KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

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The Natural Durability, Anatomy and Chemical Composition of the Stem and Branch Woods of Two Commercial Hardwood Timbers [*Aningeria robusta* (A. Chev) and *Terminalia ivorensis* (A. Chev)]

by

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DOCTOR OF PHILOSOPHY

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CERTIFICATION

I hereby declare that this submission is my own work toward the MPhil/PhD degree 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

To enhance wood economic value and effective utilization, knowledge of its properties, which impact its service behaviour, is indispensable. The biochemical properties of the sapwoods and heartwoods along the stems and branches of *T. ivorensis* and *A. robusta* were studied to provide

adequate information to enhance their efficient utilization, especially branchwood, whose use could widen the raw material base of the timber industry. Macerated samples and microtomed sections (radial, longitudinal and tangential), TAPPI and field tests respectively were employed to determine tissue dimensions and proportions, chemical component percentages and the natural durability. Analyses of variance (ANOVA) were used to test for differences between axial and radial position and tree portions and correlation and regression analysis were used to determine the relationships among the biochemical properties. Stemwood recorded wider vessel lumen diameter, greater fibre and vessel proportions with less parenchyma than the branchwood. Fibre length, diameter, lumen diameter and double wall thickness were greater for *T. ivorensis* stemwood (1296.7-1508.6, 19.8-23.4, 13.3-17.3 and 6.0-6.5µm respectively) than branchwood (1046.0-1116.5, 19.2-21.2, 13.1-15.2 and 5.7-6.3µm respectively). Similarly, *A. robusta* stemwood recorded greater values (1182.9-1302.3, 22.9-23.9, 15.3-18.6 and 6.2-7.6µm respectively) than branchwood (995.1-1145.3, 20.1-22.42, 15.1-17 and 4.9-5.6µm respectively). Fibre proportions decreased up their stems (51.5-42.5%) and branches (51.2-40.0%). Their sapwood and heartwood vessel and parenchyma percentages were greater at bases than top. Vessel lumen diameters increased with stem height but decreased along branches. *T. ivorensis* had 39.0-41.9%, 18.1-23.6%, 31.6-32.9% and 1.58-9.9% and *A. robusta* 39.1-40.5%, 32.634.0%, 24.9-26.6% and 0.37-1.6% cellulose hemicellulose, lignin and extractives percentage respectively. the amounts were greater for stemwoods, except for more branchwood hemicellulose percentages. Extractives and lignin were also greater for heartwoods than sapwoods, which also had more cellulose and hemicelluloses. *A. robusta* was rated non-durable; it was completely degrade; lost 100% weight and hardness. Natural durability of *T. ivorensis* decreased with height along the stem and branch, was greater for stem heartwood (moderately durable to very durable) than branch heartwood (moderately durable) and for heartwood than sapwood. Chemical components were great

determinants of natural durability, while the anatomical features were poor determinants of natural durability for *T. ivorensis.* The biochemical properties of the branchwoods of *T. ivorensis* and *A. robusta*, compare favourably with their stemwoods and with utilizable hardwoods. The branchwoods could suitably be utilized

to avoid wastage and increase the raw material base of the wood industry.

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CHAPTER ONE

INTRODUCTION

1.1 The significance of wood waste on the forest and wood industry

Forest degradation is occurring throughout the world at an alarming rate and accordingly it features prominently in relevant international objectives, goals and targets (Tavani *et al*., 2009; Worldwild life, 2014). The decline in forest resources in developing countries is due to their depletion (Ashori, 2006). This is as a result of higher demand for wood in the forest industry due to the increasing population and new application areas (such as agriculture, ranching and development), and environmental pressures (Gurau *et al*., 2010; Amin *et al*., 2013).

This destruction threatens some of the world‘s most famous and valuable forests, including rainforests in the Amazon, Congo Basin and other parts of Africa, Indonesia and the forests of the Russian and Far East as well as parts of Eastern Europe (Szalay, 2013; Worldwild life, 2014). According to European Commission (2015), the tropical forests are disappearing at a rate of about 13 million ha p.a. Carlos *et al*. (2013), estimated that annual forest degradation increased by 20% from 2000 to 2010. In Indonesia, the forest stock is decreasing by 6% per year (Marklund and Schoene, 2006) and 17% of the forest of Amazon has been lost in the last 50 years (Worldwild life, 2014). From 2000 to 2010, 169,074 km^2 of Amazonian forest was converted to human-dominated land uses, such as agriculture, while 50,815 km^2 of forest, equivalent to 30% of the area converted by deforestation was directly altered by timber harvesting and/or fire (Carlos *et al*., 2013).

Similarly, from the mid-1990s, Ghana's forests have been under excessive exploitation, with illegal harvesting being rampant and the neglect for established harvesting procedures (Donkor, 2003). The alarming depletion rate of Ghana's forests has become one major challenge facing the wood-related industries, foresters and environmentalists. This is because, depletion of forest and wood lands do not only affect industrial and economic growth negatively, but also disturb the whole forest ecosystem (Dadzie, 2013). In Ghana, the depletion trend has been attributed to demand for wood, inefficient logging and processing practices, and misuse of wood secondary resources like branches (Ayarkwa *et al.*, 2000; Dadzie, 2013).

Even though the global demand for wood and fibrous materials in the wood-based industry has been growing, the production of industrial wood from natural forests continues to decline (Kiaei, 2011), resulting in the depletion of certain timber species as well as reduced availability of large-sized trees (Gurau *et al.*, 2010). In addition, massive wood exploitation continues to be the major concern of the near future (Gurau *et al.*, 2010). However, commercial logging operations concentrate all interest on the straight part of the main stem, leaving large quantities of timber as residue (Kollmann and Côte, 1984), as wood-processing industries have also limited their use of wood to stemwood (Amoah, 2008; Gurau *et al.*, 2010; Amoah *et al.*, 2012; Dadzie, 2013).

Consequently, approximately 50% of wood is wasted during the extraction of timber (Okai *et al.*, 2004). A study conducted by NOACK (1995) in Cameroun, Indonesia, Ghana and Malaysia, indicated that, on average, 4.6% waste is generated in stumps and 5.2 % in buttresses. Main bole off-cuts account for 10.4% waste, whilst 26.3 % of the branches with diameters greater than 20 cm are also left as waste. Similarly, Amoah (2008) noted that about 25% of merchantable wood in the form of branches and stems are left as residues during logging operations in Ghana's forests. Again, according to Bentley and Johnson (2008), 13% and 21%

of softwood and hardwood respectively harvested in South California is not utilized and over 30% of the tree volume including logs, tops and branchwood are left as logging residue. About 15% of logging waste is generated in upcountry eucalyptus in Sri-Lanka (Ruwanpathirana, 2011). Likewise, 45.35% of upper portion of trees including branches, smaller branches and twigs are left as residue in Indonesia (Ravn, 1999).

To sustain the Forestry Sector (which contributes about 7% and 14% respectively to the Gross Domestic Product (GDP) and total export earnings of Ghana and the wood industry), meet the future demand and overcome the wood shortage, logging is not to be prevented but rather managed, aiming that wood is harvested sustainably and utilized efficiently (Peprah, 1999; Ghana Gazette, 2003). Enters (2001) stated that all logging operations generate waste, about 24.6 million m^3 waste is generated in Asia-Pacific; the solution is not avoidance but rather of minimization and utilization. Thus, there is the need to reduce wood waste and find alternatives to stemwood from harvested trees (Gurau *et al.*, 2010) and utilize new or alternative resources in the forest industries as raw material components (Kiaei, 2011). For instance, the ―*total-tree utilization concept*‖ is stated to contribute to the solution if adopted, such that timber branches and their off-cuts (after harvesting) could all be engineered into a number of products for sustainability of the resource (Haygreen and Bowyer, 1996; Gurau *et al.*, 2010). It is important to note that reducing waste could increase yield from every harvested timber and prevent collapse of the wood industry (Okai *et al.*, 2004).

Haygreen and Bowyer (1996) found that the use of other portions of trees (such as branches, twigs and stumps) in addition to the main stem could increase yield of timber from 60 to 100%. The unmarketable portions could be used as a source of fiber for pulp and paper and other wood products such as furniture parts, toys and packaging containers, while innovative goods could be made from such portions for local consumptions because of excessive demands on timber

resources. Consequently, the efficient utilization of wood residue or secondary resources such as branches would not only aid the sustenance of the natural forests by maximizing yield from wood but it would also lower the overall cost of export-oriented sawmills to be able to produce for the local market as well (Ghana Gazette, 2004).

1.2 Utilization of Branchwood.

Branchwood represents an important secondary wooden resource (Olarescu *et al.,* 2009). In Romania the annual volume of exploited branches of the main forest species is 3, 2268 millions m^3 per hectar. This value represents 30% from the annually exploited volume of different species (Olarescu, 2007). In the estimation of Hilton (2001), branch wood represents 25-30% of the total wood volume. Similarly, overall average merchantable branchwood volume was found to be 28.602% of the total extracted wood volume harvested for a study (Dadzie, 2013). Dadzie (2013) further argued that the amount of branchwood translates into preserving or conserving about 6 hectares of forest land area, should branchwood be extracted for use, and that, the quantities of branchwood obtained suggest that branchwood has considerable volume to supplement stemwood. Thus, warranting their commercialization, to provide raw materials for inhabitants of the forest area. On the whole, if branch logs are also extracted, it can supplement the main stem logs to an appreciable level and provide additional lumber volume for additional economic gains and reduce the high depletion rate of the forest (Dadzie, 2013). According to Haygreen and Bowyer (1996) and Okai *et al.* (2004), branchwood can also be used judiciously to increase the total tree volume yield per unit area of the natural forest. Thus, increasing the added value of branches indicates finding alternative uses other than firewood or particleboard for wood-based panels (Gurua *et al.,* 2010). Amoah *et al.* (2012) declared that the dimensions of branches suggest that branchwood could be used to manufacture a wide range of products including furniture parts, tongue and groove and door frames.

Even though the trend towards utilization of greater portions of trees is increasing, the conversion of branchwood and tree crowns into usable material is only done where it is considered economically realistic (Kollmann and Côte, 1968). Branchwoods are considered ―unattractive‖ regarding their processing problems and low product quality and are therefore usually rejected particularly because of extensive disparity in their properties from stemwoods. Nonetheless, branchwood could be used in new added-value products as an alternative to stemwood provided its characteristics are known and understood (Haygreen and Bowyer, 1996; Gurau *et al.*, 2010). Consequently, variations between the stemwood and branchwood need to be evaluated to obtain adequate information on the properties of branchwood (Oteng-Amoako, 2002). This would facilitate the determination of its particular end-use requirements (Gartner *et al.*, 1996) and modified manufacturing processes to accommodate the variations (Haygreen and Bowyer, 1996).

1.3 The significance of wood properties in the utilization of wood.

The practical knowledge of wood properties is important for knowing how to convert wood into products (McBroom, 2013). Till now, the utilization of branch wood considers the following criteria: form of branches; some mechanical properties such as elasticity; aesthetic qualities; the maximal utilization of valuable species; utilization at industrial scale as raw material for cellulose, particleboards and fiberboards (Lessard, 1999; Bowyer *et al*., 2003; Cionca, 2007). Even though branchwood represents a secondary resource, its potential utilization has less been investigated (Amoah *et al.*, 2012). The economic value of wood is affected by its properties, which are generally influenced by the anatomical features. For instance, the knowledge of wood anatomy and chemical composition is widely regarded decisive in understanding wood properties and its behavior in service (Dinwoodie 1981; Bowyer *et al*., 2003; Barnett and Jeronimidis 2003; Sehlstedt-persson and Olov, 2010).

Understanding the agents and conditions that can cause wood decay or other forms of deterioration is imperative for wood utilization (Haygreen and Bowyer, 1996). In addition, the chemical composition, anatomical properties and natural durability are interrelated and may directly or indirectly influence each other and the other properties of wood (Wilson and white, 1986).

The tropical hardwood trade is conducted on the basis of their known properties and performance (Ajala and Ogunsanwo, 2010). Therefore, evaluation of the properties of branchwood of hardwoods is imperative for its efficient utilization so as to alleviate the pressure on the tropical forest (Gurau *et al.*, 2010). There is inadequate information on the within-tree variation of many tree species (Gartner *et al.*, 1996). However, the physicomechanical properties of the stem- and branchwoods of *A. robusta* and *T. ivorensis* were studied by Okai *et al.* (2004) who found that the specific gravity and compression strength parallel to the grain were greater for branchwood than corresponding stemwood, whereas static bending, modulus of rupture and modulus of elasticity were greater for the stemwood. These authors consequently recommended the branchwood of *Aningeria robusta* and *Terminalia ivorensis* as a suitable material for downstream processing. Nonetheless, their utilization will not be optimum because there is inadequate information on their anatomical properties, which are known to be responsible for several of their properties including the physical and mechanical properties (Barnett and Jeronimidis, 2003). Moreover, the chemical composition and natural durability are important properties of wood as a building and construction material (Olfat, 2011). They determine the stability and duration of wood in service.

1.4 Research Questions

The study is undertaken with the following research questions:

- What is the anatomical properties of the stemwood and branchwood of *T. ivorensis* and *A. robusta*
- What is the chemical composition of the stemwood and branchwood of *T. ivorensis* and *A. robusta*
- What is the natural durability of the stemwood and branchwood of *T. ivorensis* and *A. robusta*
- What are the relationships between natural durability, chemical components and anatomical features of wood?

1.5 Research objectives

Main objective

This study therefore sought to investigate the bio-chemical properties of the stem- and branch-wood of *A. robusta* and *T. ivorensis* in order promote their efficient utilization.

Specific objectives

The specific objectives of this study are to determine the:

1. Anatomical properties of the stemwood and branchwood of *A. robusta* and *T. ivorensis.*
2. Chemical composition of the stemwood and branchwood of *A. robusta* and *T. ivorensis*
3. Natural durability of the stemwood and branchwood of *A. robusta* and *T. ivorensis* and the relationships among the anatomical features, chemical components and natural durability.

1.6 Relevance of the Research

This study will establish essential properties for improved processing and utilization of *T. ivorensis* and *A. robusta*, especially their branchwoods in the wood industry. The attractiveness of wood from different portions of these timbers for product manufacturing will also be augmented, since increased information on their behaviour in service will be made accessible, and their potential utilization statuses could be established. Thus, the commercial relevance of both the stem- and branch-woods to the wood industry will be emphasized, which will in turn reduce waste in the forestry sector and the wood industry. The scientific data base of wood, particularly branchwood properties of hardwoods will also be enriched.

CHAPTER TWO

2.1 LITERATURE REVIEW

2.1 Natural durability of wood

Natural durability is defined in EN350-1 (CEN, 1994) as ‗the inherent resistance of wood to attack by wood-destroying organisms'. The principal biological agents that degrade wood are bacteria, fungi, insects, (e.g. termites and beetles), and marine borers (Tsunoda, 1990). Eaton and Hale (1993) and Johnson *et al.* (2006), defined natural durability as the inherent ability of wood species to resist biological deterioration. Similarly, Hunt and Garatt (1967) and CIRAD (2009), referred to natural durability as the resistance of untreated heartwood of timber species against the attack of decay fungi and termites when the timber is used under exposed or outdoor conditions. Natural durability reflects both the natural genetic potential of wood and the environmental stresses to which the wood is subjected (Ali, 2011); the higher the risk of decay, the shorter the expected service life for a given wood product.

Knowledge about natural durability of untreated wood to wood-destroying fungi comes either from experience, from observation and from systematic field tests (sometimes referred to as ‗graveyard trials') with different wood species in ground contact trials (Eaton and Hale 1993); or from laboratory tests using the basidiomycete fungi (Willeitner and Peek 1997; Gierlinger *et al.*, 2003; Råberg *et. al*., 2005). Field tests expose specimens to real service conditions, but takes longer and results from different test sites are not comparable because of different exposure conditions (Yamamoto and Hong, 1994). Based on the results of these tests, wood is assigned to one of five natural durability classes, 1–5, where 1 is very durable and 5 is not durable (EN 350-1 CEN, 1994a).

Some naturally durable wood species (such as mahogany) resist attack by insects and marine borers, as some species are also naturally resistant to fungal attack, but have little or no protection against other organisms (Scheffer and Morrell, 1973). They further, asserted that a wood species might be resistant to one group of termites, but susceptible to others, as resistance to *Limnoria* may not translate to similar resistance to *Teredo, Bankia*, or *Martesia*. Thus, natural durability against fungi, as well as resistance to insects or marine borers, can vary widely (Ncube, 2010; Nascimento *et al.,* 2013). In this regard, Chudnoff (1984) and Lemmens (2007) observed that *A. robusta* is not durable and are susceptible to termites, fungi and dry-wood borers. However, the heartwood of *T. ivorensis* is rated as durable and moderately resistant to termite attack, but its sapwood is liable to powder-post beetle attack (Chudnoff, 1984).

2.1.1 Factors that influence natural durability of wood.

2.1.1.1 Extractives

Distinctions that occur in the resistance to decay of different species of wood and even sections cut from the same tree exposed to the same fungi are owed mainly to the composition and amount of fungi-toxic extractives in the wood. Thus, extractives are mainly responsible for the natural durability of wood (Scheffer and Cowling, 1966), and their amount sometimes indicates the degree of resistance of wood to decay (Takahashi and Kishima, 1973; Yatagai and Takahashi, 1980). Durable wood from which extractives are removed become susceptible to decay (Scheffer and Cowling, 1966; Smith *et al.*, 1989; Antwi-Boasiako *et al*., 2011). Similarly, adding extractives to decay prone wood can render it decay resistant (Smith *et al.*, 1989; Kamden, 1994; Antwi-Boasiako *et al.*, 2011). This is because most extractives are produced by trees to provide protection from predators that wish to consume the cell wall structural components (Helm, 2000). Combined toxicity and antioxidant properties of extractives, makes them resistant to decay organisms (Schultz *et al.,* 2008). Extractives may

also have other properties besides toxicity and antioxidant that could also affect termites (Schultz *et al.*, 2008).

However, extractive concentrations in heartwood do not necessarily correspond to natural durability (Kumar, 1971; Hillis, 1987; Gartner *et al.*, 1999). In some cases, decay resistance is poorly correlated with variations in heartwood compounds that are largely responsible for preventing decay (Hillis, 1987; DeBell *et al.*, 1999), suggesting that more subtile differences in extractive composition or distribution may be important (Gartner *et al*., 1999). For instance, extractives may exhibit activities that are specific to the organisms that normally attack the tree (Etheridge, 1962; Ohsawa *et al.*, 1992). In addition, some durable heartwood may contain multiple low-toxicity extractive compounds that interact synergistically (Schultz *et al.*, 1995; Schultz and Nicholas, 2002; Antwi-Boasiako and Damoah, 2010), while some species (e.g. Larix *spp*) may produce large amounts of extractive materials that apparently provide little or no protection to the wood (Srinivasan *et al.*, 1999).

2.1.1.2 Cell wall components

According to Jeffries (1987) and Rózanska *et al.* (2011), aside extractives which contribute to decay resistance in wood, the gross chemical composition of wood actually shows relatively little about its potential for degradation. Yet, cellulose is reported to make wood somewhat resistant to microbial attack (Scheffer and Morrell, 1973), while lignin content is also stated to add to the natural durability of wood (Moya and Tomazello, 2007; Ali, 2011), by impeding the penetration of destructive enzymes through the cell wall (Sarkanen *et al*., 1971). Moreover lignification is often discussed as an additional factor in decay resistance (Zabel and Morrell 1992), as the decay resistance of wood is provided by the lignified cell walls (Zabel and Morrell 1992). Even slight variations in the lignin composition within cell types and/or cell wall layers, and the proportion of parenchyma cells may influence the durability of wood (Schwarze 1995;

Schwarze *et al.,* 2004). Moreover, a general response to fungal infection of wood is the formation of lignin and lignin-related compounds (Majaila, 2000). Thus, the lignin component presents the most significant barrier to wood decay as it is a complex polymer that encrusts the cell walls, preventing access of low molecular weight diffusible agents, which are required for decomposition of cellulose and hemicelluloses (Schwarze, 2007).

A. mellea, which has the capacity to degrade all cell wall constituents, preferentially degraded cell walls with relatively low lignin content (Schwarze *et al.,* 2000). In another case, a slight decrease in decay resistance after extraction of some Malaysian hardwood timbers was influenced by the presence of lignin in cells (Syafii *et al.,* 1988). Moreover, Highley (1982) has shown that differences in the type of lignin apparently are a key factor in slower degradation of woods. Besides, insect gut systems do not have the capacity to degrade lignin (Ohkuma, 2003), rendering it much resistance to termite and microbial attacks.

The extensive intermolecular bonding pattern of cellulose generates a crystalline structure that, together with hemicellulose and lignin, results in very complex morphologies, and multiple enzyme systems are thus required to efficiently degrade cellulose (Sjostrom, 1993; Scheffer and Morrel, 1998). In addition, the insolubility and complexity of lignin adds to wood‘s toxicity and makes wood resistant to degradation by most micro-organisms (Campbell and Sederoff, 1996), hence to decay and insect attack (Zabel and Morrell 1992; McBroom, 2013). Various studies have emphasized the resistance of vessel cell walls to decomposition by white rot fungi (Olfat, 2011). The resistance of vessels to decomposition appears to be related to their high lignin: carbohydrate ratio, lignin monomer composition and cell wall morphology (Olfat, 2011).

Nonetheless, Harju *et al.* (2003) found no differences in lignin content between decay resistant and decay-susceptible pine trees and larch wood, and stated that lignin seems to be of minor importance in decay resistance of wood. Furthermore lignin is cross-linked mostly into the hemicellulose, which is accessible due to its porosity. Hemicellulose is also more readily depolymerized (Paice and Jurasek, 1984), usually being removed first during degradation (Jeffries, 1987). Organisms have also developed the ability to attack one or more of the polymers in the wood cell wall (Scheffer and Morrell, 1988). Cellulolytic microorganisms typically secrete a range of different cellulases with overlapping specificities to be able to adequately degrade cellulose and hemicellulose (Tomme *et al*., 1995) and many wood-feeding insects overcome the lignin barrier by feeding on pre-degraded wood (Kukor *et al.*, 1988) or through exo-symbiotic relationships with wood-degrading fungi (Taprab, *et al*., 2005; Johjima *et al.*, 2006).

Studies have also shown that, superior decay resistance is associated with less weight loss in many tropical hardwoods and most realistic description of microbiological deterioration is the monitoring of density changes by weight loss and decrease of some strength characteristics, e.g. hardness, modulus of elasticity and compression strength (Ali, 2011; Antwi-Boasiako, 2010). Where fungi utilize the wood carbohydrates and degrade the complex cell wall polymers of lignin, cellulose and hemicelluloses through production of extracellular enzymes, structural degradation, weight and hardness loss, as well as loss of other strength properties of the wood block are substantial (Rayner and Boddy,1988). Consequently the unity of density, strength and wood durability is even standardised (e.g. EN 252) to give a comprehensive description of wood behaviour.

2.1.1.3 Tyloses

Tyloses, which also serve as mechanical barriers to attack; may prevent or slow wood decay in some species by physically blocking the penetration of insects or fungal hyphae (Taylor *et al.*, 2002). Thus, they function as part of the defensive strategy of trees by blocking the movement of pathogens along vessels and by allowing toxic extractives to accumulate without being diluted by the transpiration stream (Bell, 1980). Tyloses are defined as parenchyma cell outgrowths through a pit into the cavity of a vessel (Esau, 1960; Fahn,

1990). They are composed of materials similar to the cell wall of adjacent cells (Chattaway, 1949), and are a regular feature of many heartwood vessels in many hardwoods species, but may also occur in the sapwood of these species (Gerry, 1914). Their presence reduces heartwood permeability to fluids (McIntosh, 1970; Bierman, 1996) as they inhibit fluid flow, which can limit moisture uptake and may physically impede the movement of pathogens through wood (Taylor *et al.*, 2002).

Moisture has great impact on wood durability and service life because it is a prerequisite of vital importance for the wood destroying organisms without which they cannot attack wood (Ali, 2011). The amount of decay that occurs in timber in service will depend on the moisture content of the timber (Moore, 2011). The surrounding temperature, relative humidity, and the availability of oxygen will also influence the amount of decay (Ali, 2011). Consequently, the impedance of tyloses to fluid flow in wood is important to utilization since it influences durability. Chudnoff (1984) observed that *A. robusta* is very permeable, but *T. ivorensis* is highly resistant to preservative treatments due to the presence of tyloses. The obstruction of the cells makes it difficult for biotic attack and thus magnifies heartwood natural durability (Moore, 2011). There was also a correlation between regular occurrence of tyloses and high decay resistance in a study by (Gerry, 1914).

2.1.1.4 Wood Tissues

Wood tissues are known to vary in the composition of their cell walls, dimensions and proportions, with the variability being greater and more complex in hardwood (Olfat, 2011). These variations appear to influence the natural durability of wood because, the abundance of extractives and the other chemical substances and the movement of the biodegrading agents in wood are influenced by these cell characteristics (Schwarze, 2004). Moreover, Jeffries (1987) agreed that the physical structure of the tissue and the microstructures of the components determine the accessibility of degrading organisms and enzymes in wood. Similarly, Tiemann (1951) and Haygreen and Bowyer (1996) confirmed that fibre dimensions affect the ligno-cellulosic content of wood and have a direct bearing on natural durability of wood. This is due to the fact that chemical components of wood, which tells about the potential of the wood's durability (Jefferies, 1987) are distributed non-uniformly as a result of the anatomical structure of wood (Iversen and Wannstrom, 1986).

For instance, the proportion of parenchyma could influence the amount of extractives produced (Taylor *et al.,* 2002), as heartwood extractive synthesis occurs in axial and ray parenchyma (Taylor *et al.,* 2002). To substantiate this, a positive correlation was observed between parenchyma volume and heartwood extractives in *Psedotsugo menziesii* (Hermingway and Hillis, 1970). In addition, Hillis *et al.* (1962) realized fewer parenchyma and less heartwood extractives in tension wood than in normal wood of *Angophora costata.* Interestingly, weight loss from different wood species appeared to correlate with the content of parenchyma cells found in the xylem (Olfat, 2011). Moreover, recent studies show that, parenchyma cells, which have been regarded as strongly susceptible to decay, are highly resistant to brown rot fungi (Schwarze 1995; Schwarze *et al.,* 2004). The resistance of parenchyma cells to decomposition by brown rot fungi is not associated with the lignin composition or the total lignin content within parenchyma cells, but appears to be associated with the cell wall morphology (Olfat,

2011). Nevertheless, Nelson (1975) concluded that physiological conditions at the heartwood/sapwood boundary were more important than the amount of parenchyma in determining the amount of extractives produced in hardwood.

Vessel elements have also been reported to be more decay resistant than fibres (Olfat, 2011; Koyani and Raput, 2015), particularly to soft rot fungi because of a greater proportion of guaiacyl lignin (Schwarze *et al.*, 1995). As a result, even fibres surrounding vessels and xylem ray parenchyma were observed to be more resistant to decomposition (Olfat, 2011). On the other hand, extractives in general are also found in cell lumina and even in cell walls of fibres and high proportion of such fibres may increase durability (Yamamoto and Hong, 1989). It is important to also note that wide vessels that lack extractives provide high permeability and consequently, easy moisture uptake and thus increased susceptibility to biodegradation as shown in metil wood (Uetimane, 2010). Results from the work by AntwiBoasiako and Atta-Obeng (2009) correlated increased durability with fibres, as they found *A. toxicaria* with greatest number of vessels, but least number of fibres having very low durability and *M. excels* with the strongest Vessel-Fibre ratio being very durable.

However, wide-lumen fibres would also easily absorb moisture into their voids, creating conducive environment for bio-degraders. Hence, a wide-lumen fibred wood would be more susceptible to decay (especially soft-rot) (Antwi-Boasiako and Ayimasu, 2012). In confirmation, Kleist and Seehaan (1997) and Schwarze (2004) reported that abundant longitudinal hyphal growth of *Stereum sanguinolentum* occurred rapidly within the fibres with large lumina, while hyphal growth in the cell lumen of thick-walled fibres was sparse, as the narrow cell lumina passively hamper colonization (Schwarze, 2004). Besides, thickwalled fibres assist timber to withstand nibbling by bio-degraders (Antwi-Boasiako and Ayimasu, 2012).

During early stages of colonization, most hyphae grow within the lumen of the wood fibres (Schwarze *et al.*, 2004), and in the degradation of whole wood, fungi mycelia initially invade the wood through the ray cells and move throughout the tissue by way of the intracellular lumens and pit connections (Jeffries, 1987). The hyphae are initially concentrated in the ray cells and propagate into the center of the wood along the inside of the cell lumens. The hyphae grow in the cell lumina in some cases, so that the lignin is dissolved out of the adjacent cell wall. In other cases, hyphae penetrate the cell walls and initially delignify the middle lamella so that the cells tend to separate. Thus, intracellular lumen and wall pits are particularly important in degradation because they provide access for the invading mycelium to pass from one cell to another (Jeffries, 1987). In addition, Zabel and Morrell (1992) and Kollmann and Côtè (1984) stated that the diameter of vessel lumen is most significant in the susceptibility of sawn lumber to powder post beetles; they only infest timbers with pores large enough to take their insect ovipositor. For instance, *Lyctus brunneus* will need vessel lumen diameter of 90µm or more to be able to invade the wood (Kollmann and Côtè, 1984).

The relationship between wood structure and microbial degradation is somewhat ambiguous because of the many separate variables such as lignin content and composition, the presence of extractives, the density of the tissue structure, moisture content and the relation of these variables to the invading organism (Wilcox, 1973). The natural durability of wood cannot be attributed to a single chemical component but their combined effect (Ali, 2011). The interaction between cellulose, hemicellulose and lignin together with the effects of fungitoxic extractives influences durability (Wilcox, 1973). Besides, several factors apart from chemical components of wood are used to explain the natural durability of wood (Nzokou *et al.*, 2005).

2.2 General anatomical structure of hardwoods

Wood properties can be grouped into two: microscopic and macroscopic properties (Megraw, 1986). Microscopic properties are linked to the anatomical structure of wood as well as its chemical composition, while macroscopic properties are primarily growth-related features and include knots, compression wood and spiral grain (Moore, 2011). Macroscopic properties of wood such as density, hardness, and bending strength, among others, are properties derived from the cells that compose wood (microscopic properties) (Wiedenhoeft and Miller, 2005).

The anatomical structure of the wood of *A. robusta* and *T. ivorensis*, like that of other hardwood species is composed of different types of woody cells mainly fibres (for mechanical support), parenchyma (for storage of starch) and vessel elements (in hardwoods for water and mineral salt conduction) (Tiemann 1951; Kollmann and Côtè, 1984; Haygreen and Bowyer 1996), whose origins are in the vascular cambium (Plomion *et al.*, 2001). Each of the wood cells has a precise structure of tiny openings, membranes, and intricately layered walls (McBroom, 2013). They also differ in size (length, diameter, wall thickness and lumen diameter), shape, and proportion (i.e, percentage) (Kollmann and Côte, 1984, Sujatha *et al.*, 2007). For example, the mean tangential diameter of vessel lumina of *A. robusta* is observed to range from 50–100µm, with fibres of medium wall thickness (thin-to-thick walled) and ranging averagely between 928-1310µm in length (Lemmens, 2007). According to Insidewood (2014), however, the average fibre length of *A. robusta* ranges between 900-1600µm. Similarly, Insidewood (2014) stated that *T. ivorensis* has average fibre lengths ranging between 900-1600µm or above 1600µm, with thin-to-thick walls. Likewise, Richter and Dallwitz (2009) reported that fibres of *T. ivorensis* are very thin-walled, or of medium wall thickness, having an average length of 1800-2850µm. Lamb and Ntima (1971) recorded ultimate fibre dimensions of *T. ivorensis* to be 1.52mm fibre length, 0.036mm fibre diameter, 0.0046mm cell wall thickness and 0.027mm lumen diameter. The fibre tissue proportion of *T.*

ivorensis is low to medium, with tyloses present in vessels (Oteng-Amoako, 2002).

The dimensions, amounts and differences in cellular structures (e.g. size of openings in cells and in the thickness of the cell walls) of various wood species influence properties such as physical, mechanical, chemical, and anatomical properties. The durability and appearance, as well as resistance to penetration by water and chemicals (Panshin, and de Zeeuw, 1980; Miller, 1997; Rao *et al*., 1997; Roque and Filho, 2007) and behaviour during processing and in service are also influenced (Panshin and de Zeeuw, 1980; Little, 1997).

2.3 General chemical composition of hardwood

At an elemental level, wood is approximately 50% carbon, 6% hydrogen and 44% oxygen (Pettersen, 1984). There are also small amounts of extraneous chemicals which include extractives and inorganic compounds such as calcium, magnesium and potassium (Moore, 2011). These elements are combined into organic polymers: Cellulose, Hemicellulose, Lignin (Iversen and Wannstrom, 1986; McBroom, 2013). Hardwoods contain 40-44% cellulose, 1535% hemicelluloses and 18-25% lignin, while softwoods contain 40-44% cellulose, 20-32% hemicelluloses and 25-35% lignin (Sjostrom, 1993; Cole, 2012; McBroom, 2013). In variance to the above, Walker (2006) reported that hardwoods contain about 40-50% cellulose, 20-30% hemicelluloses, 18–25% lignin and less than 10% extractives; usually ranging 1-5% of the wood.

Rózanska *et al.* (2011), on the other hand, accounted that dry wood is primarily composed of minor amounts (5-10%) of extraneous materials, which are both organic and inorganic. The organic component takes the form of extractives, which contribute to such wood properties as color, odor, taste, decay resistance, density, hygroscopicity, and flammability. Extractives include tannins and other polyphenolics, colouring matter, essential oils, fats, resins, waxes,

gum starch, and simple metabolic intermediates. These components are collectively termed extractives because they can be removed from wood by extraction with solvents and are not structural components like the major constituents of wood (Rózanska, 2011).

The walls of cells are made up of the three major components: cellulose microfibrils (with characteristic distributions and organization), hemicelluloses and a matrix or encrusting material, typically pectin in primary walls and lignin in secondary walls (Panshin and de Zeeuw, 1980). Each of these components (organic polymers) is distributed non uniformly as a result of the anatomical structure, and contributes to fiber properties, which ultimately impact product properties (Iversen and Wannstrom, 1986; McBroom, 2013). They also provide structural support to the living tree and some resistance against microbial attack (Iversen and Wannstrom, 1986).

2.1.1.1 2.3.1 Characteristics of chemical components

Cellulose is the major and the most important component for its effect on the properties of wood (Little, 1997; Rózanska, 2011). It is a high molecular weight linear polymer (Rózanska, 2011), consisting of a linear chain of several hundred to over ten thousand β(1→4) linked Dglucose units, whereas hemicelluloses consist of several different sugar units and substituted side chains forming a low molecular weight linear or branched polymer (Updegraff, 1969), composed of several different kinds of pentose and hexose sugar monomers (Rózanska, 2011). Hemicelluloses, which are associated with cellulose, are composed of shorter molecules than cellulose and makes up a large part of wood (Little, 1997).

Cellulose and hemicelluloses are polysaccharides and together make up the holocellulose content in wood. However, hemicelluloses are more soluble than cellulose, and are named according to their main sugar residues in the backbone. Xylans, consisting of D-xylose units, and glucomannans, consisting of D-glucose and D-mannose units, contribute to the main

hemicelluloses in hardwoods and softwoods, respectively (Sjostrom, 1993). Hemicellulose is important for some properties of wood (Little, 1997), however, the exact role of hemicelluloses in the plant cell wall is uncertain, but in the most general terms they provide a link between the cellulose and lignin, which in turn affects the mechanical behaviour of wood and its dimensional stability (Moore, 2011).

On the other hand, cellulose is the structural component of the primary cell wall and the most common organic compound in plants. Though it is a carbohydrate with much food value as sucrose, cellulose cannot be digested by humans and most animals because digestive enzymes cannot hydrolyze the linkages between glucose units (McBroom, 2013). Ruminants and termites maintain intestinal colonies of microorganisms that produce cellulose enzymes, which convert cellulose to glucose, (Sjostrom, 1993; McBroom, 2013). Although chemically simple, the extensive intermolecular bonding pattern of cellulose and its relation with hemicellulose and lignin, results in very complex morphologies, and multiple enzyme systems are thus required to efficiently degrade cellulose (Sjostrom, 1993). Nonetheless, the polysaccharide components (cellulose and hemicellulose) of plant cell walls are highly hydrophilic and thus permeable to water, whereas lignin is more hydrophobic.

Lignin is a three dimensional phenylpropane polymer, and its structure and distribution in wood are still not fully understood (Rózanska, 2011). Though composed of carbon, hydrogen and oxygen, lignin is not a carbohydrate but it is phenolic in nature (Campbell and Sederoff, 1996; McBroom, 2013), and has a heterogeneous structure (Jarvis and McCann, 2000). It is an aromatic substance (Moore, 2011), a complex and high molecular weight polymer built upon phenylpropane units and an integral part of the secondary cell walls (Lebo *et al.*, 2001). Although it occurs in wood throughout the cell wall, it is concentrated toward the outside of the cells and between cells (Rózanska, 2011).

Lignin is important for mechanical support, water transport and defense in vascular plants; it decreases the permeation of water through the cell walls of the xylem, thereby playing an intricate role in the transport of water and nutrients (Iversen and Wannstrom, 1986). It occurs between cell walls as a binding agent, holding cells together and within cell walls giving rigidity to the cell (McBroom, 2013). It helps reduce dimensional change with moisturecontent in wood (McBroom, 2013) and resistance of the wood structures is largely determined by lignin (Zabel and Morrell, 1992; Majaila, 2000). It impedes the penetration of destructive enzymes through the cell wall (Iversen and Wannstrom, 1986) and also serves to protect cellulose and hemicellulose from degradation (Jeffries, 1990; Zabel and Morrell, 1992). Lignin as well as extractives are however undesirable components in the conversion of wood into pulp and paper, because their remova1 is a major step in the paper making process (Campbell and Sederoff, 1996).

The resistance of lignin to microbial degradation hence enhances its persistence in soils (Campbell and Sederoff, 1996) and therefore, a significant component in the global carbon cycle. Highly lignified wood is durable and therefore low-lignin-content trees may have enhanced invasiveness by deteriorating organisms (Sjöström, 1993), and may pose environmental risks in terms of enhancing CO_2 emissions from faster decomposition of litter, contributing to atmospheric concentrations of greenhouse gases and affecting feeding, population dynamics and growth rates of wood-rotting organisms (Sjöström, 1993).

Extractive is the collective term given to the different classes of chemical compounds that can be extracted from wood or bark by means of polar and non-polar solvents, e.g. ether, acetone, ethanol, water (Cole, 2011). They include tannins and other polyphenolics, colouring matter, essential oils, fats, gums, resins, waxes and starch (Wilson and White, 1986). These generally

have no structural significance, but are responsible for imparting several larger-scale characteristics to wood, such as colour, odour, taste, density, hygroscopicity and decay resistance (Pettersen, 1984). Extractives provide natural durability to timbers that have a resistance to decay fungi (Wiedenhoeft and Miller, 2005). In the case of a wood such as teak (*Tectona grandis*), famed for its stability and water resistance, these properties are conferred by the waxes and oils formed and deposited in the heartwood. Many woods valued for their colors, such as mahogany (*Swietenia mahagoni*), African blackwood (*Diospyros melanoxylon*), Brazilian rosewood (*Dalbergia nigra*) owe their value to the type and quantity of extractives in the heartwood (Wiedenhoeft and Miller, 2005), which vary by species (Cole, 2011).

In addition, the extractives combined toxicity and antioxidant properties give a heartwood termite resistance, (Schultz *et al.*, 2008). Extractives are also reported to have a direct influence on the modulus of rupture and the modulus of elasticity, in addition to their effect on wood density (Arganbright, 1971; Kuo and Arganbright, 1980; Grabner, 2002).

2.4 Variability in wood properties

A large concern in the utilization of wood is the degree of variation of its properties (Hua *et al.*, 1996), which can result from site-to-site differences in wood and from population level differences within a site (Hernández and Restrep, 1995). However, a major portion of the variability is often within the trees themselves (Kandeel and Bensend, 1969; Panshin and de Zeeuw, 1980; Zobel and Van Buijtenen, 1989; Zhang *et al.*, 1994). Wilson and White (1986) defined wood variability as the range of appearance, anatomy, chemical and physical properties to be found within the wood of trees of a given species, or in that individual tree.

Wood anatomists in the field look at variability in three ways: the differences between species, genera and families; the variations observed within individuals of the same species and the

variations occurring in the individual trees as they grow older, from the pith outwards and from the bottom upwards; radial and axial directions (Jayeola *et al*., 2009).

2.4.1 Variations in anatomical features of wood

Within the main stem of a tree, variation of cell characteristics is often quite large (Larson, 1960, 1962, 1964; 1sebrands, 1972), having been influenced to different degrees by both environmental and genetic factors such as site, ecological conditions, management**,** and age for trees growing in plantation conditions (Zobel and Van Buijtenen, 1989). Dimensions of the micro-structures (cells) in an individual tree vary from pith to bark (radial), from the tree base to the top (axial) and even from the stem to the branches and roots (Rupert *et al.*, 2002), and variations in wood properties are attributable to the different distribution patterns, arrangement, size and dimension of the micro structures (Wilson and White, 1986). Even significant differences in mechanical performance between sapwood and heartwood are usually attributed to the radial changes in wood density or anatomical structure and not to whether the sample is heartwood or sapwood, *per se* (Panshin and de Zeeuw, 1980).

2.1.1.1.1 2.4.1.1 Variations in fibre dimensions and vessel lumen diameter between stemwood and branchwood

In most cases, stem samples have significantly different values of fibre dimensions than branch samples (Phelps *et al.*, 1982). This is because, longitudinal cells in the branch are generally narrower in diameter and shorter in length than those of the stem (Tsoumis, 1968); being about 25-35% shorter (Manwiller, 1974; Taylor, 1977; Phelps *et al.*, 1982; Panshin and de Zeeuw, 1964). In many other instances, branchwood fibres have been found to be shorter than stemwood fibres (Lonnberg, 1975; Vurdu and Bensend, 1979; Bhat and Karkkainen, 1981). Branch fibres were observed to be 16-20 % shorter in benteak, cashew and padri whereas in

coraltree, irul and rubberwood the difference were 5-7 % (Bhat *et al.,* 1985). Similarly, Wilson and White (1986) affirmed that branchwood has smaller wood elements than the stemwood, resulting in closed-textured wood of the branch as compared to the stemwood. A study of *Ailanthus altissima* recorded 940±167, 22.8±4.63, 16.16±4.69, 3.34±1.18µm respectively for the fibre length, diameter, lumen width, cell wall thickness of the stem, whereas for branchwood the corresponding values were 594±134, 17.81±3.53, 12.78±3.71, 2.49±0.6, µm respectively (Samariha *et al.,* 2011), and vessel lumen diameter was lower in the branch than the trunk in *Fagus sylvatica* and in *Q. ilex* (Gasson, 1985). Shorter fibers occurred also in the branch of *Eriotheca gracilipes* (Longui *et al.*, 2012).

On the contrary, no difference was observed for stem and branch fibre diameter in *Eriotheca gracilipes* (Longui *et al.*, 2012). Similarly, Core and Moschler (1980) reported that fibre diameter and wall thickness were not substantially different in branchwood and stemwood of yellow-popular**,** however confirmed that fibre length of branchwood averaged 20% shorter than stemwood. Similarly, fiber wall thickness showed a lower value in the branch than those observed in the stem of *Eriotheca gracilipes* (Longui *et al.*, 2012). Gurau *et al.* (2010) also found the vessel lumina in branchwood to be approximately the same size as in stem of maple wood, but also confirmed it was slightly smaller in branch wood. Wide vessels are more efficient at water transport than narrow ones, and the trunk would be expected to have wider vessels because they are from a cambium of greater age (Luizon and Gasson, 2012).

Shorter fibres in the branch could be attributed to the influence of the growth promotion substances which are close to the tip (Sadegh, 2011). These growth promoting substances initiate rapid production of cells at this point with decreasing maturation time thereby resulting in the production of shorter cells in the branch than in the stem. Bailey (1920) and Zobel and

Jett (1995) acknowledged that faster growth results in the formation of shorter cells, while Desch and Dinwoodie (1996) expressed that increase in cell length is due to marked elongation at the cell tips. Production of large diameter cells is as a result of high auxin content in the apical mersitem, while reduction in auxin content will result in narrow diameter cells (Larson, 1960); anything that reduces apical activity will result in small diameter cells (Larson, 1960). These variations in the size and shape of wood cells, the thickness and chemical composition of their cells make other wood properties from the branches of trees differ from that of the stem (Wilson and White, 1986); (Sujatha *et al.*, 2007).

2.4.1.2 Variations in cell proportions between stemwood and branchwood

According to Bhat *et al.* (1985), significant differences do not exist in tissue proportions between branches and stem. In corroboration, the proportion of fibres and parenchyma in *Poincianella pyramidalis* was not significantly different in the stemwood and branchwood (Luizon and Gasson, 2012). However, a smaller proportion of vessels were recorded in the stemwood than the branchwood, as was also recorded in maple wood, which also had a greater proportion of parenchyma in the branch than stem (Gurau *et al.*, 2010). Stem samples of *Aigeiros tacamahaca* were also observed to have fewer vessels than branch samples (Phelps *et al.*, 1982). Accordingly, Haygreen and Bowyer (1996) and Joshi (2008) accounted that hardwood branches have more vessels and parenchyma with fewer fibres than the stem.

Structurally, a large number of parenchyma cells relate positively with higher mechanical fragility and a low proportion of vessels and high proportion of fibres result in a higher density. A large proportion of vessel characterizes a more fragile tissue due to the occurrence of several vessels together, which can decrease the resistance in this portion (Luizon and Gasson, 2012). Consequently, regions of the wood with larger and more frequent vessel diameters have lower resistance (Baas *et al.*, 2004). The parenchyma cells are however more fragile than the vessel elements and especially the fibres (Luizon and Gasson, 2012).

2.4.1.3 Variations in fibre dimensions and vessel lumen diameter between sapwood and heartwood

Generally, there are no structural differences between sapwood and heartwood cells (Panshin and de Zeeuw 1980; Sehlstedt-persson and Olov, 2010). However, most reports on radial pattern of variation in hardwoods dealing with fiber dimensions agrees that fibres near the centre of the tree are shorter, thin walled and narrow in diameter as compared to periphery fibres (Bhat *et al*., 1990; Peszlen, 1994; Baillères *et al.,* 1995; Kauba *et al.,* 1998; Adamopoulos and Voulgaridis, 2002; Marsoem *et al.*, 2002; Tavares *et al.*, 2010). Thus differences may occur between sapwood and heartwood (Taylor *et al.*, 2002). In support, Emerhi (2012) recorded the fibre length and diameter for *R. racemosa* and *R. harrisonii* to be higher for sapwood than the heartwood in the stem. Similarly, sapwood had thicker cell wall fibres in *E. globulus* than the heartwood (Monteiro, 2003) and fibre length increase from inner wood (heartwood) to outer wood (sapwood) in teak stands (Izokor and Fuwape, 2011) and also increased from heartwood to sapwood in *Populus* (De Bell *et al.,* 2002). Similarly, vessel lumen diameter is smaller in the inner part of stem, and gradually increases in size outwards before leveling off in the outer part of the stem (Peszlen, 1994; Lei *et al.*, 1996 and Bhat *et al.*, 2001).

On the other hand, Sudin and Wahab (2013) observed that younger and more actively expanding cambial wood at sapwood may have thinner cell walls than the older heartwood region. Panshin and de Zeeuw (1980) also noticed that only slight variations between sapwood and heartwood cell composition in stem, but concluded that the younger and more actively expanding cambial wood at sapwood may have thinner cell walls than the older heartwood region.

Increase in fibre dimensions can be associated with the many molecular and physiological changes that occur in the vascular cambium as well as the increase in wood cell walls during

the tree growing processes (Plomion *et al.*, 2001; Roger *et al.*, 2007). The increase of fiber length from pith to periphery could be explained on the basis of the increase in length of cambial initials with increasing cambial age from pith to periphery (Ghouse and Siddiqui, 1976; Jorge *et al.*, 2000).

2.4.1.4 Variations in fibre dimensions and vessel lumen diameter along the stem and branch

A number of trends have been reported for axial variations in fibre dimensions. To begin with, fiber dimensions increase up to certain height in the tree and thereafter decrease. This pattern was observed in various hardwood species by several researchers including (Bisset and Dadswell, 1949; Carvalho, 1962; Panshin and de Zeeuw, 1980; Megraw, 1985; Zobel and Van Buijtenen, 1989; Wilkes, 1998; Bhat *et al*., 1990; Jorge, 1994; Jorge *et. al.*, 2000).

This same trend was described by Stringer and Olson (1987) for *Robinia pseudoacacia* L. (Ridoutt and Sands, 1993), for *Eucalyptus globulus* Labill (Chauhan *et. al.*, 2001), for *Populus deltoides* Bartram. ex Marsh, for *Eucalyptus globulus* (Jorge, 1994), for *Rhizophora racemosa* (Emerhi, 2012) and for the wall thickness of *Eucalyptus globules* (Tavares *et al.*, 2011). According to Zobel and Talbert (1984), increase in fibre dimensions from base up to certain height and there after decreasing up to top of trees in vertical direction is due to the differential proportion of juvenile wood in trees.

Panshin and de Zeeuw (1964) and Fougler and Eicher (1975) reported another trend where fibre dimensions decrease from base to the top of the stem. This trend was confirmed by Izekor and Fuwape (2011) in teak stands, by Voorhies and Jameson (1969), Shashikala and Rao (2009) and Kiaei (2011) in *Plantanus occidentalis, Eucalyptus citriodora* and *Acer velutinum boiss*. Griffioen (1972) and Taylor and Wooten (1973) in *Populus hybrids* and *Quercus phellos*, Kibblewhite *et al*. (2004) in *E. fastigata* also observed a similar trend. Tyree and Evers (1991) and Fan *et al.* (2009) similarly recorded this pattern in their research works. Longer fibers were

also noted at the base of the stem of *Eriotheca gracilipes*; the two highest positions of the stem, however, did not differ significantly (Longui *et al.*, 2012).

The decreasing trend in wood fibre dimensions is attributable to the influence of the growth promotion substances which are close to the tip (Sadegh, 2011). These growth promoting substances initiate rapid production of cells at this point with decreasing maturation time thereby resulting in the production of smaller cells at the tree top. In addition, decrease in fibre dimensions with height in the stem could be mainly due to the differences in the juvenile and mature wood as juvenile wood is expected to increase with an increase in height (Panshin and de Zeeuw, 1964). Growth rate affects fibre dimensions too (Moya and Tomazello, 2007). Ohbayashi and Shiokura (1989) carried out a study on fibre length in 15year-old trees and found that a high growth rate was strongly correlated with short fiber length. Frimpong-Mensah (1992) found that cell wall thickness was significantly correlated with cambial age. Hughes and Esan (1969) found strong correlations between fibre length and tree age with distance from the pith in 9-year-old trees in Nigeria.

In another instance, Panshin and de Zeeuw (1964) reported longest fibre lengths at the top, similar to report by Anderson (1951) and Wellwood and Jurazs (1968) for *Abies concolor* and *Thuja plicata*. Roszaini (2000) and Kibblewhite *et al*. (2004) reported an increasing fibre lumen diameter and fibre wall thickness with height in *E. nitens* and *R. harrisonii*. Fibre diameter was highest at top of the stem, followed by the base and least at the middle portion (Emerhi, 2012). On the contrary, fiber diameter did not vary among the three positions of stem of *Eriotheca gracilipes,* even as fiber lumen diameter showed no clear variation among positions (Longui *et al.*, 2012). Teresa *et al.,* (2006) accounted that the axial variation of fibre width and wall thickness was of very small magnitude, and differences between height levels were not

statistically significant in *Eucalyptus grandis*. Ogunsanwo *(2006) in the same way found in his study of Triplochiton scleroxylon* that, fibre length varied inconsistently along the stem.

Fibre dimension variations along the branch are not significant (Ververis, 2004); Taylor (2007) found no differences in fibre length from base to top of branch. However, in a study, olive and almond tree branches exhibited a different trend with the longer fibers at the base and the shorter at the top of the branch (Ververis, 2004). Correspondingly, a pattern of general decrease in fibre length from the base to the top, with the longest fibres present at the basal portion was observed by (Bhat *et al.,* 1985). However, in rubberwood the maximum fibre length was found in the middle position (50 percent of the length) of branches as reported earlier for some hardwood stems (Panshin and de Zeeuw, 1980).

The optimum network of vessels has wide vessels at the base that feed an increasing number of narrower vessels (Murray, 1926; McCulloh *et al.*, 2003). Thus the diameters of vessels decrease with height in both trunks and branches, usually being greatest in the roots (Zimmermann, 1983; Aloni, 1987; Carlquist, 2001). Trees have more and narrower vessel moving from the trunks to the branches. Vessel lumen diameters have also been found to increase from the crown to the roots in temperate tree species (Zimmermann, 1978, 1983; Gartner, 1995). However, Mejia *et al.* (2003) found that vessel lumen diameter of *Anacardium excelsum, Ficus insipida, Schefflera morototoni,* and *Cordia alliodora* did not exhibit a consistent trend axially from the base of the stem to the base of the branch. But found that, vessel lumen diameter decreased sharply from the base of the crown to the branches. Similarly, four of fourteen sampled angiosperm trees studied by Fan *et al.* (2009) exhibited a uniform linear increase of vessel lumen diameter with distance from the top to the base of the trunk. According to him, the remaining of the fourteen trees, increased in vessel lumen diameter from the top of the crown and then stabilized near the base of the crown.

2.4.1.5 Variations in tissue proportions along the stem and branch

Vessel percentage increases with tree height; that is, smaller and more vessels occur in the upper portions of trees (Isebrands, 1972; Cheng and Bensend, 1979). In line, Gartner *et al.*, (1996), realized a higher proportion of vessels at the top of the stem of *Quercus garryana* Dougl. Ismail *et al.* (1995), also observed that vessel proportion increased while ray proportion decreased with height in *Neolamarckia cadamba*, but with no significant trends in the proportion of fibre. However, higher fiber proportion was reported at the butt of the stem of *Eriotheca gracilipes* (Longui *et al.*, 2012), as vessel percentage negatively correlated with tree height in *Gmelina arborea* (Akachuku and Burley, 1979; Akachuku, 1985; Nobuchi *et al.*, 1997). Bosman *et al.* (1994) argued that increase in relative amount of vessels indicates decrease in relative amount of fibres.

2.4.2 Variations in natural durability in wood

Timber species vary significantly in their resistant to both fungi and insect attack and even sections cut from the same tree frequently show disparity in the durability (Ocloo, 1975; Liese and Peters, 1977), and selection of wood depends upon the conditions it is required to endure (Bilal and Khan, 2011). Within a tree, the large variations in natural durability may occur in the axial and radial patterns just as cell morphology (Sehlstedt-Persson and Olov., 2010).

2.4.2.1 Variations of natural durability of stemwood and branchwood

From the perspective of this present research work, information is limited on comparative the natural durability of branchwood and especially where stem and branchwood are compared. However, the branchwood of *Persea americana* was found to be highly susceptible to biological degradation by decay fungi (Fuentes-Talavera *et al.*, 2011). Similarly, the

branchwood of *Taxus canadensis* was resistant to decay (Richter *et al.*, 2012), as its stemwood in another study was found to be strongly decay-resistant (U.S. Forest Products Laboratory 1974; Rayner and Boddy, 1988). These studies were however not comparative, between stem and branchwood, but were done in isolation. It is therefore not possible to relate the natural durabilities of the stem and branchwood of the above mentioned species. Hence, the conclusion that very limited study has been done on the natural durability of branchwood. However, the results of the present study will adequately relate the durability status of stemwood and branchwood.

2.4.2.2Variations of natural durability between sapwood and heartwood

For both softwoods and hardwoods, the wood in the trunk of the tree is typically divided into two physiological zones: sapwood and heartwood (Lourenço, 2008), each of which serves an important function distinct from the other (Wiedenhoeft and Miller, 2005; Lourenço, 2008). Sapwood is the outer part of the trunk and contains almost 80 % of living cells; it is responsible for sap conduction between roots and leaves and participates in respiration (Bierman, 1996). Because of its susceptibility to fungi and wood destroying insects and lack of colour, sapwood is generally considered inferior to heartwood and is often discarded during conversion (Bamber, 1987). However, by use of the appropriate preservative treatment, sapwood can be made equal if not superior to heartwood of the same species in durability, thus reducing waste and in addition enabling the marketing of species with little or no heartwood. It is possible, if the properties of sapwood are also well understood, to use untreated sapwood of many species in numerous situations with safety (Bamber, 1987).

Largely, sapwood and heartwood differ in natural durability; the natural durability of sapwood is generally low, but heartwood may have certain properties that can significantly influence its

usefulness to the end user of wood products; notable among these is natural resistance to deterioration by insects, marine borers and microorganisms (Eslyn and Highley, 1976; Taylor *et al.*, 2002). Sapwood may encourage termites or the growth of fungi (Bamber, 1987), but heartwood may be less attractive than sapwood for some pathogens simply because it lacks the requisite nutrients or because the nutrients it contains may be less accessible (Scheffer and Cowling, 1966). The result of higher decay in sapwood compared to the heartwood of *P. malaanonan* was in line with the general understanding that sapwood are more susceptible to degradation by fungi (Rayner and Boddy, 1988); lacking in some metabolic compounds such as phytoalexin and other phenolic extractives for protection against decay fungi compared to the heartwood (Pearce and Woodward, 1986; Rayner and Boddy, 1988).

Infestations by almost all timber borers are either limited to the sapwood or else sapwood is infested in preference to heartwood, undoubtedly due to the presence of food materials such as starch and the absence of unpalatable and perhaps toxic heartwood substances (Bamber, 1987). *Lyctus* beetles for instance rarely attack heartwood which is free from starch (Wilson, 1933; Parkin, 1938; Humphreys and Humphreys, 1966). Equally Cypress pine flooring enjoys great popularity, partly because of the resistance of the heartwood to fungi and termites (Bamber, 1987).

As the sapwood of most tree species has low amounts of extractives, it is generally considered susceptible to decay (EN 350-1 1994). However, clearly durability of sapwood can vary greatly between different wood species. Wilson (1933) observed that sapwood with less starch suffered fewer discolourations. Similarly, Taylor and Cooper (2002) found that sapstain and mould fungi did not grow as well on *Pinus resinosa* sapwood with reduced starch content as on sapwood with normal amounts of starch.

2.4.2.3 Variations in natural durability along the stem and branch

There are variations in the natural durability of the heartwood of individual trees (Taylor *et al.*, 2002).The outer heartwood at the base of the tree in most species is the most decayresistant (Anderson *et al.*, 1963), which also decreases in durability with height (Scheffer and Cowling, 1966). This pattern has been associated with extractive content decrease towards the pith and up the tree (Hillis, 1987). There are exceptions to this trend, especially when individual components are considered. While Morita *et al.* (1995) observed slightly increased concentrations of extractives in the upper portions of the heartwood of *Cryptomenia japonica* tree, Gartner *et al.,* (1999) found no vertical variation in the decay resistance of *Psedotsuga menziesii*.

2.4.3 Variations in chemical composition in wood

Chemical composition of wood cannot be defined precisely for a given tree species or even for a given tree (Pettersen, 1984). The composition varies considerably within any single tree as well as between different trees (Sehlstedt-Persson and Olov, 2010). These variations in chemical components of wood and the differences in cellular structure make woods heavy or light, stiff or flexible and hard or soft (Forest product laboratory, 2010), and lead to large variations in natural durability (Sehlstedt-Persson and Olov, 2010). Chemical composition varies with tree part (root, stem, or branch, sapwood or heartwood), type of wood (i. e., normal, tension, or compression) geographic location, climate, and soil conditions (Pettersen, 1984).

2.4.3.1Variations of chemical components of stemwood and branchwood

Wood from the branches of trees differ from that of the stem in chemical composition (Wilson and White, 1986; Sujatha *et al.*, 2007). Ververis *et al.* (2004) acknowledged that lignin and cellulose content depends on tissue maturity. In corroboration, Nault (1988) observed higher concentrations of extractives in older trees than in younger trees of *Thuja plicata* and Krilov

and Lasander (1989) found that wood of matured trees of *Eucalptus spp* had more principal heartwood extractives than did regrowth. In both cases, however, the effect seems to be a result of the maturity rather than any consistent difference in the heartwood quality. Similarly, significant differences were noticed between the cellulose, lignin and extractive contents of branchood and stemwood of *Ailanthus altissima* (Ahmad and Kiaei, 2011); with the chemical components of stemwood generally higher in substance than branchwood: they found cellulose to be 47.18 and 44.12 %, lignin, 25.19 and 23.86 % and extractives, 3.5 and 3.2 % respectively for stemwood and branchwood.

2.4.3.2 Variations in chemical components of sapwood and heartwood

Compared to heartwood, sapwood is less dark, has higher water content in green wood (Hills, 1962; 1987; Wiedenhoeft and Miller, 2005), and is mainly for the storage of photosynthate (primarily starch and lipids) and synthesis of biochemicals (Wiedenhoeft and Miller, 2005). In order for the tree to accumulate biochemicals, they must be actively synthesized and translocated by living cells (Wiedenhoeft and Miller, 2005). Hence living cells of the sapwood are also the agents of heartwood formation (Wiedenhoeft and Miller, 2005). For this reason, living cells at the border between the heartwood and sapwood are responsible for the formation and deposition of heartwood chemicals, one of the important steps leading to heartwood formation (Hillis 1996).

This chemical modification is important (Lourenço, 2008), and involves the production of extractives in parenchyma cells, followed by accumulation and transport through the bordered pit to the neighbouring lignified cells (Wiedenhoeft and Miller, 2005). The ray parenchyma cells accumulate several organic compounds in the neighbour cell wall (such as tannins, gums, resins, and other coloured materials) which will originate heartwood cells (Kramer and Kozlowski, 1960; Hills, 1962; Desh and Dinwoodie, 1996; Buchanan *et al.*, 2000).

Heartwood, on the other hand, is found in the centre of the tree stems and contains only dead cells, from where the accumulated substances were removed (*e.g.* starch) or transformed to protective substances, which give a darker coloration (Lourenço, 2008). Its formation induces changes at chemical levels which are responsible for different behaviour of sapwood and heartwood (Clark, 1978; Lourenço, 2008), and it functions in the long-term storage of biochemicals of many varieties depending on the species in question (Wiedenhoeft and Miller, 2005).

Heartwood has more extractives of phenolic type (*e.g.* flavonoids), while sapwood is composed of starch, soluble sugars and triglycerides that are accumulated in the ray cells and axial parenchyma cells (Hills, 1962; 1987). Heartwood extractives are composed of a heterogeneous group of chemical compounds, including terpenoids, tropolones, flavonoids, stilbenes, and other aromatic compounds (Scheffer and Cowling, 1966). Consequently, sapwood and heartwood differ chemically (Sehlstedt-persson and Olov, 2010), with heartwood presenting higher extractives content (Lourenço, 2008). Gominho (2003) obtained in 9-year-old *E. globulus* trees, values of ethanol extractives ranging from 1.8 to 5.4 % in heartwood and 1.0 % to 1.5 % in sapwood. In 8-year-old trees, values for ethanol extractives ranged from 1.9 % to 4.3 % in heartwood and 1.3 % to 2.2 % in sapwood (Miranda *et. al*., 2007). Similar differences between heartwood and sapwood are found in other species in respect to total extractives; Gominho *et al*. (2001) with *Eucalyptus urograndis* obtained in one instance 3.7 % and 7.6 % and in another 1.8 % and 3.9 % respectively, in sapwood and heartwood. Overall, the contents of total extractable substances in heartwood of Larch wood ranged between 4.0 and 28.5% dry weight, and in sapwood between 0.6 and 4.4% (Grabner *et al.*, 2005).

The deposition of toxic extractives in the heartwood is the major chemical variation that occurs between sapwood and heartwood, with no modification of cell wall or cell wall chemical

components (Kai, 1991). In conformity, Lourenço (2008) reported that lignin content in sapwood and heartwood presented similar values for *E. globulus* (i.e, 25.3% and 25.8% respectively). On the other hand, Jouin *et al*. (1988) reported more lignin in the heartwood than the sapwood of *Quercus*: 24.3% and 23.5% respectively, as Mariani *et al.,* (2005) reported 25.1% and 21.8% lignin for heartwood and sapwood respectively in *E. nitens*. Higher heartwood lignin was again confirmed in maritime pine by Esteves *et al*.

(2005) when extractive-free heartwood presented higher lignin value than sapwood (i.e, 28.7 % and 26.7 % repsectively), as Raiskila (2008) also acknowledged that lignin content in the inner part of the stem is higher than the outer region. Correspondingly, Lourenço (2008) stated that heartwood presents higher residual lignin than sapwood. Magel (2000) indicated that heartwood content of phenolic compounds and lignin is higher than in sapwood. However, Magel *et al.* (1995) and Gang *et al.* (1998) were careful to note that the formation of extractives is a different process from lignification.

Lignin variability may be due to the control of metabolite flux into and through the lignin biosynthetic pathway (Campbell and Sederoff, 1996). Flux into the pathway is likely to be affected by entry-point enzymes, whereas flux through the pathway may be influenced by levels of enzyme activity and by metabolic channeling of substrates and products (Kacser and Burns, 1973).

With reference to cellulose content, Ritter and Fleck (1923) reported that in hardwoods, there are those with high cellulose content in the sapwood, and those with high cellulose content in the heartwood. According to Lourenço (2008), the content in extractives may obscure the composition of cell wall structural components such that high extractive content will result in the reduction of the other chemical components. In this regard, Madison (1923) had earlier declared that hardwoods with relatively high extractives in the sapwood have low cellulose (e.g. white ash and pignut hickory), while those with high extractives in the heartwood have

low cellulose. Browning (1974) also accounted that chemical composition differences in sapwood and heartwood are such that, in softwoods, the heartwood generally contains more extractives and less lignin and cellulose than the sapwood, whereas the heartwood and sapwood of the hardwoods do not show consistent differences in chemical contents.

CHAPTER THREE

ANATOMY OF STEMWOOD AND BRANCHWOOD OF *T. IVORENSIS* AND *A. ROBUSTA* Introduction

This section detailed the fibre dimensions (length, diameter, lumina and double wall thickness), vessel lumina and tissue (fibre, vessel and parenchyma) percentages of the radial (sawpwoods and heartwoods) and axial positions (base, middle and top) of the wood types (stemwood and branchwood) for *T. ivorensis* and *A.robusta*.

3.1 Materials and methods

3.1.1 Materials and Conversion

Four mature trees, two each for *A. robusta* and *T. ivorensis*, were randomly harvested in the Fum Headwater Forest in the Adansi North District of Ghana, located on Longitude 1.50 W and Latitude 6.30 N (www.ghanadistricts.com, 2014). Their diameters ranged from 18 to 34 cm for branches and 38.5 to 61.5 cm for stems. Billets (1m) were removed from three axial positions of the stems; the base (1.3m above ground), the middle (50% stem heigh) and the top (1m to branch insertion) and 3 axial positions of the large branches; the base, middle (50% branch height, depending on the length) and top (1m from branch tip) of each timber (Fig. 3.1). The billets were transported for preparation at the Wood Science Workshop, Department of Wood Science and Technology of the Faculty of Renewable Natural Resources (FRNR). The billets were plain sawn, and slabs were randomly chosen and further divided to obtain boards from two radial positions (heartwood and sapwood boards). From the sapwood and heartwood boards, specimens were further removed from three axial positions (base, middle and top) of the two tree portions (stems and branches) of each timber for natural durability and anatomical studies and from stem and branch bases for chemical composition analysis.

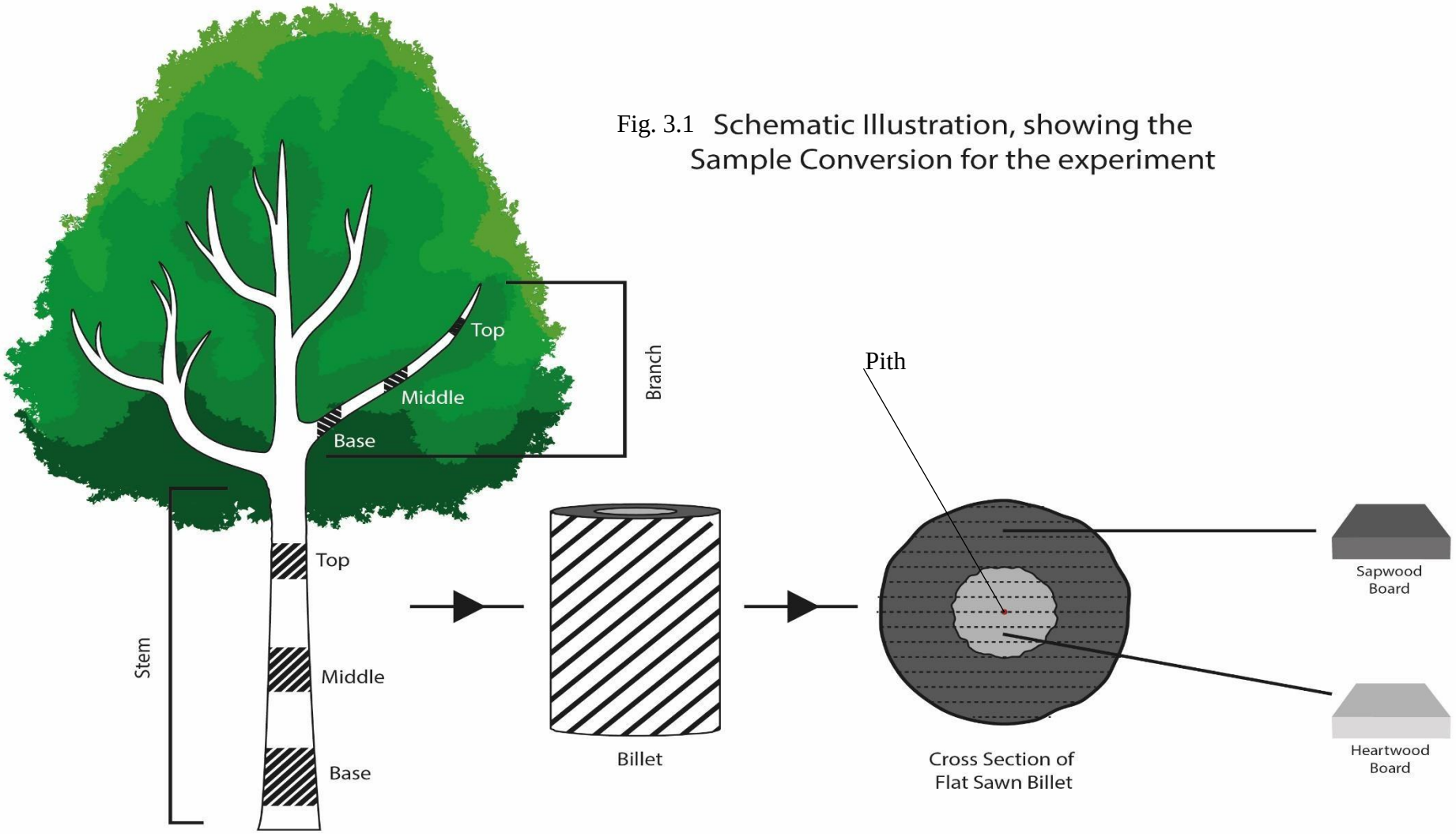


Fig. 3.1 Schematic Illustration, showing the Sample Conversion for the experiment

3.1.2 Anatomical investigations of stem- and branch-woods of *T. ivorensis* and *A. robusta*

The methodology for anatomical features followed the IAWA list of microscopic features for hardwood identification (IAWA committee, 1989). Microtomed sections and macerated tissues were prepared from sapwood and heartwood of the base, middle and top of the stem and the branch of each timber for the determination of tissue (fibre, vessel and parenchyma) proportions, vessel lumen diameter measurement and fibre characteristics (which included length, diameter, lumen diameter and double wall thickness). Parenchyma proportion included ray and axial types.

3.1.3 Wood sectioning and measurement of vessel lumen diameter and cell proportions

Microtomed sections were prepared using 20×20×20mm wood blocks from the sapwood and heartwood of the base, middle and top of the stem and the branch of the timbers. The wood blocks were softened by soaking in cold water for 7 days, and later soaked in a mixture of 100ml ethanol and 100ml glycerol for 7 more days for further softening. A Reichert sledge microtome was used to take 15µm-thick sections of each block. Tangential Longitudinal Section (TLS), Radial Longitudinal Section (RLS) and Transverse Section (TS) were taken from each block. The sections were washed in water and stained in 1% Safranin for 10 minutes to make the cell walls easily distinguishable from the cell contents. The stained sections were washed in water and dehydrated in increasing concentrations of ethanol: 30, 50, 70, 90 and 100%. After dehydration, the sections were covered with a mixture of 5ml clove oil and 5ml xylene for 10 minutes and mounted in Canada balsam on glass slides. All prepared slides were dried at 60^0C overnight and stored for photomicrographs and measurements of the vessel lumen diameter (which is not clearly detectable for measurements in macerated tissues) and cell proportion (Antwi-Boasiako and Atta Obeng, 2009). Vessel lumen diameter was measured from TLS using a compound microscope and a ×40 objective lens. Readings were then multiplied by a factor of 2.8571 into microns (µm). From each sample, Two hundred measurements were taken from the widest part of the vessels

perpendicular to the axis.

Determination of tissue proportions was done from TS. A microscope was fitted with an eyepiece with dot-grid scale of 20 points. The dot-grid scale was placed 5 times progressively from the periphery towards the centre of the central cylinder of each slide and was repeated for 5 slides. Proportions of fibre, vessel and parenchyma cells were determined from each slide. At each placement, the number of points covering any tissue was counted and expressed as a percentage of the total number of points (IAWA, 1989):

$$\text{Percentage of tissue} = \frac{\text{Number of points covering the tissue}}{\text{Total number of points on grid}} \times 100$$

3.1.4 Maceration of tissues and determination of fibre dimensions

Wood strips (20 × 2× 2 mm) were soaked in a mixture of 50 ml of 6% hydrogen peroxide and 50ml of 97% glacial acetic acid in test tubes. The test tubes were covered and incubated at 60^{0C} until the samples bleached white. Macerated samples were rinsed thoroughly with water and mounted in glycerol. A compound microscope was equipped with a micrometer eye piece for the measurement of fibre dimensions. For fibre length measurement, an objective lens of —× 10" was used and the figures obtained for fibre lengths were multiplied by a factor of 11.4286 to obtain the dimension in micrometers (µm). For the measurement of fibre diameters, lumen diameters and double wall thicknesses, objective lens of —× 40‖ was used and each reading multiplied by a factor of 2.8571 to obtain results in micrometers (µm). Two hundred unbroken fibres were measured from sapwood and heartwood of the base, middle and top of the stem- and the branch-wood. All sizes of the fibres except broken ones were included.

3.2 Data analysis

Data obtained on anatomical features were subjected to Analysis of variance (ANOVA) to determine if the differences were significant for the various factors; wood types (stemwood

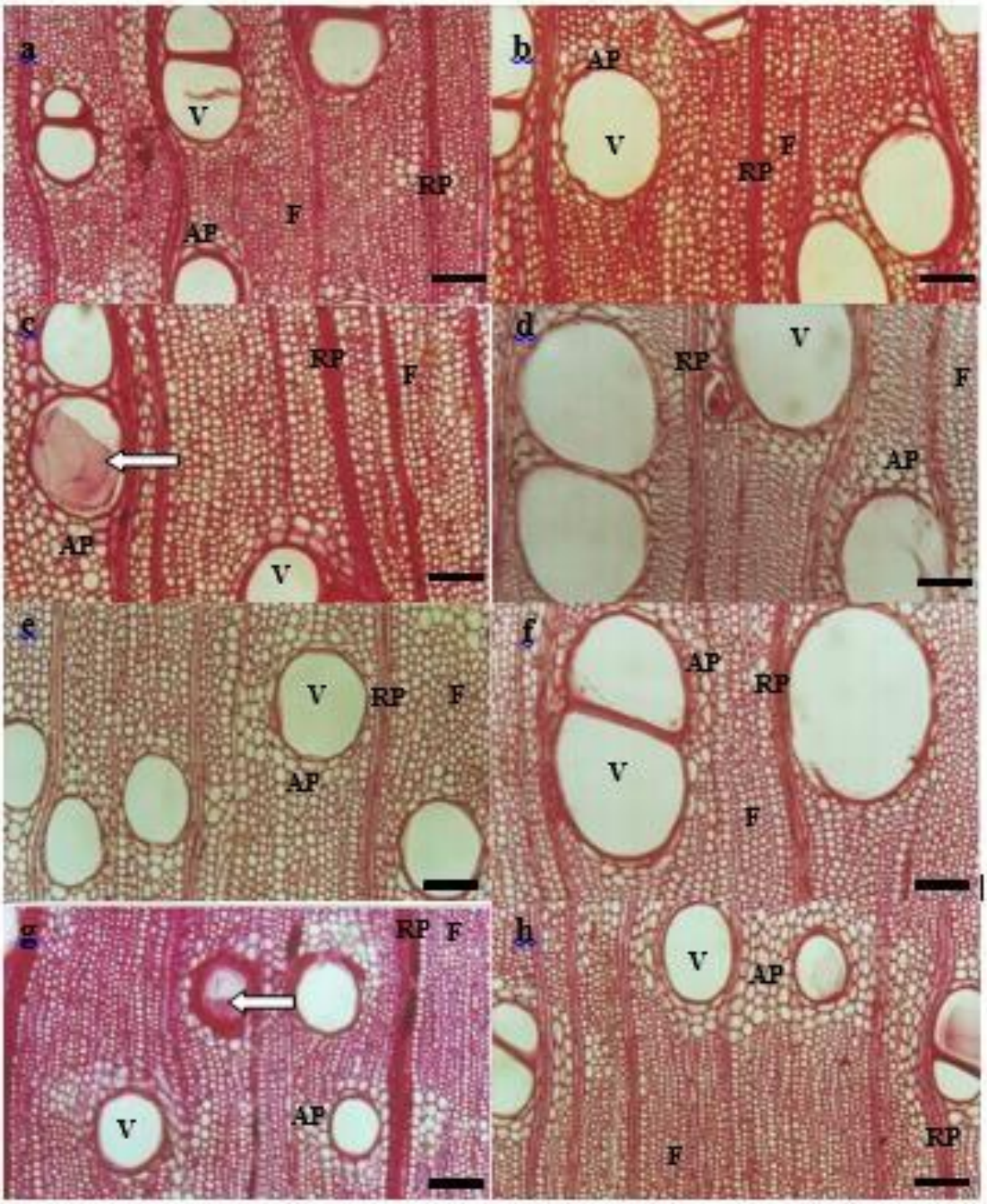
and branchwood), radial positions (sapwood and heartwood) and axial positions (base, middle and top) for *T. ivorensis* and *A. robusta*.

3.3 Results

3.3.1 Descriptive anatomy of *T. ivorensis* and *A. robusta*

Plates 3.1 to 3.5 shows anatomical descriptions of *T. ivorensis* and *A. robusta*. Transverse Section (TS) shows vessels solitary with radial multiples of 2, axial parenchyma predominantly paratracheal, vasicentric in *T. ivorensis* (Plate 3.1).Tangential Longitudinal Section (TLS) shows irregularly storied rays 1-3 cells wide and tylosis occluding some vessels in *T. ivorensis* (Plate 3.4). Radial Longitudinal Section (RLS) shows body ray cells procumbent, with one row of square marginal cells in *T. ivorensis* (Plate 3.5).

For *A. robusta,* Transverse Section (TS) shows vessels solitary with radial multiples of 2-4, axial parenchyma apotracheal, diffuse-in-aggregates in (Plate 3.2). Tangential Longitudinal Section (TLS) shows irregularly storied rays 1-3 cells wide, with multiseriate portions as wide as uniseriate portions (Plate 3.4) and Radial Longitudinal Section (RLS) shows body ray cells procumbent with mostly 2-4 rows of upright and square marginal cells, with silica bodies present in rays of *A. robusta* (Plate 3.5). Plate 4.3 shows distinctly open fibre lumina of both timbers.


a
V
RP
AP
F
b
AP
V
F
RP
c
RP
F
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g
RP
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h
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RP

Plate 3.1: TS of *T.ivorensis* from butt heartwood (a) and sapwood (b), middle heartwood (c) and sapwood (d), top heartwood (e) and sapwood (f) and branch base heartwood (g) and sapwood (h). V: vessel; F: fibre; AP: axial parenchyma; RP: ray parenchyma. Tyloses (arrowed). Scale bar: 20µm

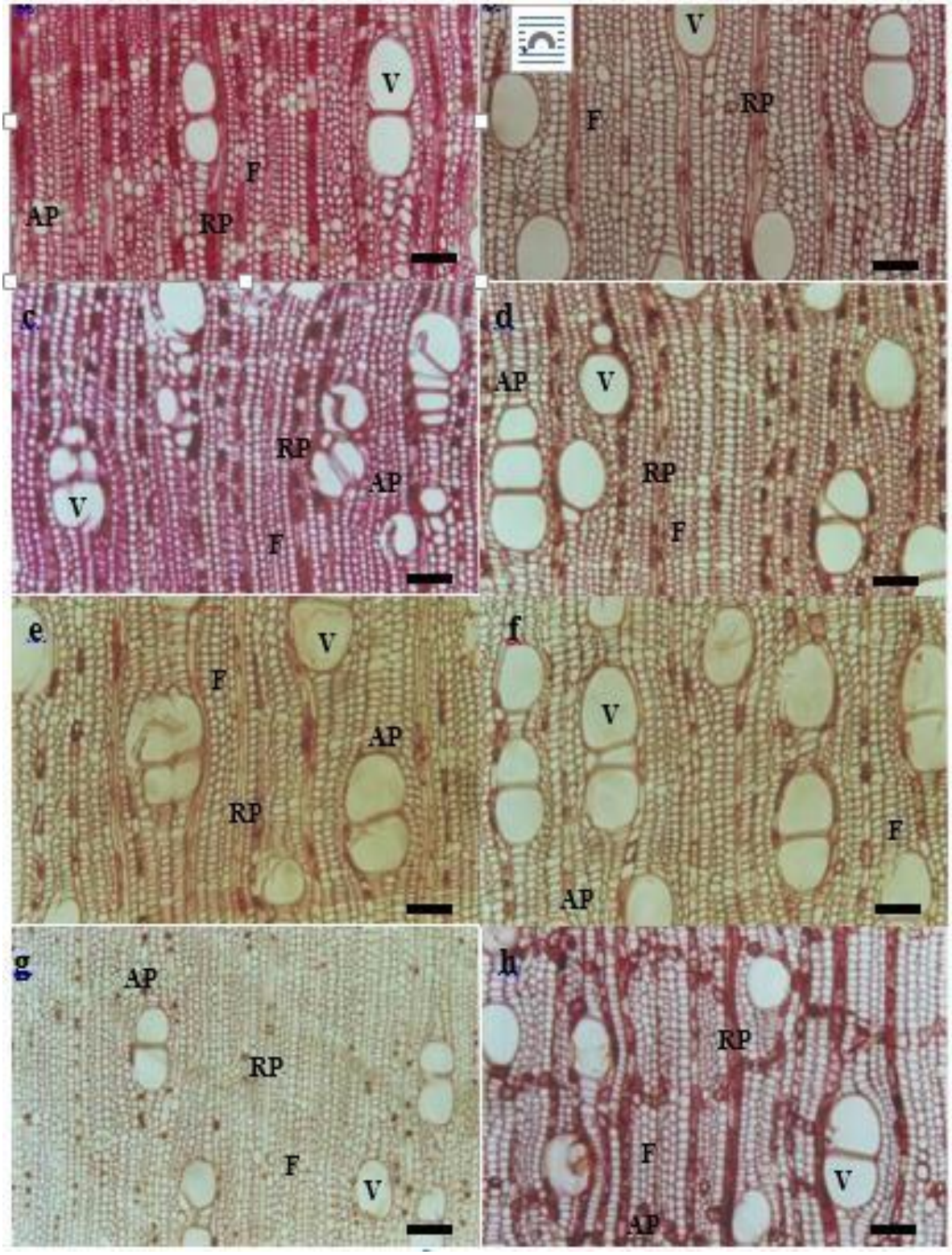

Plate 3.2 TS of *A. robusta* base heartwood (a) and sapwood (b), middle heartwood (c) and sapwood (d), top heartwood (e) and sapwood (f) and branch base heartwood (g) and sapwood (h). V: vessel; F: fibre; AP: axial parenchyma; RP: ray parenchyma. Scale bar: 20 µm

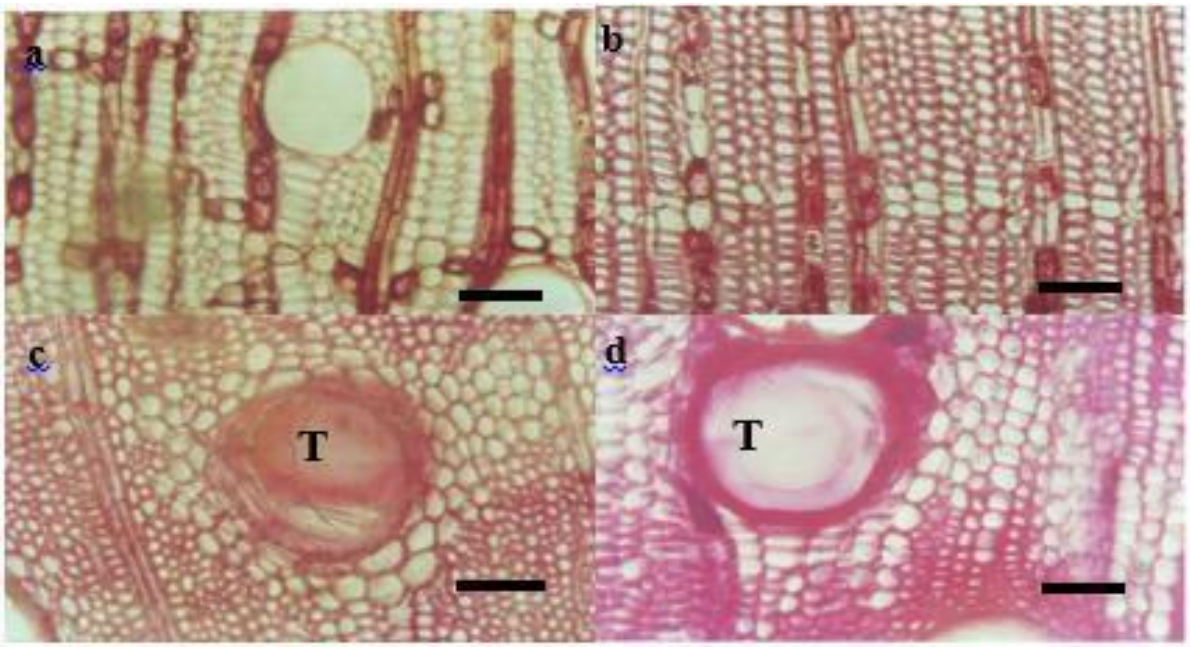

Plate 3.3 TS of heartwood from stem base (a) and branch base (b) of *A. robusta,* and stem base (c) and branch base (d) of *T. ivorensis.* Vessels of *T. ivorensis* completely clogged with tyloses (T) and fibre lumina distinctly open. Scale bar = 50 µm

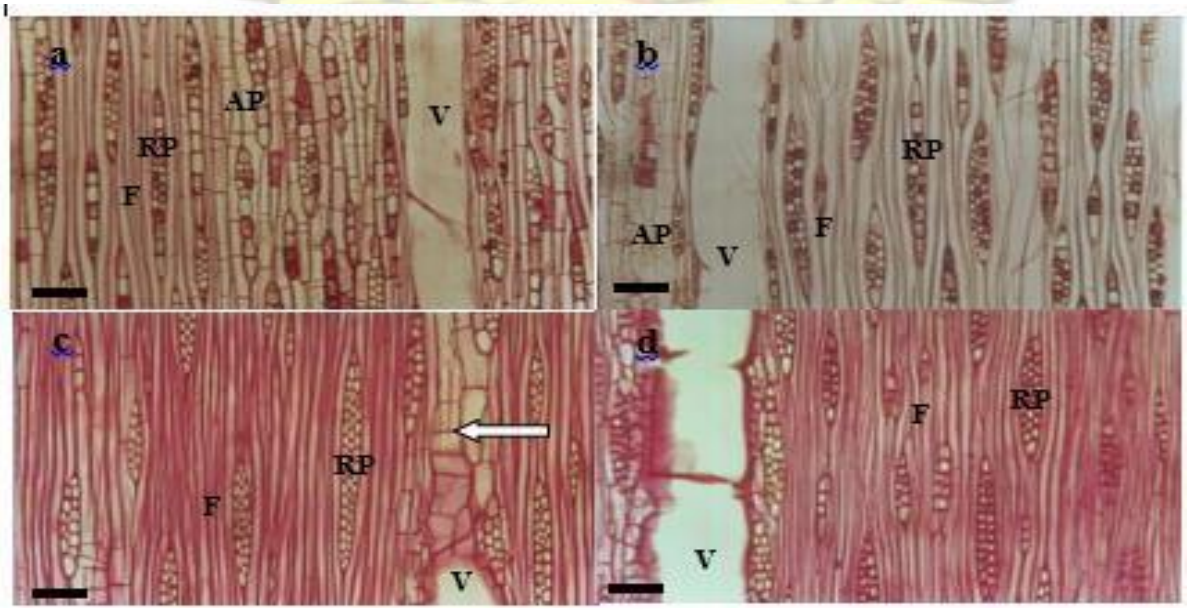

Plate 3.4: TLS of heartwood from stem base of *A. robusta* (a) and *T. ivorensis* (c) and branch base of *A. robusta* (b) and *T. ivorensis* (d). Tylosis in vessel of *T.*

***ivorensis* (arrowed). Scale bar = 20µm**

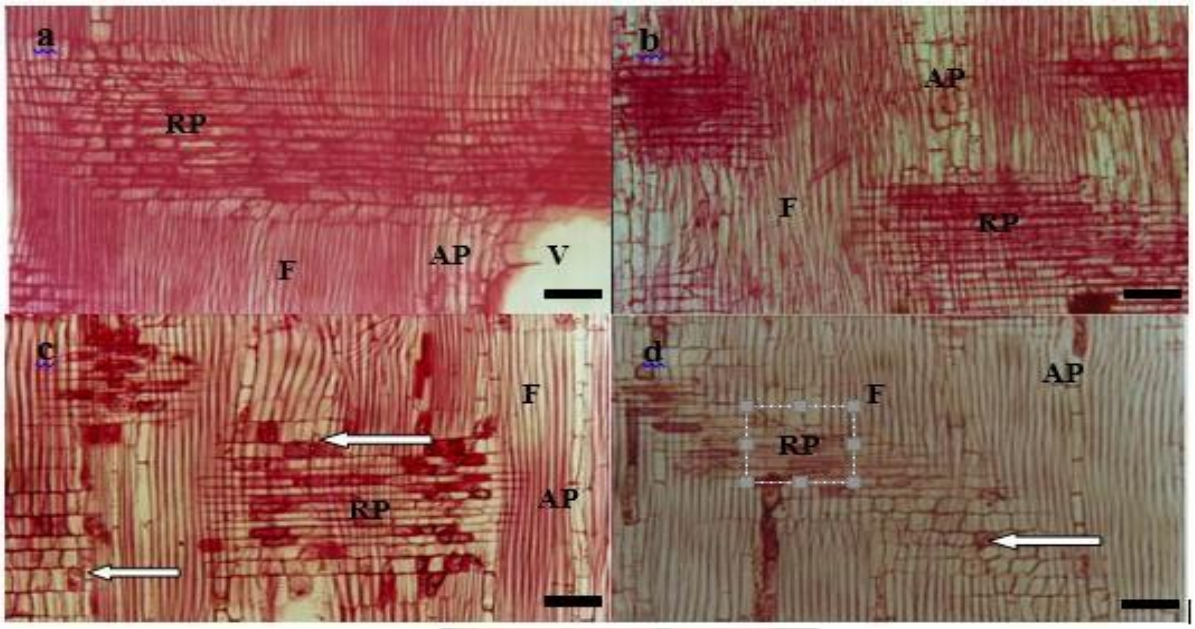

Plate 3.5: RLS of heartwoods from base of *T. ivorensis* (a) and *A. robusta* stems (c) and base of *T. ivorensis* (b) and *A. robusta* (d) branches. Silica bodies in rays of *A. robusta* (arrowed) Scale bar = 20µm.

3.3.2 Tissue dimensions of the stemwood and branchwood of *T. ivorensis* and *A. robusta*

3.3.2.1 Fibre length

According to Fig. 3.2, stemwood fibres were longer than those of the branchwooods in all cases for *T. ivorensis* and *A. robusta*. Stemwood fibres ranged from 1294.7 to 1508.6 µm and 1182.9 to 1321.5 µm and branchwood fibres 1046.0 to 1116.5 µm and 995.1 to 1145.3 µm respectively for *T. ivorensis* and *A. robusta.* Fibres of the heartwoods were also longer than those of the sapwoods, except along *T. ivorensis* branch, where sapwood fibres were longer than those of the heartwood. Fibres also increased in length from the base to the middle and decreased at the top of the stems, but decreased with height along the branches. The heartwoods from the middle of the stems thus, had the longest fibres in both timbers, and the fibres from the branch top sapwood and heartwood repectively for *A. robusta* and *T. ivorensis* had the shortest. Variations in the fibre lengths were not significant ($P > 0.05$) for the the radial positions and their interactions with the wood types and axial positions (Tables 3.1 and

3.2).

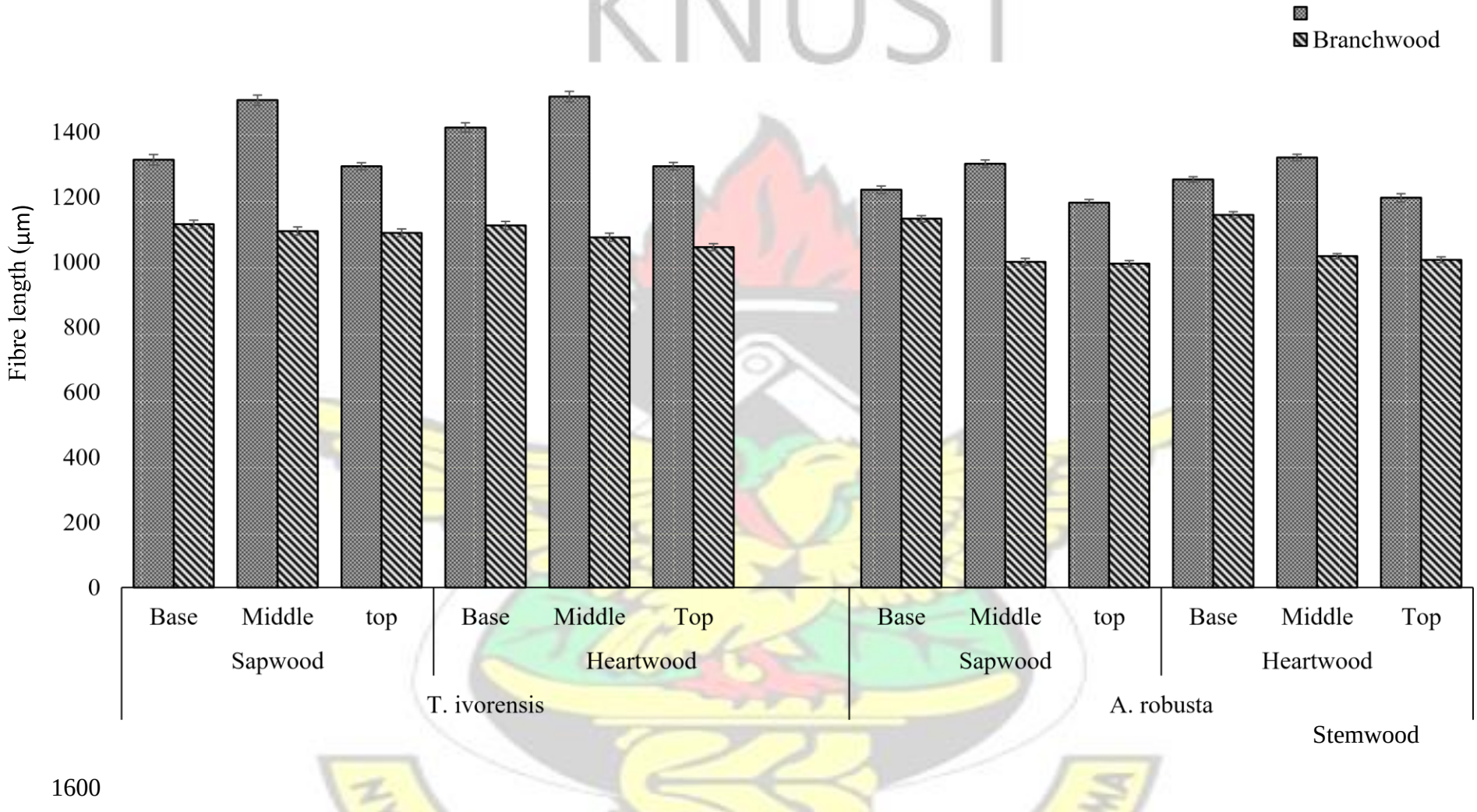

Fig. 3.2: Fibre length of the stemwood and branchwood of *T. ivorensis* and *A. robusta*

Table 3.1: ANOVA for fibre length of axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P. value
Axial position	2	4882608.786	2441304.393	69.506	0.000*
*Wood type	1	53232672.190	53232672.19	1515.57	0.000*
Radial position	1	31182.899	31182.899	0.888	0.346
Axial position x Wood type	2	4548909.475	2274454.738	64.755	0.000*
Axial position x Radial position	2	547295.342	273647.671	7.791	0.000*
Wood type x Radial position	1	519962.476	519962.476	14.804	0.000*
Axial position x Wood type x Radial position	2	161236.904	80618.452	2.295	0.101
Error	2388	83875559.337	35123.769		
Total	2400	3828577631.00			
Corrected Total	2399	147799427.408			

***Wood type:** Stemwood, branchwood

Table 3.2: ANOVA for fibre length of of *A. robusta* axial and radial positions of the stem and branch

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P. value
Axial position	2	3644306.769	1822153.385	89.162	0.000*
*Wood type	1	23272449.051	23272449.05	1138.770	0.000*
Radial position	1	39219.446	39219.446	1.919	0.166
Axial position x Wood type	2	4161513.886	2080756.943	101.816	0.000*
Axial position x Radial position	2	56026.628	28013.314	1.371	0.254
Wood type x Radial position	1	113960.464	113960.464	5.576	0.018*
Axial position x Wood type x Radial position	2	7454.144	3727.072	0.182	0.833
Error	2388	48802314.896	20436.480		
Total	2400	3244890476.46			
Corrected Total	2399	80097245.284			

***Wood type:** Stemwood, branchwood

3.3.2.2 Fibre diameter

Fibre diameters increased with height along the stems, but decreased along the branches of *T. ivorensis* and *A. robusta*. In all cases except between the *T. ivorensis* stem and branch base heartwoods, stemwoods had greater fibre diameters than branchwoods (Fig. 3.3). Stemwood fibre diameters ranged from 19.8 to 23.4 µm and 22.9 to 23.9 µm and those of the branchwoods, 19.2 to 21.2 µm and 20.1 to 22.42 µm respectively for *T. ivorensis* and *A. robusta*. Fibre

diameters of the sapwoods were also greater than the heartwoods, except at the middle and top of *T. ivorensis* stem, where heartwood fibre diameters were greater than their corresponding sapwoods. In both species, sapwoods from the stem bases had the greatest fibre diameters, while heartwoods from the branch tops had the least. The variations of fibre diameters between the various tree parts were not significant ($P > 0.05$) the radial positions and their interactions with wood types (stemwood and branchwood) in *T. ivorensis* (Table 3.3). Again the variations between the axial postions and their interactions with the radial positions, as well as the interactions between wood types and radial positions in *A. robusta* were not significant ($P > 0.05$) (Table 3.4).

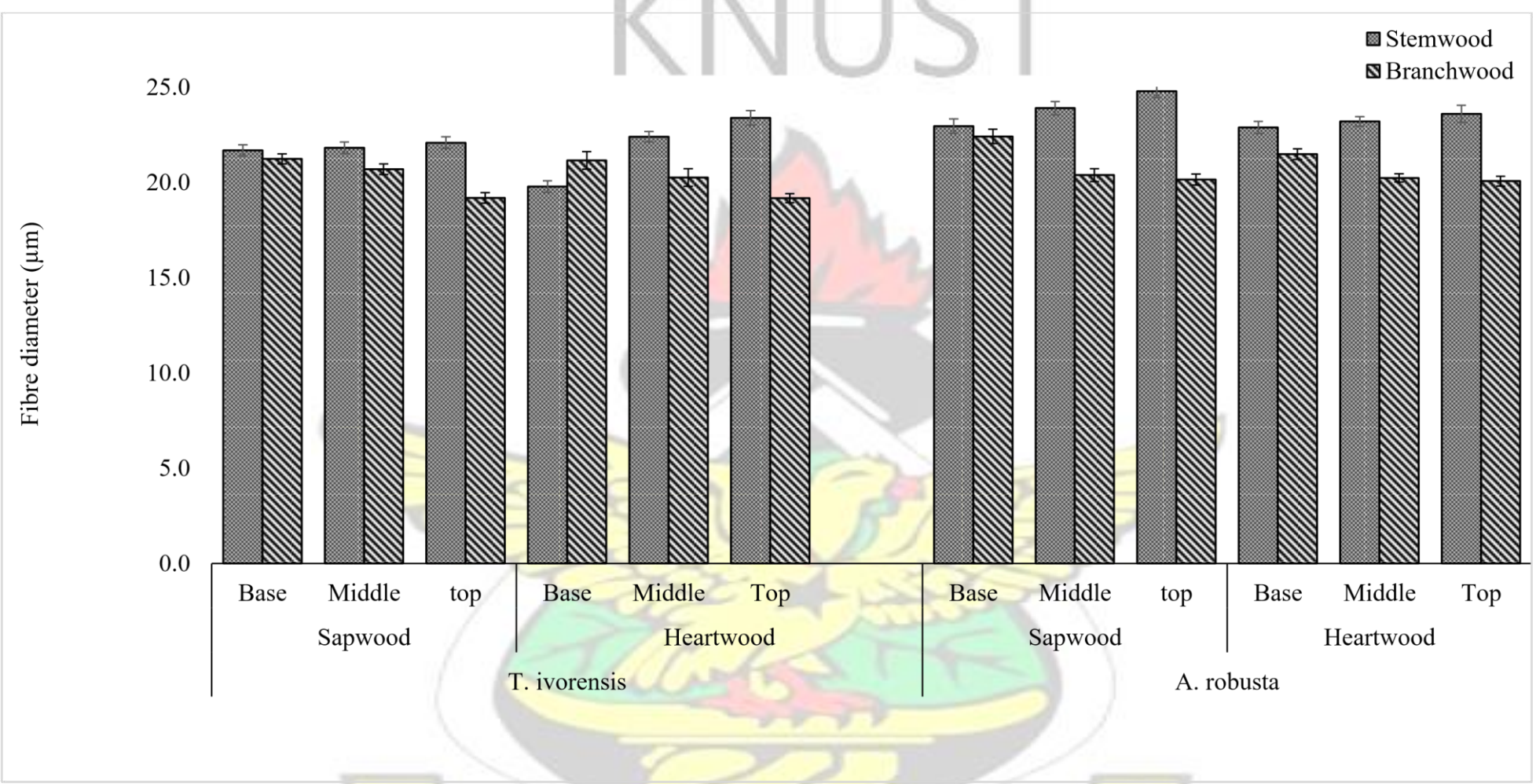

Fig. 3.3: Fibre diameter of the stemwood and branchwood of *T. ivorensis* and *A. robusta*

Table 3.3: ANOVA for fibre diameter of axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	57.831	28.916	1.357	0.258
*Wood type	1	1488.375	1488.375	69.832	0.000*
Radial position	1	5.056	5.056	.237	0.626
Axial position x Wood type	2	1613.041	806.521	37.841	0.000*
Axial position x Radial position	2	274.887	137.443	6.449	0.002*
Wood type x Radial position	1	4.347	4.347	0.204	0.652
Axial position x Wood type x Radial position	2	299.022	149.511	7.015	0.001*
Error	2388	50896.988	21.314		
Total	2400	1120696.506			
Corrected Total	2399	54639.547			

***Wood type:** Stemwood, branchwood

Table 3.4: ANOVA for fibre diameter of axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	Pvalue
Axial position	2	114.427	57.214	2.697	0.068
*Wood type	1	6391.369	6391.369	301.259	0.000*
Radial position	1	282.934	282.934	13.336	0.000*
Axial position x Wood type	2	1303.392	651.696	30.718	0.000*
Axial position x Radial position	2	34.356	17.178	0.810	0.445
Wood type x Radial position	1	0.822	0.822	0.039	0.844
Axial position x Wood type x Radial position	2	247.286	123.643	5.828	0.003*
Error	2388	50662.703	21.216		
Total	2400	1212911.458			
Corrected Total	2399	59037.289			

***Wood type:** Stemwood, branchwood

3.3.2.3 Fibre double wall thickness

Fibre double wall thickness decreased with height along the stems and branches and were greater in heartwoods than sapwoods (Fig. 3.4). Stemwood fibre double walls ranged from 6.0 to 6.5µm and 6.2 to 7.6µm and those of branchwoods 5.7 to 6.3µm, 4.9 to 5.6µm µm

respectively for *T. ivorensis* and *A. robusta*. In all cases except between the *T. ivorensis* stem and branch top sapwoods, fibre double wall thicknesses were greater in stemwoods than branchwoods. For both timber species, heartwoods from the base of the stems and sapwoods from the top of the branches respectively had the greatest and least fibre double walls. The variations in fibre double walls were not significant ($P > 0.05$) for the interactions between axial and radial positions and wood types in *T. ivorensis* (Table 3.5). In *A. robusta*, the variations were also not significant ($P > 0.05$) for the radial positions and their interactions with the axial positions (Table 3.6).

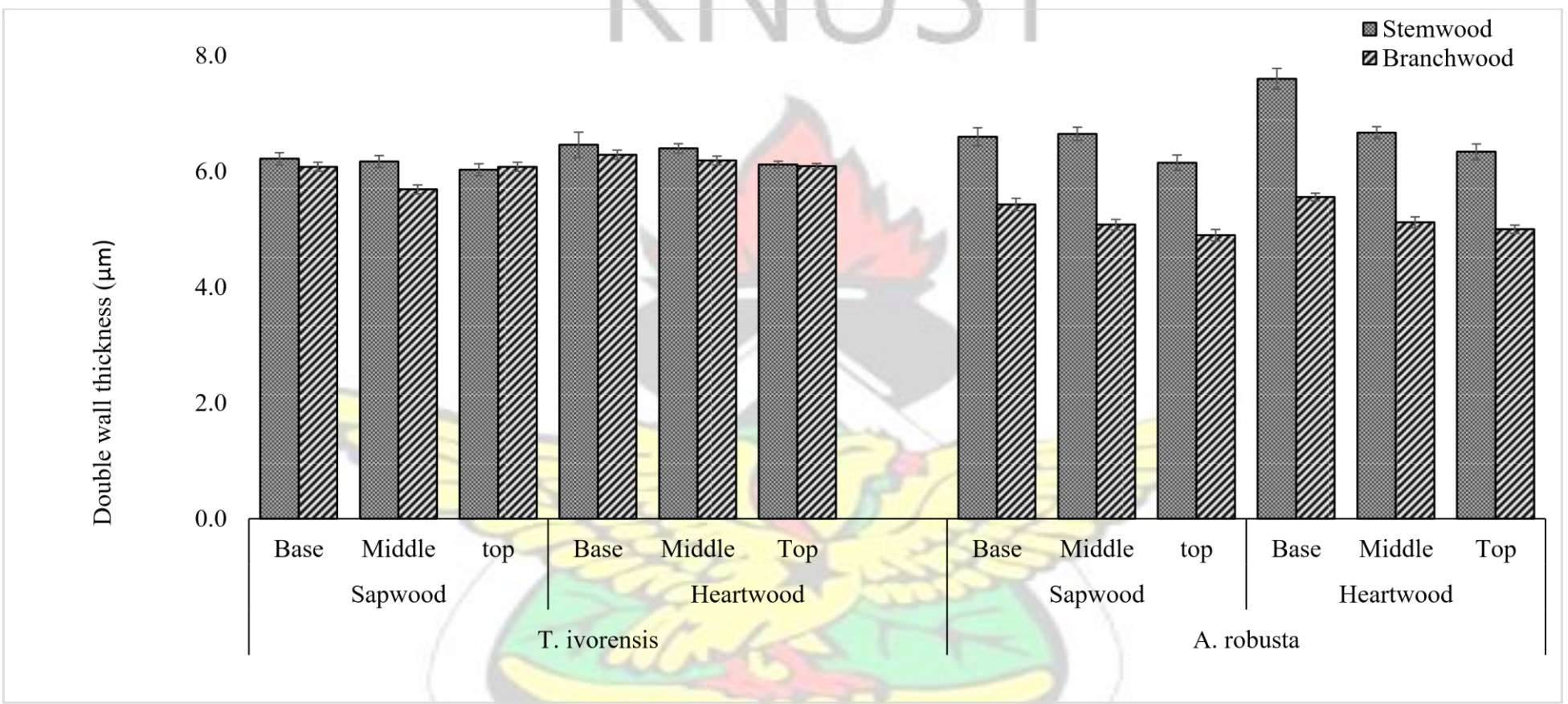

Fig. 3.4: Fibre double wall thickness of the stemwood and branchwood of *T. ivorensis* and *A. robusta*.

Table 3.5: ANOVA for fibre double wall thickness of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	15.088	7.544	3.685	0.025*
*Wood type	1	16.066	16.066	7.847	0.005*
Radial position	1	26.822	26.822	13.102	0.000*
Axial position x Wood type	2	13.055	6.528	3.189	0.041*
Axial position x Radial position	2	9.986	4.993	2.439	0.087
Wood type x Radial position	1	.405	0.405	0.198	0.657
Axial position x Wood type x Radial position	2	3.431	1.716	0.838	0.433
Error	2388	4888.848	2.047		
Total	2400	95811.672			
Corrected Total	2399	4973.701			

*__Wood type:__ Stemwood, branchwood

Table 3.6: ANOVA for fibre double wall thickness of the the stem and branch of *A. robusta* radial posi

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	661.354	330.677	121.673	0.0008*
*Wood type	1	1430.964	1430.964	526.524	0.000*
Radial position	1	0.000	0.000	0.000	0.994
Axial position x Wood type	2	74.319	37.160	13.673	0.000*
Axial position x Radial position	2	2.175	1.087	0.400	0.670
Wood type x Radial position	1	96.653	96.653	35.564	0.000*
Axial position x Wood type x Radial position	2	133.186	66.593	24.503	0.000*
Error	2388	6490.001	2.718		
Total	2400	92286.986			
Corrected Total	2399	8888.652			

*__Wood type:__ Stemwood, branchwood

3.3.2.4 Fibre lumen diameter

From Fig. 3.5, fibre lumina increased with height along the stems but decreased along the branches of *T. ivorensis* and *A. robusta.* Generally, fibre lumina were wider in stemwoods than brancwoods in both timber species, with the exception of the heartwoods from the stem and branch bases, where branchwood fibre lumina were wider. The ranges of fibre lumina were 13.3 to 17.3 µm and 15.3 to 18.6 µm for the stemwoods and 13.1 to 15.2 µm and 15.1 to 17 µm for branchwoods respectively in *T. ivorensis* and *A. robusta.* Differences between the fibre lumina were not significant (P > 0.05) for the radial positions and their interaction with wood types in *T. ivorensis* (Table 3.7) and the interactions between axial and radial positions wood types in *A. robusta* (Table 3.8).

3.3.2.5 Vessel lumen diameter

Vessel lumina for both timber species increased with height along the stems but decreased along the branches, and were wider and in sapwood than heartwood (Fig. 3.6). Their values ranged from 122.8-189.3 µm and 87.96-125.5 µm for the stemwoods and 98.5-120.1 µm and 79.95-90.6 µm for the branchwoods of *T. ivorensis* and *A. robusta* respectively. In all cases except between *A. robusta* stem and branch base heartwooods, vessel lumina were wider in stemwood than branchwood (Fig. 3.6). The variations in vessel lumina were not significant (P > 0.05) for the axial positions in *T. ivorensis* (Table 3.9 and 3.10).

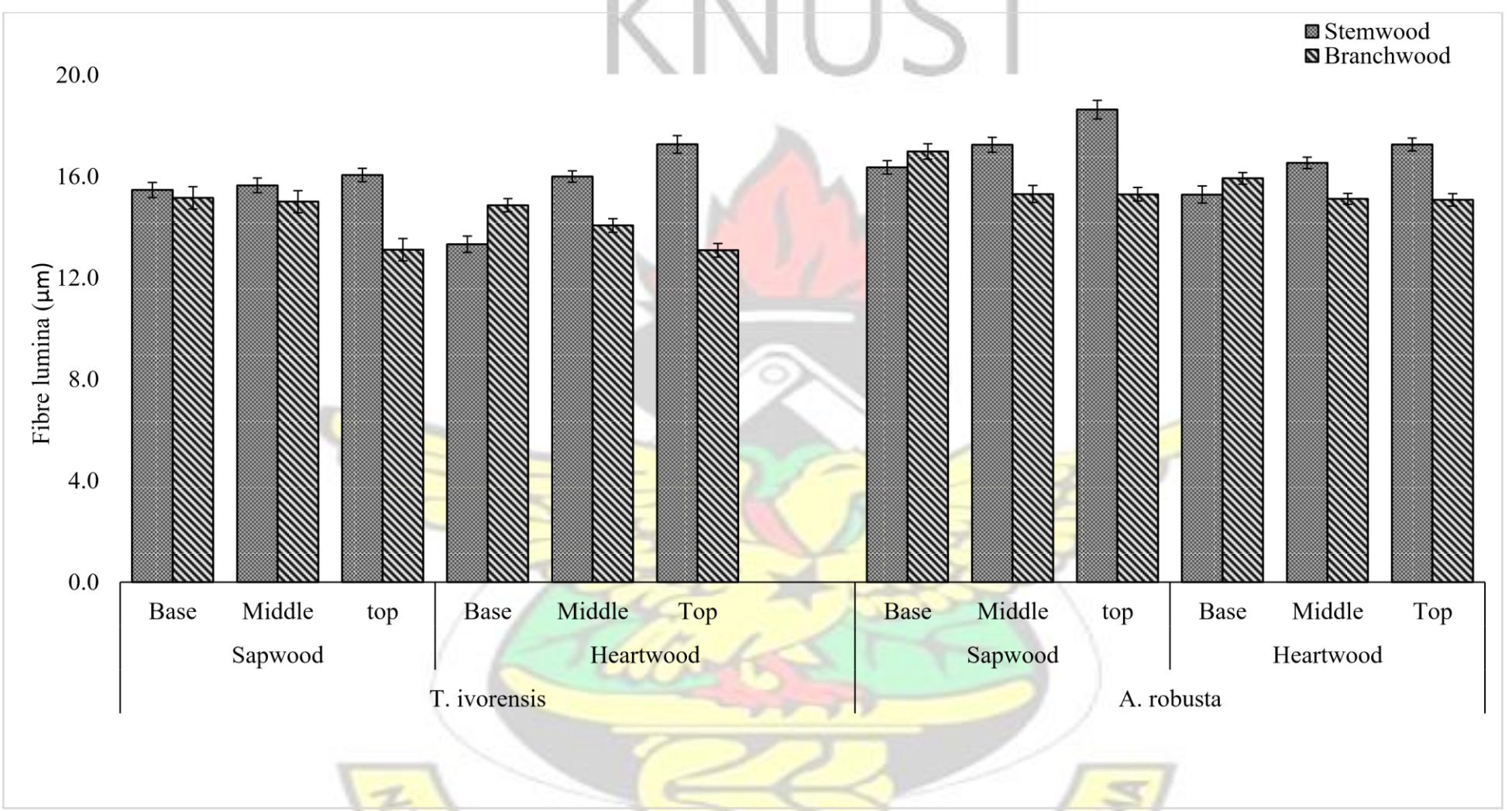

Fig. 3.5: Fibre lumen diameter of the stemwood and branchwood of *T. ivorensis* and *A. robusta*

Table 3.7: ANOVA for fibre lumen diameter of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	92.377	46.188	2.114	0.121
*Wood type	1	1195.470	1195.470	54.729	0.000*
Radial position	1	55.873	55.873	2.558	0.110
Axial position x Wood type	2	1752.141	876.070	40.106	0.000*
Axial position x Radial position	2	327.595	163.797	7.499	0.001*
Wood type x Radial position	1	7.463	7.463	.342	0.559
Axial position x Wood type x Radial position	2	322.869	161.435	7.390	0.001*
Error	2388	52162.578	21.844		
Total	2400	590443.602			
Corrected Total	2399	55916.365			

*__Wood type__: Stemwood, branchwood

Table 3.8: ANOVA for fibre lumen diameter of the axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	227.098	113.549	7.121	0.001*
*Wood type	1	1771.481	1771.481	111.102	0.000*
Radial position	1	284.247	284.247	17.827	0.000*
Axial position x Wood type	2	753.871	376.935	23.640	0.000*
Axial position x Radial position	2	27.726	13.863	0.869	0.419
Wood type x Radial position	1	79.785	79.785	5.004	0.025*
Axial position x Wood type x Radial position	2	28.844	14.422	0.905	0.405
Error	2388	38075.690	15.945		
Total	2400	658036.016			
Corrected Total	2399	41248.742			

*__Wood type__: Stemwood, branchwood

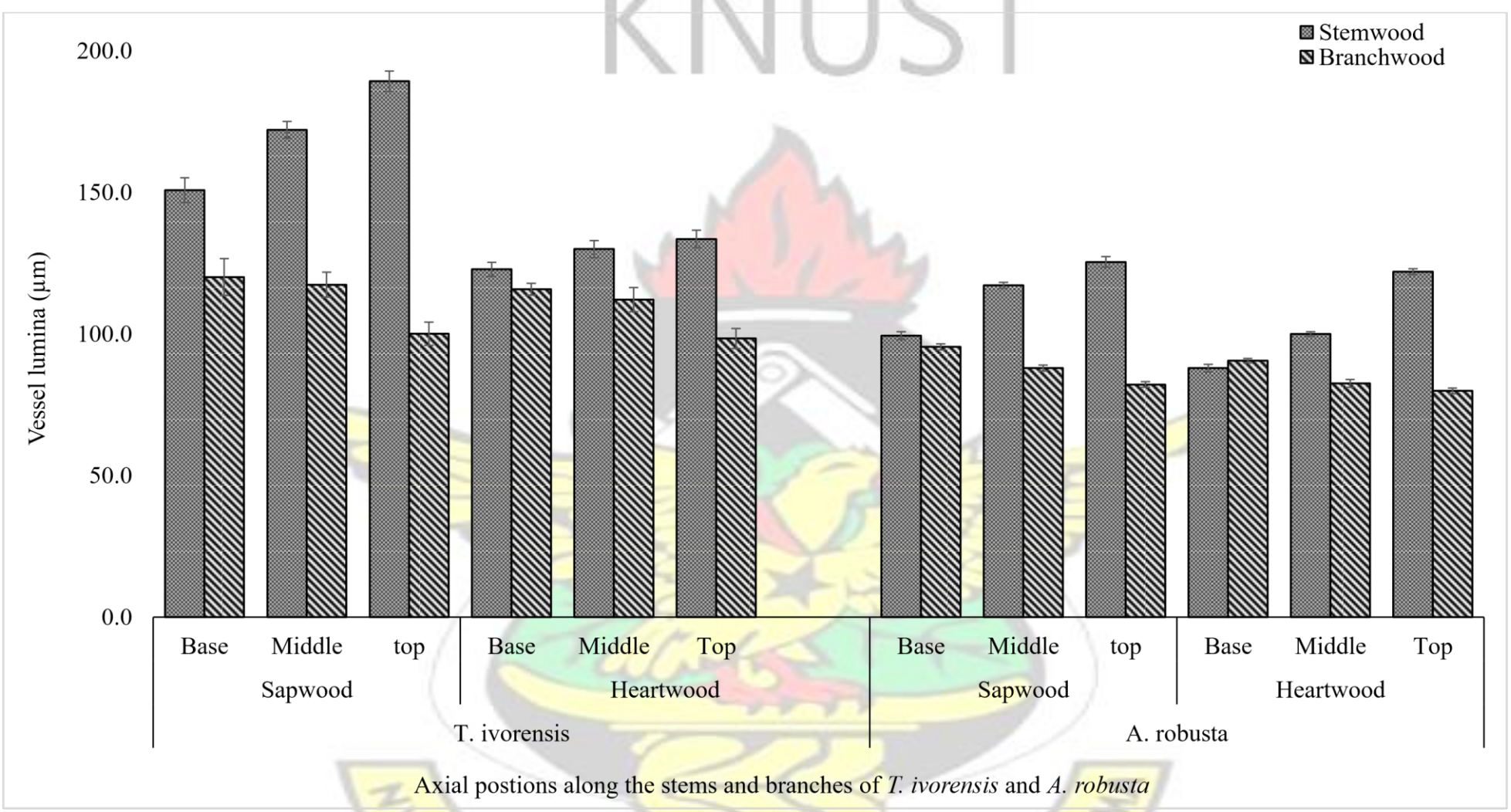

Fig. 3.6: Vessel lumen diameter of the stemwoods and branchwoods of *T. ivorensis* and *A. robusta*

Table 3.9: ANOVA for vessel lumen diameter of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	12208.072	6104.036	2.043	0.130
*Wood type	1	917756.824	917756.824	307.155	0.000*
Radial position	1	313009.410	313009.410	104.758	0.000*
Axial position x Wood type	2	189810.586	94905.293	31.763	0.000*
Axial position x Radial position	2	15982.423	7991.211	2.675	0.069
Wood type x Radial position	1	218505.312	218505.312	73.130	0.000*
Axial position x Wood type x Radial position	2	23250.248	11625.124	3.891	0.021*
Error	2388	7135159.257	2987.923		
Total	2400	49533512.18			
Corrected Total	2399	8825682.132			

*__Wood type__: Stemwood, branchwood

Table 3.10: ANOVA for vessel lumen diameter of the axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	33068.830	16534.415	58.347	0.000*
*Wood type	1	296674.491	296674.491	1046.912	0.000*
Radial position	1	33087.583	33087.583	116.760	0.000*
Axial position x Wood type	2	176912.334	88456.167	312.146	0.000*
Axial position x Radial position	2	7354.957	3677.479	12.977	0.000*
Wood type x Radial position	1	6429.285	6429.285	22.688	0.000*
Axial position x Wood type x Radial position	2	2810.456	1405.228	4.959	0.007*
Error	2388	676712.422	283.380		
Total	2400	24084666.53			

Corrected Total	2399	1233050.358

*__Wood type__: Stemwood, branchwood

3.3.3 Tissue percentages of the stemwoods and branchwoods of *T. ivorensis* and *A. robusta*

3.3.3.1 Fibre percentage

From Table 3.11, fibre percentage decreased along the stems and branches for *T. ivorensis* and *A. robusta*. The sapwoods from the middle and top of *T. ivorensis* branch however had similar values of for their fibre percentages. Fibre percentages were also greater for the stemwoods than branchwoods and for heartwoods than sapwoods. Fibre percentage variations observed, was only significant ($P < 0.05$) for the axial positions in *T. ivorensis* (Tables 3.12 and 3.13).

3.3.2.2 Vessel percentage

Vessel percentage increased with height along the stems and branches (Table 3.11). The values for *T. ivorensis* and *A. robusta* respectively ranged from 15 to 20.9 and 16 to 22% in the stems and 14 to 17% and 13 to 18.4% in the branches, with greater stemwood values than those of the branchwoods. Vessel percentages of the sapwoods were also greater than those of the heartwoods (Table 3.11). Significant variations ($P < 0.05$) were observed for the radial and axial positions and for wood types in *T. ivorensis* (Table 3.14) and for radial and axial positions in *A. robusta* (Table 3.15).

Wood species	Radial positions	Axial positions	% Fibre		% Vessel		% Parenchyma	
			Stemwood	Branchwood	Stemwood	Branchwood	Stemwood	Branchwood
T. ivorensis	Sapwood	Base	48.4	48.0	16	15	35.6	37
		Middle	47.2	46.0	20.5	16.7	32.3	36.8
		Top	47.0	46.0	20.9	17	32.1	37
	Heartwood	Base	51.5	51.2	15	14	33.5	34.8
		Middle	50.0	49.5	16.7	15	33.3	35.5
		Top	49.8	49.0	17	15.7	33.2	35.3
A. robusta	Sapwood	Base	43.5	41.7	15	17	41.5	41.3
		Middle	42.9	40.9	17	17.7	40.1	41.4
		Top	42.5	40.0	22	18.4	35.5	41.6
	Heartwood	Base	45.7	43.2	16	13	41.3	40.8
		Middle	45.5	42.0	16.8	14.5	40	41.2
		Top	44.5	41.5	17.2	17.7	37.4	41.3

Table 3.11: Tisssue percentage of the stemwoods and branchwoods of *T. ivorensis* and *A. robusta*

Table 3.12: ANOVA for fibre percentages of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	198.042	99.021	1.897	0.152
*Wood type	1	36.750	36.750	0.704	0.402
Radial position	1	705.333	705.333	13.510	0.000*
Axial position x Wood type	2	4.625	2.312	0.044	0.957
Axial position x Radial position	2	1.042	0.521	0.010	0.990
Wood type x Radial position	1	2.083	2.083	0.040	0.842
Axial position x Wood type x Radial position	2	1.292	0.646	0.012	0.988
Error	288	15036.000	52.208		
Total	300	725545.500			
Corrected Total	299	15985.167			

*__Wood type:__ Stemwood, branchwood

Table 3.13: ANOVA for fibre percentages of the axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value.
Axial position	2	103.042	51.521	0.658	0.519
*Wood type	1	130.021	130.021	1.661	0.199
Radial position	1	28.521	28.521	0.364	0.547
Axial position x Wood type	2	52.542	26.271	0.336	0.715
Axial position x Radial position	2	59.292	29.646	0.379	0.685
Wood type x Radial position	1	1.021	1.021	0.013	0.909
Axial position x Wood type x Radial position	2	30.792	15.396	0.197	0.822
Error	288	22549.440	78.297		
Total	300	426104.690			
Corrected Total	299	22954.669			

*__Wood type:__ Stemwood, branchwood

Table 3.14: ANOVA for vessel percentages of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	405.125	202.562	8.152	0.000*
*Wood type	1	336.021	336.021	13.523	0.000*
Radial position	1	336.021	336.021	13.523	0.000*
Axial position x Wood type	2	47.042	23.521	0.947	0.389
Axial position x Radial position	2	47.042	23.521	0.947	0.389
Wood type x Radial position	1	46.021	46.021	1.852	0.175
Axial position x Wood type x Radial position	2	23.792	11.896	0.479	0.620
Error	288	7156.000	24.847		
Total	300	123939.250			
Corrected Total	299	8397.063			

***Wood type:** Stemwood, branchwood

Table 3.15: ANOVA for vessel percentages of the axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	605.792	302.896	3.453	0.033*
*Wood type	1	52.083	52.083	0.594	0.442
Radial position	1	1365.333	1365.333	15.564	0.000*
Axial position x Wood type	2	437.792	218.896	2.495	0.084
Axial position x Radial position	2	6.542	3.271	0.037	0.963
Wood type x Radial position	1	75.000	75.000	0.855	0.356
Axial position x Wood type x Radial position	2	27.375	13.687	0.156	0.856
Error	288	25264.000	87.722		
Total	300	170188.000			
Corrected Total	299	27833.917			

***Wood type:** Stemwood, branchwood

3.3.3.3 Parenchyma percentage

Parenchyma percentages were mostly greater in branchwoods than stemwoods for both *T. ivorensis* and *A. robusta.* The stemwood values for *T. ivorensis* and *A.robusta* respectively ranged from of 32.1 to 35.6 and 35.5 to 41.5% and those of the branchwoods, 34.8 to 37% and

40.8 to 41.6% respectively for *T. ivorensis* and *A.robusta* (Table 3.11). Again sapwood had more parenchyma than heartwoods in both timber species. Variations in parenchyma percentages were significant for wood types in *T. ivorensis* (Table 3.16) and for wood types, axial and radial positions and their interactions in *A. robusta* (Table 3.17).

Table 3.16: ANOVA for parenchyma percentages of the axial and radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	41.625	20.812	0.282	0.755
*Wood type	1	560.333	560.333	7.583	0.006*
Radial position	1	56.333	56.333	0.762	0.383
Axial position x Wood type	2	72.042	36.021	0.488	0.615
Axial position x Radial position	2	62.042	31.021	0.420	0.658
Wood type x Radial position	1	56.333	56.333	0.762	0.383
Axial position x Wood type x Radial position	2	25.792	12.896	0.175	0.840
Error	288	21280.000	73.889		
Total	300	323621.500			
Corrected Total	299	22154.500			

*__Wood type:__ Stemwood, branchwood

Table 3.17: ANOVA for parenchyma percentages of the axial and radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	3589.292	1794.646	16.996	0.000*
*Wood type	1	2436.750	2436.750	23.077	0.000*
Radial position	1	4144.083	4144.083	39.246	0.000*
Axial position x Wood type	2	657.125	328.562	3.112	0.046*
Axial position x Radial position	2	2786.792	1393.396	13.196	0.000*
Wood type x Radial position	1	1633.333	1633.333	15.468	0.000*
Axial position x Wood type x Radial position	2	2103.792	1051.896	9.962	0.000*
Error	288	30410.480	105.592		
Total	300	519794.980			
Corrected Total	299	47761.647			

*__Wood type:__ Stemwood, branchwood

3.4 Discussion

3.4.1 Anatomical descriptions of *T. ivorensis* and *A. robusta*

A. robusta and *T. ivorensis* showed general characteristics of hardwoods; exhibiting the major hardwood cells (fibres, vessels, rays and axial parenchyma) (Haygreen and Bowyer, 1996; Antwi-Boasiako and Atta-Obeng, 2009). *T. ivorensis* showed solitary vessels with radial multiples of 2, axial parenchyma, paratracheal vasicentric, irregularly storied rays (1-3 cells wide) and body ray cells procumbent, with one row of square marginal cells, whereas *A. robusta* has solitary vessels with radial multiples of 2-4, axial parenchyma apotracheal diffuse-in-aggregates and irregularly storied rays, 1-3 cells wide with multiseriate portions as wide as uniseriate portions. Its body ray cells are procumbent with mostly 2-4 rows upright and square marginal cells.

In agreement with Oteng-Amoako (2002) and Lemmens (2007), silica bodies were observed in the rays of *A. robusta,* as tyloses occluded some vessels in *T. ivorensis.* Tyloses and silica present varying effects on wood species during utlilization. Silica in *A. robusta* would have a high blunting effect on saws and cutting tools (Lemmens, 2007). The amount and frequency of tyloses also contribute to a general reduction of permeability in wood to fluid flow (McIntosh, 1970; Bierman, 1996), limit moisture uptake and consequently resist pulping liquor as well as preservatives (Hills, 1972). Their presence would also likely affect water movement in living trees (Sano and Fukazawa, 1991). Consequently, Chudnoff (1984) observed that *A. robusta* is very permeable, but *T. ivorensis* is highly resistant to preservative treatments due to the presence of tyloses in its vessels.

However, the presence of tyloses may also be advantageous as they increase the durability of the wood (Meyer, 1967). Moisture has great impact on wood durability and service life; it is a prerequisite of vital importance for wood-destroying organisms to attack wood (Ali, 2011). Thus, the amount of decay in timber in service depends on the moisture content of the timber (Moore, 2011). The impedance of tyloses to fluid flow in wood is thus important to its durability, since they also physically impede the movement of pathogens through wood by blocking vessel lumina (Taylor *et al.*, 2002).

3.4.2 Variations in the tissue dimensions of *T. ivorensis* and *A. robusta* stem and branch woods

3.4.2.1 Fibre length

Izokor and Fuwape (2011) and Emerhi (2012) reported the sapwood fibres of *Tectona grandis*, *Rhizophora racemosa* and *Rhizophora harrisonii* stems were longer than those of the heartwoods, similar to the observation along the branch of *T. ivorensis*. Ghouse and Siddiqui (1976), Jorge *et al.* (2000) and Amoah *et al.* (2012) explained that cambial initials usually increase with increasing cambial age from the pith to periphery. Consequently, sapwood, which is closer to the periphery will have longer fibres than the heartwood. However, faster growth results in the formation of shorter cells, while the extent of the intrusive growth of the tip of fibres during their differentiation also influence the length of the fibres (Bailey, 1920; Wilson and White, 1986). Consequently, longer heartwood fibres, compared to shorter sapwood fibres for *A. robusta* and *T. ivorensis* stem could be due to the growth rate and intrusive growth of fibre tips during their growth.

Even though various trends have been reported for fibre dimensions along the stems of trees, the trend of fibre length in this study is consistent with the report of Panshin and de Zeeuw (1964) that the length of cells increase with height in the stem to a maximum height and above

this the fibre lengths decrease with increasing height. This same pattern of wood fiber dimensions was described by Jorge (1994) and Tavares *et al.* (2010) for *Eucalyptus globulus*, by (Chauhan *et. al.*, 2001) for *Populus deltoides* Bartram. ex Marsh, and also for *Rhizophora racemosa* by (Emerhi, 2012). The decreasing trend of fibre length in the branches observed presently was also earlier reported by Ververis (2004) for olive and almond branches. Samariha *et al.* (2011) for *Ailanthus altissima* and Longui *et al.* (2012) for *Eriotheca gracilipes* reported shorter fibres in the branches than stems, comparable to longer stemwood fibres than branchwood observed for *T. ivorensis* and *A. robusta* in the current study.

Longer fibres sufficiently overlap each other and appropriately transfer stress from one cell to the next, thus increasing the load bearing capacity of wood (Desch and Dinwoodie, 1996). However, shorter fibres result in lower Modulus of Elasticity (MOE) due to the flattening of microfibrillar helices in their cell walls (Cowdrey and Cave, 1968; Wilson and White, 1986). Moreover, longer fibres are preferred in paper making than shorter fibres (Dickmann, 1975); they give higher the tear resistance to paper produced from them than shorter ones (Ademiluyi and Okeke, 1979). Hence, heartwoods from the middle of the stems with the longest fibres (1508.6 and 1321.5 µm respectively for *T. ivorensis* and *A. robusta*) are most likely to have the greatest MOE, greater load bearing capacity and produce paper with highest tear resistance, while heartwood from the top of *T. ivorensis* branch and sapwood from the top of *A. robusta* branch with the shortest fibres (1046 and 995 µm respectively for *T. ivorensis* and *A. robusta*) will have the lowest MOE and produce papers with the least tear resistance. Even though stemwood fibres were longer than those of the branch, both wood types, have fibres lengths ranging between 900-1600 µm; 1046-1508.6 µm and 995.1-1321.5 µm respectively for *T. ivorensis* and *A. robusta*. These are medium length fibres (Lemmens, 2007; Insidewood, 2014) and are comparable to those of utilizable hardwoods.

3.4.2.2 Fibre diameter and fibre lumen diameter

Increasing fibre diameter and fibre lumen diameter with height observed in the stems of the two timber species is consistent with the trends recorded in *E. nitens* and *R. harrisonii* by (Roszaini, 2000; Kibblewhite *et al*., 2004; Emerhi, 2012). Decreasing trend of fibre diameters along the branches of the two timber species under investigation also corresponds to reports for olive and almond branches (Ververis, 2004). Wider fibre diameter and fibre lumen diameter observed in sapwood than heartwood was earlier found in *R. harrisonii* and *R. racemosa* (Emerhi, 2012) and in *Tectona grandis* (Izekor and Fuwape, 2011). Generally, the variation in fibre diameter and fibre lumen diameter in both radial and longitudinal directions is attributable to the increase in cell size and physiological development of the wood as the tree grows in girth (Ververis, 2004). Roger *et al.* (2007) reported a positive relationship in fibre lumen diameter and cambium age in their study, while Adamopoulos and Voulgaridis (2002), Marsoem *et al.* (2002) and Tavares *et al.* (2010) reported that fibre dimensions increase from pith to bark, which corroborates wider sapwood fibres with wider lumina observed in this study.

On the other hand, wider heartwood than sapwood fibres at the middle and top of *T. ivorensis* stem, could be due to inconsistencies in auxin contents in the apical meristem during the time of growth. Larson (1960) indicated that high auxin content in the apical meristem will result in the production of large diameter cells; anything that reduces apical activity will result in small diameter cells. Fibre diameter variations were however not significant between sapwood and heartwood of *T. ivorensis.*Thus, decreasing fibre diameter and fibre lumen diameter along the branches, could result from reduction in apical activity. Moreover, Panshin and de Zeeuw (1980) observed that the measurable variables in wood is influenced by several factors: changes in cambium as it ages, genetic controls that govern the form and growth of the tree and environmental influences such as seasonal and geographical conditions or nutrient supply. The interactions of these influences thus, makes it difficult to ascribe variability in wood or any

inconsistencies to a single factor or even to a combination of factors affecting tree growth, except from detailed individual study.

Generally, fibre diameter was 19.2 to 23.4 and 20.1 to 24.8 µm and fibre lumen diameter fibre lumen diameter, 13.1-17.3 and 15.1-18.6 µm for *T. ivorensis* and *A. robusta* respectively. According to Bolza and Keating (1972) and Panshin and de Zeeuw (1980), medium texture fibres have diameters between 16-25 µm. In line with the present study, Awuku (1979) recorded the average fibre diameter of *T. ivorensis* to be 20.52 µm. The two timbers have medium texture fibres. This includes those of their stem and branch woods. However, fibre diameters and fibre lumina recorded for the branches were mostly smaller than the stems. In support, Panshin and de Zeeuw (1964), Tsoumis (1968), Manwiller (1974), Taylor (1977), Phelps *et al.* (1982), Wilson and White (1986) and Samariha et al. (2011) reported that branchwood cells have narrower diameter and lumina than their corresponding stemwoods. Wider lumen diameters from most of the stem portions than the branch might result in less cell wall materials and, most likely, less density than the narrower ones in the branch. Martinez-Cabrera *et al*. (2009) and Rana *et al*. (2009) earlier reported that increased fibre lumen fraction has a negative relationship with wood density. Okai *et al* (2004) also recorded greater branchwood densities than stemwood for *T. ivorensis* and *A. robusta.* Larger fibre lumen widths are, however, more favourable for pulp and paper; they are better for the beating of pulp because of the penetration of liquids into the empty spaces (Emerhi, 2012). Hence, in terms of their fibre lumina, stemwood (particularly sapwood at the crown of *A. robusta* and heartwood of *T. ivorensis* top with the widest fibre lumina) would be better for pulp beating than wood from the top of branch.

3.4.2.3 Fibre double wall thickness

Decrease in double wall thickness with height observed along the stems and branches in the current study supports Panshin and de Zeeuw (1964), as well as Taylor and Wooten (1973). According to them, the general pattern for fibre wall thickness is a decrease from base to top of the tree. Likewise, Izekor and Fuwape (2011), Shashikala and Rao (2009) and Kiaei (2011) reported similar trends for *Tectona grandis, Plantanus occidentalis, Eucalyptus citriodora* and *Acer velutinum boiss*. Furthermore, fibres from the various axial positions of the branchwood had lesser double wall thicknesses than the stemwood fibres, as was observed by Samariha *et al.* (2011) and Longui *et al*. (2012) for *Ailanthus altissima* and *Eriotheca gracilipes* respectively. This was however with the exception of the top of *T. ivorensis*, where branchwood fibre double wall was thicker than stemwood. Likewise, thicker fibre double walls for heartwood is inconsistent with the finding of Monteiro (2003) for *E. globulus*, which had thicker cell wall fibres in sapwood than the heartwood. To explain the decreasing axial trends, as well as the thicker heartwood double wall presently studied, Panshin and de Zeeuw (1980) and Sudin and Wahab (2013) observed that younger and more actively expanding cambial wood at sapwood may have thinner cell walls than the older heartwood region. Moreover, cell wall growth is dependent on the accumulation of metabolic products (cellulose, hemicellulose, lignin, waxes), which increase with maturity (Fahn, 1990; Vallet *et al*., 1996; Ververis, 2004). Thus, matured wood fibres are thick-walled, while juvenile wood fibres are thin-walled (Gbadamosi, 2001). Besides, Larson (1960) further expressed that wall thickness generally increases when cell diameter decreases, and that they are both related to nutrition. In consequence, sapwood and the upper parts of the stems, which had wider cell diameters, had thinner fibre double walls, while the more matured heartwood and the lower parts of the stems probably with higher accumulated metabolic products, had thicker fibre double walls. Similarly, fibre double walls in the more matured stemwoods were mostly thicker than branchwood.

Variations observed for fibre double wall thicknesses between the stems and branches of the two timbers would influence their density, paper properties and natural durability. Thicker fibre walls correlate with greater wood density and they also give bulky sheets of low tensile but greater tearing strength (Dadswell and Watson, 1962; Wardrop, 1969). Wood with thicker fibre walls also withstand grazing or nibbling by bio-degraders (Schwarze, 2004; AntwiBoasiako and Ayimasu, 2012). Even though fibre double walls were mostly greater for stemwood portions, their densities might not be greater than the branchwoods. This is because density variations depend mostly on cell wall materials, differences in ratio of cell wall to cell cavity and cell diameter (Desch and Dinwoodie, 1996; Jacobsen *et al.*, 2007; Martinez-abrera *et al.*, 2009). Greater cell wall materials would give greater wood density, thus, the branchwood with relatively lower fibre double wall thickness but maller fibres and narrower fibre lumen diameters, and as such closer textured wood than stemwood, would have more cell wall materials and greater density (Haygreen and Bowyer, 1996; Okai et al., 2004; Roque and Filho, 2007).

Thin-to-thick walled fibres have their lumina less than 3 times the double wall thickness, and distinctly open (Wheeler *et al.*, 1989). Currently, the average fibre lumen diameters are less than 3 times the average fibre double wall thicknesses (i.e. 14.9 < 18.6 and 16.3 < 17.7) for *T. ivorensis* and *A. robusta*. Moreover, the fibre lumina of the timbers were distinctly opened. Consequently, the current study agrees with Lemmens (2007) and Richter and Dallwitz (2009) who indicated that *T. ivorensis* and *A. robusta* have thin-to-thick walled fibres.

3.4.2.4 Vessel lumen diameter

Vessel lumina of the stem and branch woods *T. ivorensis* (98.5-189.3 µm) and *A. robusta* (80.0-125.5 µm) compares with those of utilizable hardwoods and with Lemmens (2007), and Richter Dallwitz (2009) and Insidewood (2014) who reported vessel lumen diameters of 50100 µm and

100-200 µm respectively for *A. robusta* and *T. ivorensis.* Wider vessels of sapwood than heartwood along the stems and branches and decreasing vessel lumen diameter along the branches of *T. ivorensis* and *A. robusta*, is consistent with Tyree and Ewers (1991) and Carlquist (2001) that the lumen diameter of vessels decrease with height in branches of timbers and with Peszlen (1994) and Bhat *et al.* (2001) that vessel lumina increases in size from inner wood to the outer. Moreover, James *et al.* (2003) found vessel lumina to decrease from the base to the top of *Anacardium excelsum, Cordia alliodora, Ficus insipida* and *Schefflera morototoni* branches.

Conversely, increasing vessel lumina along the stems of *T. ivorensis* and *A. robusta* opposes the decreasing trend along the stem of *Poincianella pyramidalis* reported by Luizon and Gasson (2012). To explain this contradiction, Tyree and Zimmermann (2002) emphasized that plants can alter wood properties in several distinct ways, based on changes in fraction of sapwood occupied by vessel lumens, vessel composition and from many narrow to few wide vessel lumina, in order to adjust the rates of water supply. These adjustments are not necessarily mutually exclusive; thus, plants can alter a combination of these traits (Zanne *et al.*, 2010). Consequently, the disparities observed in the trends of vessel lumen diameter along the stems of *T. ivorensis* and *A. robusta* could be as a result of adjustments made by the plants for optimum water supply. Preston *et al*. (2006) and Sperry *et al*. (2008) also explained that the influence of the mechanical-support requirement that leads to different anatomical designs or different mechanical strength requirements can lead to different trends of vessel lumen in wood. Again, McCulloh *et al*. (2004) and McCulloh and Sperry (2005) stated that different types of stem construction have different levels of vessel lumina.

Luizon and Gasson (2012), expressed that, the stemwood is expected to have wider vessels and hence wider lumina than branchwood because of the age of their cambium. In confirmation,

stemwood vessels of the timbers under study had wider lumina than branchwood vessels. This corresponds to smaller vessel lumina observed in the branches than stems of *Fagus sylvatica* and *Quercus ilex* by (Gasson, 1985) and in maple wood by (Gurau *et al*., 2010). Vessel lumen diameter is critical in moisture absorption, wood degradation and density variations (Zabel and Morrell, 1992; Kollmann and Côté, 1984; Uetimane, 2010). As the vessel lumen does not contribute to the mass and thus to the wood density (a property which is considered an indicator of strength properties), wood regions with more and larger diameters have lower resistance (Baas *et al*., 2004). Moreover, as Antwi-Boasiako and Ayimasu (2012) explained for fibre lumina, wide-lumen vessels would also easily absorb more moisture into their voids thereby creating conducive environment for bio-degraders, especially decay-fungi. Large vessel diameters are also unfavourable for paper-making; they lead to problems in refining and printing processes and pose difficulties in the finishing of solid wood products (Kasia *et al.*, 2013). Subsequently, stemwoods from the crown of the stem (especially sapwoods) of the two timbers with the widest vessel lumina (189.3 and 125.5 µm respectively for *T. ivorensis* and *A. robusta*) would easily absorb moisture, be more disposed to decay and less desirable for paper making and solid products than their branchwoods (particularly heartwoods at the branch top). *Lyctus* beetles, require wide vessel lumina (> 90 µm) that could accommodate their ovipositor to invade wood (Kollmann and Côtè, 1984). Accordingly, both the stem and branch woods of *T. ivorensis* would be generally disposed to their invasion as well as along the stem and the branch base of *A. robusta*, which all possess vessel lumina greater than 90 µm.

3.4.3 Variations in the tissue percentages of *T. ivorensis* and *A. robusta* stem and branch woods

3.4.3.1 Fibre percentage

Fibre proportion generally decreased along the stems and branches and was also greater for the heartwoods than sapwoods and for the stemwoods than branchwoods of *T. ivorensis* than

A. robusta. The present axial trend and radial variation is in line with Isebrands' (1972) report that fibre percentage generally decreases from pith outward and along tree height. This implies that fibre content would be greater at the base than upwards and heartwood fibres more than those of sapwood. Correspondingly, Longui *et al.* (2012) recorded greater fibre content at the butt than the top of *Eriotheca gracilipes*, just as Antwi-Boasiako and AttaObeng (2009) recorded greater fibre content at the butt than top portions of *T. ivorensis*, *M. excela, A. toxicaria* and *E. cylindricum.* Haygreen and Bowyer (1996), Joshi (2008) and Luizon and Gasson (2012) also accounted that hardwood branches have fewer fibres than those from the stem. Nonetheless, the variations in fibre percentages were not significant for wood types in both timber species. Bhat *et al.* (1985) noted that significant differences do not exist in tissue proportions between branchwood and stemwood. This indicates similar fibre yields for their pulps (Hua *et al.*, 1996) and comparable wood toughness (Longui *et al.*, 2012). Furthermore, 46-51.5% fibre proportion for *T. ivorensis* (including the stem and branch woods) is in agreement with the studies by Oteng-Amoako (2002) and AntwiBoasiako and Atta-Obeng (2009) that *T. ivorensis* fibre content would be classified as medium (41-60%). Similarly, low to medium fibre proportion (40-45.7%) recorded for *A. robusta* is close to that of *A. altissima* of the same Genus (Oteng-Amoako, 2002). The branchwoods could thus be utilized as supplementary wood for these timbers.

3.4.3.2 Vessel percentage

Vessel percentage generally increased from the base to the top of the stems and along the branches of *T. ivorensis* and *A. robusta*. According to Carlquist (2001) and Luizon and Gasson (2012), the number of vessels increase with height in a tree. Moreover, Rao *et al*. (2003) and Ishiguri *et al.* (2009) observed that vessel percentage increased from the pith toward the bark of trees, implying more vessels in the sapwood than the heartwood. This was so for *A. robusta* and *T. ivorensis.* Similarly, Antwi-Boasiako and Atta-Boateng (2009) recorded more vessels

in sapwood than heartwoods of *T. ivorensis* and *E. cylindricum*. More vessels were also recorded in the stem than in branch woods of *T. ivorensis* and *A. robusta*. The lowest amount of vessels were in the base of the branch of *T. ivorensis* and the stem base of *A. robusta* heartwoods, whereas the sapwoods at the stem top had the most vessels in both timbers. However, Haygreen and Bowyer (1996) found hardwood branches to possess more vessels than the stems. McCulloh *et al*. (2004), McCulloh and Sperry (2005), Preston *et al*. (2006) and Sperry *et al*. (2008) explained the contradictions of the previous and present studies to be due to the fact that trees modify the distribution of their vessels to suit different stem constructions, mechanical strength and their requirements for adequate water supply.

Vessel proportions in wood affects its utilization. The occurrence of several vessels together can decrease the density and strength properties of wood but increase its water absorption capacity (Luizon and Gasson, 2012). However, the abundance of vessels in wood is unfavorable for pulp production. Consequently, more stemwood vessels could result in reduced density and strength properties.

3.4.3.3 Parenchyma percentage

Decrease in parenchyma percentage from the base to the top of the stems of *T. ivorensis* and *A. robusta* was earlier noted by Ismail *et al.* (1995) for ray proportion in *Neolamarckia cadamba*. Patel (1965) and Pate and Jeschke (1995) acknowledged that the greatest amount of parenchyma cells is found at the base of the tree stems. Moreover, more parenchyma cells in sapwood than heartwoods currently observed are also in line with radial increase in axial parenchyma proportion (from the pith to the bark) in *Paraserianthes falcataria* (Ishiguri *et al.*, 2009). Sauter and van Cleve (1994) and Pratt *et al*. (2007) explained that parenchyma is the storage compartment of wood; it functions as storage and distribution of reserve food materials,

as well as storage and transport of water. It also has the greatest potential of starch and water storage (Longui *et al*., 2012). Consequently, the root of *Eriotheca gracilipes* had more parenchyma cells than the stem and branch (Longui *et al*., 2012), just as the base of the tree stems than the crown had more parenchyma cells in the current study.

Greater proportions of parenchyma cells observed for the branches than the stems of *T. ivorensis* and *A. robusta*, supports findings of Haygreen and Bowyer (1996) and Joshi (2008). Greater parenchyma percentage would adversely influence the strength properties of the branch than the stem, since many parenchyma cells relate positively with greater mechanical fragility, thus, reduction of the mechanical resistance of wood (Luizon and Gasson, 2012). Thin cell walls and abundant parenchyma cells are expected to exhibit low density and strength properties (Sint and Hapla, 2008). However, it indicates a great tendency for the timber species for impregnation with preservatives to enhance their durability (Sint *et al*., 2011; 2012). The abundant presence of non-structural tissue, such as ray and axial parenchyma, may also inflict significant damage and drying defects such as splitting and cracking (Damayanti and Rulliaty, 2010), especially in the branchwoods and the sapwoods of the base of the stem of *T. ivorensis* and the sapwood and heartwood of the base of *A. robusta* stem. In general, sapwoods from the crown of the branches (especially those of *A. robusta* with the most abundant parenchyma cells) would be most fragile and susceptible to splitting and cracking during drying but it would have the greatest propensity for impregnation with chemicals.

3.5 CONCLUSION

There were variations in the tissue characteristics from the sapwoods and heartwoods along the stems and branches of *T. ivorensis* and *A. robusta*; stemwoods had more, longer, wider, thicker-walled fibres with wider lumina than branchwoods. They also had more vessels with wider lumina, but less parenchyma than branchwoods. However the tissue characteristics of the

branchwoods are generally within the limits for utilizable hardwoods and they could be utilized for various products including furniture parts, cabinets, papers suitable for many uses including news prints and packaging. Sapwoods had wider fibre and vessel lumina, shorter and less fibres, but more vessels and parenchyma than heartwoods.Stem middle heartwoods had the longest fibres, *T. ivorensis* and *A. robusta* branch top heartwood and sapwood respectively, the shortest. Stem base heartwoods had the greatest fibre percentages, *T. ivorensis* and *A. robusta* branch middle and top sapwoods respectively, the least. Stem crown sapwoods had the widest vessel lumina, branch top heartwoods the smallest. *T. ivorensis* and *A. robusta* stem crown heartwood and sapwood respectively had the widest fibres and lumina, branch top heartwoods the smallest. Based on the variations in tissue characteristics, wood selection from any of the tree parts (stem and branch) must be done carefully to match their end-use requirements where specific properties are required for satisfactory functioning.

CHAPTER FOUR

4.1 CHEMICAL COMPOSITION OF THE STEM AND BRANCH WOODS OF *T. IVORENSIS* AND *A. ROBUSTA*

Introduction

The percentage of chemical components (extractives, lignin, cellulose and hemicellulose) of the radial positions (sawpwoods and heartwoods) of the wood types (stemwood and branchwood) for *T. ivorensis* and *A.robusta* were determined and compared and their results discussed in this section.

4.1 Materials and methods

4.1.1 Materials and Conversion

Sample origin and conversion is as described in Chapter 3 (page 43). Samples for the determination of amount of chemical components were removed from the sapwood and heartwood regions of the bases of the stems and branches.

4.1.2 Preparation of wood samples for the determination of amount of chemical components

Samples from sapwood and heartwood from the base of the stems and the base of the branches were milled in a Wiley Mill. The materials were then sieved manually to pass through a No. 40 mesh sieve (425 μm) but retained on a No. 60 mesh sieve (250 μm). Each material was air-dried and placed in a glass jar for chemical analysis. All tests were conducted according to the standards of Technical Association of the Pulp and Paper Industry TAPPI (1997) testing procedures to determine the proportion of extractive, cellulose, hemicellulose and lignin.

4.1.3 Preparation of Extractive–free samples from wood meal.

Extractive-free samples were prepared in accordance with the TAPPI standard T264 (TAPPI, 1997) to remove waxes, fats, resins and other insoluble components including portions of wood

gums, tannins, sugars, starches, and colouring matter. 36g of wood meal was poured into a thimble, plugged with a cotton wool and placed in position in a Soxhlet apparatus. Extraction was carried out with 200ml of alcohol-acetone (1:2) for 6 hours, after which the excess solvent was removed and the sample washed with ethanol to remove acetone. Extraction was done again for 4 hours using 200 ml of 95% ethanol, after which excess solvent was also removed and the sample dried. 200ml of boiling distilled water was again used to extract the wood meal for 1 hour. The sample was air-dried thoroughly and stored in an air tight container.

4.1.4 Determination of the amount of extractives in the stemwood and branchwood of *T. ivorensis* and *A. robusta*

Extractive content was determined in accordance with T 204 of TAPPI (1997). 2g of unextracted wood meal was weighed and poured into a thimble, plugged with a cotton wool and placed in position in a Soxhlet apparatus. Extraction was carried out with 150ml of alcohol-acetone (1:2) for 3 hours. The solvent was then evaporated and the extract oven-dried at 105^0C until a constant weight was obtained. It was then cooled in a dessicator and weighed. 150ml of the solvent was evaporated to dryness, oven-dried and weighed until a constant weight was obtained to represent the blank extract. Extractions were replicated three times. Extractive content was then calculated using the formula: $\text{Total extractives (\%)} = \frac{A-C}{B} \times 100$

A = oven- dry weight of extract
B = oven- dry weight of wood meal
C = oven- dry weight of blank extract

4.1.5 Determination of the amount of lignin in the stemwood and branchwood of *T. ivorensis* and *A. robusta*

1g of the extractive-free sample was put into a glass-stoppered weighing bottle with a watchglass cover and cold 72% sulphric acid was added slowly. The sample was mixed well by stirring constantly for a minute. The sample was then left for 2 hours with frequent stirring

at 20^0C in a water bath. The material was then washed into a 1 litre beaker, diluted to a 3% sulphric acid concentration with distilled water, and boiled for 4 hours under reflux condenser. The insoluble material was then allowed to settle, and filtered into a filtering crucible (which was previously dried at 105^0C and weighted in a glass–stoppered weighting bottle). The residue was then washed free of acid with hot water, the crucible and the contents was dried in an oven at 105^0C for 2 hours, placed in a tarred stoppered weighing bottle and cooled in a desiccator. The stopper was removed and weighing was done. Drying and weighing was repeated until a constant weight was obtained. The weight of lignin was then expressed based on the moisture-free sample using the formula:

$$\text{Lignin (\%)} = \frac{A}{B} \times_{100}$$

A = Oven–dry weight of lignin
B = Weight of moisture – free sample

4.1.6 Determination of the amount of holocellulose in the stemwood and branchwood of *T. ivorensis* and *A. robusta*

2g of the extractive–free material was mixed with 180ml of distilled water and a mixture of 8.6g of sodium acetate, 5.7ml of ethanoic acid and 6.6g of sodium chlorite. The extractive–free sample was digested with the reagent in a covered conical flask and placed in a water bath at 70^0C. After 3 hours, the sample was filtered, washed with distilled water and dried in an oven and weighed. Oven-drying and weighing were repeated to obtain constant weight. The weight of each sample was then expressed as a percentage based on the moisture-free sample using the formula:

$$\text{Holocellulose (\%)} = \frac{A}{B} \times 100$$

A = Oven–dry weight of holocellulose B
= weight of moisture–free sample.

4.1.7 Determination of the amount of alpha cellulose in *T. ivorensis* and *A. robusta*

2g of holocellulose was weighed into a beaker and placed in a water bath at 25^0C. 100ml of 17.5% NaOH solution was added to the sample in the beaker and stirred. After 45 minutes, 100 ml of distilled water at 25^0C was added, stirred and left for 30 minutes. The beaker was then removed from the water bath and filtered using the filtering crucible. The cellulose was transferred into a crucible, washed with 10% NaOH solution and then with water at 25^0C. It was further washed with water and 10% Acetic acid and again with water, then oven dried and weighed repeatedly until a constant weight was realized. The quantity of cellulose was expressed as percentage based on the moisture-free sample using the formula:

$$\text{Cellulose (\%)} = \frac{A}{B} \times 100$$

A = Oven–dry weight of cellulose
B = Weight of moisture–free sample used.

4.1.8 Determination of the amount of hemicellulose in *T. ivorensis* and *A. robusta*

Hemicellulose was determined as the difference between the weight of holocellulose and weight of cellulose present in it. This was then expressed as a percentage of moisture–free sample using the formula:

$$\text{Hemicellulose (\%)} = \frac{A}{B} \times 100$$

A = Oven – dry weight of hemicellulose B = weight of moisture–free sample used.

4.2 Data analysis

Data collected on chemical composition was subjected to Analysis of variance test to determine if differences were any significant for the various factors; wood types (stemwood and branchwood) and radial positions (sapwood and heartwood) for *T. ivorensis* and *A. robusta*.

4.3 Results

4.3.1 Percentage of chemical components in the stem and branch woods of *T. ivorensis* and *A. robusta*

4.3.1.1 Extractives percentages

From Table 4.1, extractive percentage of *T. ivorensis* and *A. robusta* respectively ranged from 3.65-9.88 and 0.37-1.63% for the stems and 1.58-8.33 and 0.37-1.02% for the branches. Extractive percentage was greater in heartwoods than sapwoods and in stemwoods than branchwoods, except for the sapwoods of *A. robusta* stemwood and branchwood, which had similar values (Table 4.1). The variations in extractive percentage was significant ($P < 0.05$) for the wood types and radial positions in both timber species, as well as their interactions in *A. robusta* (Tables 4.2 and 4.3).

4.3.1.2 Lignin percentages

From Table 4.1, lignin percentage of *T. ivorensis* and *A. robusta* respectively ranged from 31.93-32.85 and 25.38-26.56 for the stems and 31.57-32.67 and 24.90-26.12 for the branches. Lignin percentage was greater in heartwoods than sapwoods and in stemwoods than branchwoods (Table 4.1), with significant differences ($P < 0.05$) for wood types in *T. ivorensis* (Tale 4.4), and radial positions in *A. robusta* (Table 4.5).

Table 4.1: Chemical components of sapwoods and heartwoods from *T. ivorensis* and *A. robusta* stem and branch bases.

Timber species	Radial positions	% extrac		% lig		% cellu		% hemicellulc	
		Stemwood	Branchwood	Stemwood	Branchwood	Stemwood	Branchwood	Stemwood	Branchwood
T. ivorensis	Sapwood	3.65	1.58	31.9	31.6	41.9	41.9	22.5	23.6
	Heartwood	9.88	8.33	32.9	32.7	39.2	39.0	18.1	20.0
A. robusta	Sapwood	0.37	0.37	25.4	24.9	40.5	40.5	33.8	34.0
	Heartwood	1.63	1.02	26.6	26.1	39.3	39.1	32.6	33.5

Table 4.2: ANOVA for extractive percentage of the radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	13.161	13.161	65.723	0.0000*
Radial positions	1	168.709	168.709	842.524	0.000*
Wood types x Radial positions	1	0.277	0.277	1.381	0.263
Error	12	2.403	0.200		
Total	16	734.328			
Corrected Total	15	184.549			

*__Wood types:__ stemwood, branchwwood

Table 4.3: ANOVA for extractive percentage of the radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	.365	0.365	7.115	0.021*
Radial position	1	3.644	3.644	71.080	0.000*
Wood types x Radial position	1	0.379	0.379	7.399	0.019*
Error	12	0.615	0.051		
Total	16	16.445			
Corrected Total	15	5.003			

*__Wood types:__ stemwood, branchwwood

Table 4.4: ANOVA for lignin percentage of the radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	2.389	2.389	7.080	0.021*
Radial position	1	1.029	1.029	3.048	0.106
Wood types x Radial position	1	0.675	0.675	2.000	0.183
Error	12	4.050	0.337		
Total	16	16398.393			
Corrected Total	15	8.142			

ANOVA for

*__Wood types:__ stemwood, branchwwood

Table 4.5: lignin percentage of the radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	0.861	0.861	4.115	0.065
Radial position	1	5.808	5.808	27.766	0.000*
Wood types x Radial position	1	0.003	0.003	0.015	0.904
Error	12	2.510	0.209		
Total	16	10607.957			
Corrected Total	15	9.182			

*__Wood types:__ stemwood, branchwwood

4.3.1.3 Cellulose percentages

From Table 4.1, cellulose percentage of *T. ivorensis* and *A. robusta* respectively ranged from 39.2 to 41.9 and 39.3 to 40.5% for the stems and 39 to 41.9 and 39.1 to 40.5 for the branches. Cellulose percentage was greater in sapwood than heartwood and in stem heartwood than branch heartwood of both timber species (Table 4.1). However, sapwoods of both the stems and branches of the two timbers had similar values of cellulose percentage. Variations in cellulose percentages was significant ($P < 0.05$) for the wood types and radial positions in *T. ivorensis* (Table 4.8), but without significant differences ($P > 0.05$) in *A. robusta* (Table 4.9).

Table 4.6: ANOVA for cellulose percentage of the radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	1.526	1.526	9.015	0.011*
Radial position	1	20.447	20.447	120.747	0.000*
Wood types x Radial position	1	0.702	0.702	4.148	0.064

ANOVA for					
Error	12	2.032	0.169		
Total	16	25976.338			
Corrected Total	15	24.707			

*__Wood types:__ stemwood, branchwwood

Table 4.7: cellulose percentage of the radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	0.015	0.015	0.006	0.941
Radial position	1	6.817	6.817	2.655	0.129
Wood types x Radial position	1	0.008	0.008	0.003	0.957
Error	12	30.810	2.568		
Total	16	25445.557			
Corrected Total	15	37.649			

*__Wood types:__ stemwood, branchwwood

4.3.1.4 Hemicellulose percentages

From Table 4.1, hemicellulose percentage ranged from 18.1 to 22.5 and 32.6 to 33.8 for the stems and 20 to 23.6 and 33.5 to 34 for the branches of *T. ivorensis* and *A. robusta* respectively. Hemicellulose percentage was greater in sapwood than heartwood and in branchwood than stemwood (Table 4.1), with significant differences (P< 0.05) for the wood types and radial positions in *T. ivorensis* (Table 4.8), but without significant differences (P > 0.05) in *A. robusta* (Table 4.9).

Table 4.8: ANOVA for hemicellulose percentage of the radial positions of the stem and branch of *T. ivorensis*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	8.859	8.859	44.485	0.0008*
Radial position	1	63.841	63.841	320.593	0.000*
Wood types x Radial position	1	0.796	0.796	3.998	0.069
Error	12	2.390	0.199		
Total	16	7156.992			

ANOVA for		
Corrected Total	15	75.886

*__Wood types:__ stemwood, branchwwood

Table 4.9: hemicellulose percentage of the radial positions of the stem and branch of *A. robusta*

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
*Wood types	1	1.397	1.397	1.497	0.245
Radial position	1	2.591	2.591	2.776	0.122
Wood types x Radial position	1	0.515	0.515	0.551	0.472
Error	12	11.202	0.933		
Total	16	17939.743			
Corrected Total	15	15.704			

*__Wood types:__ stemwood, branchwwood

4.4 Discussion

4.4.1 Percentage of chemical components in the stem and branch woods of *A. robusta* and *T. ivorensis*

4.4.1.1 Extractive percentage

Greater percentages of extractives recorded for the stemwoods than branchwoods of the two timbers are consistent with the report of Ahmad and Kiaei (2011) for *Ailanthus altissima*. Ververis *et al.* (2004) explained that the content of chemical components in wood depends on tissue maturity. Nault (1988) and Krilov and Lasander (1989) observed higher concentrations of extractives in older trees than in younger trees of *Thuja plicata* and *Eucalptus spp.* This corresponds to stemwoods of *T. ivorensis* and *A. robusta* with doubtless older tissues such as fibres, vessels and parenchyma having greater extractive percentage than the branchwoods with younger tissues. Likewise, Magel (2000), agrees that heartwood has more extractive content

ANOVA for

than sapwood. Jouin *et al*. (1988), Gominho *et al*. (2001), Gominho (2003), Mariani *et al.* (2005) and Miranda *et al*. (2007) found lower extractive contents in sapwoods of *E. globulus*, *Quercus*, similar to lesser extractive percentages in the sapwoods than heartwoods of *A. robusta* and *T. ivorensis.* Greater content of extractives in the heartwoods than

sapwoods is usually because the production of extractives is one of the main changes in the transformation of sapwood to heartwood (Wiedenhoeft and Miller, 2005). Carina and Lourenço (2008) explained that the chemical modification during the transition of sapwood to heartwood involves the production of extractives in parenchyma cells (Lourenço, 2008), with no changes in cell wall chemical components (Kai, 1991). In the current study, *T. ivorensis* had 1.58-9.88%% extractives, while *A. robusta* had 0.37-1.63% extractives. Extractives were the least of the chemical components in the two timbers. Moore (2011) explained that the extraneous chemicals which include extractives in wood are in small amounts; Cole (2011), extractives are less than 10%; usually 0-5%. Greater extractive contents in wood increases its natural durability (Lourenço, 2008; Sehlstedt-persson and Olov, 2010), but has a negative influence on pulp yield and brightness; decreasing amounts of extractives increase pulp yield and decrease chemicals used in pulping and bleaching process, even as pulp brightness is also increased (Gominho *et al*., 2001; Esteves, 2005; Miranda *et. al*., 2007). Thus, extractive percentages for both the stem and branch woods of *T. ivorensis* and *A. robusta* make them suitable for use as hardwoods for both solid products and pulp and paper. However, the sapwoods and branchwoods of *T. ivorensis* and *A. robusta* would have greater pulp brightness, but less natural durability than their comparable heartwood and stemwood.

4.4.1.2 Lignin percentage

According to Ververis *et al.* (2004) the content of chemical components especially lignin in wood depends on tissue maturity. This corresponds to greater lignin percentage in the stemwoods than the branchwoods for *T. ivorensis* and *A. robusta*, which are expected to have older tissues such as fibres, vessels and parenchyma than branchwoods. Additionally, Ahmad and Kiaei (2011) recorded greater percentage of lignin for the stemwood than branchwood of *Ailanthus altissima*. Lignin content was also greater in heartwood than sapwood, supporting

Gominho *et al*. (2001), Gominho (2003), Mariani *et al.* (2005) and Miranda *et al*. (2007) who recorded lower lignin contents in sapwoods of *E. globulus*, *Quercus* and *E. nitens.* Rózanska *et al.* (2011) and Cole (2012) reported that hardwoods contain 18-25% lignin. However, in the current study, *T. ivorensis* had 31.57-32.85% lignin while *A. robusta* had 24.90-26.56%, this includes the stem and branch woods. Thus, the lignin content of *T. ivorensis* was more than indicated by previous researhers for hardwoods, but compares with Foli (2009), who recorded 31-32% lignin in *T. ivorensis* and supports Kennedy *et al.* (1996) that *T. ivorensis* has great lignin content. Lignin decreases the permeation of water through the cell walls of the xylem, thereby playing an intricate role in the transport of water and nutrients (Iversen and Wannstrom, 1986). It also impedes the penetration of destructive enzymes through the cell wall (Iversen and Wannstrom, 1986) and protect cellulose and hemicellulose from degradation (Jeffries, 1990; Zabel and Morrell, 1992). Hence, resistance of the wood structures is largely influenced by lignin (Zabel and Morrell, 1992; Majaila, 2000). It is also the adhesive or binder in wood that holds the fibers together (Biermann 1996). Thus, giving rigidity to the cell, reduce dimensional change with moisture-content in wood (McBroom, 2013). However, lignin can reduce paper strength because it could be a barrier for hydrogen bonding in the fiber formation, and could be an inhibitor in the hydrolysis process. Hence, wood with low lignin content are usually preferred for pulp and paper making (Rowell, 2005; Abdel-Aal, 2011). Greater lignin and extractive contents in the heartwood than sapwood of *A. robusta* and in the stemwood than branchwood of *T. ivorensis* is advantageous for their natural durability but would reduce their suitability for pulp and paper production.

4.4.1.3 Cellulose percentage

According to Little (1997) and Rózanska *et al.* (2011), cellulose is the major and most important component for its effect on the properties of wood. It is also the structural component of the primary cell wall and the most common organic compound in plants. In the current study,

cellulose percentage ranged from 39.2 to 41.9% and 39.3 to 40.5% for the stems and 39 to 41.9 and 39.1 to 40.5 for the branches of *T. ivorensis* and *A. robusta* respectively, comparable to 40-50% cellulose contained in hardwoods (Rózanska *et al.*, 2011; Cole, 2012). The heartwoods of the stems of both timber species had greater cellulose percentages than the branch heartwoods. This agrees with Ververis *et al.* (2004) that more mature tissues in wood (in this case stemwood) have greater contents of chemical components than juvenile wood (branchwood). Similarly, greater cellulose percentage recorded for the sapwoods than heartwoods agrees with (Magel, 2000). Cellulose is a polysaccharide, containing many sugar units (Danang *et al.*, 2011) and can easily be hydrolyzed to glucose under controlled (acidic) conditions (Smook 1994). Hence, wood with great cellulose content are usually preferred for pulp and paper making (Rowell, 2005; Abdel-Aal, 2011) and bioethanol production (Danang *et al.*, 2011). According to Abdulkhalil *et al* (2006) wood with cellulose content close to or above 40% is suitable for pulp and paper production. Consequently, with regards to their cellulose contents, the stem and branch woods of both timbers (*A. robusta* and *T. ivorensis*), especially their sapwoods are appropriate for the production of pulp and paper.

4.4.1.4 Hemicellulose percentage

Hemicellulose content was greater in branchwoods than the stemwoods, in agrrement with Zobel *et al* (2012) who reported more hemicellulose in branchwood than stemwood. Heartwood hemicellulose content was also less than those of the sapwoods for both timber species, supporting Timell (1986), Fengel and Wegener (1989) and Magel (2000) that heartwood has less hemicellulose content than sapwood. In the current study, *T. ivorensis* had
18.1 to 23.6%, while *A. robusta* had 32.6 to 34% hemicellulose. These are within the range of 15 to 35% stated for hardwoods (Walker, 2006; Cole, 2011; Rózanska *et al.*, 2011). Hemicelluloses are very soluble polysaccharides that are highly hydrophilic and permeable to water, making wood susceptible to microbial and insect attack (Sjostrom, 1993; McBroom,

2013). Consequently, the branchwoods and sapwoods greater hemicellulose percentage, especially of *T. ivorensis* (with significant variations), would be less durable than their corresponding stemwood and heartwood.

4.5 CONCLUSION

The percentage of chemical components varied for the radial positions (sapwood and heartwood) and wood types (stemwood and branchwood) in *T. ivorensis* and *A. robusta*. Stemwoods had greater extractive, lignin and cellulose percentages than branchwoods, with the exception of the stem and branch sapwoods, which had similar cellulose percentge.

Hemicellulose percentage however, was greater for the branchwoods than stemwoods. Cellulose and hemicellulose percentages were also greater for sapwoods than heartwoods, whereas lignin and extractive percentages were greater for the heartwoods than the sapwoods. The study shows that the percentage of chemical components for both the stem and branch woods are comparable with those of utilizable hardwoods. Hence branchwood could serve as suitable supplements for wood obtained from *T. ivorensis* and *A. robusta.*

CHAPTER FIVE

NATURAL DURABILITY

5.1 Introduction

The natural durability (mass and hardness losses and visual durability ratings) of the radial (sawpwoods and heartwoods) and axial positions (base, middle and top) of the wood types (stemwood and branchwood) for *T. ivorensis* and *A.robusta* were determined and compared and their results discussed.

5.1 Materials and method

5.1.1 Description of experimental area

The test field ranges between 250 and 350m above sea level with semi-deciduous forest type and wet sub-equatorial climate within the plateau of the South - West physiological region on the KNUST Kumasi campus. Temperature ranges from a minimum of 20^0C to a maximum of 34^0C, with humidity also ranging between 60-80% (www.ghanadistricts.com, 2014). The soil type is forest ochrosol (www.ghanadistricts.com, 2014). The field has a high decay index with a very high decay hazard (Kumi-Woode, 1996). The test area is a domain to many of termitarian mounds, with loamy sand of medium to fine-texture with a pore space varying from 40 to 60% (Antwi-Boasiako, 2004; Quartey, 2009).

The ecology of the termite species in Kumasi and some of those attacking timber, according to Usher (1975) in Quartey (2009), are *Coptotermes intermedius* Silvestri [family Rhinotermitidae (Coptotermitinae)], *Amitermes evuncifer* Silvestri [family Termitidae (Amitermitinae)], *Ancistrotermes* spp. mostly *A. crutifer* (Sjostedt) but occasionally, *A. guineensis* (Silvestri) [family Termitidae (Macrotermitinae)], *Macrotermes* spp. (both *M. Bellicosus* (Srneathman) and *M. subhyalinus* (Rambur). There are also *Microtermes subhyalinus* Silvestri, *Odontotermes pauperans* (Silvestri), *Pseudacanthotermes militaris* (Hagen), and *Nasutitermes latifrons* (Sjostedt) [family Termitidae (Nasutitermetinae)]. Before tests was conducted, the test site was cut cleared of grass re-growth.

5.1.2 Determination of natural durability of the stemwood and branchwood of *T. ivorensis* and *A. robusta*

The boards from the sapwoods and heartwoods from the base, middle and top of the stems and branches were later sawn into specimen dimensions of 25 x 12.5 x 250 mm. Clear wood specimens without defects were used. There were 120 replicates from each species (10

heartwood and 10 sapwood samples from the base, middle and top of the stems as well as the base, middle and top of the branches), thus 240 samples were used for the testing. Additionally, 10 replicates of *C. pentandra* of the same size served as control. The hardness of all stakes were determined using a pilodyn and then weighed using Sartorius BP 6100 electric balance, tagged and weighed again. Weighing and hardness determination of samples was done in the Pathology Laboratory of FRNR. Two extra stakes from each set and the references were oven-dried at 103^0C to a constant weight. Their average moisture contents were determined and used to correct for moisture in the conditioned stakes and to calculate for the oven dry weight of the stakes (i.e. initial oven-dried weight) using the formula: M_{to}

$$= \frac{100Mu}{100+U}$$

M_{to} = the theoretical oven-dry mass of test specimen
M_u = mass of test specimen after conditioning
U = the average percentage moisture content

The wood samples were exposed to biodegraders, especially termites (*Macrotermes* spp) in a termite prone area on the FRNR farm in accordance with EN 252. The samples were inserted vertically in the soil to half their length in an even distribution and a spacing of 30 cm between stakes. The field test was carried out from the beginning of April to end of December, 2008. The stakes were inspected monthly and data collected accordingly. All sides of the stake were examined for changes in the wood; alterations in colour, form or texture and the presence of fungal formations (mycelium, strands and sporophores) and termite runways. They were weighed to find out the degree of degradation and then carefully reinstalled in their original position.

After final withdrawal from the field, stakes were cleaned and air-dried for a week to a constant weight after which the final hardness and weight were evaluated. The percentage hardness loss

was given by the percentage of the difference between the final hardness and the initial hardness taken to establish the firmness of stakes after exposure to fungi:

$$\text{Percentage hardness loss} = \frac{\text{Final Hardness} - \text{Initial Hardness}}{\text{Final Hardness}} \times 100$$

The percentage weight loss (i.e. percentage of the difference between the calculated initial weight (corrected oven-dry weight) and the final oven-dry weight), as an indication of the level of deterioration of each stake were determined

$$\text{Percentage weight loss} = \frac{\text{Corrected Oven-dry Weight} - \text{Final Weight}}{\text{Corrected Oven-dry Weight}} \times 100$$

The ratings used for the weight loss according to Eaton and Hale (1993) were: 0-5% very durable, 6-10% durable, 11-40% moderately durable, 41-100% non-durable

Visual rating codes used to grade the wood samples according to EN 252: 1989 were:

0 – No attack, 1 = Slight attack, 2 = Moderate attack, 3 = Severe attack, 4 =Failure

5.2 Data analysis

Data obtained on percentage weight and hardness losses were subjected to Analysis of variance (ANOVA) to determine if the diifferences were significant for the various factors; wood types wood types (stemwood and branchwood), radial positions (sapwood and heartwood) and axial positions (base, middle and top) for *T. ivorensis* and *A. robusta*.

5.3 Results

5.3.1 Mass losses for stemwood and branchwood of *T. ivorensis* and *A. robusta*

Table 5.1 indicates that percentage mass loss was total (100%) along the stem and branch of *A. robusta*, but increased with height along the stem and branch of *T. ivorensis*. Percentage mass

loss was also greater for the branchwood than the stemwood and for the sapwood than the heartwood of *T. ivorensis,* with significant differences ($P < 0.05$) between the radial positions (Table 5.2). On the other hand, Table 5.4 shows that according to durability classifications based on mass loss, the stem heartwood would be rated very durable, durable and moderately durable respectively for the base, middle and top, and branch heartwood moderately durable. The sapwood at the base of the stem would be rated moderately durable, the middle and top of the stem and the base to the top of the branch sapwoods, non-durable.

5.3.2 Hardness losses for stemwood and branchwood of *A. robusta* and *T. ivorensis*

From Table 5.1, Percentage hardness loss was complete (100%) along the stem and branch of *A. robusta*, but increased with height along the stem and branch of *T. ivorensis*. In all cases, percentage hardness loss was greater for the branchwood than the stemwood and for the sapwood than the heartwood in *T. ivorensis*, without significant differences (Table 5.3).

Table 5.1: Perentage mass and hardness losses along the stems and branches of *T. ivorensis* and *A. robusta* after 36 weeks of field exposure.

Wood species	Radial position	Axial position	% mass loss		% hardness loss	
			Stemwood	Branchwood	Stemwood	Branchwood
T. ivorensis						
Sapwood	Base	19.2	45	15	33.3	
middle		35.1	46.9	30.1	36.1	
	Top	43.3	48.7	30.3	37.5	
	Heartwood	Base	4.3	19.8	5.4	25.1
		Middle	8.8	23.4	7.1	27
		Top	17	24.5	22.6	28.7
A. robusta	Sapwood	Base	100	100	100	100
		Middle	100	100	100	100
		Top	100	100	100	100

			100		100		100		100
Heartwood	Base	100	100	100	100		middle		100
							100	100	100
	Top		100		100		100		100

Table 5.2: ANOVA for mass losses of the axial and radial positions of the stems and branches of

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	3916.251	1958.125	2.139	0.123
Wood type	1	3036.110	3036.110	3.317	0.071
Radial position	1	16847.582	16847.582	18.404	0.000*
Axial position x Wood type	2	1631.197	815.599	0.891	0.413
Axial position x Radial position	2	185.067	92.534	0.101	0.904
Wood type x Radial position	1	292.891	292.891	0.320	0.573
Axial position x Wood type x Radial position	2	143.494	71.747	0.078	0.925
Error	108	98864.881	915.416		
Total	120	218007.950			
Corrected Total	119	124917.474			

*significant at P (0.000) < 0.05

Table 5.3: ANOVA for hardness losses of the axial and radial positions the stems and branches of

Sources of variation	Degrees of freedom	Sum of Squares	Mean Square	F	P-value
Axial position	2	692.458	346.229	0.251	0.778
Wood type	1	2838.545	2838.545	2.058	0.154
Radial position	1	3024.879	3024.879	2.193	0.142
Axial position x Wood type	2	124.496	62.248	0.045	0.956
Axial position x Radial position	2	3269.534	1634.767	1.185	0.310
Wood type x Radial position	1	20.525	20.525	0.015	0.903

Axial position x Wood type x Radial position	2	3265.844	1632.922	1.184	0.310
Error	108	148942.768	1379.100		
Total	120	239364.729			
Corrected Total	119	162179.049			

Table 5.4: Durability of *C. pentandra*, sapwood and heartwood along the stems and branches of *T. ivorensis* and *A. robusta* after 36 weeks of field exposure.

Wood species	Tree part	Axial position	Durability ratings			
			Visual durability		Percentage mass loss	
			Stemwood	Branchwood	Stemwood	Branchwood
T. ivorensis	Sapwood	Base	Moderate attack	Severe attack	Moderately durable	Non- durable
		Middle	Severe attack	Severe attack	Non- durable	Non- durable
		Top	Severe attack	Severe attack	Non- durable	Non- durable
	Heartwood	Base	Slight attack	Moderate attack	Very durable	Moderately durable
		Mid	Moderate attack	Moderate attack	Durable	Moderately durable
		Top	Moderate attack	Moderate attack	Moderately durable	Moderately durable
A. robusta	Sapwood	Base	Failed	Failed	Non- durable	Non- durable
		Middle	Failed	Failed	Non- durable	Non- durable
		Top	Failed	Failed	Non- durable	Non- durable
	Heartwood	Base	Failed	Failed	Non- durable	Non- durable
		Mid	Failed	Failed	Non- durable	Non- durable
		Top	Failed	Failed	Non- durable	Non- durable
C. Pentandra			Failed	Failed	Non- durable	Non- durable

4.1.1.1 5.3.3 Visual durability rating of *A. robusta* and *T. ivorensis*

Table 5.4 shows that sapwood from the base of the stem of *T. ivorensis* was moderately attacked (2), while the middle of the stem to the top of the branch were severely attacked (3) by termites. Heartwood from the base of the stem was slightly attacked (1), whereas the middle of the stem to the top of the branch were moderately attacked (2) by termites (Table 5.4). At its axial positions, *T. ivorensis* sapwoods had greater termite attacks than the heartwoods, whilst stemwood had less termite attack than branchwoods, except at the top. *A. robusta* had greater termite attack than *T. ivorensis* (Table 5.4). Sapwoods and heartwoods along the stem and branch of *A. robusta* failed (4) by the end of the exposure period.

Plate 5.1: Stem (s) and branch (b) heartwoods of *T. ivorensis* during 16th week of exposure

Plate 5.2: Stem (s) and branch (b) sapwoods of *T. ivorensis* during 16th week of exposure.

Plate 5.3: Failed heartwood stakes of *A. robusta* stem by the 16th week of exposure

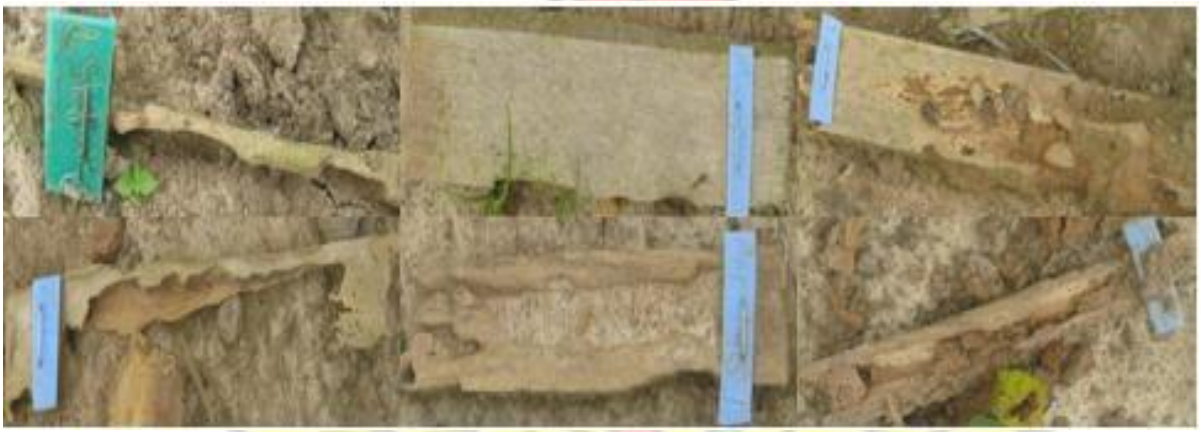

Plate 5.4: Failed sapwood stakes of *A. robusta* stem by the 16th week of exposure

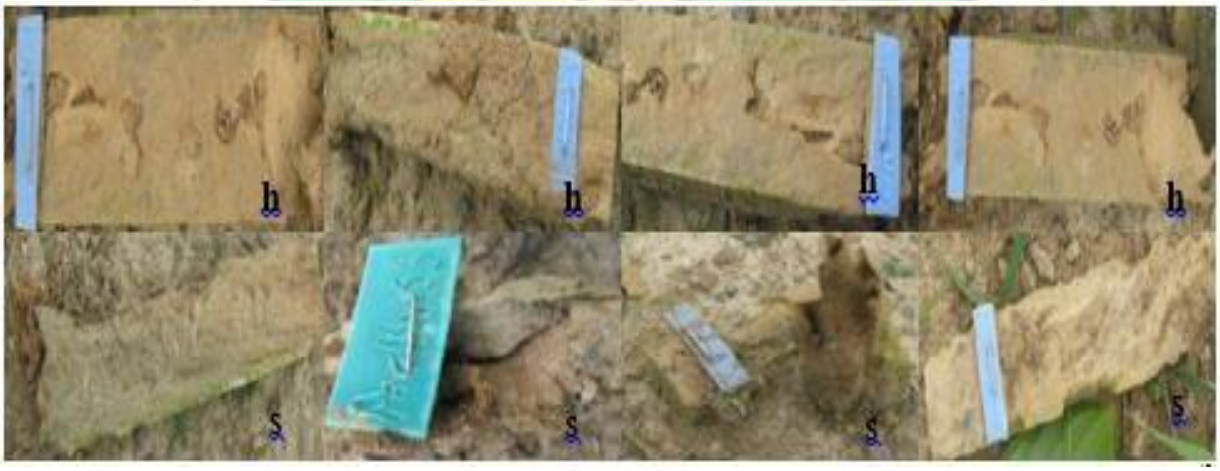

Plate 5.5: Failed heartwood (h) and sapwood (s) of *A. robusta* branch by the 16th week of exposure.

5.3.4 Relationships among natural durability, the anatomical features and chemical components

Due to total degradation of *A. robusta* stakes in the field test, correlations between its anatomical features, chemical components weight and hardness losses could not be evaluated. Similarly, the regression analysis could not determine the variations of weight and hardness losses from its anatomical features and the chemical components. Subsequently, the detailed results in this section will only include *T. ivorensis*. Anatomical features correlated very weakly ($r < 40\%$) and were also were poor estimators ($R^2 < 50\%$) of the variations observed for weight and hardness losses, hence natural durability in *T. ivorensis* (Tables 5.5 and 5.6). In all cases, the coefficient of determination (R^2) was less than 10%. The highest value of R^2 was observed for parenchyma proportion, where it accounted for 5% of the variation of weight loss (Table 6.2).

From Table 5.5, correlations of percentage extractive ($r = 0.66$) against weight loss and percentage lignin ($r = 0.54$), cellulose ($r = 0.82$) and hemicellulose ($r = 0.72$) against hardness loss were strong. Those of percentage lignin, cellulose, hemicellulose against percentage weight loss and extractive percentage against hardness loss were weak ($r < 0.5$). Inverse correlations of lignin and extractive percentages against weight and hardness losses indicates that increase of lignin and extractive in *T. ivorensis* reduced weight and hardness losses. Positive correlation indicates that increase in cellulose and hemicellulose percentages increased the weight and hardness losses, thus decreasing the natural durability. From Table 5.6, chemical components were good predictors ($R^2 > 50\%$) of the variations in weight loss and hardness losses and thus natural durability in *T. ivorensis*.

Table 5.5: Correlation coefficients between chemical components and anatomical properties and weight and hardness losses of *T. ivorensis* and *A. robusta*

Chemical components and anatomical features	*T. ivorensis*		*A. robusta*	
	% Weight loss	% Hardness loss	% Weight loss	% Hardness loss
% extractives	-0.66*	-0.05	-	-
% lignin	-0.16	-0.54*	-	-
% cellulose	0.10	0.82*	-	-
% hemicellulose	0.37	0.72*	-	-
Fibre length	-0.06	-0.07	-	-
Fibre diameter	0.04	0.02	-	-
Fibre double wall thickness	-0.07	-0.05	-	-
Fibre lumen diameter	0.04	0.02	-	-
Vessel lumen diameter	0.02	0.00	-	-
Fibre proportion	-0.05	-0.07	-	-
Vessel proportion	0.01	0.05	-	-
Parenchyma proportion	0.05	0.04	-	-

*significant correlation coefficients at p (0.00) = 0.05

Table 5.6: Regression analysis of chemical components and anatomical properties against weight loss and hardness loss for the individual species (*T. ivorensis* and *A. robusta*)

Wood property	Variables	*T. ivorensis*				*A. robusta*			
		% weight loss		% hardness loss		% weight loss		% hardness loss	
		R^2(%)	Bcoefficient	R^2(%)	Bcoefficient	R^2	Bcoefficient	R^2	Bcoefficient
Chemical components									
	% extractives	67.6	-4.18	85.4	3.35	-	-	-	-
	% lignin	54.9	-3.28	87.8	-21.42	-	-	-	-
	% cellulose	59.0	-4.25	88.8	12.14	-	-	-	-
	% hemicellulose	59.0	4.1	88.8	20.13	-	-	-	-
Anatomical properties									
	Fibre length	1.6	-0.01	1.5	-0.01	-	-	-	-
	Fibre diameter	1.7	0.52	1.7	0.20	-	-	-	-
	Fibre double wall thickness	1.7	-1.06	1.7	-1.02	-	-	-	-
	Fibre lumen diameter	1.7	0.10	1.7	0.17	-	-	-	-
	Vessel lumen diameter	1.7	0.05	1.7	0.03	-	-	-	-
	Fibre proportion	2.0	-41.50	1.7	-15.96	-	-	-	-
	Vessel proportion	4.3	-41.49	1.8	-15.56	-	-	-	-
	Parenchyma proportion	5.0	-41.06	2.1	-15.61	-	-	-	-

5.4 Discussion

5.4.1 Natural durability of the stem and branch woods of *T. ivorensis* and *A. robusta*

Natural durability in *T. ivorensis* generally decreased with height along the stem and branch; weight and hardness losses increased with height. The heartwood from the base of the *T. ivorensis* stem was most resistant to attack by bio-degraders. This supports Anderson *et al.* (1963), Scheffer and Cowling (1966), Zabel and Morrell (1992) and DeBell *et al*. (1999) that the most durable heartwood is often present at the heartwood of the base of the stem, since it has the highest concentrations of extractives. Morita *et al*. (1995), Haygreen and Bowyer (1996) and DeBell *et al*. (1999), explained that the relative amount of extractives decrease with increasing height above the ground. Juvenile wood is expected to increase with an increase in height (Panshin and de Zeeuw, 1964) and older tissues have more extractives than younger ones (Ververis *et al.,* 2004). This could also explain why *T. ivorensis* stem heartwood was more durable than the branchwood heartwood at all axial positions. Nonetheless, the branchwood heartwood, rated moderately durable could be employed for interior joinery, moulding, light carpentry work and cabinet work. The stem base and middle heartwoods, rated very durable and durable respectively could be used for out door purposes. Their sapwoods could also be used for services, which do not require much durability and for products such as matchsticks, blackboards, artefacts and pencils for which durability is not essential.

T. ivorensis is a durable to moderately durable wood and moderately resistant to termite attack (Forest product laboratory, 2009; CIRAD, 2011). In the present study however, *T. ivorensis* was very durable to moderately durable. Variation in the range of durability classes observed between the present study and previous studies may be due to variations in genetic factors, silvicultural systems, and different conditions between the sites of exposure at the time of study. Scheffer and Hopp (1949) and Edmonton (1947) explained that individual trees of the same

species may differ considerably in their decay resistance due to variations in these factors. Moreover, modification of the standard; reduction in the time of exposure and dimensions of stakes adopted for the present study is also likely to account for the variations observed in the durability classes of the present and previous studies.

Sapwoods of all species are regarded as having low natural durability (Eaton and Hale, 1993; Sulaiman and Choon, 1993; Desch and Dinwoodie, 1996) because they contain very little or no extractives and are laden with starches normally intended for the growth of the tree, but also essential for the growth of fungi, making it non-durable (Hunt and Garratt, 1967). However, sapwood from the base of *T. ivorensis* stem was moderately durable, comparable to heartwoods from the top of the stem and base to top of the branch. Consequently, durability of sapwoods in a given tree, may vary depending on its position in the tree. Browning (1974) and EN 350-1 (1994) argued that the amounts of extractives found in some sapwoods can influence their natural durability. Sapwood from the base of the stem, is thus most likely to have higher concentrations of extractives than the upper parts of the tree.

For *A. robusta*, sapwoods and heartwoods along its stem and branch were non–durable and also susceptible to termite attack. Sereda and Litvan (1980), Chudnoff (1984), Forest product laboratory (2009), CIRAD (2011) and Wood Explorer (2012) acknowledged that *A. robusta* and *C. pentandra* are perishable; that is vulnerable to decay and liable to insect and fungi attack. Regardless of its low natural durability, the stemwood of *A. robusta* is a commercially important wood with several end-uses including the production of sliced veneer, interior joinery, moulding, light carpentry work and cabinet work (high class furniture) (Chudnoff, 1984; Insidewood, 2014). Thus, with similar natural durability, *A. robusta* branch (sapwood and heartwood) could suitably supplement its stem in order to increase the supply of its wood to the timber industry and reduce pressure on this timber.

On the other hand, *A. robusta* heartwood and sapwood and *T. ivorensis* sapwood could be treated with preservative chemicals to enhance their durability. On the whole, *T. ivorensis* and *T. ivorensis* and *A. robusta* stemwood and branchwood natural durability confirms the potential of branchwood to ensure regular supply of wood and sustain the wood industry and other related sectors.

5.4.2 Relationships among natural durability, anatomical features and chemical components

The dimensions and proportions of wood tissues (fibres, vessels and parenchyma), their ligno-cellulose contents and extractives are acknowledged to influence the natural durability of wood (Tiemann, 1951; Scheffer and Morrell, 1973; Jeffries, 1987; Haygreen and Bowyer, 1996; Schwarze, 2004; Ali, 2011). In this study however, the relationships between the measured wood tissue dimensions and proportions and natural durabilty were very weak and non significant. However, increase in cellulose and hemicellulose percentages had an adverse effect on the natural durability of *T. ivorensis*, whereas more extractives and lignin improved it. Earlier, Gupta and Sen Sarma (1978) reported that lignin and toxic extractives play a vital role in preventing the degradation of wood. High extractive and lignin contents in wood, thus increases its natural durability (Hills, 1962; 1987; Lourenço, 2008; Antwi-Boasiako and Pitmann, 2009; Sehlstedt-persson and Olov, 2010). Lignin gives rigidity to cells (McBroom, 2013), decreases the permeation of water through the cell walls of the xylem, impedes the penetration of destructive enzymes through the cell walls (Iversen and Wannstrom, 1986) and protects cellulose and hemicellulose from degradation (Jeffries, 1990; Zabel and Morrell, 1992). Moreover, the combined toxicity and antioxidant properties of extractives, make them resistant to decay organisms (Schultz *et al.,* 2008). Consequently, lignin and extractives act as toxicants, feeding deterrents, repellants, or as non-preferred substrates (Walcott, 1946; Abushama and Abdel Nur, 1973; Scheffrahn, 1991). On the other hand, the holocellulose

(cellulose and hemicellulose) reduces the resistance of wood to decay organisms; they are carbohydrates with much food value for microorganisms and also make wood cells permeable to water, making it susceptible to microbial and insect attacks (Sjostrom, 1993; McBroom, 2013).

The chemical components were also good predictors of natural durability in *T. ivorensis*; they estimated between 54.9-67.6% and 85.4-88.8% of the variations in weight and hardness losses respectively. According to Jeffries (1987) and Rózanska *et al.* (2011), apart from extractives which contribute to decay resistance in wood, the gross chemical composition of wood actually shows relatively little about its potential for degradation. Nevertheless, the resistance of *T. ivorensis* wood to bio-degradation in this work, highly depends not only on its extractive content, but also on the amounts of its ligno-cellulose. Even though extractive content predicted greater percentage of the weight loss in *T. ivorensis*, the ligno-cellulose components also accounted for its substantial weight loss and even hardness loss in this same species, such that the effect of lignin on hardness loss was even greater than that of extractives. Thus, the natural durability of *T. ivorensis* cannot be attributed to a single chemical component but their combined effect. This supports Wilcox (1973) and Ali (2011) that the interaction between cellulose, hemicellulose and lignin together with the effects of fungi-toxic extractives influence wood natural durability.

The measured anatomical features however, accounted for less than 10 and 5% of the variations in weight and hardness losses respectively in *T. ivorensis*. The highest coefficient of determination (R^2) observed were 5 and 2.1% for the estimations of the variations of weight and hardness losses respectively from parenchyma proportions. Hence, the anatomical features were poor predictors of natural durability in *T. ivorensis*. However, the relationships between the anatomical features, chemical components, and weight and hardness losses could be

determined for *A. robusta* due to its complete deterioration, giving a consistent weight and hardness losses of 100%, hence the correlation coefficients and coefficient of determination could not be computed.

5.5 CONCLUSION

The stem and branch woods of *A. robusta* are perishable and susceptible to termite attack. The natural durability (weight and hardness losses) of *T. ivorensis* decreased with height in the stem and branch. Its sapwood from the base of the stem and heartwoods from top of the stem to the top of the branch are moderately durable, while sapwoods from the middle of the stem to the top of the branch are non-durable. The heartwoods from the base and middle of the stem were very durable and durable respectively. *T. ivorensis* and *A. robusta* branchwoods could consequently be utilized in addition to their stemwoods to increase the raw material base of the wood industry.

Chemical components were great determinants of natural durability, while anatomical features were poor determinants for *T. ivorensis*. Increase in lignin and extractive percentages and decrease in hemicellulose and cellulose percentages increased natural durability in *T. ivorensis*. Relationships among anatomical features, chemical components and natural durability could not be determined for *A. robusta* because of complete deterioration of its stakes in the field.

SUMMARY OF THE STUDY

Although the branchwood of *A. robusta* and *T. ivorensis* have been cited as suitable for use in the timber industry based on their mechanical properties, the absence of comprehensive information on their bio-chemical properties have hindered its usage. Knowledge on the biochemical properties of branchwood would however inform users about its service life and potential uses, which is needed for its optimal utilization and trade**.** The bio-chemical properties, specifically the the dimensions and proportions of the anatomical features, the

amount of chemical compoents and natural durability of the stem- and branch-woods of *A. robusta* and *T. ivorensis* were studied and compared.

Objective 1

Anatomical features (fibre dimensions, vessel lumen diameter and tissue percentages) of the sapwoods and heartwoods along stem- and branch-woods of *A. robusta* and *T. ivorensis*.

The fibre dimensions from wood macerates, vessel lumen diameter and tissue proportions from sections (Tangential, longitudinal, radial longitudinal and transverse sections) of the sapwoods and heartwoods from the base, middle and top of the stem- and branch-woods were compared for *T. ivorensis* and *A. robusta*. Results from the study showed that there were variations in the tissue characteristics from the sapwoods and heartwoods along the stems and branches of *T. ivorensis* and *A. robusta*. The stemwoods had more, longer, wider, thickerwalled fibres with wider lumina than branchwoods. They also had more vessels with wider lumina, but less parenchyma than branchwoods. Stem middle heartwoods had the longest fibres, *T. ivorensis* and *A. robusta* branch top heartwood and sapwood respectively, the shortest. Stem base heartwoods had the greatest fibre percentages, followed by *T. ivorensis* and *A. robusta* branch middle and top sapwoods respectively, the least. Stem top sapwoods had the widest vessel lumina, branch top heartwoods the smallest. *T. ivorensis* and *A. robusta* stem crown heartwood and sapwood respectively had the widest fibres and lumina, branch top heartwoods the smallest. Sapwoods had more parenchyma and vessels, with wider vessel lumina, fewer and wider fibres, with thinner double walls than heartwoods. Sapwoods had wider fibre and vessel lumina, shorter and less fibres, but more vessels and parenchyma than heartwoods. The tissue characteristics of the branchwoods are generally within the limits for utilizable hardwoods; they could be utilized for various products including furniture parts, cabinets, papers suitable for many uses including news prints and packaging. On the oher hand, wood selection from

any of the tree parts (stem and branch) must be done carefully to match their end-use requirements where specific properties are required for satisfactory functioning.

Objective 2

Chemical components between the branch and stem base sapwoods and heartwoods of *A. robusta* and *T. ivorensis*.

Extractive, lignin, cellulose and hemicellulose percentages were determined using the TAPPI (1997) standard testing procedures and compared between the stem and branchwoods. From the results, cellulose content was similar between the sapwoods of the stems and branches, but greater for the stem heartwoods than the branch heartwoods and also greater for sapwood than heartwoods. Stemwoods and heartwoods had greater amounts of extractives and lignin, but less hemicellulose than *A. robusta*, branchwoods and sapwoods. The percentage of chemical components compare favourably with those of exploitable hardwoods. The cellulose contents of the stem and branchwoods of *T. ivorensis* and *A. robusta*, especially their sapwoods, which had less extractives and lignin percentages makes them suitable for pulp and paper production.

Objective 3

Natural durability of sapwoods and heartwoods along the branch and stem-woods of *A. robusta* and *T. ivorensis* and the relationships between the biochemical properties

The percentage mass and hardness losses and visual durability ratings were determined using the field test method (36 weeks of field exposure) and compared between the radial postions (sapwoods and heartwoods), axial positions (base, middle and top) of the tree parts (stems and branches). Sapwoods were generally less durable than branchwoods in *T. ivorensis*; they lost more mass and hardness and appeared physically more deteriorated than heartwoods. The natural durability of its stemwood and branchwood also decreased along their heights, while stemwood was more durable than branchwood. *T. ivorensis* stem heartwood was rated

moderately durable to very durable, its branch heartwood and stem base sapwood moderately durable and stem middle to branch top sapwoods non-durable. The branch heartwood and stem base sapwood could be utilized for interior works such as furniture parts, door frames, ceiling joints and cabinets, whereas the stem base and middle heartwoods could be used out doors.

A. robusta stem and branchwoods were however rated non durable (even perishable) after being completely deteriorated during exposure in the field. Based on the durability, *A. robusta* branchwood could be utilized for products including interior joinery, veneer, cabinet and light carpentry works like the stemwood. They could also be treated with preservative chemicals to improve their durability. Variations in natural durability were greatly estimated by chemical components, while anatomical features poorly predicted natural durability variations in *T. ivorensis*. Increase in lignin and extractives increased natural durability in *T. ivorensis*, whereas increase in hemicellulose and cellulose amounts decreased it. Correlations and coefficient of determination between natural durability, anatomical features and chemical components could not be estimated for *A. robusta* due to total mass and hardness losses.

Conclusion

Generally, bio-chemical properties of the branchwoods of the two timbers compare favourably with those of their stemwoods and with utilizable hardwoods. The branchwoods can be suitably utilized to reduce the over dependence on stemwood to increase the raw material base of the wood industry. However, based on distinctions within trees, specific properties for satisfactory functioning, require careful wood selection from any of the tree parts (stem and branch) to match their end-use requirements.

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