6.948	204
Butt vs. Top	7.353	7.473	-0.1199	0.01521	18	18	11.15	204
Middle vs. Top	7.427	7.473	-0.04515	0.01521	18	18	4.199	204

B4 Percentage Swelling

Within each row, compare columns (simple effects within rows)

Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-0.2723	-0.2866 to -0.2581	Yes	****
Butt vs. Top	-0.5778	-0.5921 to -0.5636	Yes	****
Middle vs. Top	-0.3055	-0.3197 to -0.2913	Yes	****
NS				
Butt vs. Middle	-0.2964	-0.3106 to -0.2822	Yes	****
Butt vs. Top	-0.5755	-0.5897 to -0.5613	Yes	****
Middle vs. Top	-0.2791	-0.2933 to -0.2649	Yes	****
CH				
Butt vs. Middle	-0.2000	-0.2142 to -0.1858	Yes	****
Butt vs. Top	-0.3449	-0.3591 to -0.3307	Yes	****
Middle vs. Top	-0.1449	-0.1591 to -0.1307	Yes	****
CS				
Butt vs. Middle	-0.1719	-0.1861 to -0.1577	Yes	****
Butt vs. Top	-0.3316	-0.3459 to -0.3174	Yes	****
Middle vs. Top	-0.1597	-0.1739 to -0.1455	Yes	****

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	0.6183	0.8907	-0.2723	0.006019	18	18	63.99	204
Butt vs. Top	0.6183	1.196	-0.5778	0.006019	18	18	135.8	204

Table Multiple Comparison for

Middle vs. Top	0.8907	1.196	-0.3055	0.006019	18	18	71.78	204
NS								
Butt vs. Middle	0.7572	1.054	-0.2964	0.006019	18	18	69.63	204
Butt vs. Top	0.7572	1.333	-0.5755	0.006019	18	18	135.2	204
Middle vs. Top	1.054	1.333	-0.2791	0.006019	18	18	65.58	204
CH								
Butt vs. Middle	0.7886	0.9886	-0.2000	0.006019	18	18	46.99	204
Butt vs. Top	0.7886	1.133	-0.3449	0.006019	18	18	81.04	204
Middle vs. Top	0.9886	1.133	-0.1449	0.006019	18	18	34.04	204
CS								
Butt vs. Middle	0.9410	1.113	-0.1719	0.006019	18	18	40.39	204
Butt vs. Top	0.9410	1.273	-0.3316	0.006019	18	18	77.92	204
Middle vs. Top	1.113	1.273	-0.1597	0.006019	18	18	37.53	204

B5 Lignin Content

Within each row, compare columns (simple effects within rows)	
Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary

NH				
Butt vs. Middle	1.380	-0.3121 to 3.072	No	ns
Butt vs. Top	2.183	0.4915 to 3.875	Yes	**
Middle vs. Top	0.8036	-0.8883 to 2.496	No	ns
NS				
Butt vs. Middle	0.8449	-0.8471 to 2.537	No	ns
Butt vs. Top	1.362	-0.3297 to 3.054	No	ns
Middle vs. Top	0.5174	-1.175 to 2.209	No	ns
CH				
Butt vs. Middle	1.070	-0.6221 to 2.762	No	ns
Butt vs. Top	2.809	1.117 to 4.501	Yes	**
Middle vs. Top	1.739	0.04737 to 3.431	Yes	*
CS				
Butt vs. Middle	1.647	-0.04510 to 3.339	No	ns
Butt vs. Top	3.128	1.436 to 4.820	Yes	***
Middle vs. Top	1.481	-0.2105 to 3.173	No	ns

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	24.80	23.42	1.380	0.6775	3	3	2.880	24
Butt vs. Top	24.80	22.61	2.183	0.6775	3	3	4.558	24
Middle vs. Top	23.42	22.61	0.8036	0.6775	3	3	1.677	24

Table Multiple Comparison for

NS								
Butt vs. Middle	25.09	24.25	0.8449	0.6775	3	3	1.764	24
Butt vs. Top	25.09	23.73	1.362	0.6775	3	3	2.843	24
Middle vs. Top	24.25	23.73	0.5174	0.6775	3	3	1.080	24
CH								
Butt vs. Middle	25.01	23.94	1.070	0.6775	3	3	2.233	24
Butt vs. Top	25.01	22.20	2.809	0.6775	3	3	5.864	24
Middle vs. Top	23.94	22.20	1.739	0.6775	3	3	3.631	24
CS								
Butt vs. Middle	25.08	23.43	1.647	0.6775	3	3	3.438	24
Butt vs. Top	25.08	21.95	3.128	0.6775	3	3	6.530	24
Middle vs. Top	23.43	21.95	1.481	0.6775	3	3	3.092	24

B6 Cellulose Content

Within each row, compare columns (simple effects within rows)

Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-0.2009	-1.430 to 1.028	No	ns

Butt vs. Top	1.870	0.6415 to 3.099	Yes	**
Middle vs. Top	2.071	0.8424 to 3.300	Yes	***
NS				
Butt vs. Middle	-0.02066	-1.250 to 1.208	No	ns
Butt vs. Top	0.4461	-0.7828 to 1.675	No	ns
Middle vs. Top	0.4668	-0.7622 to 1.696	No	ns
CH				
Butt vs. Middle	3.679	2.451 to 4.908	Yes	****
Butt vs. Top	1.299	0.06992 to 2.528	Yes	*
Middle vs. Top	-2.381	-3.610 to -1.152	Yes	***
CS				
Butt vs. Middle	1.436	0.2073 to 2.665	Yes	*
Butt vs. Top	1.732	0.5034 to 2.961	Yes	**
Middle vs. Top	0.2961	-0.9328 to 1.525	No	ns

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	41.55	41.75	-0.2009	0.4921	3	3	0.5774	24
Butt vs. Top	41.55	39.68	1.870	0.4921	3	3	5.375	24
Middle vs. Top	41.75	39.68	2.071	0.4921	3	3	5.953	24
NS								
Butt vs. Middle	40.13	40.15	-0.02066	0.4921	3	3	0.05937	24
Butt vs. Top	40.13	39.68	0.4461	0.4921	3	3	1.282	24

Table Multiple Comparison for

Middle vs. Top	40.15	39.68	0.4668	0.4921	3	3	1.341	24
CH								
Butt vs. Middle	41.27	37.59	3.679	0.4921	3	3	10.57	24
Butt vs. Top	41.27	39.97	1.299	0.4921	3	3	3.733	24
Middle vs. Top	37.59	39.97	-2.381	0.4921	3	3	6.841	24
CS								
Butt vs. Middle	41.15	39.71	1.436	0.4921	3	3	4.127	24
Butt vs. Top	41.15	39.42	1.732	0.4921	3	3	4.978	24
Middle vs. Top	39.71	39.42	0.2961	0.4921	3	3	0.8509	24

B7 Holocellulose Content

Within each row, compare columns (simple effects within rows)

Number of families	4
Number of comparisons per family	3
Alpha	0.05

Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-2.241	-4.042 to -0.4403	Yes	*
Butt vs. Top	-2.493	-4.293 to -0.6919	Yes	**
Middle vs. Top	-0.2516	-2.052 to 1.549	No	ns

NS				
Butt vs. Middle	-4.702	-6.503 to -2.901	Yes	****
Butt vs. Top	-3.978	-5.779 to -2.177	Yes	****
Middle vs. Top	0.7241	-1.077 to 2.525	No	ns
CH				
Butt vs. Middle	-1.848	-3.649 to -0.04769	Yes	*
Butt vs. Top	-1.403	-3.204 to 0.3975	No	ns
Middle vs. Top	0.4451	-1.356 to 2.246	No	ns
CS				
Butt vs. Middle	-5.333	-7.134 to -3.532	Yes	****
Butt vs. Top	3.624	1.823 to 5.425	Yes	***
Middle vs. Top	8.957	7.156 to 10.76	Yes	****

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	63.07	65.31	-2.241	0.7211	3	3	4.395	24
Butt vs. Top	63.07	65.56	-2.493	0.7211	3	3	4.889	24
Middle vs. Top	65.31	65.56	-0.2516	0.7211	3	3	0.4935	24
NS								
Butt vs. Middle	68.02	72.72	-4.702	0.7211	3	3	9.222	24
Butt vs. Top	68.02	72.00	-3.978	0.7211	3	3	7.802	24
Middle vs. Top	72.72	72.00	0.7241	0.7211	3	3	1.420	24

Table Multiple Comparison for

CH								
Butt vs. Middle	62.87	64.72	-1.848	0.7211	3	3	3.625	24
Butt vs. Top	62.87	64.27	-1.403	0.7211	3	3	2.752	24
Middle vs. Top	64.72	64.27	0.4451	0.7211	3	3	0.8731	24
CS								
Butt vs. Middle	63.86	69.19	-5.333	0.7211	3	3	10.46	24
Butt vs. Top	63.86	60.23	3.624	0.7211	3	3	7.108	24
Middle vs. Top	69.19	60.23	8.957	0.7211	3	3	17.57	24

B8 Hemicellulose Content

Within each row, compare columns (simple effects within rows)				
Number of families	4			
Number of comparisons per family	3			
Alpha	0.05			
Tukey's multiple comparisons test	Mean Diff.	95% CI of diff.	Significant?	Summary
NH				
Butt vs. Middle	-1.560	-3.930 to 0.8103	No	ns
Butt vs. Top	-4.450	-6.820 to -2.080	Yes	***
Middle vs. Top	-2.890	-5.260 to -0.5197	Yes	*
NS				
Butt vs. Middle	0.1000	-2.270 to 2.470	No	ns

Butt vs. Top	-5.057	-7.427 to -2.686	Yes	****
Middle vs. Top	-5.157	-7.527 to -2.786	Yes	****
CH				
Butt vs. Middle	-10.97	-13.34 to -8.603	Yes	****
Butt vs. Top	-2.703	-5.074 to -0.3330	Yes	*
Middle vs. Top	8.270	5.900 to 10.64	Yes	****
CS				
Butt vs. Middle	-6.770	-9.140 to -4.400	Yes	****
Butt vs. Top	1.270	-1.100 to 3.640	No	ns
Middle vs. Top	8.040	5.670 to 10.41	Yes	****

Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	N1	N2	q	DF
NH								
Butt vs. Middle	21.42	22.98	-1.560	0.9492	3	3	2.324	24
Butt vs. Top	21.42	25.87	-4.450	0.9492	3	3	6.630	24
Middle vs. Top	22.98	25.87	-2.890	0.9492	3	3	4.306	24
NS								
Butt vs. Middle	27.23	27.13	0.1000	0.9492	3	3	0.1490	24
Butt vs. Top	27.23	32.29	-5.057	0.9492	3	3	7.534	24
Middle vs. Top	27.13	32.29	-5.157	0.9492	3	3	7.683	24
CH								
Butt vs. Middle	21.60	32.58	-10.97	0.9492	3	3	16.35	24
Butt vs. Top	21.60	24.31	-2.703	0.9492	3	3	4.028	24

Table Multiple Comparison for

Middle vs. Top	32.58	24.31	8.270	0.9492	3	3	12.32	24
CS								
Butt vs. Middle	22.71	29.48	-6.770	0.9492	3	3	10.09	24
Butt vs. Top	22.71	21.44	1.270	0.9492	3	3	1.892	24
Middle vs. Top	29.48	21.44	8.040	0.9492	3	3	11.98	24