RELATIONSHIPS BETWEEN SOME ANATOMICAL, PHYSICAL AND DURABILITY PROPERTIES OF THE WOOD OF SOME LESSER UTILISED GHANAIAN HARDWOODS

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CERTIFICATION/DECLARATION

I hereby declare that this submission is my own work towards the PhD 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 degree of the University, except where due acknowledgment has been made in the text.

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ABSTRACT

This thesis is the result of a comprehensive study of some anatomical structures as well as some of the properties of wood utilization of selected species and the interrelationship amongst them. The natural durability of ten lesser-known West African Species, namely *Albizia ferruginea* (Guill. & Perr.) Benth. (Awiemfosamina), *Amphimas pterocarpoides* Harms (Yaya), *Antiaris toxicaria* Lesch. (Kyenkyen), *Blighia sapida* Koenig (Akye), *Canarium schweinfurthii* Engl. (Bediwonua), *Celtis zenkeri* Engl. (Esa), *Cola gigantea* A. Chew. (Watapuo), *Petersianthus macrocarpus* (P. Beauv.) Liben (Esia), *Sterculia oblonga* Mast. (Ohaa), *Sterculia rhinopetala* K. Schum. (Wawabima), and as reference Teak (*Tectona grandis*), were evaluated by the field test according to EN 252 (1989) for a period of 6 months. Structural size samples were tested for their mechanical properties according to EN 408 (2003). Their water sorption properties were determined at relative humidity conditions of 30, 45, 60, 75, and 90 % at a temperature of 25^{o}C and compared with *Albies alba*, *Picea albies*, *Fagus sylvatica* (European species). Three of the ten species, *Albizia ferruginea*, *Blighia sapida*, and *Sterculia rhinopetala* were selected for anatomical investigations based on their performance in the durability and mechanical strength tests. Microscopic sections of the transverse and tangential planes were made on a Leica sliding microtome, stained and permanently mounted in Canada Balsam. The micrographs were analysed using the stereological technique described by Ifju (1983) and Steele et al. (1976). Maceration was also done. The results from the field test indicate that some of these less utilized species could be used as substitutes for the more standard commercial species in their end use applications. It was found that *Albizia ferruginea* was very durable, *Sterculia rhinopetala* was durable and *Blighia sapida* was moderately durable. A general trend found in the ten species was that, the denser the species the less water/moisture it takes up and the more durable it is, combined probably with specific polyphenolic substances. An exception to this trend was *Albizia ferruginea,* having the highest sorption of the three mentioned species but at the same time the highest durability and *Sterculia rhinopetala* the least. The best correlations found between the mentioned properties/features are between density and bending strength, followed by density and sorption, sorption and durability and to a lesser extent density and durability. As could be expected, durability (as a result of natural impregnation with protective substances) was in fact not completely correlated with density: *Albizia ferruginea* although the lightest of the three specially tested species, had the relatively highest durability according to the graveyard test. *Blighia sapida* was found to have crystals which could be harmful for working tools. This could explain its brittle behaviour under stress. It had a bending strength of 61.4 N/mm^2 at a moisture content of 29 % with an average density of 0.899 g/cm^3. A peculiar form of cell wall thickenings has been found in the vessels of this species with the help of scanning electron microscopy. In a third position, *Albizia ferruginea* had lowest bending strength of 50 N/mm^2 at a lower average density of 0.740 g/cm^3. In conclusion, *Sterculia rhinopetala* was used for a pedestrian bridge constructed at the KNUST campus in Kumasi due to its performance in most of the tests carried out and even though most of the tested lesser utilized species were not durable; their durability could be enhanced by impregnation with protective substances in order to be used for external applications.

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DEDICATION

To my God who has seen me through all these years and to Kwesi, Aba, Kweku and Eliel, I dedicate this work.

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CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The utilization of lesser utilized timber species as a replacement for the primary commercial wood species has been a matter of discussion for some time now. This is in the light of many efforts by research institutions such as the Forestry Research Institute of Ghana sponsored by the International Tropical Timber Organization and the Building and Road Research Institute of Ghana, in a bid to stop or minimize the extinction of some of the durable timber species due to overexploitation. A successful promotion and utilization of Lesser-used species (LUS) will yield a relief and reduce demand on the few primary species. But the efficient utilization of the lesser-used wood species depends on knowledge of properties such as their durability, water sorption behavior among others.

In Ghana, wood is exported to earn hard currency. It is also used locally for constructional purposes, e.g. for housing and bridge construction. With some of the locally available timbers, it is possible to economically construct bridges across some of the small rivers/streams for pedestrian use and for light vehicular traffic. The wood of many of the more popular and durable wood species are often exported and the species are getting extinct from our forests. There is the need to find substitutes for the popular timber species. The substitutes have to be characterized in terms of durability, strength and workability. When the characteristics are known, the knowledge will promote their acceptance for local use and for export. Some substitutes have been found and are often referred to as “Lesser Utilized Species, LUS”. However, all their properties are not completely known.

The natural forest resources in several tropical timber producing countries including Ghana are getting exhausted, resulting in reduced availability and quality of the preferred traditional commercial timber species. Although about 70 species are harvested and used commercially out of about 420 which grow to timber size in Ghana's forests, the trade is dominated by about only eight species (Cobbinah, 1998). According to Kuffour (1998), of the 60-64 Ghanaian timber species, it is noted that Afzelia (*Afzelia spp*), Asanfona *(Aningeria spp.),* Ceiba (*Ceiba pentandr*a), Emire (*Terminalia ivorensis*), Koto (*Pterygota macrocarpa*), Mahogany (*Khaya grandifoliola*), Niangon (*Tarrietia utilis*), Odum (*Milicia excelsa)*, Ofram *(Terminalia superba*), and Wawa (*Triplochiton scleroxylon),* are dominant in terms of volume exported. About 160,594 m^3 of these species were exported in 2004 (TIDD report, 2004). By 2007 the total volume of these species exported had decreased to 97,657.6 m^3 (TIDD report, 2007). Ghana forestry reports in recent years indicate that the species for which Ghana is known in international markets are becoming very scarce. Current thinking is that to reduce the pressures on the popular species, industry must take a close look at the lesser-used species (LUS).

The Forestry Inventory Management Programme (FIMP) of 1995 estimated the permanent forest estate of Ghana to be 2,316,500 ha. The high forest, which covers 1,620,000 ha contains 204 forest reserves, and the 62 forest reserves in the Savannah zone covers 600, 000 ha (Forestry Commission, 2004). The effective area of the high forest, designated for timber production is only 762,400 ha or 47% (Forestry Department, 1995). In addition, about 22% or 352,500 ha of the high forest zone are partly used for permanent protection, 122,000 ha or 7 % for rehabilitation, and 127, 000 ha or 8 % for conversion. However, the multi resource inventory of 2001 showed that the total timber production area, of the high forest had dwindled by 5.7

% to about 719,300 ha (Ghana forestry Commission, 2002). From this productive area the total growing stock for 73 identified timber species above 30 cm dbh was 162.36 m^3 ha^{-1} and 56.43 m^3 ha^{-1} for the same species above their minimum felling diameters. The total volume for each of the four utilization classes above their felling limits was as follows: 19.70 % for 13 premium species, 25.9 % for 15 commercial species, 48.8 % for 37 LUS and 5.6 % for 8 lesser known species (LKS). This further emphasizes the need to harvest, promote and use more LUS which is relatively abundant (Oteng-Amoako *et al*., 2006).

There is therefore the need for sustainable management of tropical forests, instead of overexploiting some few commercial timbers linked with degradation of forests. The pressure can be reduced by obtaining a full utilization of the different species, with optimal value added and possibilities of substitution. In this sense, lesser utilized species are being used as substitutes for the more usual well known species which are gradually becoming extinct. An example is Dahoma (*Piptadeniastrum africanum*) which was regarded as the most promising alternative to Odum (Anon, 1994) owing to their similarities in terms of physical properties (colour, texture, mechanical strength) (Anon, 1969). Currently it is successfully being used as a substitute for Odum (*Milicia excelsa*). It is expected that the efficient utilization of the lesser-used species would improve sustainability of the tropical timber resources and reduce negative ecological impacts such as reduction in biodiversity and desertification (Okai, 1998).

Timber is widely used for the construction of bridges in remote and inaccessible areas and in cases where it is uneconomical to construct concrete bridges (Negi, 1997). The utilization of lesser-used timber for bridges has been adopted in other

African countries like Cameroon with considerable gain to the economy (Jayanetti, 1998). However, timbers used for such ventures should be strong, enough to carry the load of traffic that is likely to pass over the bridge; be durable enough and withstand fungal decay and insect attack and be able to bear continued wear and tear.

A study of the properties of these LUS will help in promoting their utilization. Consumers will have the confidence to use the LUS when they know more about the species. Scientific information on the natural durability, anatomical properties, sorption behavior, and mechanical properties must be available on the LUS. A reliable knowledge of wood anatomical properties and the behavior of wood under stress are essential for engineers, architects, and carpenters in order to use timber more efficiently. The anatomical structures of wood for example, play an important role in selecting the proper wood for particular usage because it affects strength properties, appearance, resistance to preservative treatment, and resistance to decay. This study looked at one aspect of the mechanical properties; the bending strength of some selected lesser-used species by testing full-size members of the timbers of the species. Prior to 1970, the characteristics of timber were assessed on the basis of the characteristics of small clear pieces of wood. However, following the extraordinary pioneering work by Madsen (Madsen, 1992), it was realized that this could be quite misleading. This is because the strength of structural size timber is much influenced by the presence of natural defects such as knots, pith, etc. that may be in it.

Natural durability of wood is the natural resistance of wood to damage by subterranean termites, fungi and other soil micro-organisms. This is important to consider when wood is to be used for outdoor constructions. Other relevant properties to consider in constructions are density, mechanical properties, sorption characteristics and anatomical structure and the correlation between them. Some timber species have had their natural durability tests conducted in the laboratory and in the field but more work needs to be done on more species in order to widen the data base and increase the pool of timber resources to choose from when considering wood for utilization in construction. One aim of this study was therefore to determine the natural durability of ten lesser known Ghanaian wood species.

This study was undertaken with the following research questions:

- What was the natural durability of each of the species under exposed conditions in the field?
- What part do anatomical features play in the natural durability of wood species?
- Are there interrelationships between natural durability, density and mechanical properties, sorption and anatomy?
- Can the anatomical properties of a species help explain its density and other properties of the species?

1.2 Objectives of the Study

The study therefore sought to investigate the interrelationships between some selected properties of ten less utilized timber species suitable for external applications such as the construction of light bridges in Ghana.

The specific objectives therefore undertaken were investigating:

a. the variation in natural durability of the wood of the selected species

b. some anatomical features and structures of some of the selected wood species

c. their sorption properties

d. some of their physical properties, e. g. bending strength

e. determine their densities

f. determine the correlation between the features and properties and how they are related to density

1.3 Scope of the Research

It determined the natural durability of ten lesser utilized Ghanaian wood species, studied their sorption characteristics, determined the bending strength, anatomical properties and examined the interrelationship between various parameters such as anatomy, density, water sorption, durability, and physical properties and how the properties affect their end use.

1.4 Relevance of the Research

This study will help increase the scientific data base of the selected species and enhance their utilization. It will also help achieve the aim of the Department of Wood Science and Technology to train staff in the research of LUS and LKS.

1.5 Literature on the Species selected for the study

Ten tropical timber species nine of which are currently considered Less Utilized (LUS) and one Less Known (LKS) were studied in this work. The lesser utilized species are of acceptable quality and some of high strength, but are irregularly exported because of low international market demand for them. According to Oteng-Amoako *et al*. (2006), they are of variable occurrence in the forest and are generally of very low extraction rate. He explained that a comparison of harvested volume from 2000 to 2003 from the reserve forests shows that 16.92 % of premium species were harvested with 6.09, 3.20 and 0.18 % for the commercial species, LUS and LKS, respectively. On the other hand, the lesser known species are species whose properties and qualities are much less known (Oteng-Amoako *et al*., 2006) have the potential to be promoted for use locally. Their occurrence in the forest is variable, usually from frequent to sparse.

The wood species studied are: *Albizia ferruginea (*Guill. & Perr.) Benth. (Awiemfosamina), *Amphimas pterocarpoides* Harms (Yaya), *Antiaris toxicaria* Lesch. (Kyenkyen), *Blighia sapida* Koenig (Akye), *Canarium schweinfurthii* Engl. (Bediwonua), *Celtis zenkeri* Engl. (Esa), *Cola gigantea* A. Chew. (Watapuo), *Petersianthus macrocarpus* (P. Beauv.) (Esia), *Sterculia oblonga* Mast. (Ohaa), and *Sterculia rhinopetala* K. Schum. (Wawabima). Teak (*Tectona grandis*) was used as control for comparison.

CHAPTER TWO

LITERATURE REVIEW

2.1 Wood as a Building Material

Wood is a structurally sound material and compares favourably with concrete, steel, and stone and a variety of other building materials. Wood in its natural state can be used for many forms of construction (Jayanetti, 1998). Unfortunately, the properties and behaviour of wood are unlike those of other building materials and much more complex. Wood is a natural material – and over its properties man has little control. Through proper forest management however, man is beginning to control some characteristics of wood.

For most structural applications, fortunately, wood has several advantages which outweigh its disadvantages. However, structural designers must learn to cope with (1) variability in wood and (2) its response to environmental conditions. Variability is the more serious of two. Wood properties vary from species to species, from one position to another in the tree, from one tree to another grown in the same locality, and between trees grown in one locality and those grown in another. Progress is being made in controlling the quality of wood a tree produces by means of selective tree farming. It is hoped that by such means, straighter and fast growing trees may be produced with more nearly uniform properties than found in trees from the natural forests.

Stalnaker and Harris (1989) indicated that the moisture content of wood installed in a structure may change with time, eventually reaching equilibrium moisture content that depends on the average relative humidity of the surroundings. However, as the relative humidity within a building may not be constant, the equilibrium moisture content may vary with time. With any change of moisture content, wood will either shrink or swell. Dimension and shape changes due to moisture change can be reduced or avoided by proper seasoning and by proper attention to details of design. According to Stalnaker and Harris (1989), wood used where the humidity fluctuates, as it does in almost all use situations, will continually change moisture content and therefore dimension. If humidity changes are small, these dimensional changes will not be noticed and will have no impact on satisfactory performance. Even large fluctuations in humidity may have little effect if these conditions last for only short periods and the wood does not have time to come to the new equilibrium moisture content. Problems can arise, however, when a wood product is used under humidity and temperature conditions that cycle over long periods of time and the user did not provide for changes in dimension. For the most trouble-free use of wood, Haygreen and Bowyer (1996) asserted that the goal should be to fabricate it at the moisture content it will attain in use or service. This is often not possible.

Framing lumber for light-frame wood buildings, as an example, is commonly manufactured at 15 to 19 % M.C., a moisture content that is not 5-10 % above that to which it will eventually equilibrate in most areas of the United States. This is usually not a problem, because small changes in the dimensions of studs, rafters, and floor joists are not noticeable. The United States standards for the manufacture of softwood lumber (American Lumber Standards Committee, 1994) specify a small percentage of shrinkage in use, which is considered to be acceptable (Haygreen and Bowyer, 1996).

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

Duration of loading causes strength changes: the longer a load remains on a wood member, the weaker the wood member becomes. The structural designer normally considers this problem and compensate for it in the design. Duration of loading has negligible effect on modulus of elasticity but, because creep, deflection are time-dependent. Stalnaker and Harris (1989) indicated that some loss of strength will occur if aging is accompanied by continuous loading of the member. The longer a load is supported, the lower the load that can be safely carried. Even if a load is small enough that there is no danger of ultimate failure, the member may continue to deflect or deform very gradually under the constant stress. It is believed that creep occurs at the molecular level from slippage in the relative position of the long-chain molecules in the cell wall. The bonding sites that hold water or are mutually satisfied in dry wood may shift or slide with respect to adjacent molecules when the whole matrix is placed under stress. The more water present within the wall, the more easily this slippage can occur. Alternate addition and removal of water from the bonding sites also creates an opportunity for slippage (Haygreen and Bowyer, 1996).

As a construction material, wood is strong, light, flexible and easily worked with. In contrast to the other structural materials such as brick, metal, concrete and plastics, wood can be produced and transported with little energy consumed and wood is a renewable material (Koch, 1971).

In a related research, a survey was carried out in the city of Kumasi and it environs to find out how many of the bridges around were made of wood. The findings indicated that about 80 % of the bridges were either constructed from concrete or steel. The ones in wood were the ones constructed by the community members with minimal technical knowledge. Some used some of the less utilized woods, e. g. Dahoma. The bridges were in very good condition at the time of the survey.

2.2 Less Utilized Timber Species

In Ghana, there are some 680 tree species naturally growing in the High Forest Zone, of which, only the most valuable species (40) have so far been commercially exploited (ITTO 1991, Anon. 2002, Anon, 2003a). Undoubtedly, there are numerous other potentially useful timber species that are yet to be exploited. The over-exploitation of the few popular timber species has resulted in the depletion of species, like (*Milicia excelsa*) Odum, (*Khaya grandifoliola*) Mahogany, (*Entandrophragma cylindricum*) Sapele, and (*Triplochiton scleroxylon*) Wawa, etc. With increasing demand in the world markets for high quality tropical woods and increase in the local demand for timber, the lesser-utilised species are being promoted as alternative timbers for various end-uses. There are some timber species currently classified as lesser-used purely for the fact that they have no commercial value on either the international or local markets but certainly not because of their technical inferiority. Jayanetti (1998), in an address indicated that in West Africa, there are about 125 commercial timber species and 111 lesser known species. He said that timber is still an abundant resource of Africa considering the large stocks of lesser used timber species. It is believed that several of the Lesser-Known or Utilized timber species can be used for constructional purposes, considering their strength, durability and other qualities. This work set out to study some of the properties of nine of the Lesser-Used wood species to determine their suitability as construction material.

2.3 Natural Durability of Wood

One key to satisfactory use of timber as a building or construction material is an understanding of agents and conditions that can lead to its decay or other forms of deterioration (Haygreen and Bowyer, 1996). The natural durability of the LUS needs to be determined from in situ tests to enable it to be used appropriately; this can be done using field trial tests or graveyard tests.

The natural durability of wood is its ability to resist the attacks of foreign organisms including fungi, insects and marine borers (Panshin and De Zeeuw, 1980). A number of factors account for the natural durability of wood. These include the presence of extractives, and moisture content outside of the natural moisture limits of the agent of destruction. Other factors may also complicate assessments of natural durability. Individual trees of the same species may also differ considerably in their decay resistance. Observed differences may be due to genetic factors (Scheffer and Hopp, 1949) and possibly to silvicultural systems (Edmonson, 1947). Campbell and Clark (1960) reported on correlation between locality and durability. Edmonson (1947) reported that Australian natural grown *Syncarpia laurifolia* (turpentine wood) was quiet resistant to the marine borers *Teredo* and *Limnoria* while plantation-grown *S. laurifolia* grown in Hawaii was rapidly attacked.

Wood consists of sapwood and heartwood. The sapwood is constituted by a part of living cells and conducts water and mineral salts. It is frequently attacked by insects due to the presence of soluble reserve food substances in the parenchyma cells. These stored carbohydrates which serve as nutrient sources can be a factor promoting attack by fungi and insects. The sapwood undergoes a number of changes to be transformed progressively into the heartwood. Some of the changes are: increase in acidity, formation of extractives such as tannins, which gives it a specific colour and formation of gums, resins, tyloses and usually decrease in moisture content. These transformations and processes may render the heartwood more durable than the sapwood and sometimes slightly harder. The presence of these extractives in sufficient amounts prevents or minimizes the severity of attack by destructive organisms if the extractives are toxic or repellent. The toxic substances vary from species to species and in their chemical properties so that different solvent systems will effectively extract different toxins in different species (Eaton and Hale, 1993).

An indication of the effect of extractives on the durability of heartwood in some species is the early decomposition of the extractive-free sapwood from a piece of lumber. In some instances, the lower resistance of sapwood may be due to its greater permeability (Kollman and Cote, 1984). Moisture content below fiber saturation point prevents or minimizes the attack by some organisms, particularly the decay fungi, because they need sufficient and easily available moisture to facilitate metabolism. Furthermore, the heartwood’s lower rate of diffusion, the blocking of cell cavities by gums, resins, tyloses in the vessels and tylosoids in the resin canals adversely affect the balance between air and water necessary for the growth of fungi (Kollman and Cote, 1984).

The natural resistances of wood to deterioration that can be ascribed to reasons other than the toxicity of its extractive substances are the woody cell walls. These consist of highly complex, insoluble polymers of high molecular weight; these substances must be altered by enzymes produced by the attacking organisms into simpler products before they can be assimilated. Wood lignification creates a physical barrier to enzymatic attack on the polysaccharides. Therefore only those organisms that possess enzymes capable of destroying the lignin or at least of altering its protective association with the polysaccharides are capable of decaying wood. The structure of cellulose with crystalline and amorphous regions also restricts the action of depolymerizing enzymes. They can initially only affect the non-crystalline portions. Therefore, cellulose can sometimes provide some resistance to fungal and bacterial degradation.

Durability of wood varies within and between trees. Variation within a tree is particularly so especially in species with very durable heartwood. In a wide-ranging review on natural resistance, Scheffer and Cowling (1966) summarized the following general points. In many species inner heartwood is less durable from the base of the tree upward, while the opposite occurs with outer heartwood. At the base of the tree these differences are most extreme; further up the tree the resistance is intermediate. The larger the tree the greater is the differences at the base. Although no known wood is entirely immune to the attack by degrading organisms, a number of wood species possess superior resistance. It must be kept in mind; however, that timber resistant to fungal attack may or may not be durable when subjected to attack by insects or marine borers. Furthermore, the durability of a given wood species may fluctuate between wide extremes (Kollman and Cote, 1984).

2.3.1 Wood Decay by Fungi

Decay can be defined as the microbiological degradation of wood (Scheffer, 1949). The damage of wood by fungi is essentially caused by the degradation of the cell wall by fungi, which decreases the mechanical wood properties and substantially reduces wood use (Schmidt, 2006).

Different types of symptoms and effects of decay have been identified (Forti and Poliquin, 1972). They include the weight loss, strength loss, and increased permeability, reduced calorific value, increased electrical conductivity, disclouration and reduced pulp quality.

Four main types of wood decay exist and these are brown rot, white rot, wet rot and soft rot (Forti and Poliquin, 1972). Wood attacked by brown rot fungi splits longitudinally and across the grain forming large cubes. Species of fungi causing brown rot include C*oniophora cerebella, Lenzites trabeum, Meruluis lacrymans and Poria vaillantii*. White rot is a fibrous form of decay where the attack is well advanced. White rot means the degradation of cellulose, hemicelluloses, and lignin usually by Basidiomycetes and rarely by Ascomycetes. White rot has been classified by macroscopic characteristics into white-pocket, white-mottled, and white-stringy, the different types being affected by the fungal species, wood species and ecological conditions. Carbohydrates and lignin are almost uniformly degraded at the same time and at a similar rate during all decay stages by simultaneous white rot. Typical fungi with simultaneous white rot are *Fomes fomentarius, Phellinus igniarius, Phellinus robustus,* and *Trametes versicolor* in standing trees and stored hardwoods (Blanchette, 1984a). Wet rot attacks wood that has high water content. It is usually found in parts of buildings where persistent water leakage or condensation occurs and also on wood used in contact with ground or under permanent damp conditions. Wood damaged by wet rot usually exhibits cracking along the grain (Abankwa, 1970). Wet rot is caused by families of Basidiomycetes such as Fuscoporia, Formes, and Coriolus (Victoria Sawmillers Association, 1967). Soft rot occurs under extreme conditions found in wood used in cooling towers. The wood is usually darkened and shows little change on drying out. The attack is more severe in hardwoods than in softwoods (Victoria Sawmillers Association, 1967). Common species of fungi which cause soft rot include *Chaetomium globosum* and other *Chaetomium sp.* (Forti and Poliquin, 1972). Soft rot fungi differ from brown rot and white rot Basidiomycetes by growing mainly inside the woody cell wall. In hardwoods (Zabel *et al*., 1991), the hyphae erode particularly from the lumen the tertiary wall and penetrate till the middle lamella or primary wall.

2.3.2 Insect Damage to Wood

In the tropical countries, the damage insects cause to lumber and wood in service is of great economic importance. Although periodic estimates have been done for certain countries, the true worldwide losses in wood destroyed and labour expended in replacement cannot be evaluated to a satisfactory degree of accuracy, it is sufficient to state that the losses are extremely great and measures taken by wood users to reduce such damage are a sound investment (Kollman and Cote, 1984).

The class Insecta is divided into 30 orders of which five have species known to bore into wood. These are the orders Ephemeroptera (a species with wood-boring larvae), Lepidoptera (butterflies and moths) with relatively few members having adopted the wood-boring habit. For example, one primitive family, the Cossidae (goat and carpentry moths) consisting of large or very large species, has wood-boring larvae. The members of this family infest fruit and other trees, making large galleries. The Hymenoptera includes a primitive family, the Siricidae, known as Wood-Wasps or Horntail. These are large insects, the female having a long stout ovipositor, by means of which she drills a hole through the bark of a tree and passes a single egg into the wood. When the larva hatches from the egg it bores into the heartwood for about two years before completing the life cycle. The order Isoptera (Termites) is an extremely important wood-destroying group. These insects are social, and live in large communities consisting of several castes (Hickin, 1975). It is estimated that there may be as many as 5000 species of termites in the five families of the order Isoptera (Synder, 1948). In a termitarium, often deep in the ground in a special cell, lives the royal pair. These are usually the original founders of the colony, having now lost their wings (Hickin, 1975).

Termites are among the few insects capable of utilizing cellulose as food. There have been many studies on the nutrition of termites and their methods of feeding. It has been discovered that the insects do not secrete cellulase but bear symbiotic intestinal protozoa in their gut that carry out the digestion of cellulose. Since cellulose is the major constituent of most plant tissues, it implies that majority of plants and plant products are susceptible to termite damage. Under natural conditions, termites feed on roots of grasses, decaying vegetable matter, living trees and dry wood. Some species have been found to destroy a whole wooden house in 20 years. However, when given the opportunity, termites may even damage linoleums, leather and bones. Even buried telephones cables, plastic water pipes and the lagging around steam pipes have been found to suffer from termites' damage (Victoria Sawmillers Association, 1967).

Termites may be separated into three groups on the basis of their habits, namely subterranean termites, the dry wood termites, and the damp wood termites. The subterranean termites (family Rhinotermitidae) are easily of greatest significance in the US since they cause about 95 % of the type of termite damage. Kollman and Cote (1984) states that dry wood termites (family Kalotermitidae) are very destructive, but more limited in distribution. In the tropical regions, the preponderant of termites found, are of the family Termitidae and Rhinotermitidae. They are the bane of use of wood in construction. According to Wagner *et al* (1991), the family Termitidae includes 80 % of all termite species. They are mostly wood-eating and either subterranean or mound-builders. A few species build arboreal nests. The termites that cultivate fungus gardens that are very common in Ghana occur in the subfamily Macrotermitinae.

Moist woods termites are of low economic importance as their attack is usually confined to permanently buried wood in the ground and thus seldom attack materials of value.

According to Kollman and Cote (1984), subterranean termites nest in the ground or in the wood in contact with the ground. They construct earthen tubes to provide covered passageways to the wood under attack. These tubes, which often span considerable distances over building foundations or other inedible materials, provide a connection to soil moisture, an important need of this type of termite.

Drywood termite, as emphasized by Kollman and Cote (1984), attack buildings, poles, fences and other structures made of seasoned wood. They live entirely in the timber on which they feed, often hollowing large timber but leaving a thin sheet for protection. Attack, once begun, takes place largely within the timber and may be well advanced before being recognized. There is enough evidence of the interrelationship between termites and fungi in wood. The presence of fungi in wood may be the termites' main source of Nitrogen. *Cryptotermes havilandi* is the most common drywood species in Ghana and occurs mainly along the coast, but was reported once found in the Ashanti Region (Williams, 1973).

Although termites destroy all types of wood products and household items such as books and clothing, the damage to lumber in wooden structures is of primary concern. Kollman and Cote (1984) further stressed that in general, conditions leading to decay by wood-destroying fungi also invite termite attack. These two types of biological degradation are often found together in wood that has failed in service in the tropics.

2.3.3 Determination of Durability of Wood

Various methods have been used to test the durability of wood. Laboratory assays to evaluate natural durability begun in the 1940's in an attempt to explain further the nature of durability and identify the toxic compounds involved in resistance to attack (Anderson *et al*, 1963; Scheffer, 1957; Zabel, 1948 and Scheffer and Hopp, 1949).

Accelerated laboratory tests give useful comparison of decay resistance of timber species, which to date, have not been contradicted by the few service data and grave yard (outdoor) test results which are available (Osborne, 1970). The method has been used not only to evaluate the durability of various timbers, but also to assess the efficiency of wood preservative chemicals. Osborne (1970) noted that decay resistance rating is more related to above ground structural timber and is relevant to tropical timber trade. This is because interest in these rain-forest timbers lie in their use as general building timbers more than poles or posts in ground contact.

Natural decay resistance tests have in some cases involved the assessment of both the resistance of the wood species to wood decay fungi and the toxicity of the wood extractives to those fungi. In most cases, warm water, ethanol, or other solvents were used to isolate these compounds from wood. The extractives were then tested for activity against a variety of decay and non-decay fungi (Findlay, 1957; McDaniel, 1989; Zabel and Morell, 1992). Most tests were performed in petri dishes or decay chambers using nutrient agar. Although such tests provide a relative guide to chemical toxicity, they cannot evaluate more subtle effects such as variation in deposition of the extractives in the wood and interaction between different extractives that must also play roles in natural durability.

More elaborate methodologies, like the one used in this study, include graveyard or field test. This allows the resistance of a given wood species to wood deteriorating agents, especially termites and fungi, to be assessed. Two advantages of field trial tests are that: 1. it enables large sizes of wood samples to be exposed to the biodeterioration agents (e. g. termites and fungi), 2. The samples are tested under conditions similar to the end-use situation (Eaton and Hale, 1993).

2.3.4 Durability of Ghanaian Timbers

During the years spanning 1960 and 2000, much work has been done on the properties of some of the Ghanaian hardwoods by the Forest Products Research Institute (FPRI, now Forestry Research Institute of Ghana FORIG) and the Building and Road Research Institute (BRRI), both of the CSIR (Council for Scientific and Industrial Research). The works among other things covered the durability and strength properties of the woods.

Some of the publications that emanated from the works include those of Ashiabor (1967), Bentum (1969, 1970), Ofori (1985a), Okoh (1977b), Usher and Ocloo (1979), Ayensu and Bentum (1974), Ocloo and Laing (1991). Oteng-Amoako *et al*. (1998) was on the anatomical properties of some of the woods.

2.4.1 Anatomical Properties

Wood is composed mostly of hollow, elongated, spindle-shaped cells that are arranged parallel to each other along the trunk of a tree. The characteristics of these fibrous cells and their arrangement affect strength properties, appearance, resistance to penetration by water and chemical solutions, resistance to decay, and many other properties. Wood density is determined largely by the relative thickness of the cell wall and the proportions of thick- and thin- walled cells present. Many of the mechanical strength properties of wood, such as bending strength, crushing strength, and hardness, depend on the density of wood; the heavier woods are generally stronger.

Wood is a biological material so there are variations in structure and properties. Wood of different species possess individual characteristics and differ in a number of properties including grain pattern, durability, strength, density and colour. Differences in wood quality exist between samples taken from same species from different geographical areas and even from different parts of the same tree.

In order to use timber more efficiently, a reliable knowledge of anatomical wood properties and the behaviour of wood under stress are essential for engineers, architects, and carpenters. It is important for the architect or builder to have knowledge of the relationships between physical appearance, anatomical structure, mechanical strength and chemical properties (Ifju, 1983). Builders have incurred substantial losses by using timber unsuited for a particular job or by employing more or less lumber than was necessary for a project.

In this light, the work done by Oteng-Amoako *et al*. (2006) in describing 100 wood species macroscopically to aid in identification is laudable. In the work, the ten wood species selected for this study were macroscopically described. The limitation with this method is that some features were not visible to the eye when using only hand lens and complementary description was needed with the aid of a microscope. That was why the anatomical study undertaken in this study was invaluable.

There are several methods of studying the anatomy of wood. These include the use of hand lens, light microscope, and scanning electron microscope (SEM). More common techniques employ the use of the light microscope.

With the light microscope, one can survey enormous quantities of material in a short time, exploring variability and distribution of features within the wood. Sectioning that is cutting thin slices of wood on a microtome and maceration are two micro techniques popularly used to develop slides for light microscopy and can often also be used for SEM investigations with a little modification. The aim of sectioning is to prepare sections as thin as 5µm. While thin sections do reveal some details well, and while they produce photographs of admirable clarity, thicker sections have virtues not evident at first. For example, thicker radial sections often permit one to see entire scariform perforation plates intact. Walls of all kinds are seen well in thicker sections because larger portions are intact, and one can also see better the content of a particular cell (Carlquist, 2001). Macerations are essential for obtaining quantitative data on lengths of vessel elements and imperforate tracheary elements.

2.4.2 Relationship of Structure to Chemical Composition

According to Winandy and Rowell (1984), the chemical components responsible for the strength properties of wood can be theoretically viewed from three distinct levels: the macroscopic (cellular) level, the microscopic (cell wall) level, and the molecular (polymeric) level. Wood with its inherent strength is a product of growing trees. Wood exists as concentric bands of cells oriented for specific function. In softwoods, both conducting and strengthening functions are performed by a single type of cell, fibre. Softwood fibers average about 3.5 mm in length and 0.035 mm in diameter. However, in hardwoods, there is a more distinct division of labour, and the conducting cells are called vessels or pores, quite different from fibres which provide mechanical support. Hardwood fibers are generally shorter (1-1.5 mm) and smaller in diameter (0.015 mm). The fibers comprise a large mat, bonded together by a phenolic adhesive, lignin. Because wood is a reinforced composite material, its structural performance at the cellular level has been likened to reinforced concrete. The macroscopic level of consideration takes into account fiber length and differences in cell growth, reaction wood, sapwood, heartwood, mineral content, resin content among others. At the microscopic level, wood has been compared to multipart systems such as filament-wound fiber products. Each component complements the other in such a manner that when considering the overall range of physical performance, the components together outperform the components separately.

Wood is composed primarily of three main components. Cellulose, a crystalline polymer derived from glucose, constitutes about 41-43 %. Next in abundance is hemicellulose, which is around 20 % in deciduous trees but near 30 % in conifers. It is mainly five-carbon sugars that are linked in an irregular manner, in contrast to the cellulose. According to Parham and Gray (1984), these polysaccharides render wood cell walls hygroscopic. The hydroxyl groups on the cellulose and hemicellulose molecules are responsible for this great affinity for water. Lignin is the third component at around 27 % in coniferous wood verses 23 % in deciduous trees. Lignin confers the hydrophobic properties reflecting the fact that it is based on aromatic rings. These three components are interwoven, and direct covalent linkages exist between the lignin and the hemicellulose. Aside from the lignocellulose, wood consists of a variety of low molecular weight organic compounds which are called the extractives. According to Bodig and Jayne (1982) these cell wall components (cellulose, hemicellulose and lignin) are the structural members of the wood cell and largely govern the physical properties of wood. Extraneous substances are present in the cell wall but are often more prevalent in the cell cavity or in specialized anatomical structures, such as resin and gum ducts. Parham and Gray (1984) reported that these extractives bulk cell walls, block potential sites for water adsorption/absorption, alter potential wood swelling/shrinkage and thereby interfere with the accurate characterization of wood tissue.

Extractives have little or no direct effect on the mechanical properties of wood. However, they are responsible for increasing specific gravity and lowering the equilibrium moisture content. Consequently, extractives can modify many mechanical properties indirectly. Bodig and Jayne (1982) reported that, the extractives can influence durability, color, odor and taste.

Density of wood also varies with cell size, cell wall thickness and the volume proportion of cells of a given type (Parham and Gray, 1984).

2.5 Water sorption of Wood

Wood cellulose when exposed to an atmosphere of constant temperature and humidity, ultimately attains a moisture content that remains constant so long as these conditions are unaltered. Sorption is a common term used for describing the phenomenon of absorption/adsorption (gain of moisture from the surrounding air) and desorption (loss of moisture to the surrounding air). Freshly cut wood and wood which has been exposed to liquid water for a long period of time have high moisture content (well above the fiber saturation point). Water bound to hygroscopic cell wall constituents and into voids of wood of radius less than 1.5 µm is called adsorbed water. This critical point of sorption is called the fiber saturation point. It represents a water potential of -0.1 MPa and in theory, a relative humidity of 99.93 % (Griffin, 1977). The water present in the cell lumens and intercellular space is called free or absorbed water (Walker, 1993). At high moisture, the water can be found as free water, which is located in the cell lumens, and as bound water, which is located within the cell wall material. As the wood begins to dry, when exposed to ambient air, moisture first leaves the wood from the lumens while the bound water remains constant. The moisture content level which corresponds to the lumens containing no free water (only water vapour), while no bound water has been desorbed from the cell wall material, is known as the fiber saturation point (FSP), normally in the range of 26-32 % moisture content (Skaar, 1998). As the moisture content of wood decreases below the FSP the bound water will begin to leave the cell wall material. This is what is known as desorption and the gain of bound water is known as adsorption/absorption. The rate of water /moisture loss depends on the amount of water already taken up and the temperature, while the rate of gaining depends on the number of absorbing (adsorbing) points in the material that is still unoccupied and on the concentration of water vapour in the surrounding atmosphere.

Wood used in final form as furniture, building construction, musical instruments and other uses are generally subjected to fluctuating atmospheric humidity. Timber is hygroscopic, that is it will absorb moisture depending on the atmosphere when dry and correspondingly yield moisture to the atmosphere when wet, thereby attaining moisture content which is in equilibrium with the water vapour pressure of the surrounding atmosphere. Thus, for any combination of vapour pressure and temperature of the atmosphere, there is corresponding moisture content of the timber such that there is no inward or outward diffusion of water vapour. This moisture content is referred to as the equilibrium moisture content (EMC) (Dinwoodie, 2000). The curve relating the EMC of wood to the relative humidity at a constant temperature is called a sorption isotherm. It is observed that the sorption isotherm obtained when wood is losing moisture (desorption isotherm) does not coincide with the isotherm when wood is gaining moisture (absorption isotherm) - that is, moisture sorption exhibits the phenomenon known as hysteresis.

The EMC is therefore constantly changing, sometimes periodically and at other times sporadically, such as when wooden decking is exposed to rain (Skaar, 1988). Wood exposed to high humidity conditions or to liquid water during use may be subjected to biological deterioration. Kirk and Cowling (1984) said "Liquid water is needed in wood cells to provide a medium for diffusion of the enzymes or other metabolites by which wood-decomposing organisms digest the wood substance. If there is no liquid water present inside the wood cells, there will be no medium for diffusion, and therefore no biological decomposition except for certain insects of relatively minor importance. Thus as long as wood is kept below its fiber-saturation point, it will never decay." Kirk and Cowling (1984) indicated that few brown-rot fungi and subterranean termites could transport moisture from moist soil or other sources to dry wood to maintain their activity.

It is evident therefore, that wood subjected to moderately dry atmospheric conditions, which is well below 100 % humidity, will generally not decay. However, other deleterious effects may occur due to changes in moisture content associated with changes in atmospheric humidity and temperature. Hoadley (1980) pointed out that moisture (and humidity) related changes, particularly dimensional changes, in wood during manufacturing and use of consumer product are the single most important problem in wood utilization.

The EMC of wood in use is affected most dramatically by the relative humidity of the atmosphere to which it is exposed. According to Dinwoodie (2000), where timber is subjected to wide fluctuations in relative humidity, care must be exercised to select a species that has low movement values.

In buildings, wood is subjected to shrinkage, swelling, mould growth and rot if exposed to unfavorable environmental conditions. These phenomena are all related to moisture content and moisture conditions in a building. Rot may occur in wood which is in contact with liquid water for some time, while shrinkage, swelling and mould growth are mainly related to hygroscopic moisture. Wood and wooden materials during construction are exposed to changes in climate continuously. Outdoor climate changes occur throughout the day and night, and throughout the year.

Poor agreement has been reported between accepted numerical models and measurement of moisture content in wooden materials in structures (Geving and Thue 1996). In the sixties it was shown (Christensen 1965, Kelly and Hart 1970, and Skaar *et al*, 1970) that the rate of moisture sorption to equilibrium was dependent on the level of the surrounding relative humidity and the size of the increase or decrease in relative humidity. A fast sorption rate was found for situations with relatively low relative humidity and a fairly large increment. A much slower sorption rate was found for higher relative humidities and small increments. However, a two-step sorption rate was revealed for most situations. The fast and immediate sorption is fast, and according to traditional diffusion theory, the second rate of sorption is of a much slow character.

In Ghana, the monthly range of equilibrium moisture content of wood exposed to normal conditions outdoors but under cover, is 4.8 – 19.3 %. The mean annual values range from 9.8 % in Navrongo to 18.3 % in Takoradi (Ofori, J. 1991). Wood in service is exposed to both long term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air. Thus, wood is always undergoing at least slight changes in moisture content. These changes usually are gradual, and short-term fluctuations tend to influence only the wood surface. Moisture content changes can be retarded, but not prevented, by preventive coatings, such as varnish, lacquer, or paint. The objective of wood drying is to bring the wood close to the moisture content a finished product will have in service (Ofori, J. 1985). For demanding situations, where dimensional changes could obviously cause problems, the designer or user should carefully consider the moisture content of the lumber being used, the species, the conditions of use, and the amount of dimensional change that should be expected.

Rydell (1982) has done a study on the influence of the growth ring-width and density on properties which influences the durability of Swedish pine. One property that had been investigated was the absorption of water vapour from humid air. He concluded that the vapour absorption was slightly slower for specimens of higher density. On the other hand, the difference in moisture sorption of heart- and sapwood was just as big as the influence of density.

2.5.1 Fiber- Saturation Point

The fiber saturation point (FSP) is defined as the moisture content at which all the cell-cavity water has been removed but the cell walls were fully saturated with water.

The moisture content at FSP is important because of its critical relation to the dimensional, strength, electrical and other physical properties of wood (Stamm 1964).

The FSP can be estimated from sorption data by extrapolating to unity of values obtained at relative humidity near unity using computer generated models (Popper *et al*. 2001). Because of capillary condensation in cell cavities the FSP in reality corresponds to a relative vapour pressure of 0.995 (Stamm, 1964). The FSP is a valuable reference point for comparing the hygroscopic properties of wood (Cooper, 1974).

2.6 Density

Density is the one single factor used in the determination of most strength properties (Hoadley, 2000). The density of wood is defined as the relationship between the mass and volume of the specimen. Dinwoodie (2000) explains that density, like many other properties of timber, is extremely variable; it can vary by a factor of 10, ranging from an average value (at 12 % moisture content) of 176 kg/m^3 for balsa to about 1230 kg/m^3 for lignum vitae. Balsa, therefore, has a density similar to that of oak, whereas lignum vitae has a density slightly less than half that of concrete or aluminum. The values of density quoted for different timbers are merely average values. Each timber will have a range of densities reflecting differences between the pith and outer rings, and between trees on the same site. Thus, for example, the density of balsa can vary from 40 to 320 kg/m^3. The density of wood therefore, varies with cell size, cell wall thickness, and the volume proportion of cells of a given type. It affects wood shrinkage and swelling, machinability, surface texture and micro smoothness, gluability, penetrability of fluids and gases, and in other respects, governs the degradation of wood by chemicals, fire, and microorganisms. In particular, the strength of wood and its stiffness is affected by changes in the density.

Density is not an independent predictor of the strength of wood because the overall behavior of wood is much influenced by its moisture content. However, it is possible to get more information about the nature of a given wood sample by determining its density than by any other single property. Since density is dependent on the moisture content in the wood, it is therefore important to give the moisture content at which the density has been determined. In this thesis the oven dry density and air dry densities have been used. The oven-dry density was measured after the test specimens have been dried in an oven at 105^{0}C until no weight change was seen. The air dry density was however measured after the samples have been air-dried in till the specimens have a constant weight. The use of relative density as a single indicator of the strength and stiffness of wood can be misleading because wood of the same relative density can have a wide range of bending strengths due to other factors such as fibril angle and grain length.

2.7 Mechanical Properties

Wood may be described as an orthotropic material, that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial and tangential. According to Green and Evans (1987), mechanical properties most commonly measured and represented as strength properties for design include modulus of rupture in bending, modulus of elasticity parallel to the grain, compressive stress parallel and perpendicular to the grain, and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain, and hardness. Strength properties less commonly measured in clear wood include torsion, toughness, rolling shear, and fracture toughness. Other properties involving time under load include creep, creep rupture or duration of load and fatigue.

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

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

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

2.8 Published Works on Some Lesser-Utilized Wood Species

Ocloo (1976) did some work on the natural resistance of the wood of *Terminalia ivorensis to* fungi and termites. Ocloo and Usher (1979 and 1980) also did extensive work on the resistance of 85 Ghanaian hardwood timbers to damage by subterranean termites. In that work 8 of the species under study in this thesis were included. Ocloo (1985) worked on stress grading West African timbers. Kumi-Woode (1996) did some work on 14 less-utilised species; including *Amphimas pterocarpoides* (Yaya), *Antiaris toxicaria* (Kyenkyen) and *Canarium schweinfurthii* (Bediwonua). The work was done under laboratory conditions. He found out that *Amphimas pterocarpoides* (Yaya) was not durable when subjected to fungal attack. Oteng-Amoako et al (1998) worked on the identification of 14 lesser utilized species Gyimah-Boadi (1999) also worked on the treatability and durability of some of the less utilized species including *Antiaris toxicaria* (kyenkyen) and *Petersianthus macrocarpus* (Esia). He found out that though *Antiaris toxicaria* is not durable it is permeable so can be impregnated to enhance its durability. *Petersianthus macrocarpus* was found to be resistant to treatment. Nyarko (1999) also exposed *Amphimas pterocarpoides* (Yaya) to termite attack and found that, its durability was highly increased when treated with creosote and moderately high when untreated. Huang *et al*. (2004), who worked on some less-utilized Ghanaian hardwoods, reported that *Sterculia rhinopetala* (Wawabima) was very durable after 12 weeks exposure to white rot and brown rot fungi.

Okoh (1977) worked on water sorption of some Ghanaian species, of which, *Petersianthus macrocarpus,* was include in his work. By comparing the European species with the Ghanaian species, he concluded that at higher temperatures, the European species were more hygroscopic. Oteng-Amoako *et al*. (2008) recently provided a macroscopic identification manual for 100 tropical African species including mostly less utilized species.

Most of the earlier works on the Ghanaian woods were on the primary well known species including a few of the lesser utilized species. The anatomical work carried out by Oteng-Amoako et al. (2008) was to aid in the identification of the wood macroscopically while this study sought to use both the microscope and scanning electron microscope to help understand the woods of the nine LUS better.

Wimmer (1991) reported that sorption/strength properties were mainly influenced by cell-wall thickness. This study set out to find out whether some anatomical properties had influence on properties such as durability and strength. The weight and strength properties of wood, together with the behavior of wood in response to weather, chemical treatment, fire, or microbial organisms, are influenced greatly by the moisture content and mass of wood tissue per unit volume (its density).

Simpson and TenWolde (1999) reported that the versatility of wood was demonstrated by a wide variety of products. This versatility was a result of a wide spectrum of desirable physical characteristics or properties that the many species of wood possess. In many cases, more than one property of wood was important for an end product. For example, to select a wood species for a product, the value of appearance, such as texture, grain pattern, or color, may be evaluated against the influence of characteristics such as machinability, dimensional stability, or decay resistance. Wood exchanges moisture with air; the amount and direction of the exchange (gain or loss) depend on the relative humidity and temperature of the air and the current amount of water in the wood. This moisture relationship has an important influence on wood properties and performance. Anatomical features and structures also play a very important role in our understanding of the behaviour of wood species. This thesis discusses the physical properties of most interest in the use of wood products in external applications and the interrelationships that is at play that causes the wood to behave as it does when utilized for a particular end-use.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

According to Oteng-Amoako *et al.* (2006), in conformity with recent publications on timbers of Ghana, the basic nomenclature of scientific and family names follows that of Hall & Swaine (1981). Each species is first identified by its botanical name (genus and specific name) with abbreviated name of authority, followed by the local name. The materials used were: Wood samples of *Albizia ferruginea (*Guill. *&* Perr.*)* Benth (Awiemfosamina), *Amphimas pterocarpoides* Harms (Yaya), *Antiaris toxicaria* Lesch (Kyenkyen), *Blighia sapida* K. D. Koenig (Akye), *Canarium schweinfurthii* Engl. (Bediwonua), *Celtis zenkeri* Engl. (Esa), *Cola gigantea* A.Chev. (Watapuo), *Petersianthus macrocarpus* (P.Beauv.) Liben (Esia), *Sterculia oblonga* Mast. (Ohaa) and *Sterculia rhinopetala* K. Schum (Wawabima). *Tectona grandis* was added as a reference species in the natural durability test. Some European species namely *Albies alba* (Fir), *Picea albies* (Spruce), *Fagus sylvatica* (Beech) were also added for comparison in the sorption and capillarity test. They were obtained from the wood library of the University of Applied Science, Biel in Switzerland.

3.1.1 Sample Origin and Conversion

Twenty fresh trees were felled in the Fenaso Nkwanta Forest which is 60 km south of Kumasi, near the gold mining town of Obuasi in the Ashanti Region of Ghana. The trees were first identified by a technical officer from the Forestry Department and a Swiss Wood Technologist who worked on the identification of these less utilised species with Dr. Oteng-Amoako of the Forestry Research Institute of Ghana. Leaves and seeds from the trees were collected and sent to the laboratory in Kumasi for the confirmation of the field identification using the field guide to the forest trees of

Ghana by Hawthorne (1990 and 1994). For each species, two trees of diameter greater than 50 cm at breast height and lengths of 15 m were felled. Discs of about 10 cm thickness were cut at breast height of each tree for anatomical investigations when the trees were harvested. Care was taken not to include the pith area in all the samples prepared for the tests. The clear bole of each tree was then cut into three logs each of length 5 m. These were sawn into required lumber at Modern Wood Processing Factory in Kumasi and brought to the Wood Science workshop of the Faculty of Renewable Natural Resources (FRNR) where they were stacked and air dried for three months to a moisture content of about 15-35 %. Figure 3.1 depicts the sawing pattern of a log and the parts sawn. All parts of the cross section labeled B (thickness = 62 mm) were used for determining the mechanical properties. Between 10 and 16 beams were obtained for each of the ten timber species. The cross section labelled A (thickness = 40 mm) was used to prepare samples for the graveyard test as well as for hygroscopicity and capillarity tests.

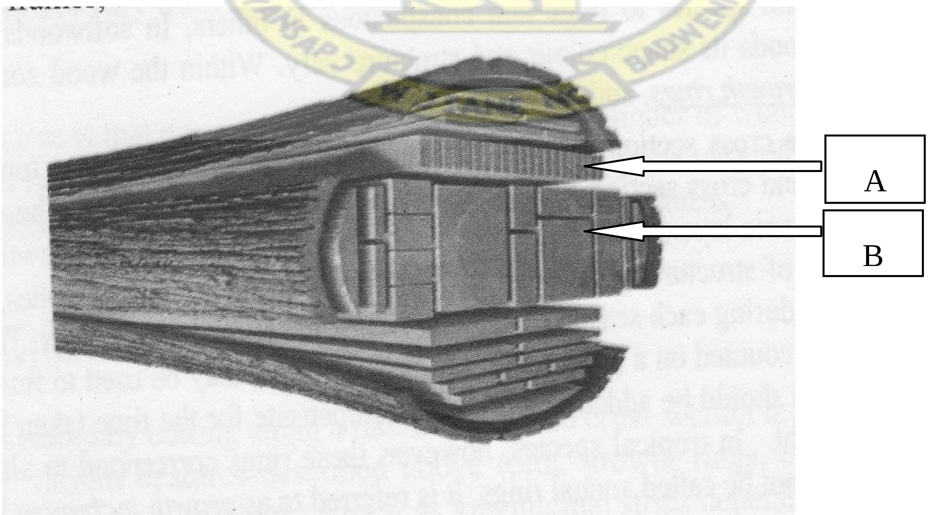


Figure. 3.1 Log showing a diagramatic sawing pattern

A= Section used for durability tests

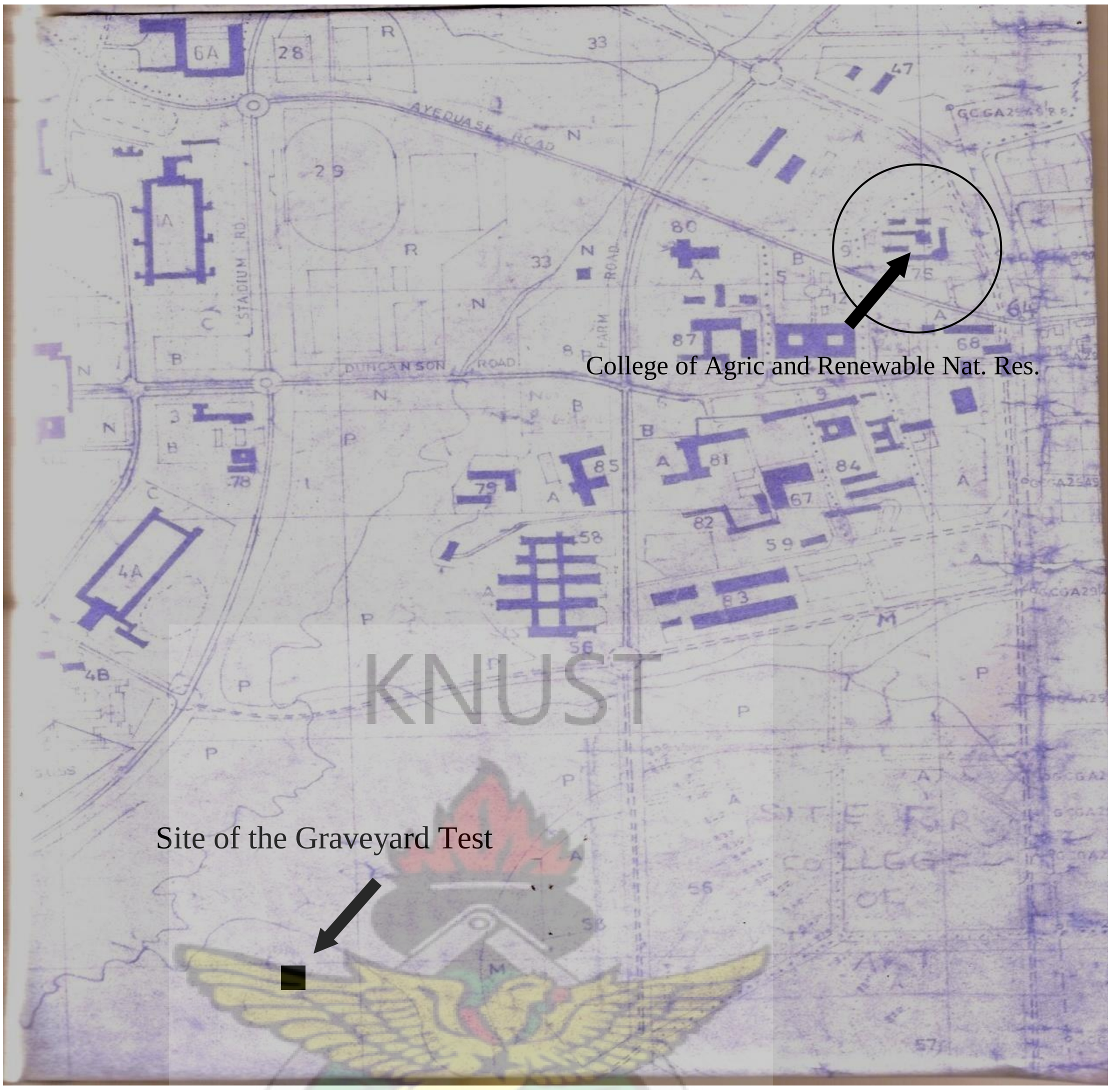
B= Section for bending tests

For the durability test (graveyard), thirty specimens (15 sapwood samples and 15 heartwood samples) for each of the 10 species were cut and sawn in the dimensions 25 x 12.5 x 250 mm. Teak (*Tectona grandis*) was included as a reference species. In all there were a total of 330 samples. Additionally, 324 samples comprising 300 wood samples of the ten lesser utilized wood species prepared in dimensions of 3 x 3 x 3 cm and 24 wood specimens each of the European species Fir, Beech and Spruce were also prepared in dimensions of 3 x 3 x 3 cm for the absorption and adsorption tests. 10 – 15 beams were prepared for each of the ten wood species for the bending tests. All test pieces were sawn and planed to the appropriate size, and they were lightly sanded with medium or fine sandpaper so as to remove all rough edges. Test pieces with cracks or other defects were rejected and not included in the experiments.

3.1.2 Description of Experimental Area

The test field was on KNUST Kumasi campus. The main vegetation formations as described by Benneh *et al*. (1990) are: coastal savannah, coastal strand and mangrove, evergreen forest, semi-deciduous forest and savannah. Kumasi, the location for the field test, is of the semi-deciduous forest type. The town is within the plateau of south-west physiological region, which ranges between 250 and 350 metres above sea level. The metropolis has the wet sub-equatorial type of climate. Both temperature and humidity are moderate. The soil type is forest ochrosol (www.ghanadistricts.com). According to Kumi-Woode (1996), Kumasi has a high decay index with a very high decay hazard. The soil of the test area is of medium to fine-texture with a pore space varying from 40 to 60 %. The area is also home to a lot of termitarian mounts. The ecology of the termite species in Kumasi has been described by Usher (1975), and some of the species attacking timber as given by him are *Coptotermes intermedius* Silvestri from the family Rhinotermitidae (Coptotermitinae), *Amitermes evuncifer* Silvestri from the family Termitidae (Amitermitinae), *Ancistrotermes* spp. (mostly *A. crutifer* (Sjostedt) but with the occassional *A. guineensis* (Silvestri) from the family Termitidae (Macrotermitinae), *Macrotermes* spp. (both *M. Bellicosus* (Srneathman) and *M. subhyalinus* (Rambur) were present, but the latter was more frequent), *Microtermes subhyalinus* Silvestri, *Odontotermes pauperans* (Silvestri), *Pseudacanthotermes militaris* (Hagen), and *Nasutitermes latifrons* (Sjostedt) from the family Termitidae (*Nasutitermetinae*). Before tests were conducted the area was a farm scrub, having been cultivated and abandoned. The scrub re-growth was mostly cut down, leaving scattered trees and bushes so that access to the whole site was simple and so that the majority of the site was shaded from the sun for most of the day. By the time that the experiments were begun there was an almost complete ground cover of grasses, and during the experiments there was little visual change in the test site. Figure 3.2 shows a map of KNUST showing the test site.

The sample preparation was done in the Wood Science Workshop of the Department of Wood Science and Technology of the Faculty of Renewable Natural Resources (FRNR). The weighing of samples was done in the Pathology Laboratory of FRNR. Since the natural durability of the wood samples were been sought, the wood samples were exposed to biodegraders -specifically termites in a termite's prone area on the FRNR farm, which permitted easy, and regular monitoring of test samples.



Source: University master plan G. 50 from Development Office

Fig. 3.2 Site map of KNUST with the location of the graveyard

3.2 Methodology - Sample Preparation

3.2.1 Natural Durability

The boards prepared from the logs obtained from the forest were later cut into lumber stripes of 40 x 40 x 1000 mm and later sawn and sand papered into specimen dimensions of 25 x 12.5 x 250 mm. Clear wood specimens (without defects) were used. There were 30 replicates of each species (15 sapwood samples and 15 heartwood samples), thus 300 samples were used for testing. Additionally, 30 replicates of *Tectona grandis* (Teak) as reference material were prepared and also sawn into specimen dimensions of 25 x 12.5 x 250 mm. All the samples were randomly selected. All specimens were first weighed using the electronic balance, tagged and weighed again. Their air-dry densities were determined by dividing their weights by their volume by the displacement method. The water displacement method is a technique used to measure the volume of objects by calculating how much water it displaces, when it's placed into a sample of water. The volume of the water displaced can then be measured, and from this the volume of the immersed object can be deduced (the volume of the immersed object will be exactly equal to the volume of the displaced water).

In the field, the samples were planted to half their length in an even distribution, according to a grid of 15 x 22 (Field pattern is shown in appendix 2.1) on the demarcated termite prone site (Figure 3.3). The field test was carried out for 6 months from beginning of June to beginning of December, 2006.

Figure 3.3. Stakes inserted in the graveyard for durability determination in accordance with (EN 252 (1989) in a 15 x 22 grid and a spacing of 50 cm between stakes.

According to Eaton and Hale (1993), regular inspection of stakes was normally done every 6 or 12 months. This can however be modified depending on the country and geographical area. In this study, however, the stakes were inspected bimonthly and data collected accordingly; after every two months, all the samples were harvested, thoroughly cleaned with a brush, air dried, tested on hardness and visually inspected for deterioration and weighed to the nearest 0.01g to find out the degree of degradation and then carefully re-installed in their original position. The percentage weight loss was calculated as follows:

$$\textit{Percentage weight loss} = \left(\frac{\textit{Initial weight} - \textit{final weight}}{\textit{Initial weight}} \right) \times 100\ \%$$

The percentage weight loss by a sample was an indication of its level of preservation. Visual rating was also used to grade the wood samples.

3.3 Hygroscopicity of Wood (Capillarity and Sorption)

This part of the work was done in the laboratory of the University of Applied Science for Architecture, Civil and Wood at Biel in Switzerland from October 2006 to February 2007. To find out how the wood samples relate to water, the experiment was in two parts: absorption which is the uptake of water by wood when subjected to water in the form of rain and hygroscopicity how they adsorb moisture in a given environment. Samples of the ten wood species and *Tectona grandis*, were prepared in Kumasi, Ghana to dimensions of 3 cm x 3 cm x 3 cm. Some European species; *Albies alba* (Fir), *Fagus sylvatica* (Beech) and *Picea abies* (Spruce) also of the same dimensions were also added for comparison. The softwood species were used because of availability and differences in density. In all there were 324 wood specimens. They were acclimatized in a conditioned chamber in accordance with DIN 50014 (1985). That is, a climate with a relative humidity of 50 % and a temperature of 23° C.

Figure.3.4 Climate chamber for the sorption experiment (arrowed)

Model	***Weiss 500 SB***
Temperature range	+10 °C to +95 °C
Humidity range	15 % to 98 % R.H.
Chamber dimension	850x795x800mm (BxDxH)

3.3.1 Absorption Test

The standard used was a modification of ISO 15148 (2002). The experimental set up adopted the set up by Markus Jakob in his diploma research work at the ETH Zürich (2004). A basin made of stainless steel was filled with conditioned water (23°C). The water was untreated and had a pH of 6.98. It was pigmented with standard blue ink (Pelikan 4001, 1:20 - ink: water) to make water uptake visible. The water level was held constant at +/- 2 mm by an installation: A bottle filled with the same water was held upside down over the basin with its opening exactly at the ideal water level. As soon as water was lost during the testing and it causes a level decrease, the bottle takes up air and water flows into the basin until the level was stable at the correct level again. The parameter measured was the weight change and thus water uptake of the samples when in direct contact with water for a short time (in this experiment 5 minutes). 30 samples at a time were placed on the grid and immersed by 5 mm into the water. They were held in position by a heavy plastic board. The grid helps to move all samples at the same time in and out of the water.

3.3.1.1 Test Procedure

The conditions in the laboratory were kept constant as stated in DIN 50014 (1985): 23°C and 50 % relative humidity. All wood specimens were conditioned until the daily weight changes were less than by 0.1 %. The air was circulated inside the laboratory to maintain this condition. The samples were conditioned under standard climate (ISO 12570: 2000) for 3 weeks. They were weighed and then placed on the grid. They were immersed 5 mm below the surface of water in the basin. After 5 minutes they were taken out, cleaned of adhering water and weighed again. Afterwards they were reconditioned under standard climate (ISO 12570: 2000) for 3 weeks for density measurement.

Water uptake: To compare the uptake by the different species, the amount of water taken up was calculated as weight change:

$$M_{\text{change}} = M_{\text{test}} - M_{\text{cond}}$$

Where M_{test} = weight of sample after the test

$M_{cond.}$ = conditioned weight of the sample before the test.

M_{change} = weight change, which is the amount of water taken up by the sample

Relative water uptake is given as M_{change} in relation to M_{cond}.

$$\text{Rel. Change} = \frac{M_{change}}{M_{cond.}} \times 100$$

Uptake in relation to volume:

Rel. Change/vol. = rel. Change * ρ_u

Where ρ_u = green density at standardised climate

Density calculated as defined in DIN 52 183 (1977) for oven dry density:

$\rho_o \sim 0 = Mo/Vo$

and according to DIN 52 182 (1976) for green density as:

ρ_u = Mu/Vu...(Equation 1)

Where Mo = oven dry weight of samples

Mu = weight of samples at moisture content u

Vo = volume at oven dry (volume determined after the samples have been oven-dried)

Vu = volume at moisture content u

Mu is measured after acclimatization in standard climate (50/23) until the weight is constant. Measurements were taken every 24 hours.

For the volume determination water would have been a very convenient liquid to use, as it's density is 1 g/cm^3. Pretests showed that the samples absorbed the water so quickly, that it was not possible to measure their volume. Sunflower oil proved to be a suitable alternative. It was not that quickly absorbed by wood. The density of the oil had to be determined with a pyknometer. It was conditioned under standard climate and the weight of 100 cm^3 was taken. The density of the oil under laboratory conditions was 0.9165 g/cm^3. The set up (Figure 3.5) was used to determine the volume of the samples.

The formula used was:

$$F_{lift} = V_{body} * \rho_{liquid}$$

$$V_{body} = m/\rho_{liquid} \text{..(Equation 2)}$$

Where Flift = weight change through immersion of the sample

V_{body} = volume of the sample

ρ_{liquid} = density of liquid

m = mass of wood

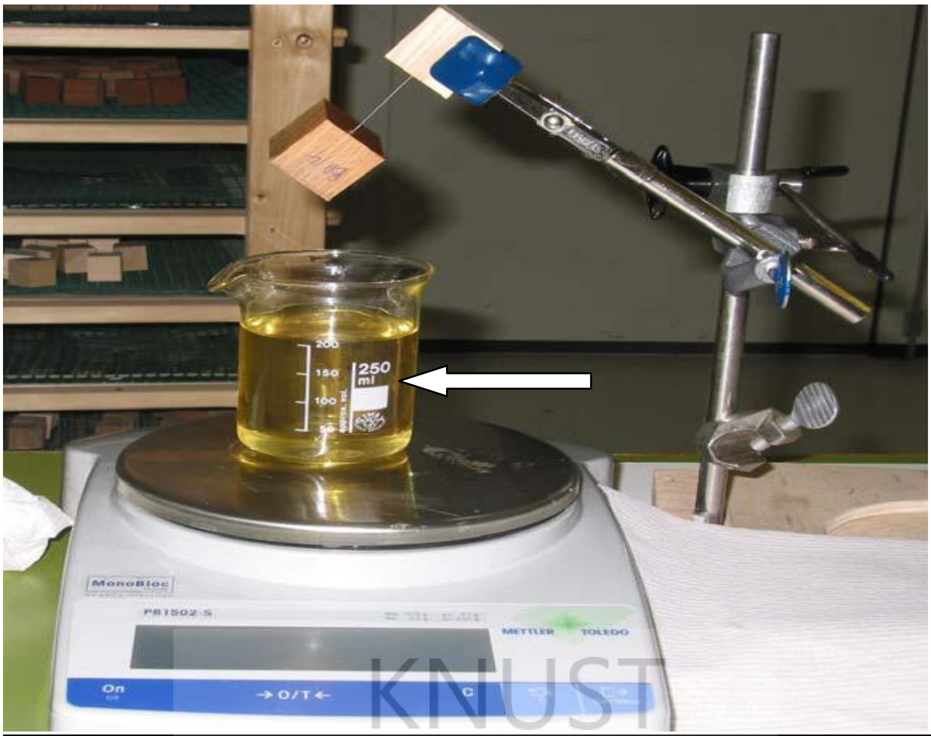


Figure 3.5 Set up for volume measurement by displacement method using sunflower oil (arrowed)

Air dry density:

The samples were conditioned under laboratory conditions (23°C and 50 % relative humidity). Their weights were taken. The samples were pinned to the holding device and immersed into the liquid. The balance shows the weight of the displaced volume of the sample. The air dry density determined under laboratory conditions (23°C and 50 % relative humidity) was then calculated with the formula in equation 1.

Oven dry density:

The samples were dried in the oven at 103°C. Their weights were taken. Volumes were determined as given in equation 2.

3.3.2 Determining Water Sorption Capacity

Adsorption of the wood species was determined. Sixteen randomly sampled specimens of each of the ten species (heartwood and sapwood) with dimensions 3 cm x 3cm x 3cm were exposed at various relative humidity conditions of 30 %, 45 %, 60 %, 75 % and 90 % in a temperature and humidity controlled climate chamber (Fig.3.4) at a temperature of 25^{o}C according to DIN 52182 (1976). Specimens of *Tectona grandis*, *Albies alba*, *Fagus sylvatica* and *Picea abies* of the same dimensions were also added as control. There were a total of 324 wood samples. Internal wood temperature and humidity were measured with datalogger. Samples were considered to have reached equilibrium at any given humidity when the daily weight changes were less than 0.1 mg according to DIN 52183 (1977). After the last measurements of the weight changes the samples were dried at 103^{0}C until there was a constant weight. The equilibrium moisture contents (EMC) were calculated on the basis of the oven-dried weight of the samples: The formula used was:

$$M = \frac{(w - w_o)}{w_o} \times 100\%$$

Where W= mass of moist wood,

W_o= oven dry mass of wood.

M= moisture content of the wood

3.4 Determining Bending Strength

This test was conducted at the Civil Engineering Laboratory of Kwame Nkrumah University of Science and Technology together with our Civil Engineering counterparts (part of this project was corroboration between the department of Civil

Engineering, KNUST, and department of Wood Science, KNUST and the University of Biel in Switzerland) between May and June, 2006. Ten to fifteen test specimens depending on the size of the bole, each of the ten species with dimensions 50 x 150 x 2900 mm were randomly sampled and loaded to failure by the three point load according to EN 408 (2003). The samples were obtained as shown in Figure 3.1. The test arrangement used (Figure 3.6), was in agreement with European testing standard EN 408 (2003) with two point loads acting on the third point. According to testing standard EN 384 (2004) the worst defect possible to test was placed in the centre between the point loads and located randomly with regard to the compression and tension side of the board. The position of the worst defect was determined based on visual inspection of the boards. After the MOE-values had been determined, the boards were tested in bending to failure. For determination of moisture content ω and density ρ, small specimens were cut out close to the cross sections where failure occurred in the boards. In accordance with the testing standard EN 408 (2003) the test pieces were conditioned at 20 °C and 65 % relative humidity. It should be noted that the timbers under study had average moisture contents of 51 % for *Albizia ferruginea*, 16 % for *Amphimas pterocarpoides*, 16 % for *Antiaris toxicaria*, 29 % for *Blighia sapida*, 30 % for *Canarium schweinfurthii*, 29 % for *Celtis zenkeri*, 19 % for *Cola gigantea*, 29 % for *Petersianthus macrocarpus*, 33 % for *Sterculia oblonga*, and 44 % for *Sterculia rhinopetala* at testing.

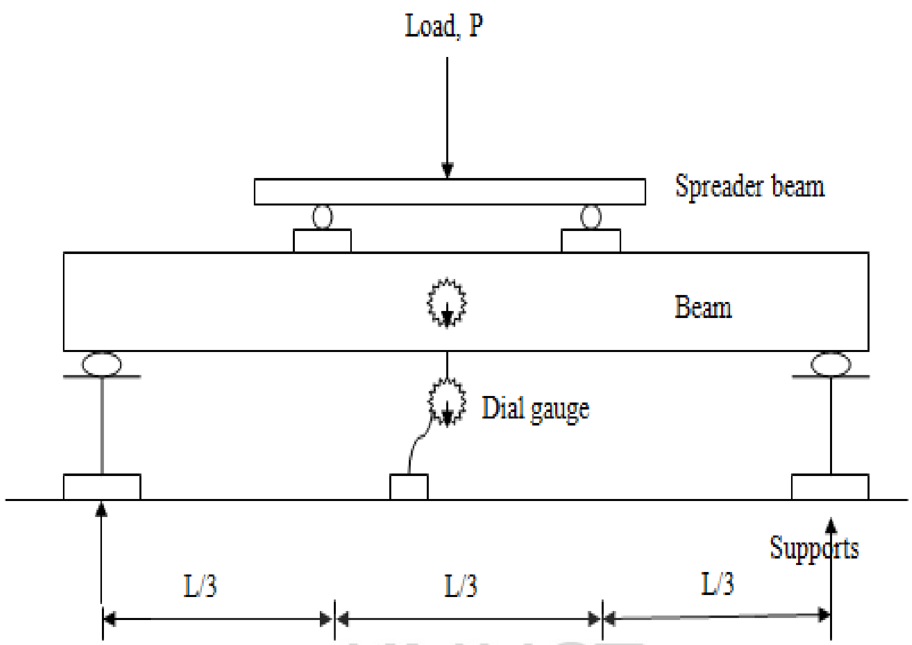


Figure 3.6 Test arrangements for determination of bending strength.

L is the span

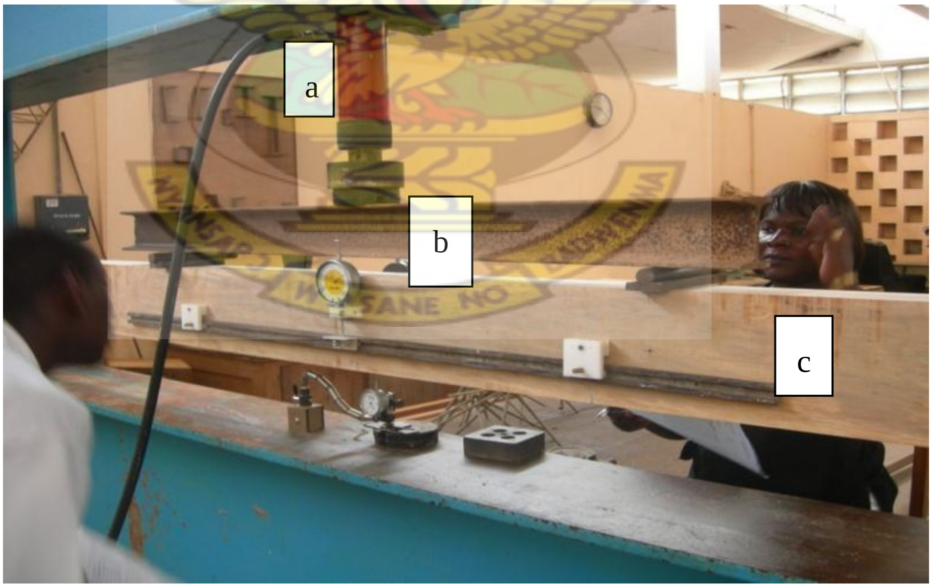


Plate 3.1 Setup for the bending test

a= hydraulic machine supplying load

b=spreader beam

c=test beam

A hydraulic test machine with static loading capacity of 100 kN was used. The load cell head had a least measurement of 2 kN. Loads were applied symmetrically. The loading was continued until the final failure of the beam. The various deflections were measured by dial gauges. Duration of bending tests to failure ranged between 8 to 14 minutes. The method of ISO 3131 (1975) was used for the density measurement for the mechanical test. The density measurement was based on oven-dry weight and volume at the moisture content during the test.

3.5 Anatomical Investigations

Three species out of the ten were selected for anatomical tests based on their performance in the field and bending strength tests. They were *Albizia ferruginea, Blighia sapida* and *Sterculia rhinopetala*. The anatomical study was carried out in the wood anatomy laboratory of University of Applied Science in Biel, Switzerland in November, 2006. Discs 10cm thick were cut from a height of 1.30 m from the butt of the trees (Figure 3.7). From each disc samples of 1cm x 3cm were taken from the heartwood portion. They were weighed and their densities determined by the oven dry methods. The samples were then softened by first saturating with water and later soaking them in mixture of ethanol and glycerol (1:1) in labeled containers for an average period of about 20-30 days. Thin sections, 20 – 30 µm thick produced on a Leica sliding microtome were first washed in water and then stained in 1 % safranin in 50 % ethanol solution for about 10-20 minutes. After staining they were washed in water and dehydrated in increasing concentration of ethanol: 30, 50, 70, 85, 90 and 100 % (Figure 3.8). After dehydration, they were permanently mounted in Canada Balsam. Slides were examined using a Leica DMLM light microscope, and photographs taken using a Leica DFC 320 digital camera (Figure 3.9) fitted to it. Photomicrographs produced were then analyzed with software Leica IM 1000

Version 4.0 Release 132 which enables measurements to be made. Vessel diameter was obtained by measuring 30 randomly selected pores, then taking an average. The frequency of vessels per mm^2 was calculated by counting the number of vessels in thirty 1-mm^2 fields, then taking an average. The micrographs were also analyzed using the stereological technique described by Ifju (1983) and Steele *et al*. (1976) for the proportion of the tissues. Thirty randomly selected micrographs for each tissue studied were used for the study and then the average taken. Dots grids were used to determine area fractions (P_p) of anatomical elements and oriented segments of predetermined length were used to determine the number of elements per unit length of the test line in the radial and tangential directions (NL_R, NL_T) (Figure 3.10). Standard areas were used to determine the number of elements per unit area (N_A). These basic counts were then used to derive other parameters such as proportion of elements in percentages. Splinters were also taken from the discs and macerated in a solution of equal parts of Acetic acid and hydrogen peroxide and heated in an oven at about 65^{o}C for 72 hours.

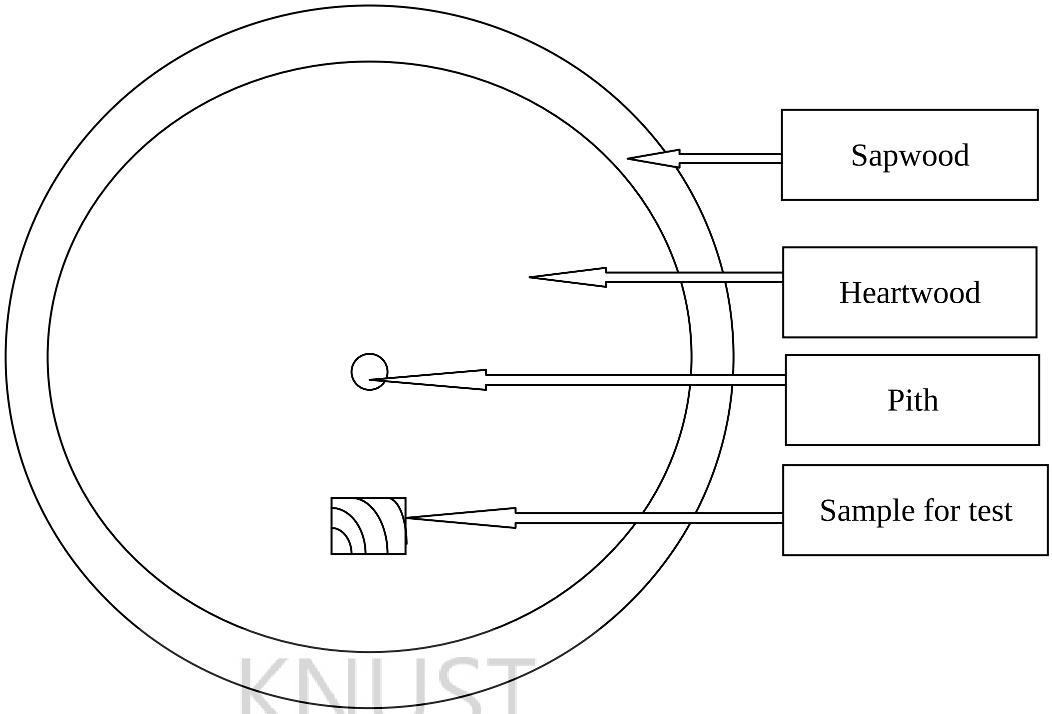


Figure 3.7 Schematic illustration showing the location of heartwood and sapwood samples in the disc.

Features such as fiber length, double fiber wall thickness were also measured using the Leica light microscope and the software earlier described in the text. Anatomical features studied were fiber length, double fiber wall thickness, fiber proportion, vessel diameter and proportion, rays and axial parenchyma proportions.

Figure 3.8 Jars containing distilled water, safranin, and alcohol in graded strengths used to stain and dehydrate during sectioning and slides preparation

Figure 3.9 Photomicrograph investigations using slides viewed under the microscope and captured on the computer

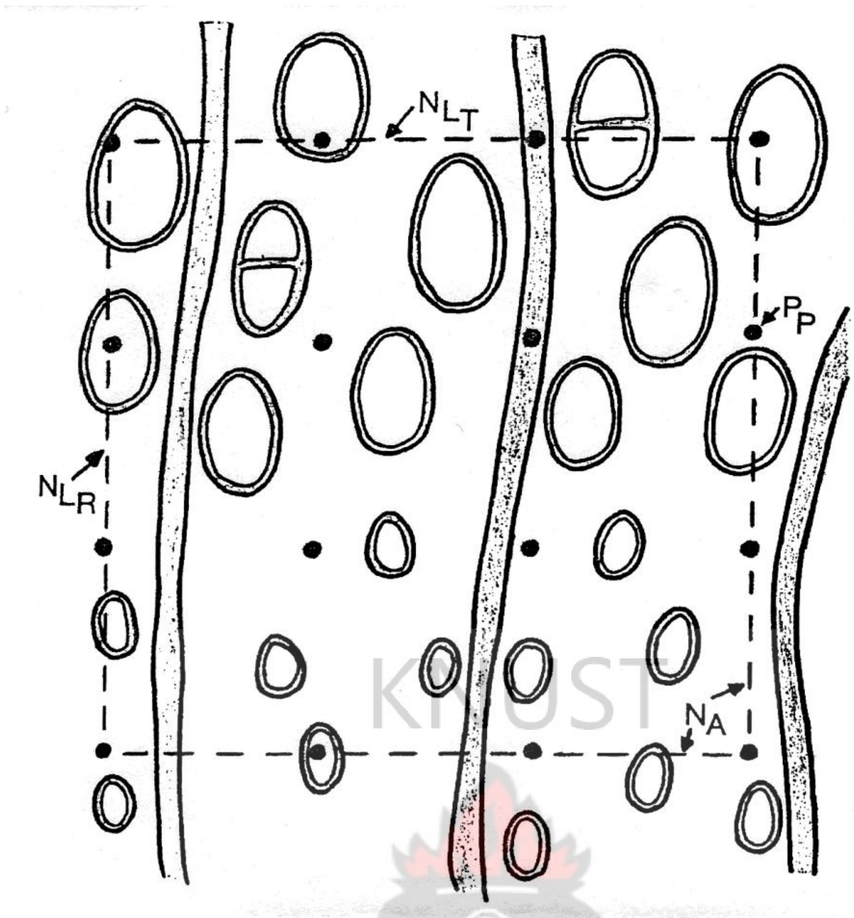


Figure 3.10 Counting grid used for stereological counts taken from Beery *et al*. 1982. P_p is area fractions of anatomical elements; NL_R and NL_T are the number of elements per unit length of the test line in the radial and tangential directions and N_A is the number of elements per unit area.

3.5.1 Preparation of samples for the Scanning Electron Microscope

Small samples of wood of three species namely *Albizia ferruginea*, *Blighia sapida* and *Sterculia rhinopetala* were thoroughly impregnated with an alkyd or acrylic resin and then allowed to cure (Taneda *et al*. 1979; Smulki and Cote 1984). The resin was known to be resistant to acids such as 72 % sulfuric acid which was used to remove the cellulose and hemicelluloses from the sample, and to a 50: 50 mixture of 10 % chromic and 10 % nitric acids which dissolve the lignin. After careful washing with distilled water, the residue was a negative or cast of the openings in the wood which had been penetrated by the resin. After careful separation of the very small casts, they were dehydrated, mounted on a specimen stub, with a fixative solution of formalin. It was then coated with a thin layer of gold in a sputter coater. The prepared sample was then placed in the sample chamber of a scanning electron microscope with a spatial resolution of 8.0 nm at 5 kV. SEM photomicrographs were produced and analyzed.

3.6 Statistical Analysis

A matrix of student's t-test was applied to test whether there was any significance difference between sapwood and heartwood. Comparative analysis of weight loss rating and visual rating (BS7282: 1990, EN 252: 1989) was used. The codes used for the visual rating were:

0 – no attack

1 – slight attack

2 – moderate attack

3 – severe attack

4 – failure

The ratings used for the weight loss according to Eaton and Hale (1993) were:

0 – 5 % represents very durable

6 – 10 % represents durable

11 – 40 % represents moderately durable

41 – 100 % represents non-durable

According to Ishengoma and Nagoda (1991), it is necessary to adjust strength values obtained at different moisture content levels before any comparison can be made. So the values obtained for the bending test were adjusted to 12 % moisture content using the equation:

$$\text{Ultimate static strength @12\% MC} = \text{the strength at the MC} + \alpha * (W - 12)$$

Where α is the correction factor for moisture content (MC) ≈0.04

W is Moisture content (MC) at the strength in this case bending strength

The correlations between bending strength, water sorption, durability and the density of each wood species were computed using Minitab statistical software.

Density is the single most important property of wood (Hoadley, 2000). Most of the time simple regression is used to find the relationship between anatomical properties. However, in this study multiple regressions were used to find the relationship between anatomical features and density and to predict which features influence the density of a species the most.

CHAPTER FOUR

RESULTS

4.1 Natural Durability

The natural durability of the eleven wood species was determined in the graveyard tests. The tests lasted for 24 weeks. The mean percentage weight loss by Teak (*Tectona grandis*), the reference species, was also determined. Table 4.1 shows the mean percentage weight loss of sapwood and heartwood with standard deviations. The visual rating of attack by fungi and termite on a scale of zero to four and the durability also on a scale of zero to hundred were presented. According to Table 4.1 *Antiaris toxicaria*, *Canarium schweinfurthii* were completely destroyed while *Celtis zenkeri* and *Cola gigantea* lost more than 60 % of their weight and therefore rated non-durable. *Sterculia oblonga* was severely attacked with a visual rating of three and was also rated non-durable. *Amphimas pterocarpoides*, *Blighia sapida, Tectona grandis* with visual rating of two were moderately attacked and rated moderately durable. Even though the sapwood was slightly attacked *Albizia ferruginea was* rated very durable. *Petersianthus macrocarpus* suffered no attack and was rated very durable. *Sterculia rhinopetala* was also slightly attacked according to the visual rating of attack with the sapwood rated moderately durable and heartwood durable. *Tectona grand*is which was added as a control species was moderately attacked with the sapwood found to be non-durable and the heartwood moderately durable. The information given in Table 4.1 has also been graphically represented in Figure 4.1 showing the variabilities. Plates 4.1a to d depict the extent of destruction in some of the samples during the exposure to termites.

Plate 4.1a Heartwood and sapwood of *Celtis zenkeri* showing about 50 % destruction by the 16th week

Plate 4. 1b Sample of *Canarium schweinfurthii* heartwood after 16 weeks of exposure showing 80 % destruction.

Plate 4.1c Samples of *Antiaris toxicaria* showing 95 % destruction by the 16th week

Plate 4.1d Samples of *A. ferruginea* and *P. macrocarpus* by the 16th week.

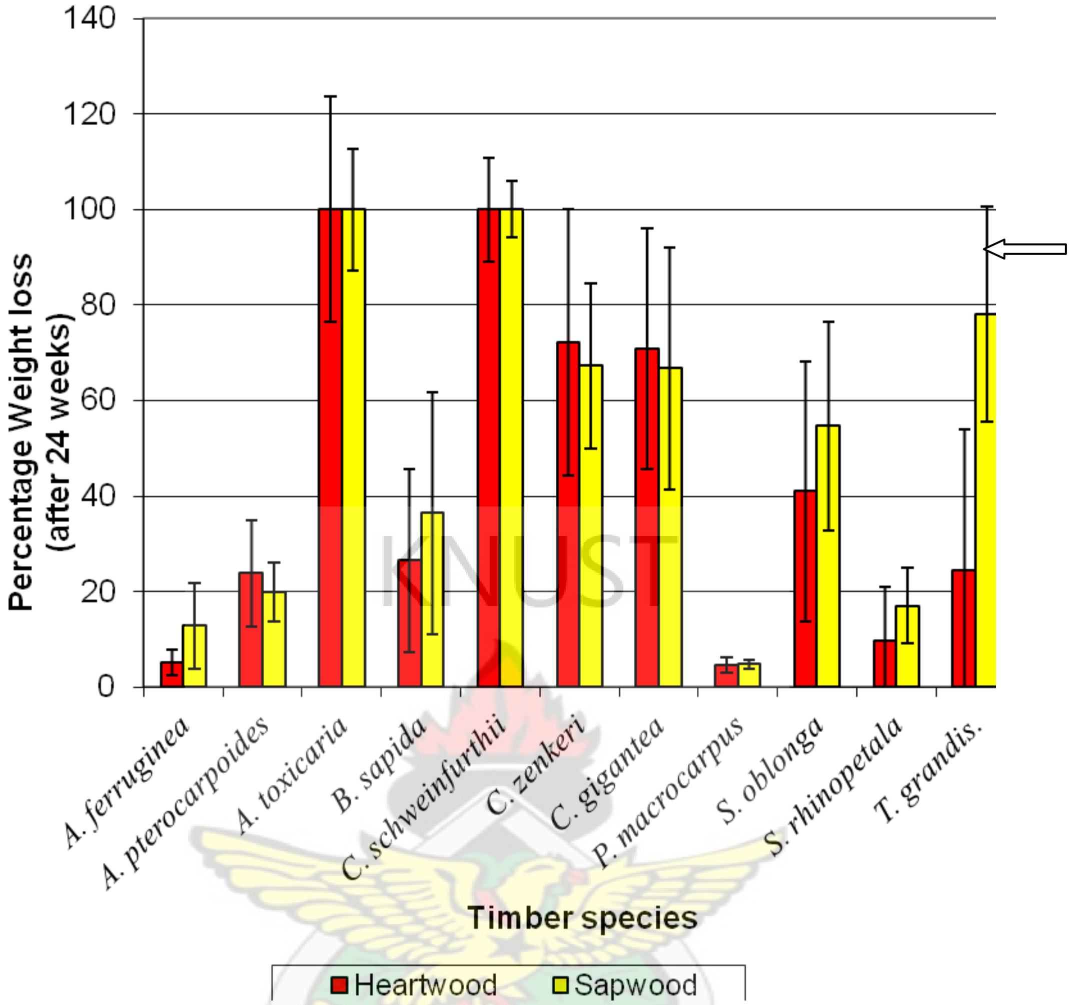


Figure.4.1 Weight loss of ten lesser utilised Ghanaian hardwood species and Teak (*Tectona grandis*) after exposure for 24 weeks.

*Bars showing variation within species (arrowed)

Table 4.1. Visual rating of attack, mean percentage weight loss and their standard deviations (STD) after 24 weeks of exposure and the durability rating of ten Ghanaian wood species and Teak (*Tectona grandis*).

Wood species	Visual rating of attack (H+S)*		Mean % weight loss (H) and STD	Mean % wt loss (S) and STD	Durability** Heartwood (H) Sapwood (S)
Albizia. ferruginea	0	1	5.15 (2.7)	12.89 (8.9)	(H) very durable, (S) moderately durable
Amphima pterocarpoides	1	2	23.95 (11.1)	19.98 (6.1)	(H+S)moderately durable
Antiaris toxicaria	4	4	100	100	(H+S) non- durable
Blighia sapida	2	2	26.57 (19.2)	36.44 (25.2)	(H+S) moderately durable
Canarium schweinfurthii	4	4	100	100	(H+S) non- durable
Celtis zenkeri	3	4	72.21 (27.9)	67.28 (17.3)	(H+S) non- durable
Cola gigantean	3	4	70.88 (25.3)	66.72 (25.4)	(H+S) non- durable
Petersianthus macrocarpus	0	0	4.75 (1.6)	4.88 (1.0)	(H+S) very durable
Sterculia oblonga	3	3	41.04 (27.2)	54.70 (21.8)	(H+S) non- durable
Sterculia rhinopetala	1	1	9.82 (11.2)	17.14 (7.9)	(H) durable, (S) moderately durable
Tectona grandis	1	2	24.48 (29.6)	78.12 (22.5)	(H) moderately durable, (S) non-durable

**Legend: H, S is Heartwood, Sapwood

*The codes used for the visual rating were:

0 – no attack

1 – slight attack

2 – moderate attack

3 – severe attack

4 – failure

The Durability based on percentage weight loss according to Eaton and Hale (1993):

0 – 5% - very durable

6 – 10% - durable

11 – 40% - moderately durable

41 – 100% - non-durable

A matrix of student's t-test was done to compare the mean weight losses differences within species. The matrix and analysis are listed Table 4.1.1 :

Table 4.1 .1 Matrix of t-test values of the differences between two pair of means of the eleven wood species

	Heartwood	Sapwood	Student t-test value
Case 1	ATH	ATS	-3.22
Case 2	APH	APS	1.21
Case 3	ATH	ATS	0.00
Case 4	BSH	BSS	-1.21
Case 5	CGH	CGS	0.45
Case 6	CSH	CSS	0.00
Case 7	CZH	CZS	0.58
Case 8	PMH	PMS	- 0.27
Case 9	SOH	SOS	- 1.52
Case 10	SRH	SRS	- 2.06
Case 11	TGH	TGS	- 5.58

Legend: AFH = *Albizia ferruginea* heartwood, AFS = Albizia ferruginea sapwood, APH = *Amphimas pterocarpoides* heartwood, APS = *Amphimas pterocarpoides* sapwood, ATH = *Antiaris toxicaria* heartwood, ATS = *Antiaris toxicaria* sapwood, BSH = *Blighia sapida* heartwood, BSS = *Blighia sapida* sapwood, CGH = *Cola gigantea* heartwood, CGS = *Cola gigantea* sapwood, CSH = *Canarium schweinfurthii* heartwood, CSS = *Canarium schweinfurthii* sapwood, CZH = *Celtis zenkeri* heartwood, CZS = *Celtis zenkeri* sapwood, PMH = *Petersianthus macrocarpus* heartwood, PMS = *Petersianthus macrocarpus* sapwood, SOH = *Sterculia oblonga* heartwood, SOS = *Sterculia oblonga* sapwood, SRH = *Sterculia* *rhinopetala* heartwood, SRS = *Sterculia rhinopetala* sapwood, TGH = *Tectona grandis* heartwood, TGS = *Tectona grandis* sapwood.

Two-Sample T-Test and CI FOR AFH AND AFS

Sample	N	Mean	StDev	SE Mean
1	15	5.15	2.72	0.70
2	15	12.89	8.89	2.3

Difference = mu (1) - mu (2)

Estimate for difference: -7.74000

95% CI for difference: (-12.82867, -2.65133)

T-Test of difference = 0 (vs not =): T-Value = -3.22 P-Value = 0.005 DF = 16

Two-Sample T-Test and C APH AND APS

Sample	N	Mean	StDev	SE Mean
1	15	24.0	11.1	2.9
2	15	19.98	6.05	1.6

Difference = mu (1) - mu (2)

Estimate for difference: 3.97000

95% CI for difference: (-2.82744, 10.76744)

T-Test of difference = 0 (vs not =): T-Value = 1.21 P-Value = 0.238 DF = 21

Two-Sample T-Test and CI FOR ATH AND ATS

Sample	N	Mean	StDev	SE Mean
1	15	100.0	23.6	6.1
2	15	100.0	12.7	3.3

Difference = mu (1) - mu (2)

Estimate for difference: 0.000000

95% CI for difference: (-14.390467, 14.390467)

T-Test of difference = 0 (vs not =): T-Value = 0.00 P-Value = 1.000 DF = 21

Two-Sample T-Test and CI FOR BSH AND BSS

Sample	N	Mean	StDev	SE Mean
1	15	26.6	19.2	5.0
2	15	36.4	25.2	6.5

Difference = mu (1) - mu (2)

Estimate for difference: -9.87000

95% CI for difference: (-26.69786, 6.95786)

T-Test of difference = 0 (vs not =): T-Value = -1.21 P-Value = 0.239 DF = 26

Two-Sample T-Test and CI FOR CSH AND CSS

Sample	N	Mean	StDev	SE Mean
1	15	100.0	23.6	6.1
2	15	100.0	12.7	3.3

Difference = mu (1) - mu (2)

Estimate for difference: 0.000000

95% CI for difference: (-14.390467, 14.390467)

T-Test of difference = 0 (vs not =): T-Value = 0.00 P-Value = 1.000 DF = 21

Two-Sample T-Test and CI FOR CGH AND CGS

Sample	N	Mean	StDev	SE Mean
1	15	70.9	25.3	6.5
2	15	66.7	25.4	6.6

Difference = mu (1) - mu (2)

Estimate for difference: 4.16000

95% CI for difference: (-14.83289, 23.15289)

T-Test of difference = 0 (vs not =): T-Value = 0.45 P-Value = 0.657 DF = 27

Two-Sample T-Test and CI FOR CZH AND CZS

Sample	N	Mean	StDev	SE Mean
1	15	72.2	27.9	7.2
2	15	67.3	17.3	4.5

Difference = mu (1) - mu (2)

Estimate for difference: 4.93000

95% CI for difference: (-12.60790, 22.46790)

T-Test of difference = 0 (vs not =): T-Value = 0.58 P-Value = 0.567 DF = 23

Two-Sample T-Test and CI FOR PMH AND PMS

Sample	N	Mean	StDev	SE Mean
1	15	4.75	1.55	0.40
2	15	4.88	1.01	0.26

Difference = mu (1) - mu (2)

Estimate for difference: -0.130000

95% CI for difference: (-1.115873, 0.855873)

T-Test of difference = 0 (vs not =): T-Value = -0.27 P-Value = 0.788 DF = 24

Two-Sample T-Test and CI FOR SOH AND SOS

Sample	N	Mean	StDev	SE Mean
1	15	41.1	27.2	7.0
2	15	54.7	21.8	5.6

Difference = mu (1) - mu (2)

Estimate for difference: -13.6500

95% CI for difference: (-32.1355, 4.8355)

T-Test of difference = 0 (vs not =): T-Value = -1.52 P-Value = 0.141 DF = 26

Two-Sample T-Test and CI FOR SRH AND SRS

Sample	N	Mean	StDev	SE Mean
1	15	9.8	11.2	2.9
2	15	17.14	7.93	2.0

Difference = mu (1) - mu (2)

Estimate for difference: -7.32000

95% CI for difference: (-14.63494, -0.00506)

T-Test of difference = 0 (vs not =): T-Value = -2.06 P-Value = 0.050 DF = 25

Two-Sample T-Test and CI FOR TGH AND TGS

Sample	N	Mean	StDev	SE Mean
1	15	24.5	29.6	7.7
2	15	78.1	22.5	5.8

Difference = mu (1) - mu (2)

Estimate for difference: -53.6400

95% CI for difference: (-73.3890, -33.8910)

T-Test of difference = 0 (vs not =): T-Value = -5.58 P-Value = 0.000 DF = 26

**N = sample size

STDev = standard deviation

SE Mean = Standard error mean

4.2 Water Sorption Capacity

Specimens of each of the ten species (heartwood and sapwood) were exposed at various relative humidity conditions of 30 %, 45 %, 60 %, 75 % and 90 % in a temperature and humidity controlled climate chamber at a temperature of 25^{o}C according to DIN 52182 (1976). In addition, *Tectona grandis*, *Albies alba*, *Fagus sylvatica* and *Picea abies* of the same dimensions were also added. The difference between the quantity of water in the sapwood and the heartwood after wetting was significant. The respective differences in the moisture content at the end of the adsorption test were nearly significant. The equilibrium moisture contents (EMC) of these wood species at the various relative humidity conditions with their standard deviations was presented in Table 4.2. According to Table 4.2, at 90 % R.H. and 25°C, *Albizia ferruginea* sapwood and *Canarium schweinfurthii* sapwood had the highest EMC of 20.5 and 20.9 respectively. The sapwoods of *Amphimas pterocarpoides, Antiaris toxicaria, Celtis zenkeri, Cola gigantea, Petersianthus macrocarpus, Sterculia oblonga* had EMC values ranging from 19.8 to 18.4. The heartwoods of the above species had EMC values ranging from 18.3 to 16.1. *Sterculia rhinopetala* had the lowest EMC with sapwood value of 11.0 and heartwood value of 9.6 while *Blighia sapida* followed with also a low value for sapwood of 16.9 and 14.7 for heartwood. An adsorption sorption relationship for *Albizia ferriginea* and *Sterculia rhinopetala* (Figure 4.2) shows *Albizia ferruginea* sapwood as having the highest EMC.

Table 4.2 Mean equilibrium moisture contents of the ten wood species at different relative humidities and at 25°C. The value in brackets against each mean is the standard deviation.

Species	Relative humidity:	30%	45%	60%	75%	90%
Albizia ferruginea	Sapwood	5.2 (0.2)	7.5 (0.2)	8.7 (0.2)	13.8 (0.1)	20.5 (0.3)
	Heartwood	5.1 (0.7)	7.8 (0.5)	8.8 (0.5)	11.9 (0.5)	17.8 (0.4)
Amphimas pterocarpoides	Sapwood	3.7 (0.8)	5.7 (1.1)	7.0 (1.0)	11.3 (1.1)	19.1 (0.9)
	Heartwood	5.4 (0.1)	7.4 (0.2)	8.7 (0.1)	10.8 (0.2)	17.8 (0.2)
Antiaris toxicaria	Sapwood	5.4 (0.2)	7.7 (0.3)	9.0 (0.2)	12.2 (0.2)	19.2 (0.3)
	Heartwood	5.3 (0.2)	7.5 (0.2)	8.9 (0.2)	11.0 (0.2)	18.3 (0.3)
Blighia sapida	Sapwood	3.0 (1.4)	4.9 (1.5)	6.1 (1.5)	9.2 (1.5)	16.9 (1.3)
	Heartwood	3.2 (1.1)	5.3 (1.2)	6.5 (1.3)	8.7 (1.3)	14.7 (1.2)
Canarium schweinfurthii	Sapwood	3.9 (0.4)	7.4 (0.3)	8.6 (0.6)	12.7 (0.7)	20.9 (1.3)
	Heartwood	5.5 (0.7)	7.3 (0.3)	8.5 (0.4)	11.7 (0.7)	19.7 (1.3)
Celtis zenkeri	Sapwood	5.2 (0.3)	7.5 (0.3)	8.6 (0.2)	11.9 (0.2)	19.8 (0.2)
	Heartwood	4.8 (0.5)	7.0 (0.5)	8.2 (0.5)	11.4 (0.5)	17.6 (0.5)
Cola gigantean	Sapwood	5.4 (0.3)	7.7 (0.2)	9.1 (0.2)	11.5 (0.2)	18.4 (0.5)
	Heartwood	5.8 (0.2)	7.7 (0.1)	10.4 (0.7)	10.7 (0.1)	16.1 (0.5)
Petersianthus macrocarpus	Sapwood	6.4 (0.2)	8.4 (0.1)	9.5 (0.1)	12.7 (0.1)	19.7 (0.3)
	Heartwood	7.0 (0.3)	9.5 (0.2)	11.0 (0.1)	14.6 (0.1)	23.4 (0.3)
Sterculia oblonga	Sapwood	6.3 (0.1)	8.2 (0.1)	9.4 (0.1)	11.3 (0.1)	19.5 (0.2)
	Heartwood	6.5 (0.1)	8.1 (0.1)	9.1 (0.0)	11.3 (0.1)	17.0 (0.4)
Sterculia rhinopetala	Sapwood	3.2 (0.9)	4.3 (0.6)	6.3 (0.4)	8.9 (0.2)	11.0 (0.2)
	Heartwood	2.5 (0.2)	3.4 (0.4)	5.3 (0.3)	7.9 (0.2)	9.6 (0.3)

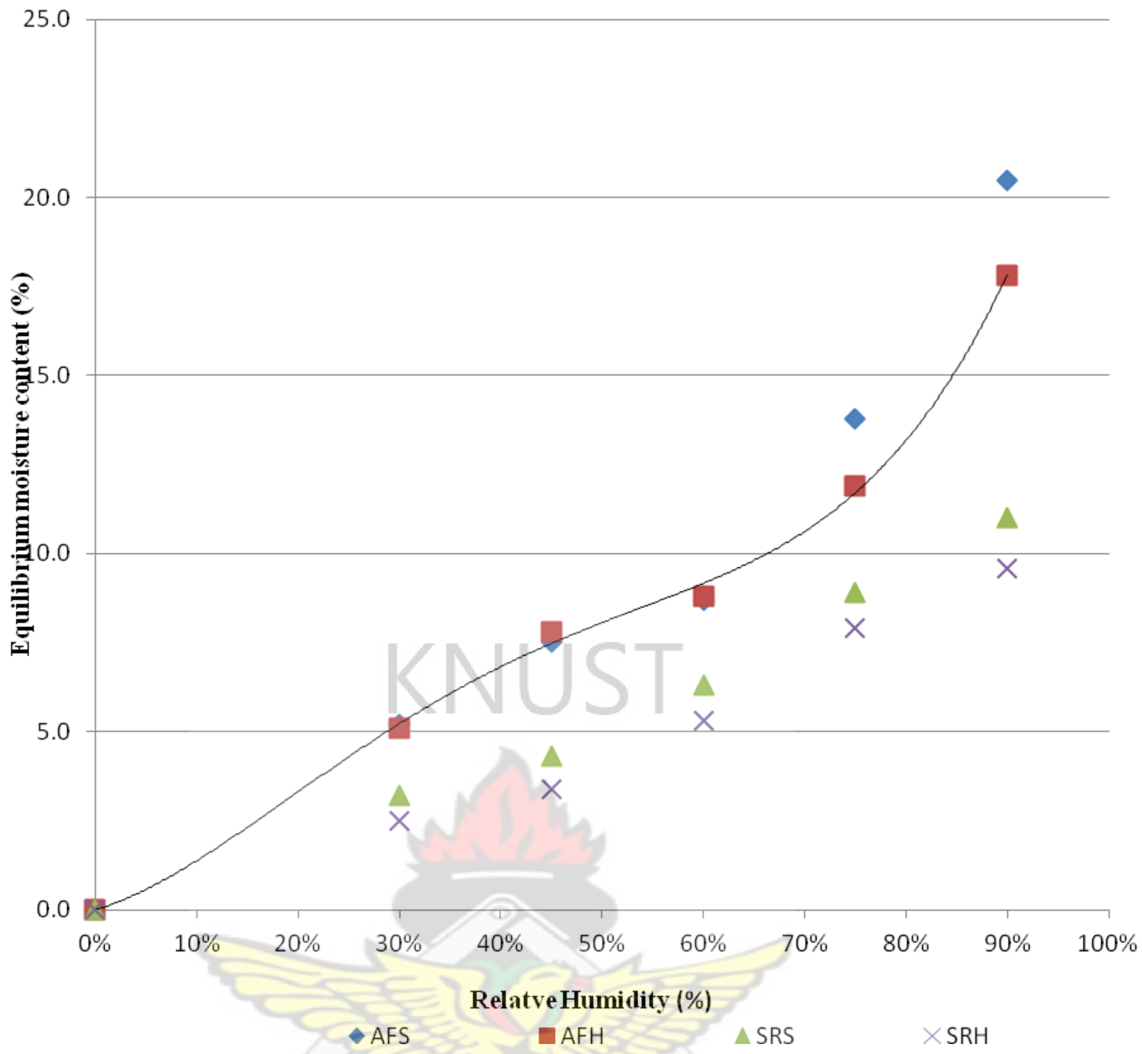


Figure 4.2 Relation between equilibrium moisture content and relative humidity at a temperature of 25^0C for *Albizia ferruginea* and *Sterculia rhinopetala*

AFS – *Albizia ferruginea* sapwood, AFH – *Albizia ferruginea* heartwood, SRS – *Sterculia rhinopetala* sapwood, SRH – *Sterculia rhinopetala* heartwood.

The equilibrium moisture contents of the European species were also presented in Table 4.3. *Abies alba* had the highest EMC of 20.3 followed by values of 19.5 and 18.2 for *Fagus sylvatica* and *Picea abies* respectively.

Table 4.3 EMC of European Species with standard deviations

Species		30%	45%	60%	75%	90%
Abies alba	x (s)	8.1 (0.2)	10.2 (0.1)	11.6 (0.1)	13.5 (0.2)	20.3 (0.2)
Picea abies	x (s)	7.6 (0.2)	9.4 (0.2)	10.6 (0.2)	12.4 (0.2)	18.2 (0.3)
Fagus sylvatica	x (s)	7.5 (0.2)	10.0 (0.2)	11.3 (0.2)	13.0 (0.0)	19.5 (0.4)

Table 4.4 Chemical composition of some of the wood species studied

Wood species	Cellulose %	Hemicellulose %	Lignin %	Extractives %
Sterculia rhinopetala	38.2 - 43.4	29.3 - 31.6	22.4 - 25.2	6.5 - 8.3
Antiaris toxicaria	39.3 - 43.5	30.5 - 33.7	20.5 - 22.7	6.2 - 8.4
Petersianthus macrocarpus	40.6 - 46.7	31.3 - 35.7	21.8 - 24.8	7.4 - 9.5
Albizia ferruginea	44.1 -46.5	28.3 - 31.6	25.2 - 28.4	8.3 - 9.0
Sterculia oblonga	41.3 - 43.7	33.4 - 36.2	24.5 - 27.6	7.6 - 9.4
Amphimas pterocarpoides	43.2 - 45.8	27.8 - 31.9	23.8 - 28.5	8.3 - 10.0
Canarium schweinfurthii	42.2 - 45.6	30.4 - 34.5	21.7 - 25.9	8.4 - 9.2

Source: By courtesy of Chemistry department of Forest Research Institute of Ghana, Kumasi, 2006

4.3 Absorption Test

The results of the absorption test are presented in Table 4.5. The data from which the Table was computed are found in appendix 2.3. The order of water uptake in terms of percentage volume is arranged from the lowest to the highest. *Sterculia rhinopetala* heartwood (SRH) had the lowest uptake per volume with a value of 0.31 and the highest uptake was *Abies alba* (AA) (Figure 4.3), with a value of 2.98 (Table 4.5). When relating them in percentages, *Sterculia rhinopetala* heartwood took 10 % in relation to *Abies alba* (AA) (100%, uptake per volume). On the uptake per weight *Sterculia rhinopetala* heartwood again had the lowest uptake with another European wood species *Picea abies* (PA) having the highest with a value of 6.77.The sapwood of *Sterculia rhinopetala (*SRS*)* had a relatively higher uptake per volume value of 0.53 and a value of uptake per weight of 0.72 compared to the heartwood (SRH). Both the sapwood and heartwood of *Tectona grandis* (TGS and TGH respectively) had lower uptake per volume and per weight of 0.41, 0.67 and 0.36 and 0.53 respectively. Of the Ghanaian wood species, *Albizia ferruginea* heartwood (AFH) and sapwood (AFS) as well as *Canarium schweinfurthii* sapwood (CSS) had the highest uptake per volume values of 1.37, 1.42, and 1.44 respectively and uptake per weight values of 2.49, 2.44 and 2.90 also respectively. The uptake per volume and per weight values of the European species were the highest of all the species under consideration. The values for *Fagus slvatica* (FSH) were 1.34 and 1.75.

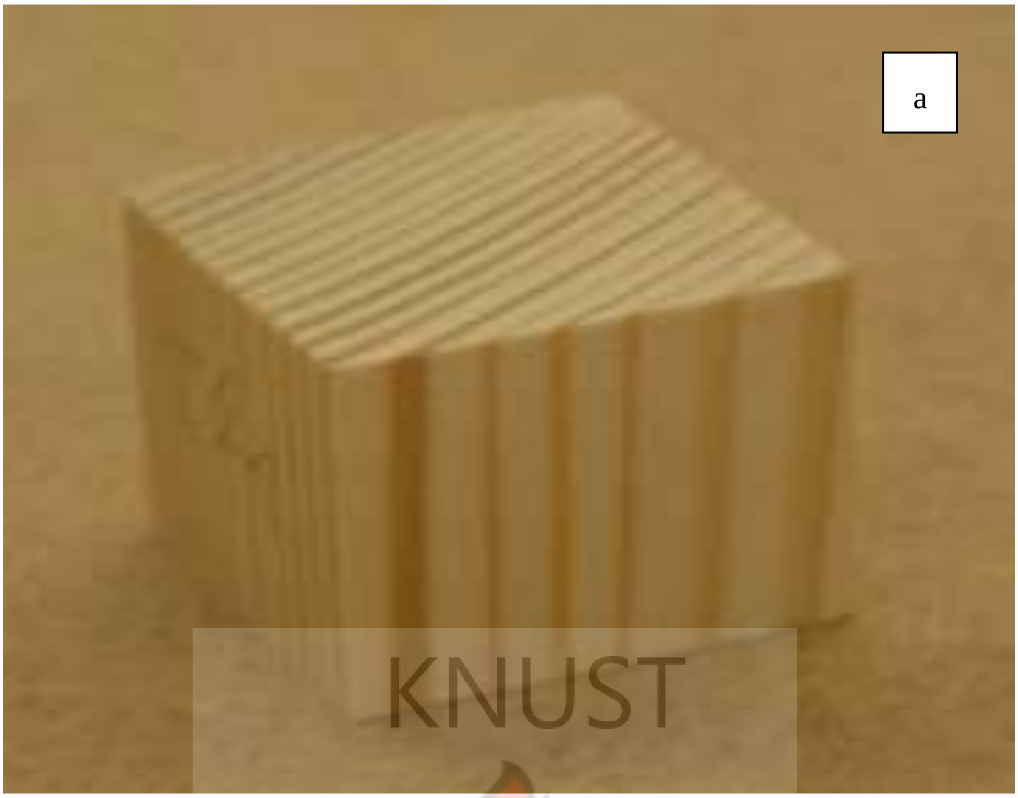


Figure 4.3a Sample of *Abies alba* before immersion.

Figure 4.3b Sample of *Sterculia rhinopetala* before immersion.

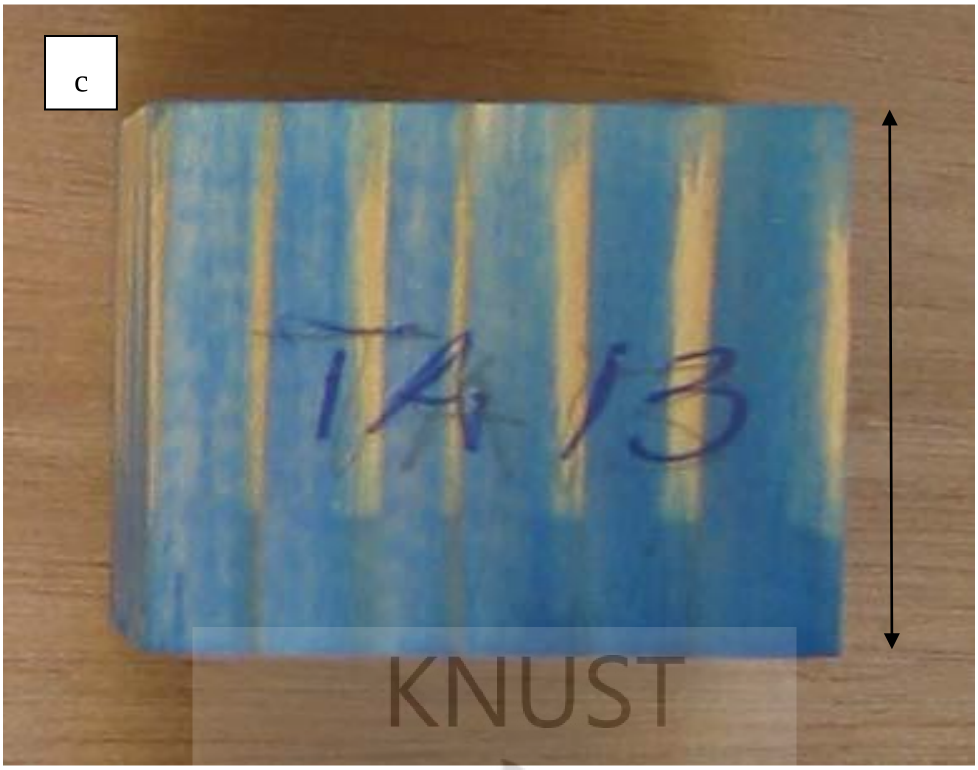


Figure 4.3c *Abies alba* after 5 minutes of immersion The arrows are indicating the level of absorption.

Figure 4.3d *Sterculia rhinopetala* after 5 minutes of immersion.

Table 4.5 Percentage water uptake in 5 minutes through absorption arranged by amount of uptake per volume (%) from the lowest to highest value for both heartwood and sapwood of the various species

Arranged by amount of uptake per volume[%]: lowest to highest Results: capillarity 5 minutes				
Species	Weight change[g]	Variation coefficient (%)	% per weight (conditioned)	% per volume (conditioned)
SRH	0.09	9.42	0.38	0.31
TGH	0.10	5.59	0.53	0.36
TGS	0.11	1.26	0.67	0.41
BSH	0.11	13.16	0.58	0.44
APS	0.13	4.91	0.64	0.50
SRS	0.14	8.55	0.72	0.53
PMS	0.18	2.24	0.87	0.64
APH	0.17	3.69	0.88	0.65
CZS	0.18	1.52	0.95	0.69
BSS	0.20	3.26	0.95	0.77
CSH	0.22	3.27	2.14	0.84
CZH	0.23	1.95	1.19	0.85
ATS	0.23	2.93	2.00	0.89
ATH	0.29	8.03	2.24	1.10
PMH	0.31	5.63	1.51	1.11
CGH	0.30	0.72	2.04	1.13
CGS	0.31	5.51	2.25	1.19
SOS	0.31	2.04	1.69	1.22
SOH	0.33	8.07	1.71	1.27
FSH	0.36	0.57	1.75	1.34
AFH	0.36	2.71	2.49	1.37
AFS	0.39	8.03	2.44	1.42
CSS	0.38	4.11	2.90	1.44
PA	0.63	7.16	6.77	2.38
AA	0.79	3.12	6.12	2.98

Legend:

SRH = *Sterculia rhinopetala* heartwood, TGH = *Tectona grandis* heartwood, TGS = *Tectona grandis* sapwood, BSH = *Blighia sapida* heartwood, APS = *Amphimas pterocarpoides* sapwood, SRS = *Sterculia rhinopetala* sapwood, PMS = *Petersianthus macrocarpus* sapwood APH = *Amphimas pterocarpoides* heartwood, CZS = *Celtis zenkeri* sapwood, BSS = *Blighia sapida* sapwood, CSH = *Canarium schweinfurthii* heartwood, CZH = *Celtis zenkeri* heartwood, ATS = *Antiaris toxicaria* sapwood, ATH = *Antiaris toxicaria* heartwood, PMH = *Petersianthus macrocarpus* heartwood, CGH = *Cola gigantea* heartwood, CGS = *Cola gigantea* sapwood, SOS = *Sterculia oblonga* sapwood, SOH = *Sterculia oblonga* heartwood, FSH = *Fagus sylvatica* heartwood, AFH = *Albizia ferruginea* heartwood, AFS = *Albizia ferruginea* sapwood, CSS = *Canarium schweinfurthii* sapwood, PA = *Picea abies*, AA = *Albies alba*

*Per volume- is the change in volume of the sample after immersion in water.

*Per weight is the change in weight of the sample after the immersion in water

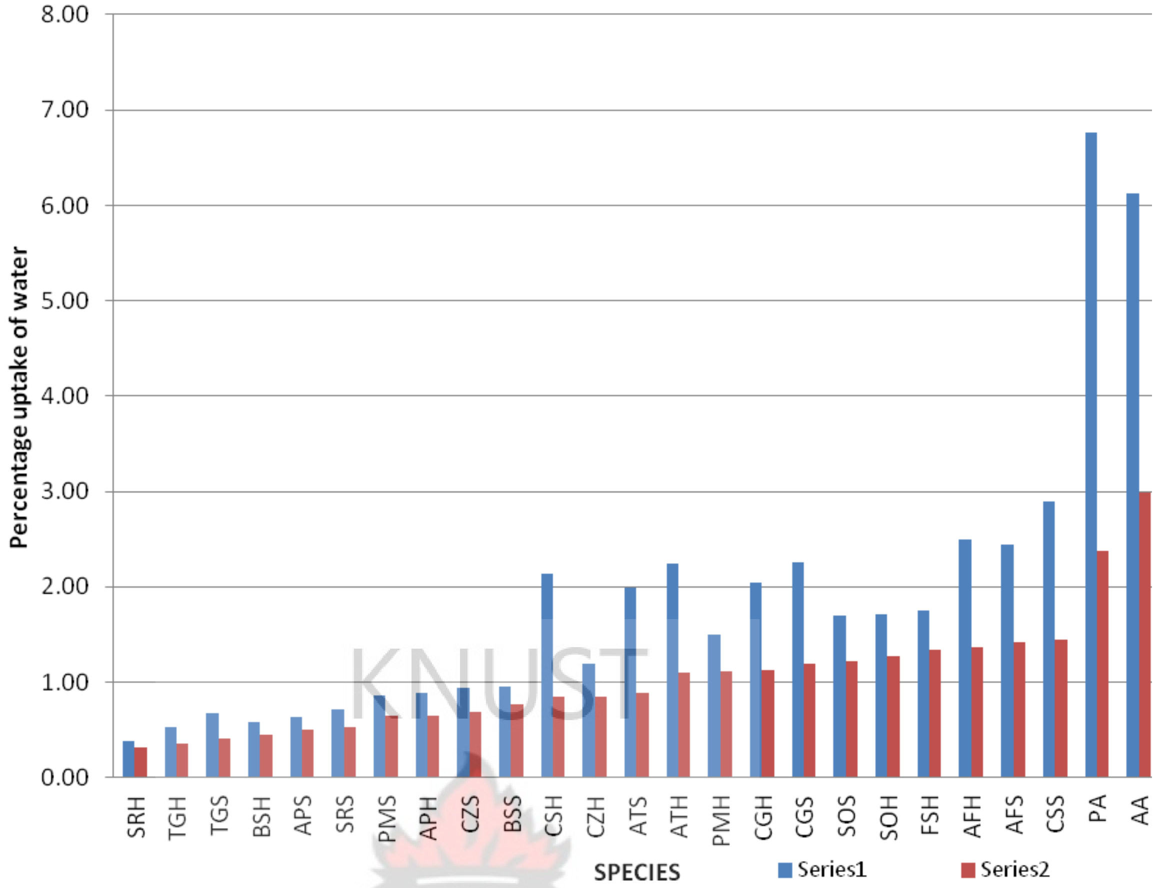


Figure.4.4 Water uptake through absorption (5 minutes) per weight (Series 1) and per volume (Series 2)

Legend:

SRH = *Sterculia rhinopetala* heartwood, TGH = *Tectona grandis* heartwood, TGS = *Tectona grandis* sapwood, BSH = *Blighia sapida* heartwood, APS = *Amphimas pterocarpoides* sapwood, SRS = *Sterculia rhinopetala* sapwood, PMS = *Petersianthus macrocarpus* sapwood APH = *Amphimas pterocarpoides* heartwood, CZS = *Celtis zenkeri* sapwood, BSS = *Blighia sapida* sapwood, CSH = *Canarium schweinfurthii* heartwood, CZH = *Celtis zenkeri* heartwood, ATS = *Antiaris toxicaria* sapwood, ATH = *Antiaris toxicaria* heartwood, PMH = *Petersianthus macrocarpus* heartwood, CGH = *Cola gigantea* heartwood, CGS = *Cola gigantea* sapwood, SOS = *Sterculia oblonga* sapwood, SOH = *Sterculia oblonga* heartwood, FSH = *Fagus sylvatica* heartwood, AFH = *Albizia ferruginea* heartwood, AFS = *Albizia ferruginea* sapwood, CSS = *Canarium schweinfurthii* sapwood, PA = *Picea abies*, AA = *Albies alba.*

Figure 4.4 is a graphical presentation of the water uptake through absorption. According to the graph *Picea abies* (PA) and *Abies alba* (AA) had the highest uptake per weight and per volume. Whilst *Sterculia rhinopetala* heartwood (SRH) and both sapwood and heartwood of *Tectona grandis* (TGS and TGH) had lower water uptakes per weight and per volume.

In Figure 4.5 the relationship between the adsorption (sorption) and absorption are shown. In the absorption (water uptake) the highest point was the value by *Canarium schweinfurthii* sapwood (CSS) and it was the same for the adsorption with highest point also taken by CSS. The lowest point was taken by *Sterculia rhinopetala* heartwood (SRH) for both situations.

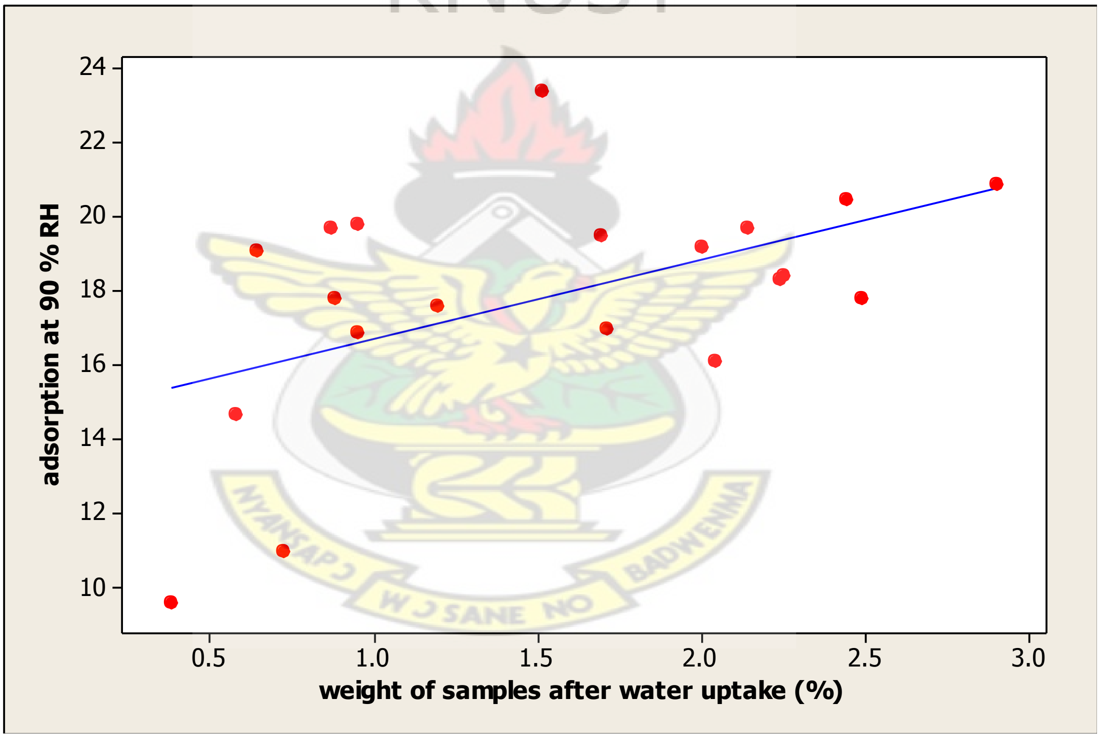


Figure. 4.5 Relationship between adsorption and weight of samples after water uptake (absorption) of the varoius wood species.

The regression equation is:

Adsorption at 90 % RH = 14.6 + 2.15 weight of samples after water uptake

R^2 = 25.8 %

4.4 Bending Strength

The bending strength results of the ten Ghanaian wood species are presented in Table 4.6. According to the Table 4.6, *Sterculia rhinopetala* with the highest density of 1.007 g/cm^3 was found to have a high bending strength of 81.7 N/mm^2 at a moisture content of 44 % with *Antiaris toxicaria* with a density of 0.440 g/cm^3 having the lowest bending strength of 38.4 N/mm^2 at a moisture content of 16 %. *Amphimas pterocarpoides* had a bending strength of 63.6 N/mm^2 at a moisture content of 16 % with a density of 0.770 g/cm^3. *Canarium schweinfurthii* and *Cola gigantea* had bending strength values of 44.0 N/mm^2 at moisture content 30 % and 45.7 N/mm^2 at moisture content 19 % with densities 0.490 g/cm^3 and 0.670 g/cm^3 respectively. The moisture contents of the species were however quiet high so their respective strengths values were adjusted to values at 12 % moisture content. However, the present strength of the wood species at the moisture contents stated reflects the true state in which most of the woods will be used in our country since many of the timber companies do not have access to kilns to dry their products before marketing.

Table 4.6 Bending strength at air dry moisture content and bending strength when adjusted to 12% moisture content, moisture content at time of testing and density of the ten selected lesser utilized wood species.

Species	Bending strength (N/mm^2) @ Air-dry	12%	Moisture content (MC) (%) Of air dried samples at time of testing	Density (g/cm^3) @ air dry MC
Albizia ferruginea	49.9(9.1)*	51.5	51	0.740
Amphimas pterocarpoides	63.6(9.7)*	63.8	16	0.770
Antiaris toxicaria	38.4(5.0)*	38.6	16	0.440
Blighia sapida	61.4(10.2)*	62.08	29	0.900
Canarium schwienfurthii	44.0(3.6)*	44.7	30	0.490
Celtis zenkeri	65.8(15.2)*	66.5	29	0.830
Cola gigantean	45.7(8.8)*	46.0	19	0.670
Petersianthus macrocarpus	60.9(9.64)*	61.6	29	0.860
Sterculia oblonga	70.0(9.4)*	70.8	33	0.820
Sterculia rhinopetala	81.7(13.6)*	83.0	44	1.007

Note: * values in brackets are standard deviations.

4.5 Anatomical Study

For the anatomical study, maceration and sectioning of the three selected species were done. Stereological analysis of the microtome sections produced quantitative anatomical measurements presented in Table 4.7. *Albizia ferruginea* had 63.3 % fibers second to *Blighia sapida* with 64.3 % of fibers. *Sterculia rhinopetala* had the lowest percentage of fibers with 43 %. In vessel proportion, *Blighia sapida* had the highest proportion of 11.5 % and a vessel density of 12 vessels/mm^2, followed by *Sterculia rhinopetala* with 7.3 % and vessel density of 7 vessels/mm^2 and *Albizia* *ferruginea* with the lowest proportion of vessels at 5.8 % and vessel density of 6 vessels/mm^2. Of the three species, *Albizia ferruginea* had an average vessel lumen diameter of 215 µm (maximum 310 µm, minimum 121 µm). *Blighia sapida* had an avearage vessel lumen diameter of 178 µm (maximum 281 µm, minimum 91 µm) whilst *Sterculia rhinopetala* had an average vessel lumen diameter of 164 µm (maximum 257 µm, minimum 85 µm). *Sterculia rhinopetala* had the highest proportion of axial parenchyma of 34.3 % followed by 23 % of axial parenchyma in *Albizia ferruginea*. Axial parenchyma was however not distinct in *Blighia sapida*. Proportion of rays was in the order of 24.3 %, 15.5 %, and 8 % for *Blighia sapida*, *Sterculia rhinopetala* and *Albizia ferruginea* respectively. *Sterculia rhinopetala* had twice as thick walled fibers as *Blighia sapida*, with average double fiber wall thickness of 806 µm and 432 µm respectively. *Albizia ferruginea* had an avearge double fiber wall thickness of 374 µm. With a mean fiber length of between 1474 – 1899 µm (Table 4.8), *Sterculia rhinopetala* had the longest fibers of the three selected species but the mean vessel lumen diameter was the smallest of the three species with a value of 164 µm. *Albizia ferruginea* had mean vessel lumen diameter value of 215 µm which was the largest of the three species while having relatively short fibers which ranged from 1196 – 1274 µm. *Blighia sapida* had a mean vessel lumen diameter of 178 µm and a mean fiber length of between 1127 – 1303 µm. This brings to the fore the fact that *Sterculia rhinopetala* has thick long fibers with small vessel lumen diameter whilst *Albizia ferruginea* had relatively short fibers with wide vessel lumens.

Table 4.7. Proportion of tissues (and standard deviation) in the three species

Species	Fibers (%)	Vessel (%) & vessel density	Axial parenchyma (%)	Rays (%)	DFWT (µm)	Density (g/cm^3)
A. ferruginea	63.3 (2.7)	5.8 (1.5) 6 vesels/mm^2	23 (1.9)	8 (0.7)	374(0.7)	0.603
B. sapida	64.3 (4.3)	11.5 (4.5) 12 vessels/mm^2	-	24.3 (3.6)	432(0.9)	0.892
S. rhinopetala	43 (2.6)	7.3 (1.1) 7 vessels/mm^2	34.3 (1.3)	15.5 (2.3)	806(1.3)	0.945

Legend : DFWT – Double fiber wall thickness

Table 4.8 Range of mean values for fiber length and vessel lumen diameter of the three selected wood species (with the maximum and minimum values in parenthesis)

Species	fiber length (µm)	Vessel lumen diameter (µm)
A. ferruginea	1196 – 1274	215 (121 – 310)
B. sapida	1127 – 1303	178 (91 – 281)
S. rhinopetala	1479 – 1899	164 (85 – 257)

4.5.1 Light Microscopic Photomicrographs

Qualitative analysis of the anatomical investigations are shown in micrographs in Figure 4.6 1-5. Figure 4.6.1 showed the transverse section of *Albizia ferruginea* showing solitary vessels with radial multiples of 2-4 vessels. Some of the vessels were occluded with tyloses. The axial parenchyma were arranged paratracheal, vasicentric, aliform and confluent. In the tangential section (B) the rays were storied and filled with inclusions.

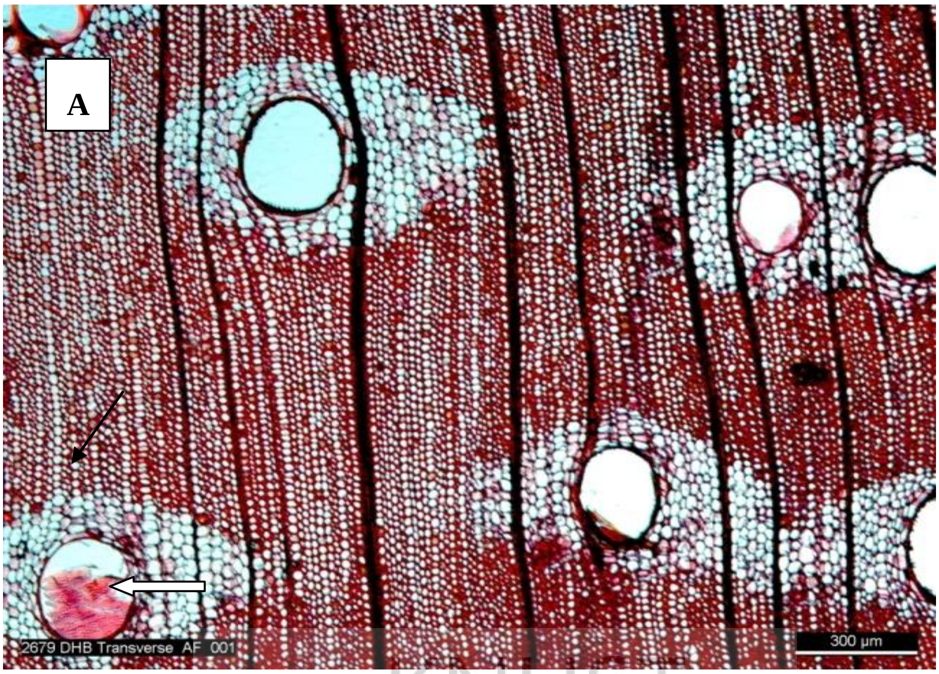


Figure. 4.6 1 (A) Transverse section of wood of *Albizia ferruginea* showing a vessel with tylosis (arrowed) and axial parenchyma aliform and confluent paratracheal. Scale bar = 300µm

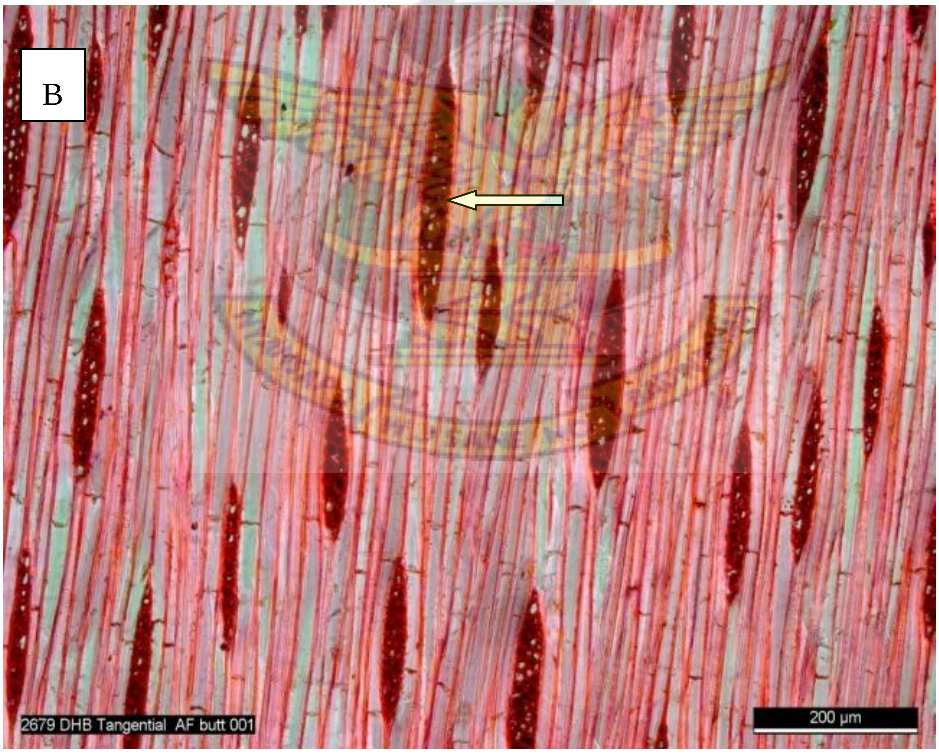


Figure. 4.6 1 (B) Tangential section of *Albizia ferruginea* showing storied rays filled with inclusions (arrowed). Scale bar = 200µm.

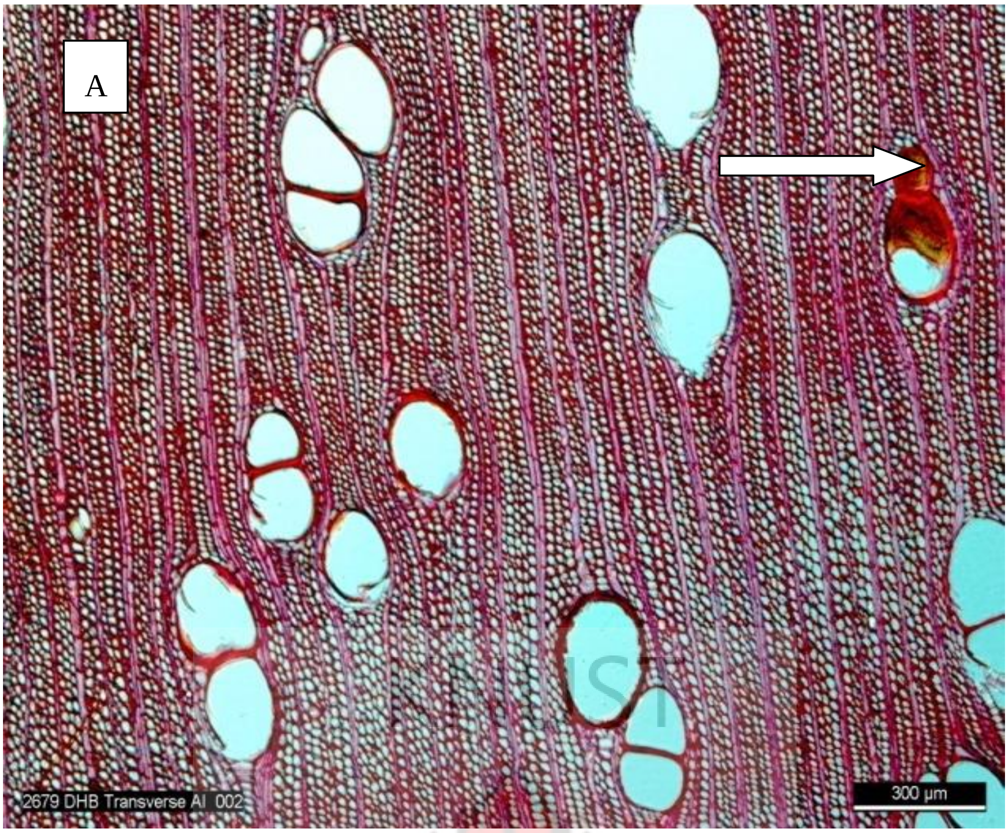


Figure. 4.6. 2 (A) Transverse section of *Blighia sapida* showing solitary vessels in radial multiples of 2-4. Scale bar = 300 µm Tylosis occluded some of the vessels (arrowed). Axial parenchyma was not distinct.

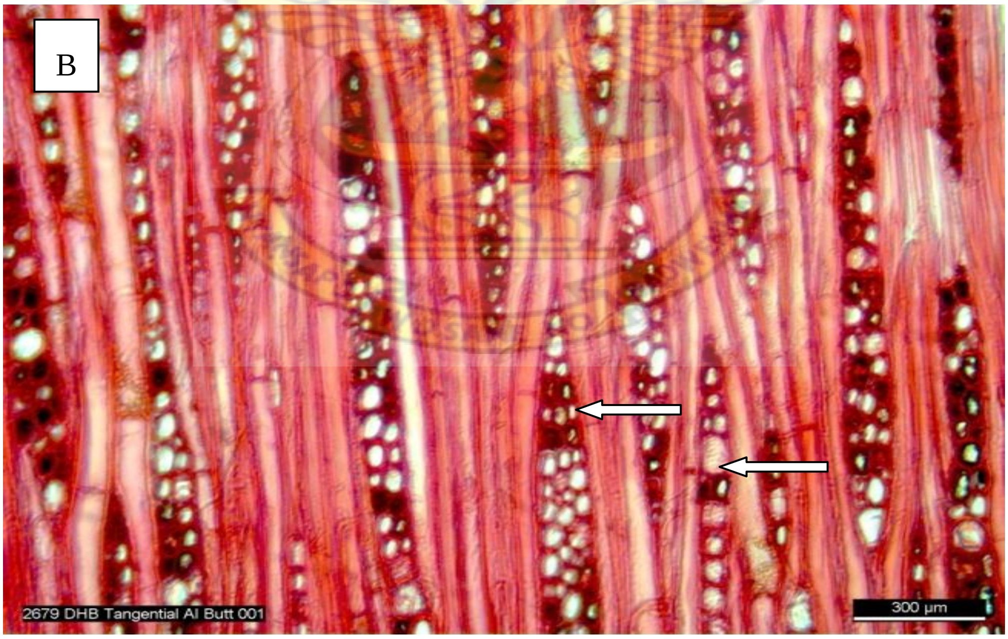


Figure. 4.6. 2 (B) Tangential section of *Blighia sapida* showing multiseriate (arrowed) and uniseriate (also arrowed) heterocellular rays with inclusions. Scale bar = 300 µm.

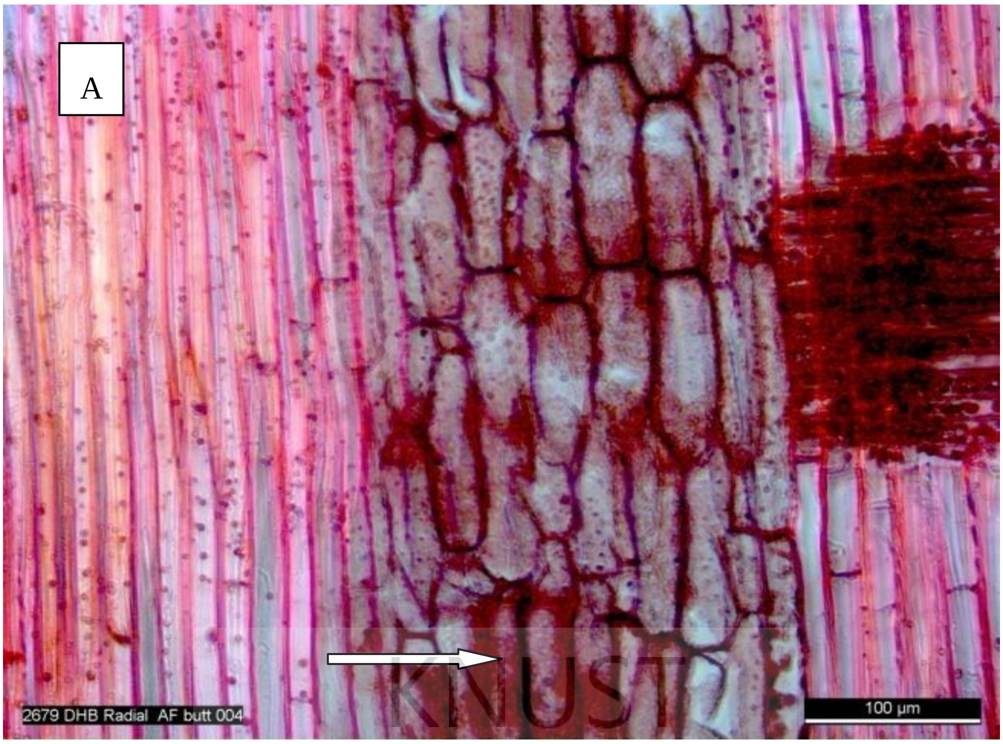


Figure. 4.6. 3 (A) Radial section of *Albizia ferruginea* showing mutiseriate rays with inclusions. Scale bar = 100 µm.

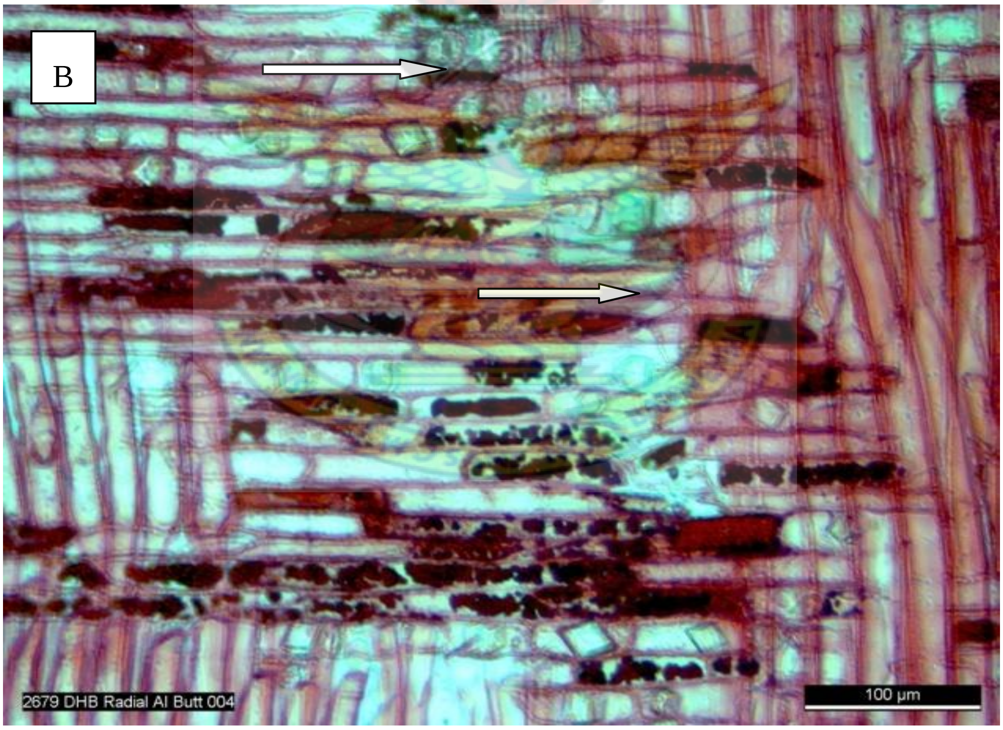


Figure. 4.6. 3 (B) Radial section of *Blighia sapida* with ray cells containing some prismatic crystals (arrowed). Scale bar = 100 µm.

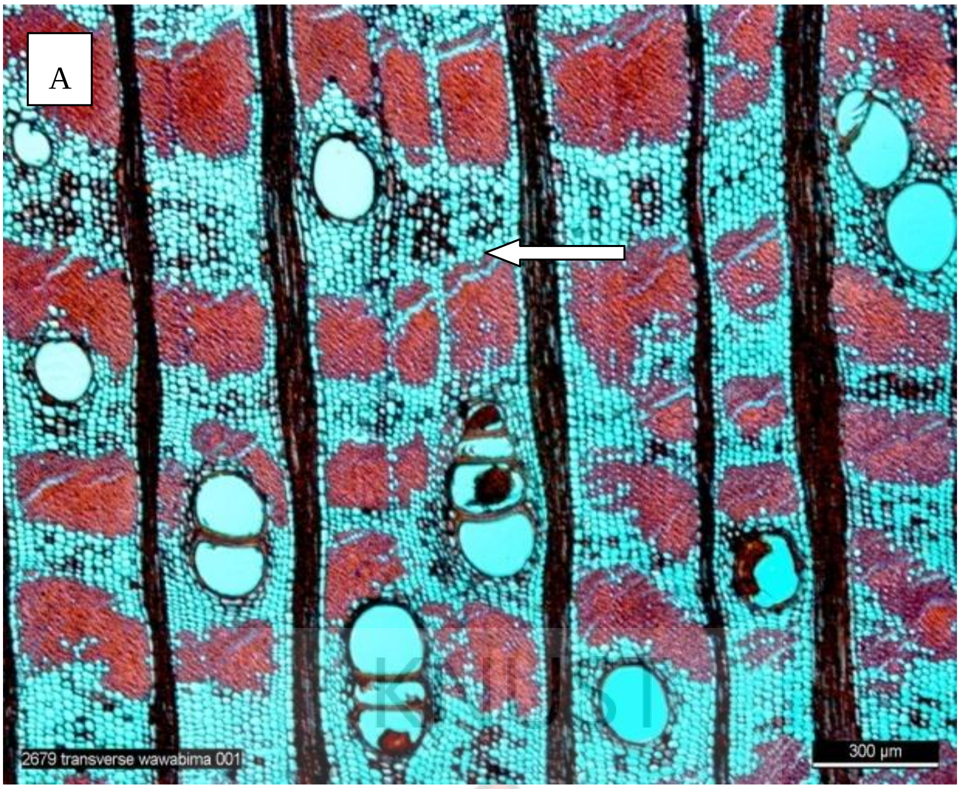


Figure. 4.6.4 (A) Transverse section of *Sterculia rhinopetala* with storied and straight to wavy broad-banded axial parenchyma with inclusions. Vessels are solitary and in radial multiples with tyloses and inclusions. Fibers are also banded. Ray parenchyma was variable, wide and narrow. Scale bar = 300 µm.

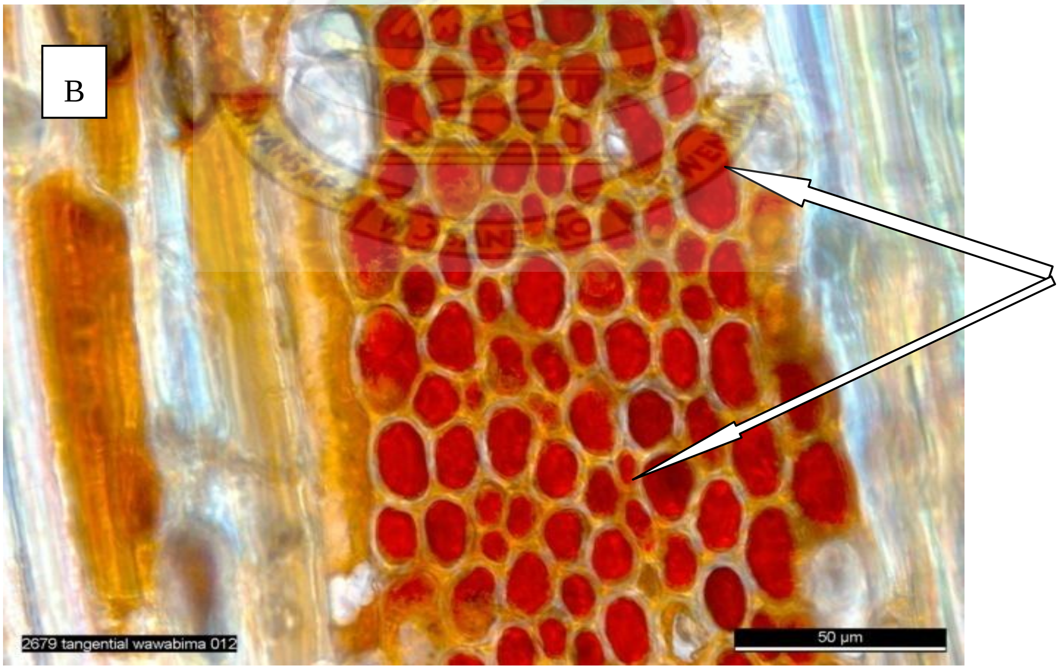


Figure. 4.6.4 (B) Unstained Tangential section of *Sterculia rhinopetala* with rays (arrowed) filled with inclusions. Scale bar = 50 µm.

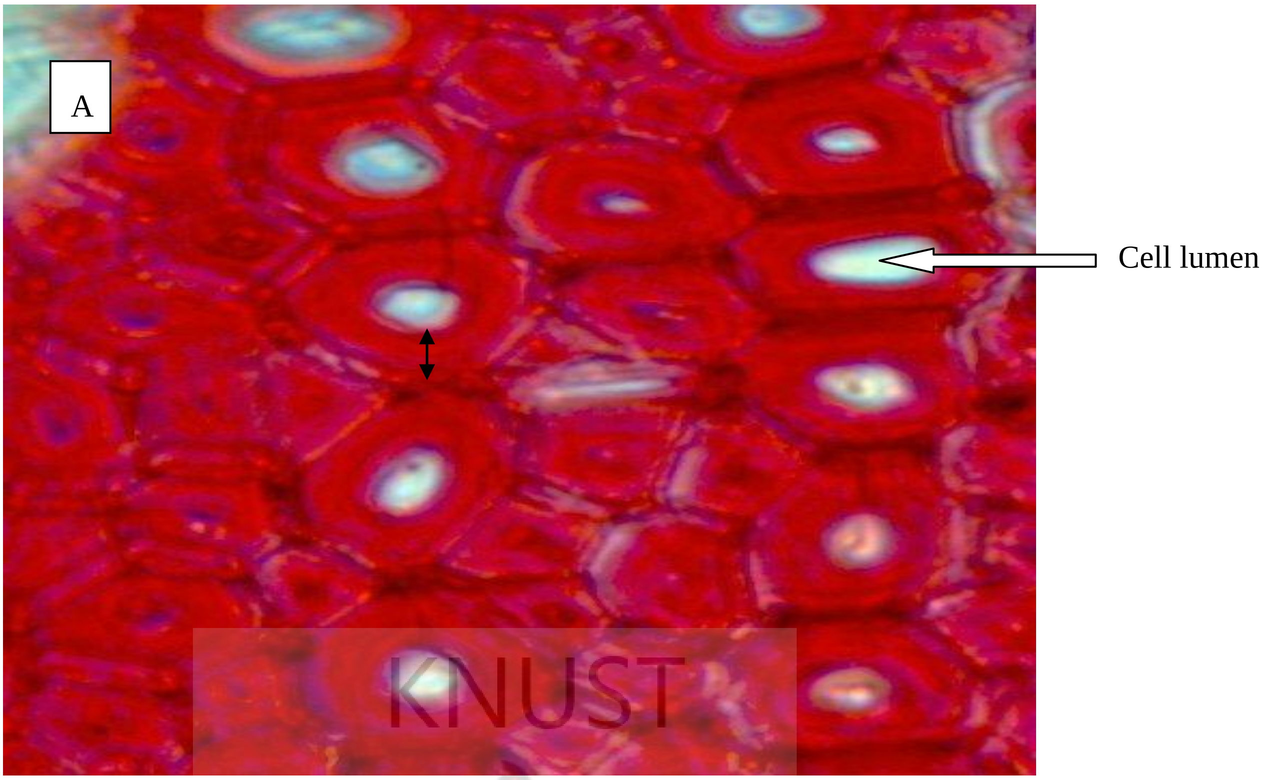


Figure. 4.6. 5 Transverse sections of (A) *Sterculia rhinopetala* depicting the presence of thick-walled fibers (arrowed).

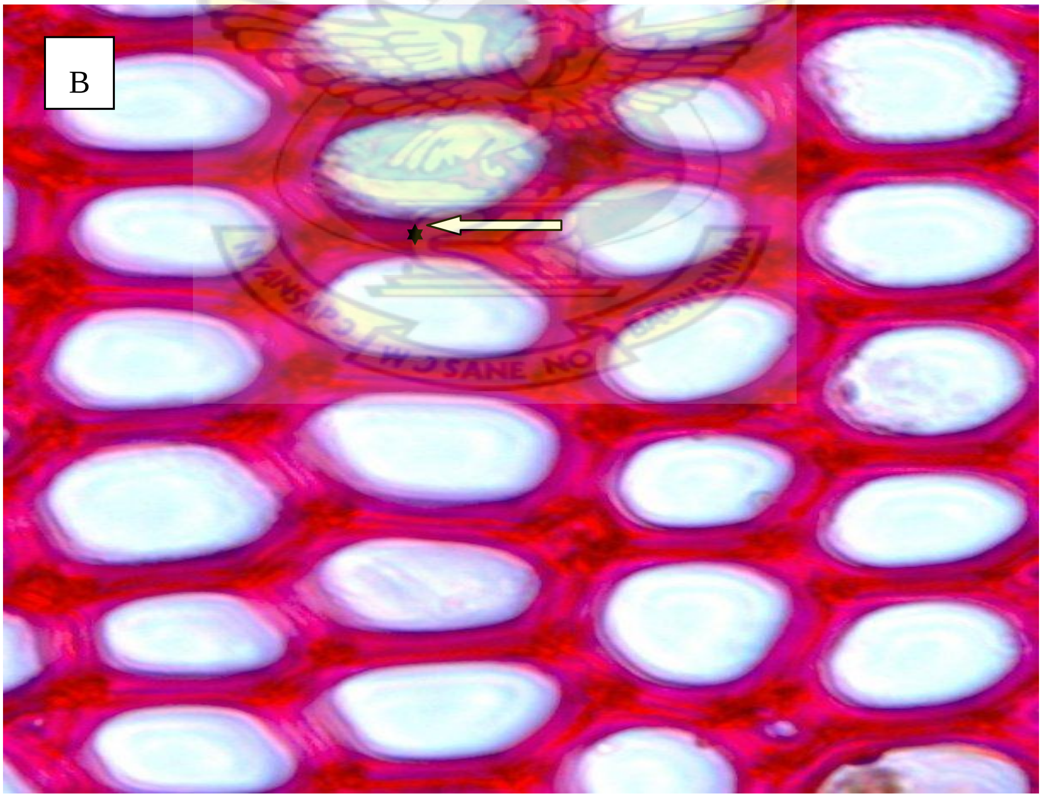


Figure. 4.6.6 Transverse sections of (B) *Albizia ferruginea* showing thin walled fibers

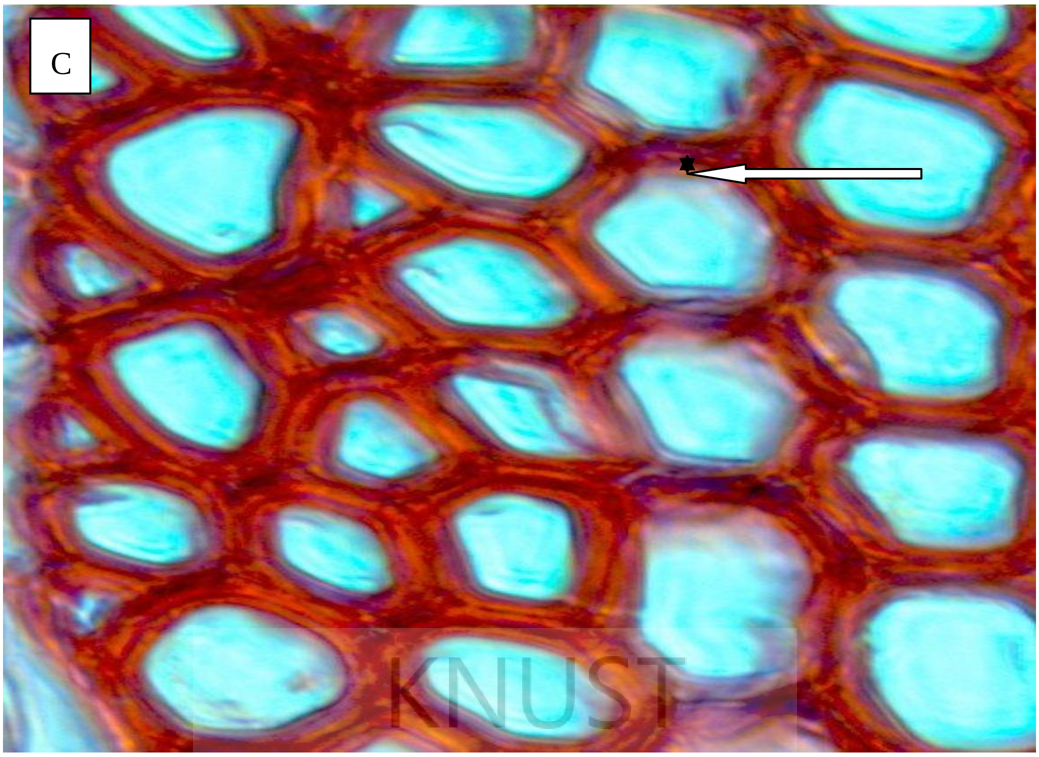


Figure. 4.6.6 (C) *Blighia sapida* medium walled fibers (arrowed).

4.5.2 SEM Photomicrographs

The photomicrographs (Figures 4.7. 1-3) explain further observations made with the light microscope. Figure 4.6.1 showed *Albizia ferruginea* with tyloses in vessel and Figure 4.7.1 (A) enhances this feature; the tyloses. In the same way, Figure 4.6. 4 (B) depicted rays in *Sterculia rhinopetala* filled with inclusions. Figure 4.6.1 (B) threw more light this feature.The sculptured wall of vessels and occluded pits in *Blighia* depicted in Figure 4.6.2 (A) and (B) helps explain why water uptake was low, whilst Figure 4.7.3 enhances the crystals in the rays in Figure 4.6. 3 (B).

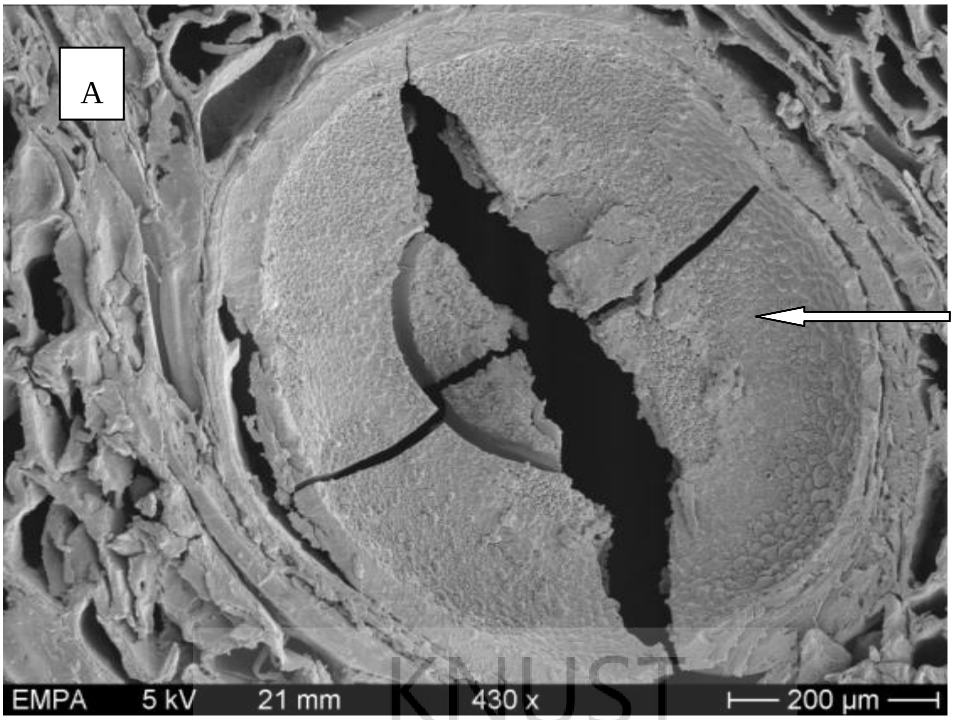


Figure 4.7. 1 (A) A vessel of *Albizia ferruginea* occluded with tylosis (arrowed). Scale bar = 200µm.

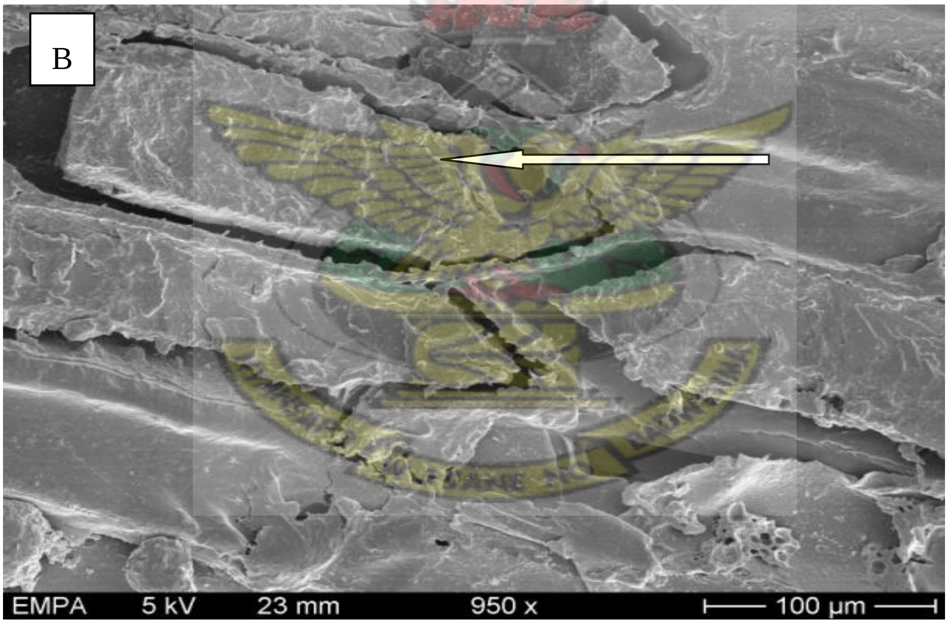


Figure 4.7. 1 (B) Parenchyma of *Sterculia rhinopetala* filled with substances (arrowed). Scale bar = 100µm.

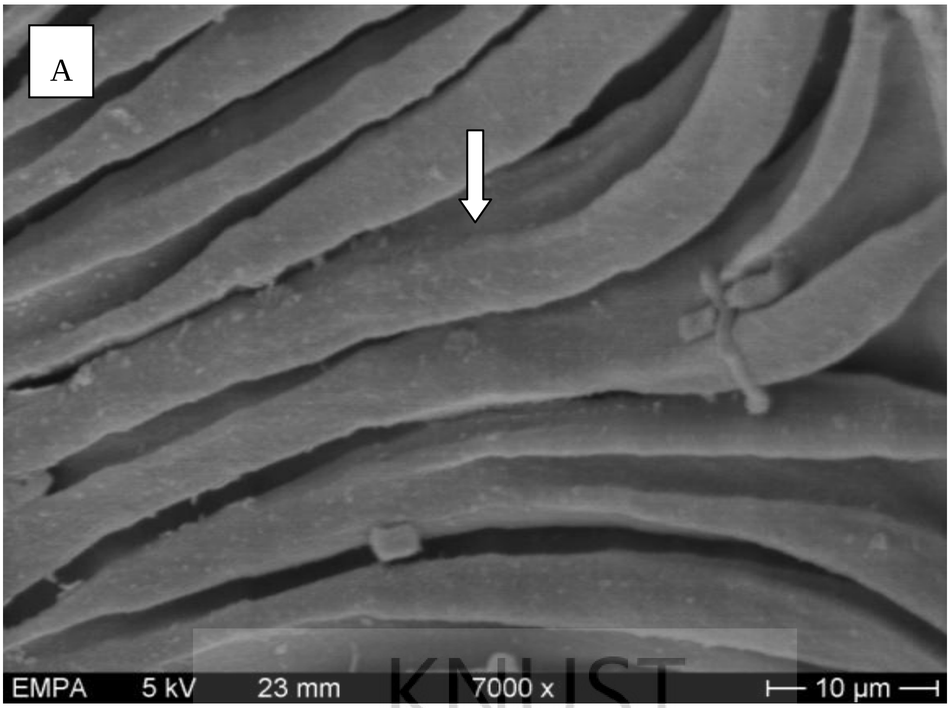


Figure 4.7. 2 (A) The sculptured vessel wall (arrowed) of *Blighia sapida*. 10µm.

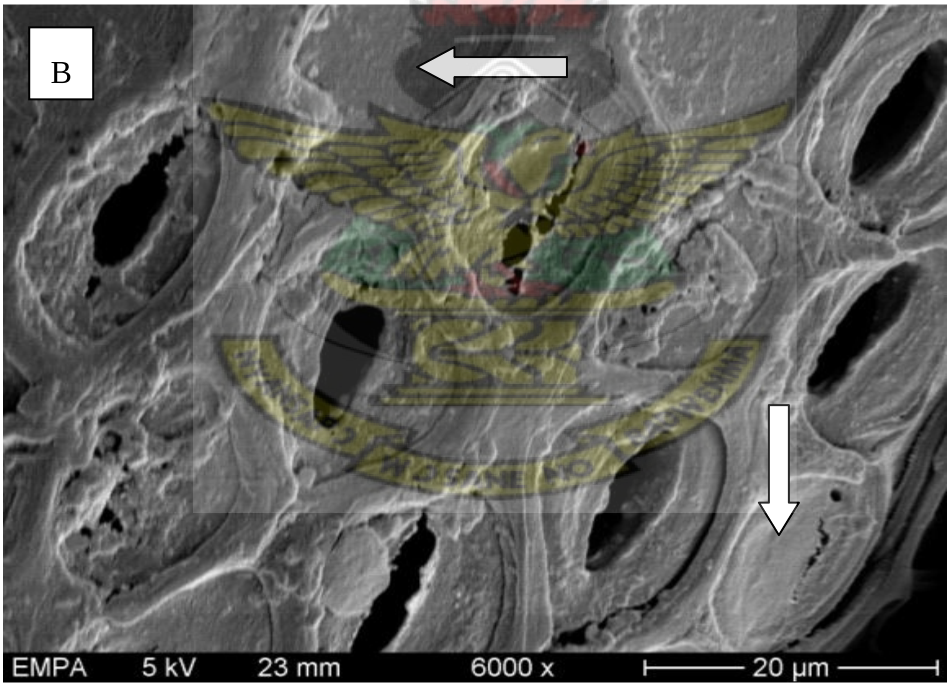


Figure 4.7. 2 (B) Some occluded pits (arrowed) of *Blighia sapida*. Scale bar = 20µm.

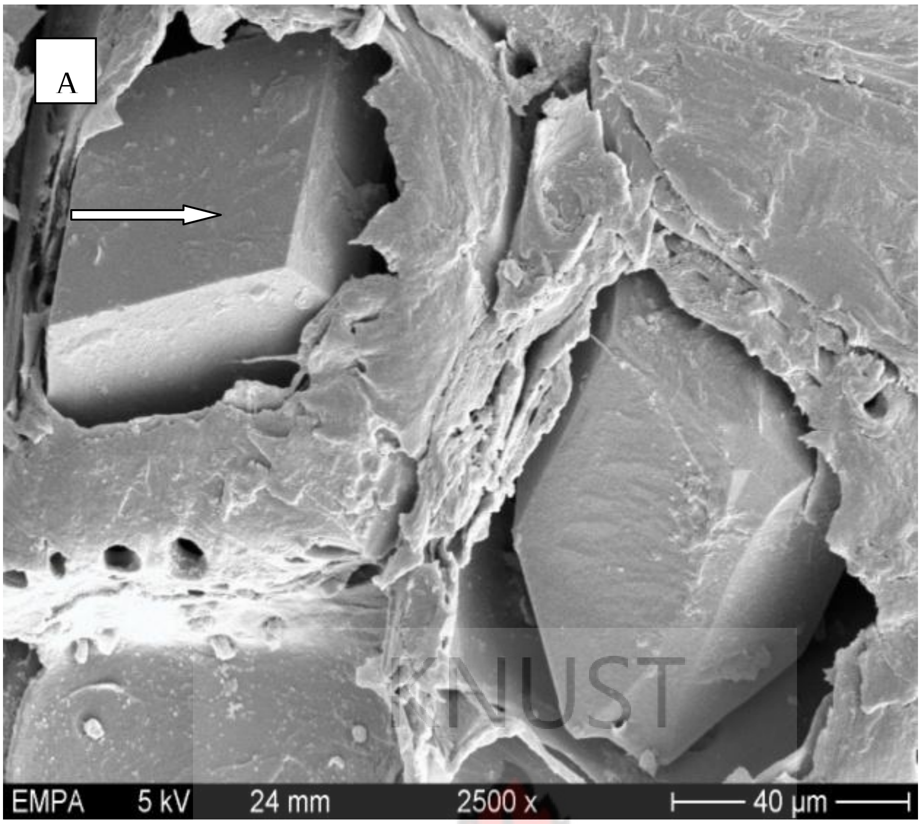


Figure 4.7 3 (A) some crystals embedded in the rays of *Blighia sapida.* Scale bar = 40µm.

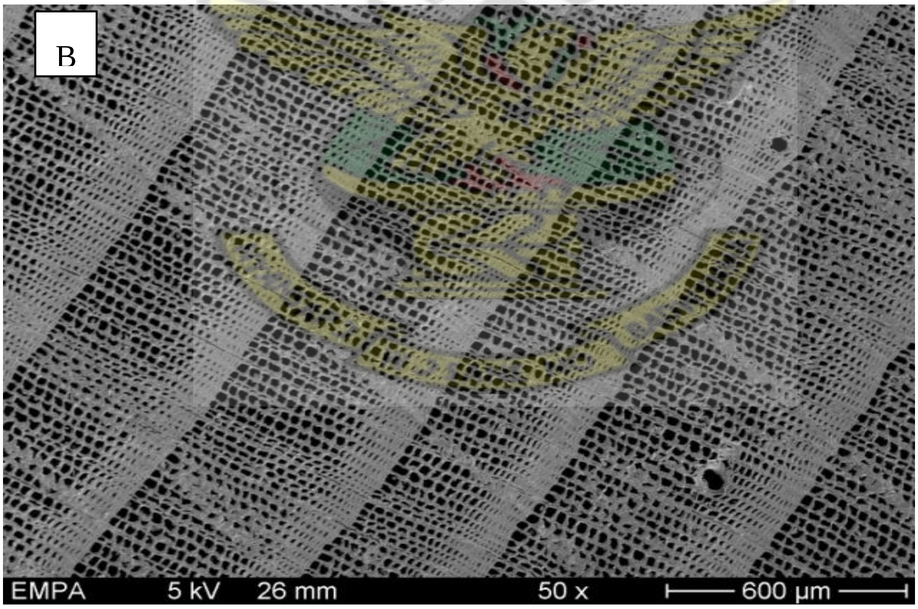


Figure 4.7 3 (B) growth increments with a gradual transition from thin-walled wide-lumined earlywood cells to the thicker walled, narrow-lumined cells of *Picea abies* (Spruce). Scale bar = 600µm

4.6 Interrelationships and Correlations

Graphs were used to depict the correlations between the various parameters. A correlation was drawn between density and bending strength at air dry moisture content and 12 % moisture content (Figure 4.9). Another relationship was drawn between density and durability for both heartwood and sapwood (Figure 4.8a and b.). Figure 4.10 and 4.11a and b. are relationships between density and sorption and sorption and durability (percentage weight loss for both heartwood and sapwood) respectively. The best correlations found between the mentioned properties/features are between density and bending strength as shown in Figure 4.9 with an R^2 value of 83.1 %, followed by density and durability as shown in Figure 4.8a with an R^2 value of 61.8 % and 8b with an R^2 value of 42.1 % for sapwood and heartwood respectively, density and sorption shown in Figure 4.10a and 10b with an R^2 values of 9 % and 35 % for sapwood and heartwood respectively and to a lesser extent sorption and durability as shown in Figure 4.11a and 11b with an R^2 values of 21.9 % and 73.5% respectively. The interrelationship between anatomical features and bending strength was also drawn. The interrelationships within the anatomical features were also drawn and between anatomical features and the physical properties. The best predictor of the density of wood species was carried out for three species by multiple regression analysis. A summary is shown in Table 4.9 and Figures 4.12 to 4.14.

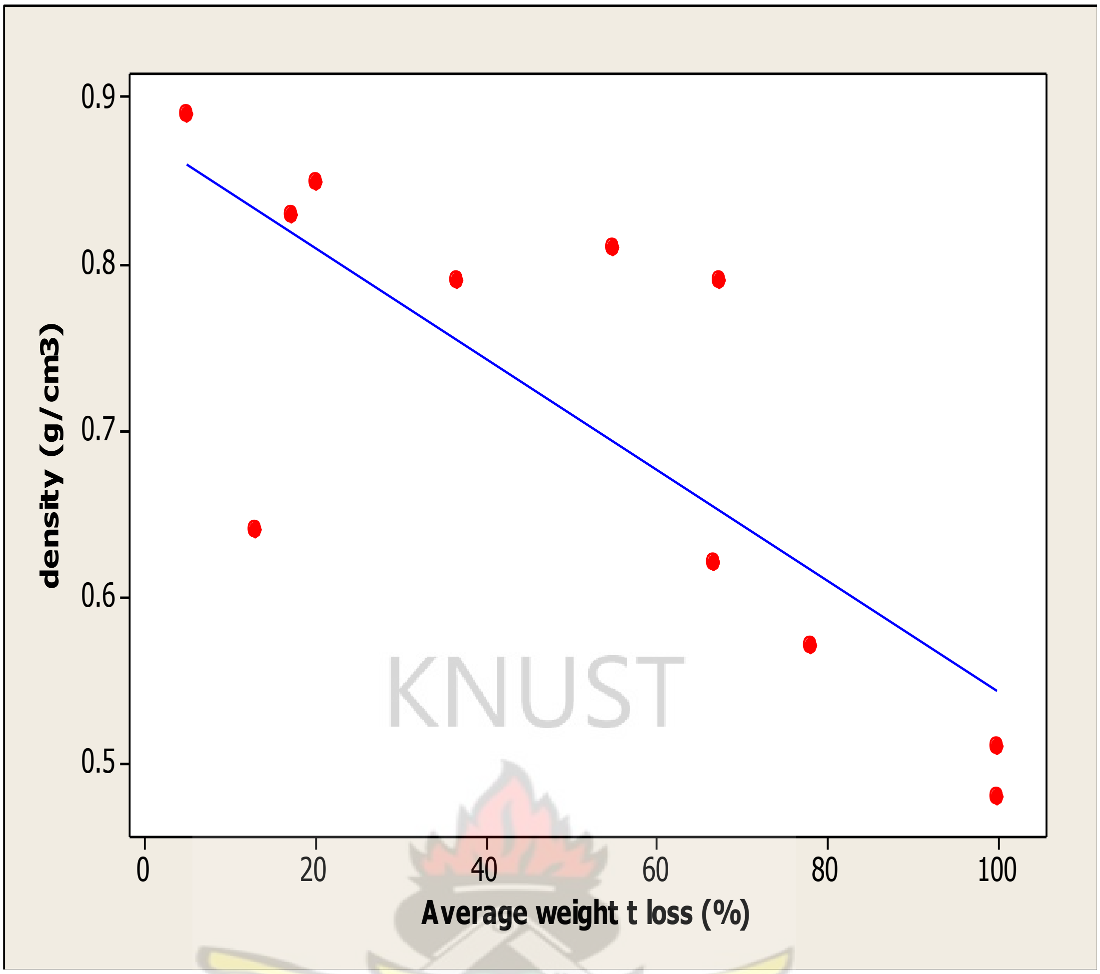


Figure 4.8a Density and average weight loss (durability) of the sapwood of the ten timber species studied.

The regression equation is:

Density = 0.850 – 0.00329 average weight loss %

R^2 = 61.8 %

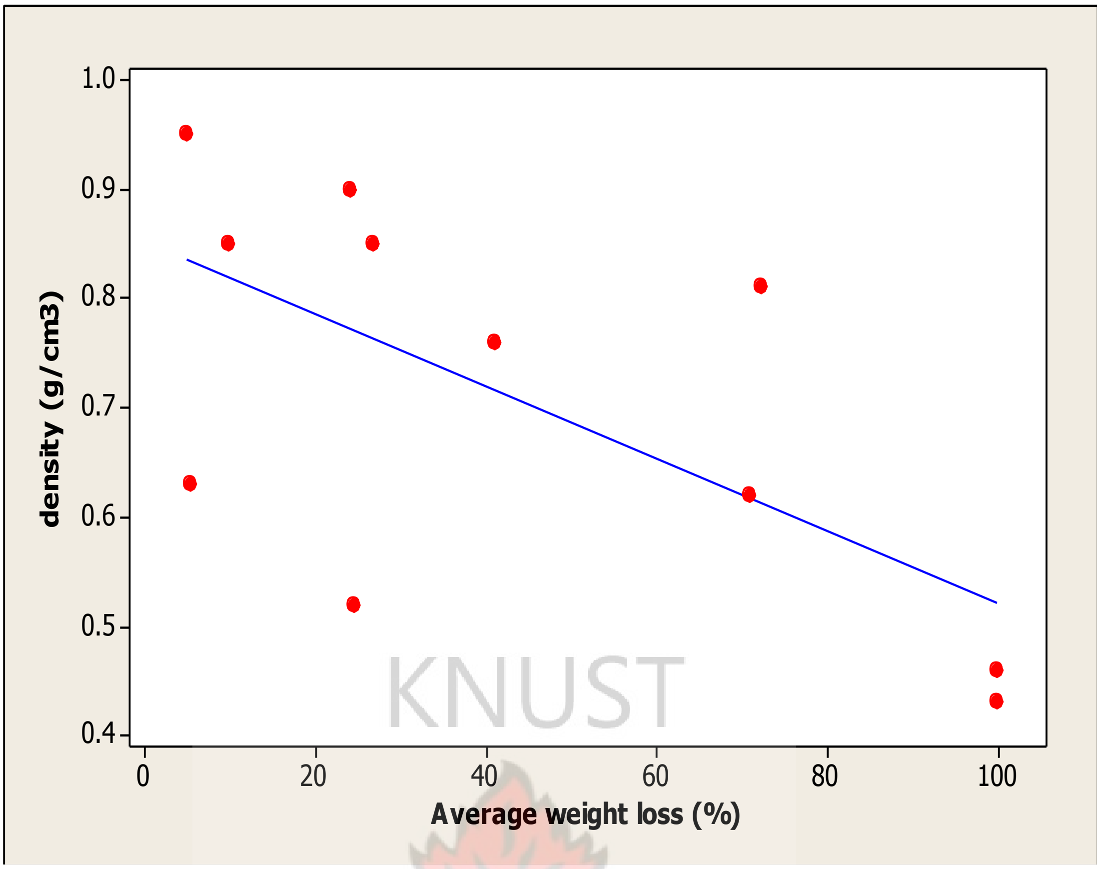


Figure 4.8b Density and average weight loss (durability) of the heartwood of the ten timber species studied.

The regression equation is:

Density = 0.850 – 0.00329 average weight loss %

R^2 = 42.1%

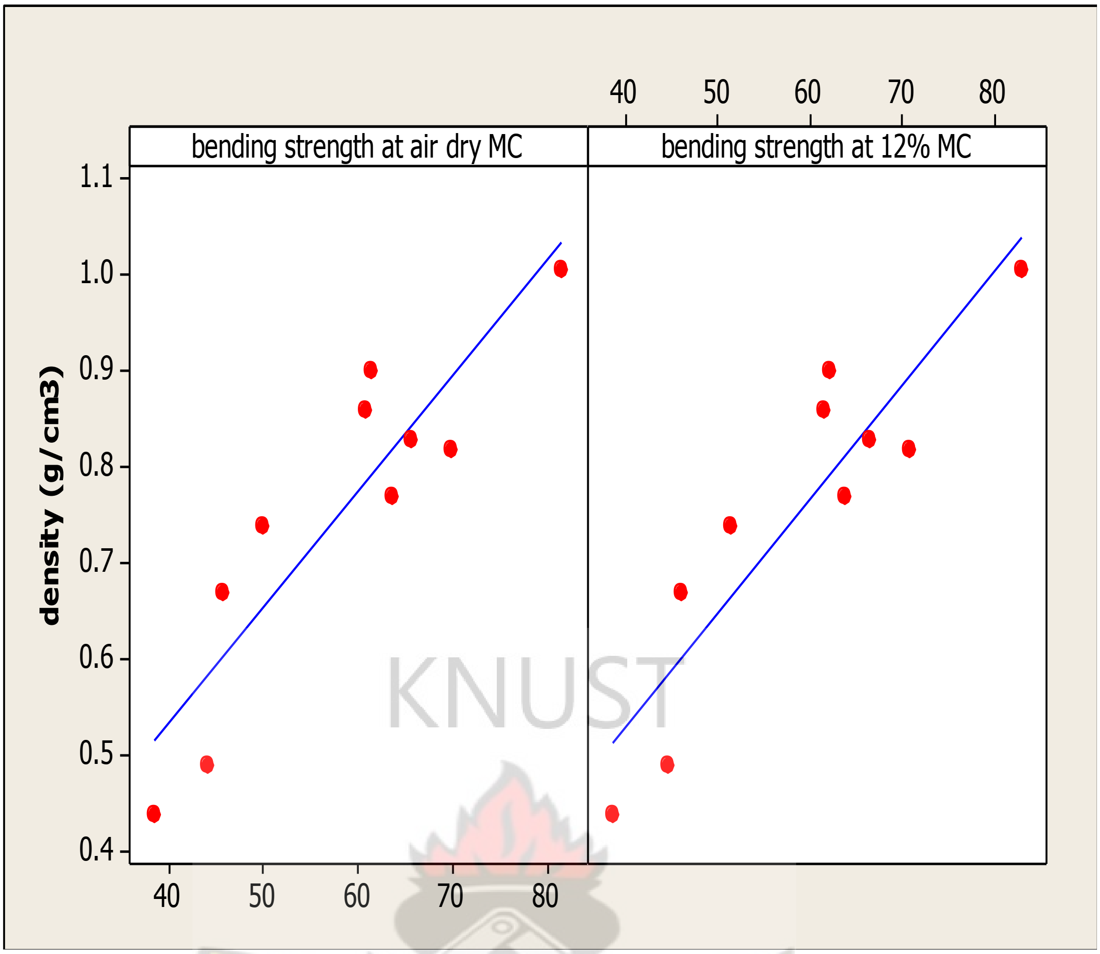


Figure.4.9 Density and bending strength at air dry and 12 % moisture content for all the ten species studied

The regression equation is:

Density = 0.059 – 0.0438 bending strength at air-dry Mc + 0.055 bending strength at 12 % MC

R^2 = 83.1 %

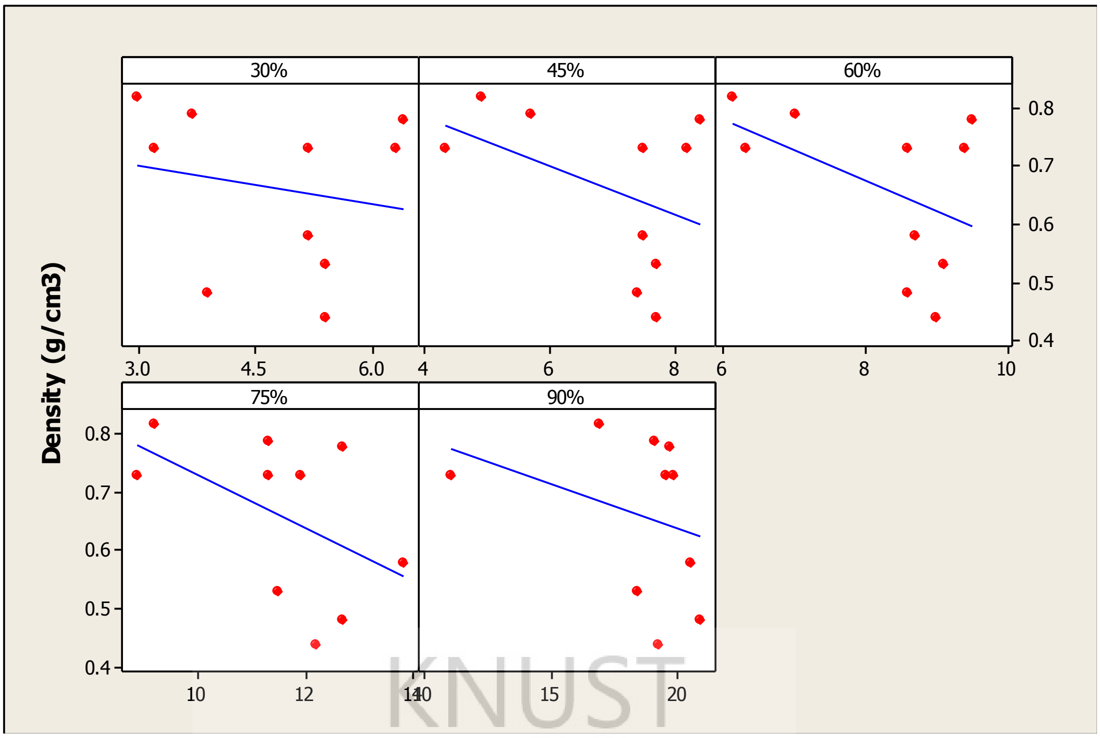


Figure.4.10a Density and water sorption for the sapwood of the ten species studied

The regression equation is:

Density = 0.707 + 0.00056 Fibres % - 0.0207 Vessel % - 0.00040 Axial Par. % - 0.00339 Ray % + 0.0040 DFWT

R^2 = 9 %

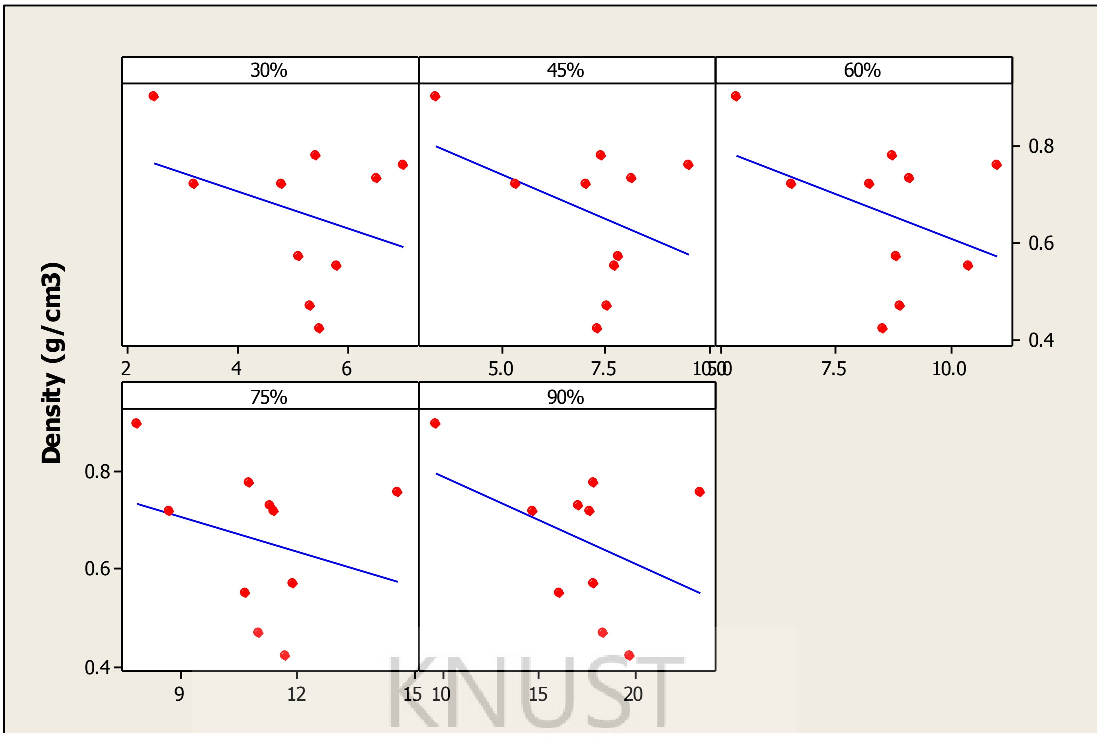


Figure.4.10b Density and water sorption for the heartwood of the ten species studied

The regression equation is:

Density = 0.798 + 0.045 30 % - 0.033 45 % - 0.054 60% + 0.108 75 % - 0.0498 90 %

R^2 = 35%

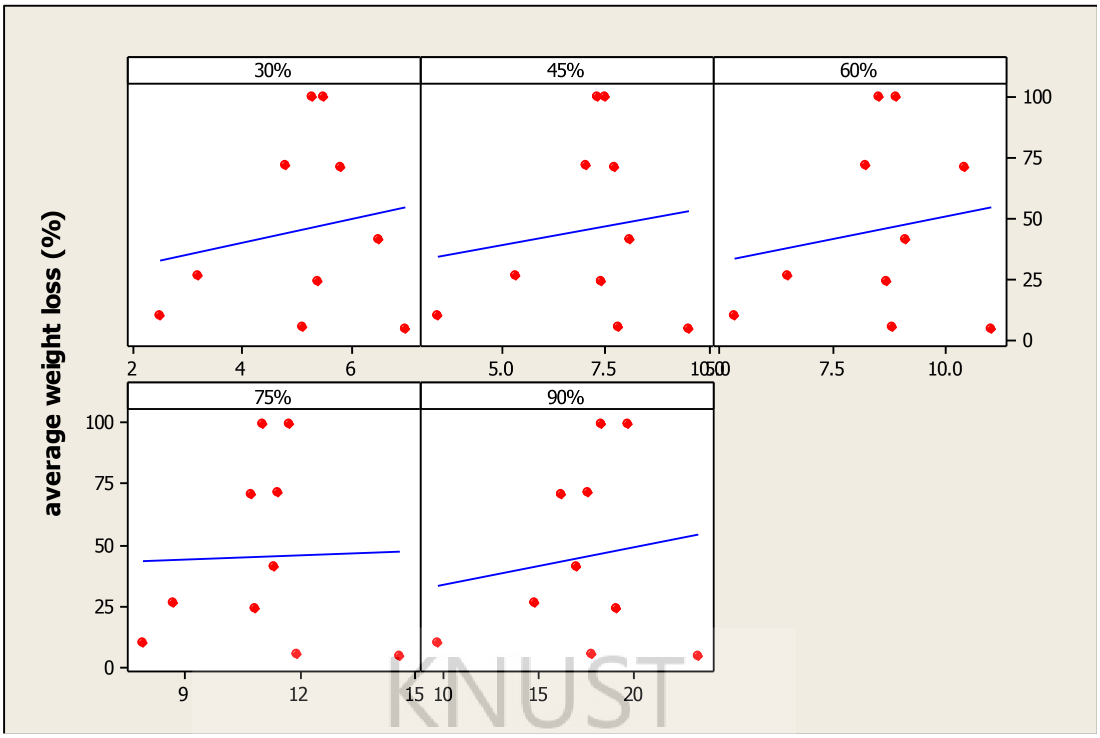


Figure 4.11a Average weight loss (durability) and water sorption of the heartwood of the ten timber species studied

The regression equation is:

Ave. weight loss % = 69 +22.8 30 % - 23.5 45 % + 11.5 60 % - 23.7 75 % + 11.0 90 %

R^2 = 21.9 %

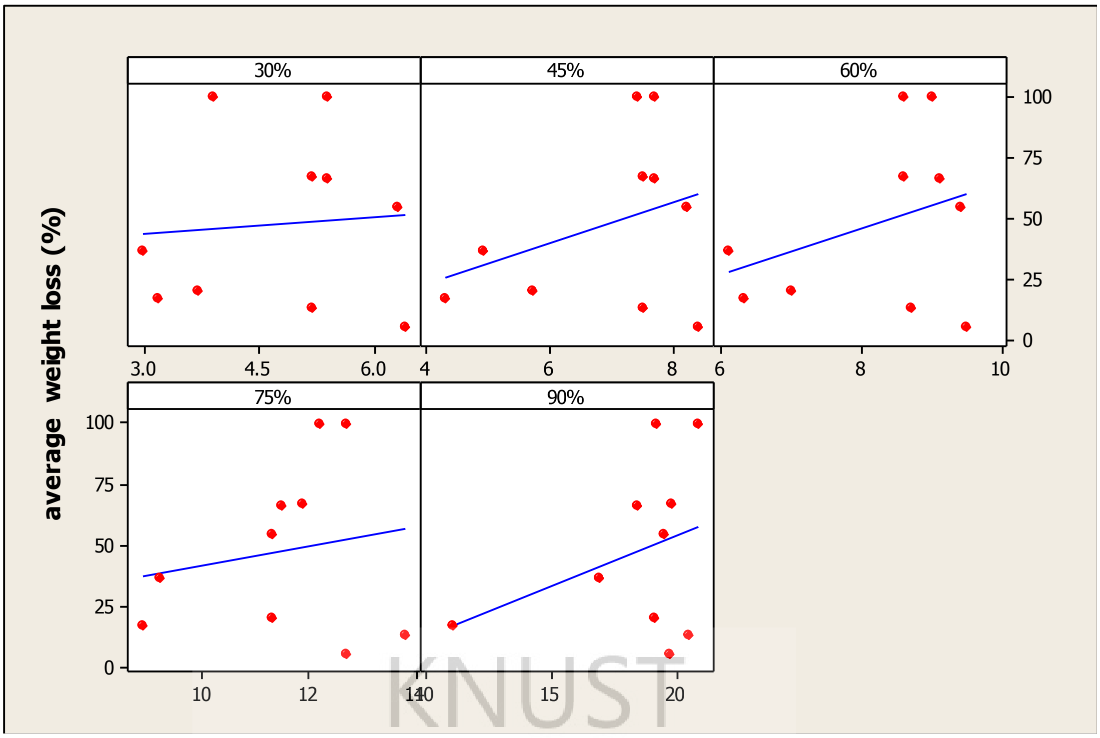


Figure 4.11b Average weight loss (durability) and water sorption of the heartwood of the ten timber species studied

The regression equation is:

Ave. wt. loss % = - 160 – 55.9 30% - 19 45% + 92 60 % - 25.4 75 % + 7.4 90%

R^2 = 73.5 %

Table 4.9. Summary of the multiple regression analysis of the density of the three wood species against some of their tissues.

Species	Tissue	R^2	R	B coefficient
Albizia ferruginea	% Fibers	0.010	0.005	0.00056
	% Axial P.	0.144	- 0.072	- 0.0004
	% Rays	0.300	- 0.150	- 0.0034
	% Vessels	0.512	- 0.256	- 0.0207
	DFWT	0.136	0.068	0.0040
Blighia sapida	% Fibers	- 0.262	-0.131	-0.0021
	% Axial P.		-	-
	% Rays	- 0.140	-0.070	0.002
	% Vessels	0.514	0.257	- 0.038
	DFWT	- 0.328	-0.164	- 0.022
Sterculia rhinopetala	% Fibers	0.446	0.223	0.009
	% Axial P.	- 0.298	- 0.149	- 0.013
	% Rays	- 0.302	- 0.151	- 0.029
	% Vessels	- 0.154	- 0.077	- 0.011
	DFWT	0.214	0.107	0.015

The relationship between density of the species and some features such as fibers, vessels, rays, axial parenchyma and double fiber wall thickness was established by multiple regression. The summary is given in Table 4.9. The degree to which two or more predictors (independent or X variables) are related to the dependent (Y) variable is expressed in the correlation coefficient R, which is the square root of R-square. The correlation coefficient can range from -1.00 to +1.00. The value of -1.00 represents a perfect negative correlation while a value of +1.00 represents a perfect positive correlation. A value of 0.00 represents a lack of correlation. In multiple regression, R can assume values between 0 and 1. To interpret the direction of the relationship between variables, look at the signs (plus or minus) of the regression or B coefficients. If a B coefficient is positive, then the relationship of this variable with the dependent variable is positive; if the B coefficient is negative then the relationship is negative. Of course, if the B coefficient is equal to 0 then there is no relationship between the variables.

The table shows R values of – 0.256 for vessels,- 0.15 for rays, 0.068 for double wall fiber thickness and axial parenchyma with an R value of – 0.072. Fibers had an R value of 0.005 in *Albizia ferruginea.* For *Blighia sapida*, R values recorded were 0.257 for vessels, 0.131 for fibers and double fiber wall thickness with an R value of – 0.164, - 0.07 for rays and 0.0 for axial parenchyma. The R values recorded for *Sterculia rhinopetala* were 0.220 for fibers, - 0.149 for axial parenchyma and rays, – 0.151, 0.107 for double fiber wall thickness and - 0.077 for vessels. Figures 4.12, 4.13 and 4.14 depicts how the the various variables relates with the dependent variable.

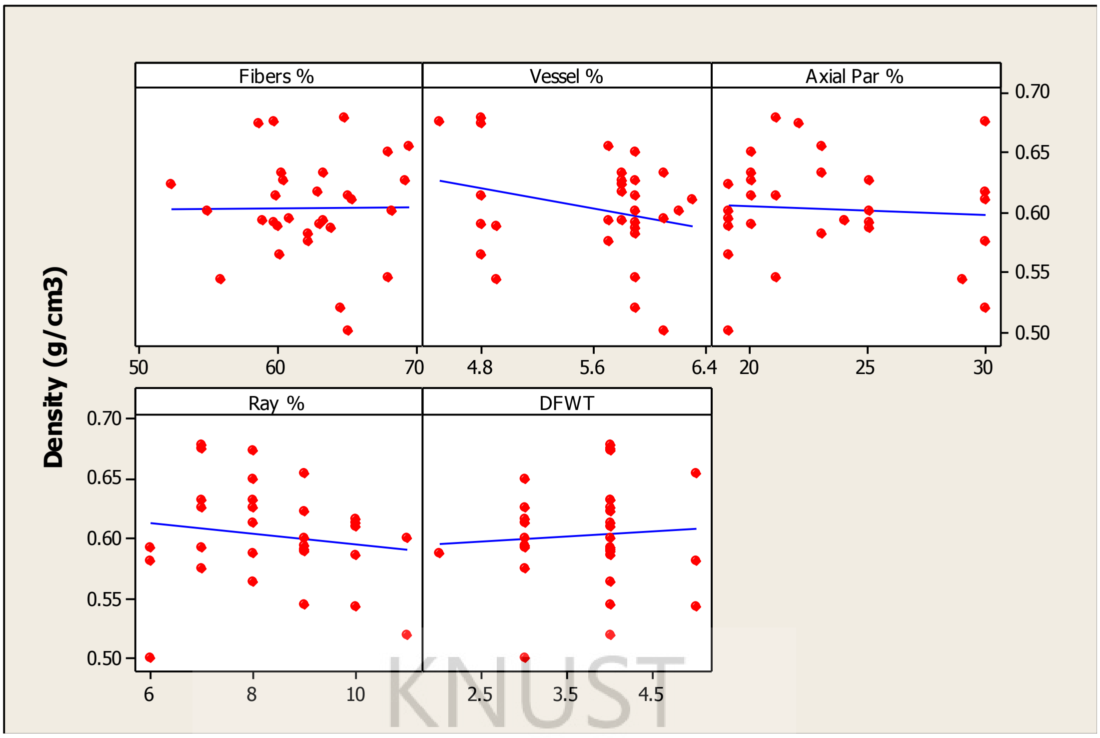


Figure 4.12 Relationship between the density of *Albizia ferruginea* and its tissues, fibers, vessels, axial parenchyma, rays and double fiber wall thickness

The regression equation is

Density = 0.707 + 0.00056 Fibers % - 0.0207 Vessel % - 0.00040 Axial Par %

- 0.00339 Ray % + 0.0040 DFWT

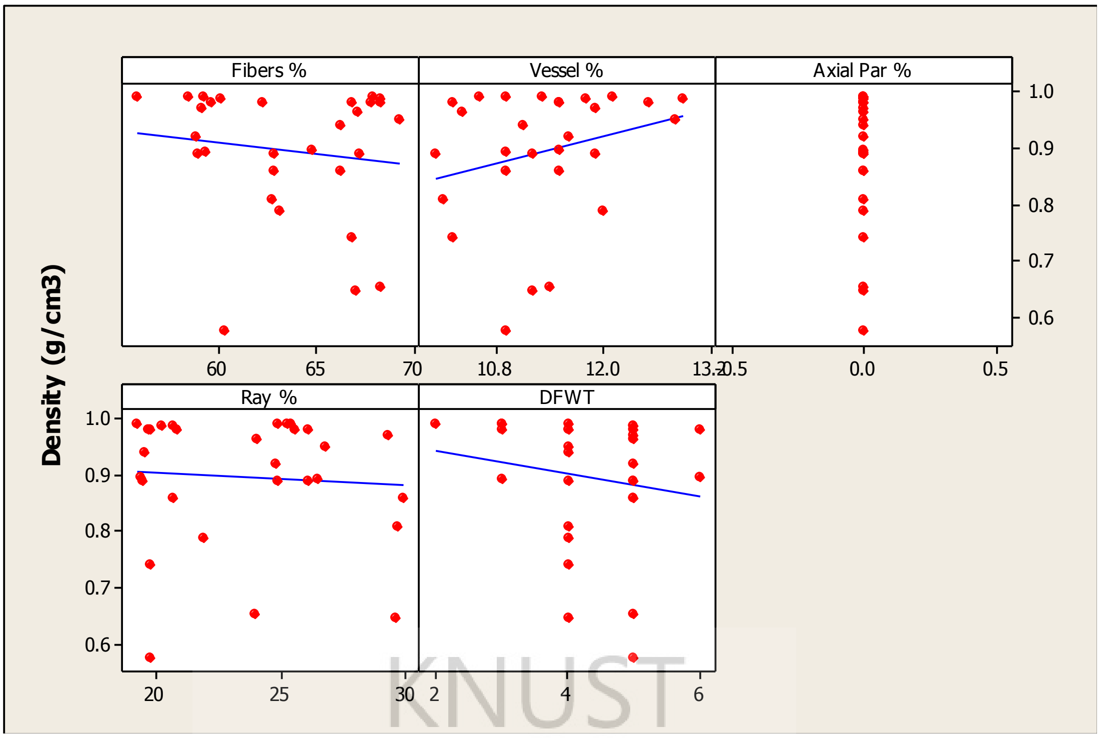


Figure 4.13 Relationship between the density of *Blighia sapida* and its tissues, fibers, vessels, axial parenchyma, rays and double fiber wall thickness.

The regression equation is :

Density = 0.744 - 0.00211 Fibers % + 0.0378 Vessel % - 0.00190 Ray %

- 0.0225 DFWT

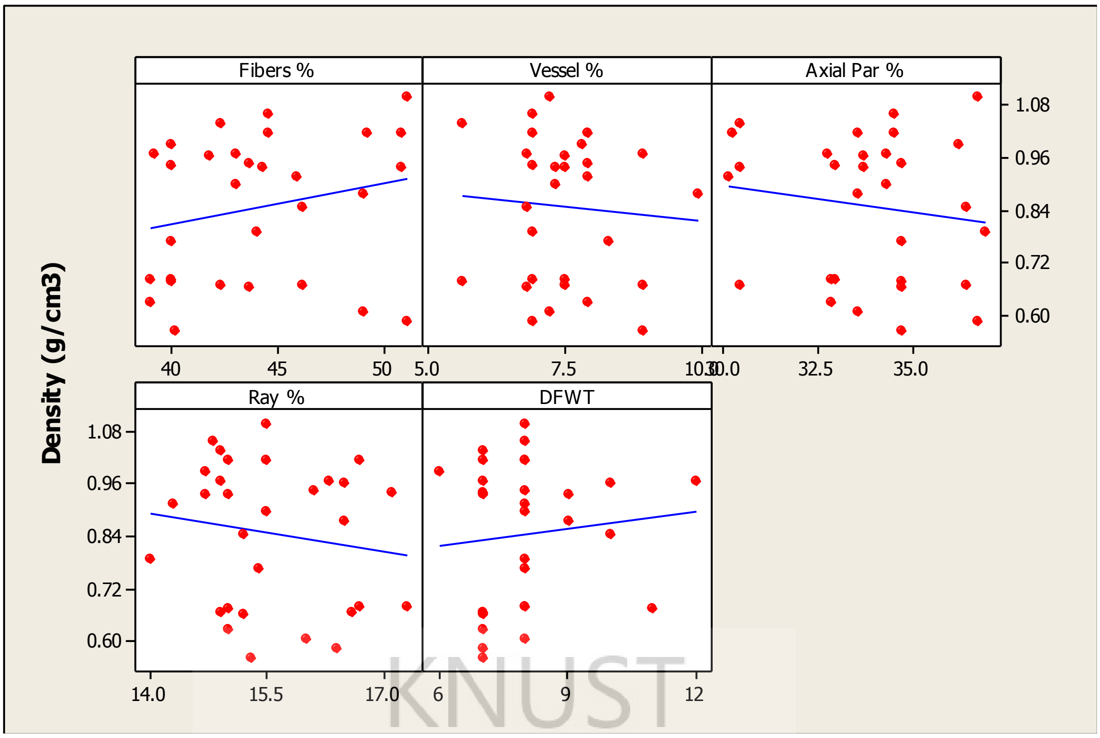


Figure 4.14 Relationship between the density of *Sterculia rhinopetala* and its tissues, fibers, vessels, axial parenchyma, rays and double fiber wall thickness.

The regression equation is:

Density = 1.28 + 0.00944 Fibers % - 0.0117 Vessel % - 0.0125 Axial Par %

- 0.0298 Ray % + 0.0151 DFWT

CHAPTER FIVE

DISCUSSION

5.1 Natural Durability

The determination of natural durability of the ten wood species was carried out through the graveyard tests in 24 weeks. This was done by finding the percentage weight loss in 24 weeks when wood samples of the species were exposed in the field to termites and other wood bio-deteriorating agents. The durability of the reference standard, *Tectona grandis* was similarly determined. Some samples were completely destroyed, while for others, there was only a slight nibbling, amounting to less than 0.5 % of the volume of the sample. In discussing the results of the tests three factors were considered.

First, there is a considerable amount of literature concerning the properties of African hardwoods. In order to restrict the amount of referencing, Bolza and Keating's (1972) review of 700 species of African timbers has been used as a standard reference. Another book dealing specifically with Ghanaian timbers have also been used; this was Irvine (1961). In this thesis the two books are referred to as 'the standard references'. Although these references include local and trade names, the non-scientific names used in the text follow the system used by the Timber Industry Development Division of Ghana’s Forestry Commission and the Forest Research Institute of Ghana.

Secondly, in thinking about weight loss it was obvious that this could be attributed to four main causes, namely, leaching (of water soluble substances by rainwater, etc.), loss of volatile chemicals (though this was thought to be negligible), microorganisms (fungi were noted to be particularly active colonisers of bare wood), and wood-feeding invertebrates. During the test no wood-boring beetles were observed to attack the samples, and hence this final category could be assigned to the termites.

Samples which had completed the full 24-week period in the graveyard were inspected for termite damage. Samples were assessed visually to estimate the amount of damage due to termites if the damage was less than an estimated 5 %. This visual assessment could then be compared with the observed weight loss during the 24 weeks in the soil. In all 330 blocks were inspected, the weight loss over the 24 weeks was substantially greater than the estimated weight loss due to termites. Hence, for species where such an inspection was possible (the more durable species) it is possible to give an indication of the proportion of the weight loss due to termites and the proportion due to leaching and microorganisms. For the less durable species, the extent of the termite attack was so great that such a division into causes of weight loss was impossible.

Finally, a matrix of student t-test (Table 4.1.1) was done. At the 0.05 % level of significance there was significant differences in the weight loss of some of the species whilst others were not significant. For instance, the T-value for *Albizia feruginea* was -3.22 with P-value of 0.005, which explains that the differences between the weight losses of the samples were highly significant within the species that is between heartwood and sapwood. The same goes for two of the wood species: *Sterculia rhinopetala* with a T-value of -2.06 and a P-value of 0.005, and *Tectona grandis* with a T-value of -5.58 and a P-value of 0.000. It shows that there were significant differences between the durability of the heartwood and that of the sapwood within these species. However, in others there were no significant differences between the durability of heartwood and sapwood within a species. These are: *Amphimas pterocarpoides* with a T-value of 1.21 and a P-value of 0.238; *Antiaris toxicaria* and *Canarium schweinfurthii* with T-values of 0.00 and P-values of 1.000 respectively. Others which were not significant were *Blighia sapida* with a T-value of -1.21 with a P-value of 0.239, *Celtis zenkeri* with a T-value of 0.58 and a

P-value of 0.567, *Cola gigantea* with a T-value of 0.45 and a P-value of 0.657, *Petersianthus macrocarpus* with a T-value of -0.27 and a P-Value of 0.788 and *Sterculia oblonga* with a T-value of -1.52 and a P-value of 0.141.

The results from the field test in Table 4.1 indicate that some of the less utilized species could be used as substitutes for the more standard commercial species in their end use applications. For instance, according to Oteng-Amoako *et al*. (2006), *Albizia ferruginea* could be used as substitute for *Milicia excelsa* and *Blighia sapida* could be used as substitute for *Heritiera utilis* (Niangon). The standard references indicated that the wood of *Albizia ferruginea* was highly resistant to termite attack, which was supported by the result of the graveyard tests in this study. In all instances the sapwood was easily attacked by termites, but the heartwood, particularly showed a marked degree of resistance. Unlike mentioned in scarce literature (Abbiw, 1990, Hawthorne, 1990), it happened that *Albizia ferruginea* which was reported to be durable has now been found to be very durable, but while both Taylor (1960) and Irvine (1961) state that *A. ferruginea* was very resistant to termite attack, Bolza and Keating (1972) state that the resistance of this species varies in Africa, being highest in Nigerian timber. Usher and Ocloo (1980) also reported that its outer heartwood showed a greater degree of termite resistance whilst its sapwood was destroyed rapidly by termites when in contact with the soil. The sapwood during the 24 weeks of exposure was only slightly attacked by termites. With a moderate occurrence in the forest it has been cited by IUCN (2004) as a vulnerable species.

Amphimas pterocarpoides heartwood was slightly attacked by termites and in this study was rated as moderately durable. Irvine (1961) however describes the wood as not durable.

Both heartwood and sapwood of *Antiaris toxicaria* were completely destroyed by termites by the fourth month of the study confirming what was in literature (Irvine, 1962) as a perishable wood.

Blighia sapida is a lesser known species so not much has been said about its properties especially its durability status in the standard references. However, another species *Blighia unijugata* of the same family was noted by Irvine (1961) as durable and Abbiw (1990) indicated some of the uses to which the species has been put to such as in building construction. In this study *Blighia sapida* has been rated moderately durable with both its heartwood and sapwood been moderately attacked by termites when visually inspected during the exposure period.

Both Irvine (1961) and the Handbook of hardwoods (1972) describes *Canarium schweinfurthii* as not resistant to termite attack and rated it non-durable. This observation was confirmed by this research with its entire stakes destroyed by the fourth month of this study.

Celtis zenkeri, according to Irvine (1961), showed variability in its durability and that in Congo it was known to be non-durable but considered a useful hard timber in Uganda. Its heartwood was severely attacked by termites whilst its sapwood completely perished during the period of this study. The species was therefore rated non-durable and confirms what in literature.

Cola gigantea was rated as non-durable in this study with its heartwood being severely attacked by termites and its sapwood completely perishing over the period of the study. The standard references both rated this species as perishable. It was found to be very abundant in the forests of Ghana with a national stocking level estimated to be about 1326 stems / km^2. Even though this species was non-durable, suffice to say, that its durability could be enhanced for efficient utilization.

The wood of *Petersianthus macrocarpus* has been reported by Irvine (1961) and Bolza and Keating (1972) to be resistant to insects including termites. With a national stocking level estimated at 738 stems / km^2 (multi-resource inventory 2001), this species was rated as very durable in conformity with literature. It was the only species with no attack by termites when visually inspected. However, it has not been utilized much due to the degrade that occurs in drying.

Sterculia oblonga with moderate occurrence in the forest of Ghana according to Oteng-Amoako *et al*., (2006), was found to be non-durable in the study during the exposure period. This finding confirms the reports in the standard references including the Handbook of Hardwoods, (1972).

The Handbook of hardwoods states that *Sterculia rhinopetala* had being reported to be moderately resistant to termites in Nigeria. Irvine (1961) also states that it was moderately resistant to decay and this study has confirmed this status by also rating it moderately durable.

So far in this study, *Sterculia rhinopetala* which was reported to be moderately durable has been found to be durable and *Blighia sapida* whose status was not much known has been found to be moderately durable.

The species used as reference, Teak, was a plantation grown teak. It was found to be moderately durable. Bhat *et al*., 2005 reported that Teak grown in plantations (and therefore in Ghana) are noted to produce inferior harvests when compared to natural growth environment. The wood is less durable and contains fewer natural oils which act as repellents or toxicants. Haupt *et al*. (2003) found that there was a positive correlation between the age of a tree and the amount of extractives and that prematurely logging Teak result in low durability, appearance and strength. Teak used in the present work was 12 years old and that may account for the slight fall in durability as confirmed by Haupt *et al*. (2003). Literature also shows the importance of the composition of extracts for the natural durability of teakwood. Particularly, tectoquinone was identified as a bioactive compound for the inhibition of *C. puteana*. Its absolute quantity as well as its ratio to deoxylapachol appears to be a good indicator for the estimation of the resistance against wood destroying fungi. It therefore follows that the lower the natural durability of teak, the lower the amount of tectoquinone (source: *www.teakIndustry.com*).

Sterculia rhinopetala and *Sterculia oblonga* both of the same genus had different durability status. The former species being more durable than the latter. This phenomenon was explained by Scheffer and Hopp (1949) and Edmonton (1947) that individual trees of the same species may also differ considerably in their decay resistance due to genetic factors and silvicultural systems.

Eaton and Hale (1993) reported that non-nutrient heartwood extractives were significantly important in determining decay resistance and that other factors including density, nitrogen and starch content, and lignin quantity and type may also contribute to the susceptibility to decay of the heart- and sapwood of woods.

The differences in the durability of the eleven species are graphically represented in Figure 4.1. The figure shows that 4 of the species were significantly more durable than the others (both for sap and heartwood: *Petersianthus macrocarpus* / *Sterculia rhinopetala* / *Amphimas pterocarpoides* / *Albizia ferruginea*). These species are followed by *Blighia sapida*, showing a high variability) and surprisingly by *Tectona grandis* (taken as introduced reference: its heartwood only has a moderately high durability.

5.2 Absorption Test

From the durability tests conducted on the wood species, it was found that the heartwood of *Antiaris toxicaria*, *Cola gigantea*, *Canarium schweinfurthii* and *Celtis zenkeri* were not durable. If they can be amenable to preservative treatment, then their durability could be improved. Knowledge of permeability of wood by different liquids is necessary in determining its preservative treatment. The ease of water uptake is an indication of ease of impregnating the wood with various preservative chemicals, so that the higher the relative uptake value obtained for a wood species, the more permeable or less resistant it is to impregnation (Findlay, 1966). The highest uptake was given by the European conifers, followed by *Albizia ferruginea*, *Canarium schweinfurthii* and *Sterculia oblonga* (Table 4.5) and depicted graphically in Figure 4.4. The lowest uptakes are given by *Sterculia rhinopetala* heartwood, *Tectona grandis, Blighia sapida* heartwood and *Amphimas pterocarpoides* sapwood. The difference between the highest and lowest uptake is 0.7 g. *Sterculia* r*hinopetala* Heartwood takes 10 % in relation to P*icea alba* (100 %, uptake per volume). The relative uptake values obtained indicate that *Antiaris toxicaria*, *Canarium schwienfurthii*, *Cola gigantia*, *Celtis zenkeri* could be impregnated with more than 50 % of their oven dry weight. Gyimah-Buadi (1999) reported that *Antiaris toxicaria* could be impregnated to more than 100 % of their oven dry weight and *Petersianthus macrocarpus* to about 50 % of its oven dry weight. *Sterculia oblonga* also had a higher water uptake with a value of 1.22 % and 1.27 % for sapwood and heartwood respectively. It therefore means that this wood species could be treated to improve its durability. With a good bending strength value of 70 N/mm^2 at a moisture content of 33 %, it could be used for outdoor construction once its durability is improved. According to Dickson (2000), permeability is known to be related to structural properties such as the pore size distribution, the conducting cell structure and the extent to which cells become clogged with tyloses and gums. In this study, it was found that *Albizia ferruginea* had vessels with lumen diameter of 310 µm which could account for its high water uptake. Wiendenhoef and Miller (2005) said that wide vessels have more permeable pit membranes which enhance more uptake of water. According to Wiendenhoef and Miller (2005) the lumen was a critical component of many cells, especially in the context of the amount of space available for water conduction. Axial parenchyma- 23 % of the section studied- could have a part to play in the the high water uptake of *Albizia ferruginea* since it serves as a storage place for the water that is taken up. *Blighia sapida,* however had a low water uptake even though it had vessel distribution of 12 vessels / mm^2, it had not very distinct axial parenchyma which may have accounted for the low water uptake. The occluded pits (Figure 4.7. 2 B) observed in *Blighia sapida* could also account for the low water uptake. Esau (1977) stated that pits can also allow one to make a prediction about how the cell might behave particularly in the context that involved fluid flow. The crystals found in the this species could also account for the low water uptake since these crystals according to literature take up space between the microfibrils which would otherwise be occupied by water molecules and also blocks pathways for liquids.

Venäläinen *et al.* (2003) reported that the quantity of water after wetting and the concentration of stilbenes (extractives) showed a significant negative correlation within the heartwood. The paper explained that there were few earlier reports on the ability of phenolics to interfere with the penetration of water inside Scots pine wood. It further iterated that the reason for this relationship does not necessarily have to be related to the chemical nature of phenolic compounds, but it could also be a specific feature in the structure of the wood that was correlated with the concentration of phenolics and the absorption of water. However in this study *Albizia ferruginea* did not follow this rule combining high water uptake with high levels of extractives. The limitation of this study was the fact that the composition of the extractives in each of the wood species was not investigated but inferences were made based on the data available. Data (Table 4.4) obtained from the chemistry department of FORIG on work done on *Albizia ferruginea* in the semi deciduous forest including where the samples for this study were collected indicate that this wood species had extractive content varying from 8.3 – 9.0 %.

Another aspect that needs mentioning was the differences in the water uptake between sapwood and heartwood of the wood species. Figure 4.4 shows *Sterculia* *rhinopetala* heartwood (SRH) with an uptake value of 0.38 whilst its sapwood (SRS) has a value of 0.72, *Tectona grandis* heartwood (TGH) has an uptake value of 0.53, its sapwood having a value of 0.67 and *Blighia sapida* heartwood (BSH) with an uptake value of 0.58 and its sapwood 0.95. There is a trend where heartwoods of the species have lower values of water uptake compared to their sapwood counterparts. According to Siau (1995), the primary reason for the drastic loss of permeability when going from sapwood to heartwood appears to be the irreversible aspiration of bordered pits and the encrustation and occlusion of the conducting elements by secondary metabolites and deposits. Heartwood cells and pits cavities become filled with hardened deposits and the pit membrane tori often cover the bordered openings into the pit and cell cavities. *Blighia sapida* for instance had crystals embedded in the cavities of its cells (Figure 4.6.3B) which also contributed to its low water uptake. Even *Canarium schweinfurthii* heartwood (CSH) which had relatively high water uptake was lower when compared to its sapwood (CSS).

The high water uptake by the European woods could also be explained by their anatomical features. Of the three European species studied, *Albies alba* (Fir) and *Picea abies* (Spruce) were softwoods with growth increments that undergo a gradual transition from the thin-walled, wide lumined earlywood cells to the thicker walled, narrow-lumined latewood cell (Figure 4.7.3 B) whilst *Fagus sylvatica* (Beech) was a semi diffuse porous hardwood. Dinwoode (2000) stated that as much as the microstructure of hardwood was much more varied than for softwoods so also permeability and capillary behaviour. Siau (1995) described tissues occurring in hardwood as: vessels (20-60 %) for diffuse-porous wood and semi diffuse porous, fibers and tracheids (20-70 %) and longitudinal parenchyma (1-18 %) going vertically through trunk; and wood rays (5-33 %) lying horizontally. Vessels are thin-walled with either partly or completely dissolved end-walls between following elements and provide conductive function. Vessels of diffuse-porous hardwoods occupy larger volume fraction (20-60 %) and the diameters of the vessels are relatively uniform. The sizes vary from 20 μ*m* to 100 μ*m*. In contrast, just two cell types can be observed in softwoods; tracheids and parenchyma cells. Tracheids (93 %) are oriented in longitudinal direction and interconnected by pits. The earlywood tracheids are thin-walled and have mainly conductive function, whereas latewood are thick-walled with support function. The number of pit pairs per tracheids varies from 50 to 300 in earlywood and fewer in latewood. Nearly all of the pits are concentrated on the radial surfaces. Resin canals (1 %) are intercellular spaces presented in longitudinal and horizontal direction. Parenchyma cells mainly occur in the form of wood rays (6 %). *Albies alba* and *Picea abies* with high proportions of thin walled cells would have high water uptake as occurred in this study with a percentage per volume value of 2.98 and 2.38 (Table 4.5) respectively. Dinwoode (2000) also stated that softwoods have a lower concentration of extractives than hardwoods. He gave values as 3 ±2 % for softwoods and 5 ±4 % for hardwoods. Therefore more sites will be made available for water molecules in softwoods than in hardwoods. Generally softwoods are more permeable than hardwoods because the vessels are more uniform, thin walled, with less extractives or incrustations. That explains the differences in water uptake even within the European species studied.

5.3 Sorption

At high humidity, sapwood was found to have a higher sorption power than heartwood for most species. An example was shown in the relationship drawn in Figure 4.2 for *Albizia ferruginea* and *Sterculia rhinopetala*. The low sorption of heartwood as against sapwood can be attributed to the bulking effect of the extractives and other inclusions in the heartwood which prevent water from being adsorbed. Skaar (1988) discussed that the sorption isotherms of all woods were generally similar in shape. However, there may be considerable variations among them with respect to absolute values of hygroscopicity. This variation, he explained, may be because of differences in the proportion of primary wood constituents, such as cellulose, hemicelluloses, and lignin in different woods; or more importantly, because of differences in the kind and quantity of extractives. According to Table 4.4, *Albizia ferruginea* had higher cellulose content of between 44.1 – 46.5 % which means more sites for adsorbed water than *Sterculia rhinopetala* with cellulose content of between 38.2 – 43.4 %. This explains in part the higher EMC value for *Albizia ferruginea* sapwood at 90 % relative humidity. The wood has a high proportion of extractives, according to Table 4.4, and this could influence its sorption power. The hygroscopicities of woods with high extractive contents were generally lower than those without extractives. This was because according to Haygreen and Bowyer (1996), these extractives occupy some sites in the cell wall that would otherwise attract water. *Amphimas pterocarpoides* was also another species whose sapwood had a high EMC value of 19.1 (Table 4.2) at 90 % RH and this could be explained by the high cellulose value of 43.2 – 45.8 % (Table 4.4) which provided more sites for the adsorption of water/moisture. Its heartwood as a result of the high extractive content of between 8.3 – 10.0 % (Table 4.4) had a lower EMC of 17.8 (Table 4.2). *Canarium schweinfurthii* sapwood also recorded a high EMC value of 20.9 at 90 % RH. This wood species has also been found to have high cellulose content ranging from 42.2 – 45.6 (Table 4.4) which may account for the high value recorded. The heartwood of *Canarium schweinfurthii* however recorded slightly lower EMC value of 19.7. Wood species like *Petersianthus macrocarpus* with high durability (Table 4.1) and high EMC (Table 4.2) would have been an ideal wood species for bridge construction but for its large movement when in contact with water which according to Kinnimonth (1976) could be stabilized when kiln dried. Kinnimonth (1976) reported that drying at high temperatures reduces equilibrium moisture contents compared with those of air dried wood when it was subsequently exposed to changing conditions of humidity. Brazier (1985) emphasized that it was the maintenance of stability which was particularly important as more demanding performance requirements were sought from timber, particularly for furniture and joinery uses, as well as in building construction.

The generally low values of sorption recorded for the ten species as shown in Table 4.2 and the high values sorption for the European species in Table 4.3 could be attributed to differences in the microstructure of the woods. According to Dinwoode (2000), European hardwoods like *Fagus sylvatica* were known to have lower extractive contents than tropical hardwoods whilst softwoods like *Abies alba* and *Picea abies* have even lower extractive contents. Out of the three species *Fagus sylvatica*, a hardwood, was supposed to have a lower EMC value than *Picea abies*, a softwood, but this was not the case because according to Fengel and Wegener (1989), *Fagus sylvatica* had high amount of polar extractives which even though occupy sites where water cannot occupy tend to attract water/moisture and dissolve in it and therefore had a slightly higher EMC value of 19.5 at 90 % RH of *Fagus sylvatica* than for *Picea abies.* Another reason why the EMC values for the European species were higher than the tropical wood species was density. All the European species used had densities ranging from 0.41 – 0.68 g/cm^3 whilst the tropical wood species had densities ranging from 0.44 – 1.0 g/cm^3.

Denser wood species also have slower absorption of vapour than lighter woods. That could also explain the reason why *Sterculia rhinopetala* of density 1.007 g/cm^3 had a lower sorption value than, say, *Canarium schweinfurthii* of density 490 g/cm^3. This is in agreement with Rydell (1982) report that vapour absorption was slightly slower for specimens of higher density.

Popper *et al.*, (2001).reported that the risk of fungal attack on lignocelluloses was very high if the water content reaches 20 % at temperature of about 20°C. All the samples used in this study with the exception of *Albizia ferruginea*, *Blighia sapida* and *Sterculia rhinopetala*, were more or less attacked by fungi at the relative humidity of 90 % and temperature of 25°C. *Petersianthus macrocarpus* was the species most attacked by fungi.

5.4 Bending Strength

According to BS 5268-2 (2002) strength properties of wood can be given for green and at 12 % moisture content. In this test therefore all the wood samples used in the bending test were tested at the green moisture content and are compared as such. The values were also adjusted to strength values at 12 % moisture content (Table 4.6). The specimens tested in this study were of structural sizes with all the defects that could be found in them and the results were compared with values obtained using small clear samples as reported in the Handbook of Hardwood (Farmer, 1972).

Sterculia rhinopetala with the highest density of 1.007 g/cm^3 was found to have a high bending strength of 81.7 N/mm^{2}at a moisture content of 44 % with *Antiaris toxicaria* having the least of 49.9 N/mm^2 at a moisture content of 16% at a density of

0.740 g/cm^3. This confirms Dickson, (2000) report that the source of strength in wood is the wood fiber. This is because from Table 4.7, *Sterculia rhinopetala* was found to have a lot of thick-walled fibers and also has the highest density. Wiedenhoeft and Miller (2005) also confirmed this statement by reporting that species with thin-walled fibers have low density and strength, whereas species with thick-walled fibers have high density and strength. According to report by Dickson (2000), resistance to applied forces is a function of the total amount and proportion of cell wall material (cellulose and lignin) in a wood sample and the amount of extractives in the cell lumen. *Sterculia rhinopetala* was also a heavy wood and because relative density is largely a measure of the amount of cell wall material present, it was also a best parameter to use to describe a wood as having a high strength property. Therefore, woods with many thick-walled cells in this case *Sterculia rhinopetala*, will be stronger, heavier, and stiffer than wood with thin-walled fibers like *Albizia ferruginea*. The analysis of results showed that the species with the overall best properties was *Sterculia rhinopetala*. This result was compared by Brunner et al 2007 to the hardwood timber grades according to the European classification system.

In the Handbook of Hardwoods (Farmer, 1972) , the bending strength of *Sterculia rhinopetala* at Green was given as 87 N/mm^2 which compares favourably with 81 N/mm^2 the value obtained from this study and it gave the strength as slightly higher than that of European Beech. The Handbook also rated *Sterculia rhinopetala* as having a high bending strength. Based on this strength and other factors (not discussed in this study but in a related research) it was chosen for a bridge construction. *Sterculia oblonga* had a bending strength value of 70 N/mm^2 but had a value of 81 N/mm^2 in the handbook of hardwoods which also rated it as having a high bending strength and even slightly higher than European Beech. *Sterculia oblonga* could not however be used for a bridge construction because it was not durable according to this study. *Antiaris toxicaria* with a density of 0.440 g/cm^3 had a bending strength of 38.4 N/mm^2 was comparable to *Ceiba pentandra* and therefore could be used as substitute for it. When the bending strength values were adjusted to 12 % moisture contents the strength values went higher for all the species which explains the fact that as wood dries it strength increases. This was confirmed when their strengths increased when it was adjusted to 12 % moisture content. *Sterculia rhinopetala* had its strength increasing from 81.7 N/mm^2 at 44 % moisture content to 83.0 N/mm^2 at 12 % moisture content. The same goes for all the species: *Albizia ferruginea* had its strength increasing from 49.9 N/mm^2 at 51 % moisture content to 51.5 N/mm^2 at 12 % moisture content, *Amphimas pterocarpoides* had its strength increasing from 63.6 N/mm^2 at 16 % moisture content to 63.8 N/mm^2 at 12 % moisture content, *Blighia sapida* had its strength increasing from 61.4 N/mm^2 at 29 % moisture content to 62.00 N/mm^2 at 12 % moisture content, *Canarium schweinfurthii* went up from 44.0N/mm^2 at 30 % moisture content to 44.7 N/mm^2 at 12 % moisture content, *Celtis zenkeri* from 65.8 N/mm^2 at 29 % moisture content to 66.5 N/mm^2 at 12 % moisture content, *Cola gigantea* also went up from 45.7 N/mm^2 at 19 % moisture content to 46.0 N/mm^2 at 12 % moisture content, *Petersianthus macrocarpus* had its strength increasing from 60.9 N/mm^2 at 29 % moisture content to 61.6 N/mm^2 at a moisture content of 12 % and *Sterculia oblonga* increasing from 70.0 N/mm^2 at 33 % moisture content to 70.8 N/mm^2 at 12 % moisture content. Generally, most of the strength properties increase as wood is dried. Above the fibre saturation point, most of the mechanical properties are not affected by change in moisture content. It is apparent that the bending strength increases associated with drying specimens from the green condition to 12 percent moisture content was generally greatest in *Sterculia rhinopetala*.

5.5 Anatomical Study

Albizia ferruginea had on the average two out of six of its vessels occluded with tyloses as shown in Figure 4.6.1 (A). The organic substances in *Albizia ferruginea* may be hydrophilic, accounting for the high water uptake even though it is highly durable. Fengel and Wegener (1989) reported and was cited in International Agency for Research on Cancer (IARC) (1995) monograph that some extractives such as tannins are polar and were generally able to dissolve in water making them hydrophilic. So if the extractives in *Albizia ferruginea* include some tannins that could explain the fact that it was durable and yet had a high water/moisture uptake. Another explanation that can be given for its high water uptake was the vessel diameter and vessel distribution. According to Zimmermann (1982), vessel diameter and vessel distribution have effect on water conduction efficiency. Therefore with vessel distribution of 6 vessels /mm^2, and a maximum vessel lumen diameter of 310 µm it could be expected of *Albizia ferruginea* to have high water uptake. Formation of tyloses in this species may be another reason for its high durability, since tyloses according to Dickson (2000) apparently assist in restricting pathogen movement. He indicated that, in elm trees, tyloses formation was correlated with increased resistance to Dutch elm disease. *Blighia sapida* (Figure 4.6.2 A) was found to have almost indistinct axial parenchyma. Vessel wall sculpturing as seen in Figure 4.7 2 (A) agreed with the findings by Klaassen (1999). The presence of this sculptured wall of the vessel may be responsible for its low uptake of water of 0.44 % per volume. Prismatic crystals occurring in the ray cells as depicted in Figure 4.6.3 (B) and highlighted by SEM micrographs in Figure 4.7.3 (A) was also confirmed by

Klaassen (1999). These could be responsible for the blunting of tools by this species and also occupy sites where water could have occupied thereby contributing to lower water/moisture uptake. Using the scanning electron microscope, it was found that most of the pits of *Blighia sapida* were closed as shown in Figure 4.7.2 (B) and this could be responsible for the low water uptake recorded. Even though *Sterculia rhinopetela* had fewer fibers than the other two species as shown in Table 4.7, most of its fibers had thicker walls and that could account for its high bending strength and density. Since according to Herendeen and Miller, (2000), fiber wall thickness is closely linked with density, i.e. the thicker the wall, the higher the density. From Figure 4.7.1 (B), it was seen that *Sterculia rhinopetela* had almost all its axial parenchyma occluded with substance which probably maybe the polyphenols and this could be responsible for its durability. The actual composition of the substances was yet to be identified. These substances could also act as bulking agents preventing moisture intake and for that matter water. This could account for its very low water uptake both per weight and per volume of 0.38 % and 0.31 % respectively. The low water uptake of *Sterculia rhinopetala* can be explained by the fact that thick-walled fibers go hand in hand with thick-walled vessels and therefore low water uptake. Another advantage of having thick-walled vessels was narrow vessel lumens which leads to resistance to embolism; that is the situation where gases fill the conduit and leads to cavitation. This was because Dickson (2000) stated that the spread of embolisms within a conducting element, and from vessel element to element through the perforation plates, causes the entire vessel to become dysfunctional. Ewers (Baas *et al*. 2004) prepared a diagram of a tradeoff triangle of wood functions and associated anatomical features, the points of the triangle being 1) resistance to embolism (narrow vessels), 2) conductive efficiency (wide vessels), and 3) mechanical strength (thick-walled fibers). It was proposed that there is a negative relationship between mechanical strength and conductive efficiency and a positive relationship between mechanical strength and safety. Wheeler *et al*. 2007, in discussing the variation in global dicotyledon wood anatomy, asserts that woods with thick-walled fibers have thick-wall vessels which result in low conductive efficiency. Therefore it is understandable that *Sterculia rhinopetala* with thick-walled fibers has low water uptake due to narrow vessel lumen.

Sterculia rhinopetala was found to have longer fibers (Table 4.7) with lengths ranging from 1479 – 1899 µm. *Albizia ferruginea* followed with fiber lengths ranging from 1196 – 1274 µm with the relatively shorter fibers belonging to *Blighia sapida* with lengths ranging from 1127 – 1303 µm. The shorter fibers may be responsible for the brittle behaviour *of Blighia sapida* observed under stress.

5.6 Interrelationships and Correlations

A negative relationship established between density and weight loss in Figure 4.8a and 8b indicate that weight loss and therefore durability was correlated with the density of a species. In this case they were negatively correlated for both sapwood and heartwood. Even though durability of a wood species was rather dependent on extractives, moisture content of the wood, genetic factors and silvicultural practises (Eaton and Hale, 1993), suffice it to say that sometimes weight loss and durability could correlate positively with density where the denser wood will take time to lose weight than a light wood when both are subjected to degradation. A positive relationship established between density and bending strength in Figure 4.9 confirms the well-established fact that denser species as a consequence of thick walled fibers and mass of wood tends to withstand bending stress.

On the durability test, *Albizia ferruginea* was rated very durable but had a high water uptake in the absorption tests had a bending strength of 49.9 N/mm^2 at a moisture content of 51 %. From the anatomy of the wood, it appeared the thin walled fibers had some influence on its low bending strength compared to that of *Blighia sapida* and *Sterculia rhinopetala.* Since thick-walled fibers were associated with high bending strength. There was however, a high amount of inclusions in the rays which would account for its high durability. The inclusions would probably be some polyphenols responsible for the durability of this species. Some relationship can be drawn between amount and type of inclusions and the durability of a wood species. A limitation of this study was that the various compositions of the extractives present in the wood species were not investigated but inferences would be made from Teak. As stated earlier in the text, the durability of Teak was found to have been lowered due to the amount of tectoquinone. Tectoquinone had been identified as a bioactive compound for the inhibition of *C. puteana*. Its absolute quantity as well as its ratio to deoxylapachol appeared to be a good indicator for the estimation of the resistance against wood destroying fungi (www.teakindustry.com). It therefore follows that the lower the natural durability of teak, the lower the amount of tectoquinone. One can therefore safely deduce that there was a direct relationship between durability and inclusions. Even though it is a generally acceptable phenomenon that low water uptake was positively correlated to durability, in the case of *Albizia* it was not so since it combined high water uptake with high durability. The relationship was however established in *Blighia sapida* where low water uptake corresponded with moderate durability. If *Blighia sapida* had complemented low water uptake with high levels of the polyphenols responsible for the natural durability, it would have been a very durable wood. However the relationship was established that low water uptake was directly related to durability.

Density is another property that correlates with a lot of factors. It is the single most important physical property. Amongst the three species, density correlated very well with bending strength. *Sterculia rhinopetala* had the highest density of 1.007 g/cm^3 and it had the highest bending strength. *Blighia sapida* with a density of 0. 900 g/cm^3 had a bending strength value of 61.4 N/mm^2 followed by *Albizia ferruginea* with a density of 0.740 g/cm^3 having a bending strength of 49.9 N/mm^2. It follows therefore that the denser the wood species the greater the bending strength. Density also had a direct relationship to fiber wall thickness. *Sterculia rhinopetala,* for instance with thick-walled fibers had a high density. Therefore if a wood species had thick-walled fibers it follows that it would have a high density and a high bending strength. The inverse is also true that thin walled fibers will give low density and low density wood will have a low bending strength (Wiedenhoeft and Miller, 2005). Density however does not correlate with fiber length. From this study it was found that *Sterculia* rhinopetala was a dense wood and also had longer fibers but *Albizia ferruginea* was less dense than *Blighia sapida* but had longer fibers than *Blighia sapida*. Density does not also correlate with vessel frequency. *Blighia sapida* had 12 vessels/mm^2 which was the highest among the three wood species but it was not denser than *Sterculia rhinopetal*a with a vessel frequency of 7 vessels/mm^2. Density and water uptake were also inversely related (Figure 4.5). When the wood species was dense it took up less water. *Sterculia rhinopetala* which was the densest species tested, had the lowest water uptake whilst the lightest species tested which was *Antiaris toxicaria* had a higher water uptake second only to *Albizia ferruginea.* The same could be said for density and adsorption (Figure 4.10a and b) where a negative correlation was established between density and sorption. The extractives in *Albizia ferruginea* would probably be polar (Fengel and Wegener, 1989) so were hydrophilic which could explain its high water uptake. Another property which did not correlate with density is natural durability. As already discussed in text, *Albizia ferruginea* was found to be very durable even though it was not as heavy as *Sterculia rhinopetala*. A wood species like *Sterculia oblonga* with a density of 0.820 g/cm^3 which was denser than A*lbizia ferruginea* was found to be non-durable. Therefore density correlates with thick walled fibers, bending strength, water uptake, but does not correlate with fiber length, vessel frequency, and durability.

The correlation between anatomical properties and sorption was found to be very strong. For instance *Albizia ferruginea* was found to have a higher sorption than *Sterculia rhinopetala*. This can be explained by the fact that cellulose which is the main chemical constituent of the wood species was found to be high in *Albizia ferruginea* than in *Sterculia rhinopetala*. Findings made available by the chemistry department of FORIG give the cellulose value for *Albizia* to be between 44.1 – 46.5 % and that of *Sterculia* to be between 38.2 – 43.4 %. There were more sites for the water molecules to be adsorbed in *Albizia ferruginea* than in *Sterculia rhinopetala* therefore explaining the reason for high sorption in *Albizia ferruginea*. It therefore follows that the higher the amount of these chemical constituents, the higher the sorption giving a direct relationship between some anatomical features and sorption.

The relationship between durability and sorption was a positive one though with a weak R^2 of 0.219 (Figure 4.11a) for heartwood and an R^2 of 0.735 (Figure 4.11b) for sapwood which suggests that as water adsorption increases durability or weight loss also increases more for sapwood than for heartwood. This was true since as the moisture content of a wood increases, its weight loss increases because it becomes susceptible to biodegraders. Dickson (2000), however, stated that if it loses water, its durability was increased significantly. On the other hand, if a wood species was said to be durable then it means that it must have extractives in higher proportions and these extractives will have a bulking effect during sorption which will reduce the amount of water molecules to be adsorbed and therefore the wood species will have a lower sorption power. This was the case for *Sterculia rhinopetala*. However, for *Albizia ferruginea* which came out of this study very durable also had a high sorption power but this wood species behavior had been explained earlier in the text and attributed the trend to be due to the proportion of cellulose. It can be concluded that the relationship between durability and sorption is a positive one though together with other factors the direction of the relationship could change.

Durability and mechanical properties are not correlated at all. Since one can have a very durable wood performing poorly when it comes to mechanical properties, especially with bending strength. This is because the factors that control natural durability and those that control bending strength of wood are different. An example was *Sterculia oblonga*. This wood species had a bending strength of 70 N/mm^2 which was good considering the fact that the wood with the best bending strength of the ten tested species had a value of 81.7 N/mm^2. *Sterculia oblonga*, however was found to be non-durable in the durability test. *Albizia ferruginea* was rated very durable in the durability test but had a low bending strength.

The interrelationships found are between anatomical features, density, and bending strength. It follows that if a wood species has thick walled fibers, then it will be dense and so will have a high bending strength. They are all directly correlated.

Another relationship drawn in this study was between adsorption and absorption in Figure 4.5. The result showed no significant relationship (P-value 0.022) between the moisture content (adsorption) and the quantity of water after wetting (adsorption + absorption). Venäläinen *et al*. 2003 reported that adsorption and absorption, both of which depict the interaction between the wood and water, actually reflect completely different wood properties.

Density of wood is a complex physical property since the tissue is made up of different proportions of cells of variable size and chemical composition. These variations depend on the species and its interactions with the environment. Generally, density of mature trees is higher than that from young trees. Density varies in trees, from pith to bark and from base to apex and it is affected also by the age of the tree. The multiple regression analysis showed that for *Albizia ferruginea*, percentage of vessels could influence about 51 % of the density of the species but the B coefficient (If a B coefficient is positive, then the relationship of this variable with the dependent variable is positive; if the B coefficient is negative then the relationship is negative. If the B coefficient is equal to 0 then there is no relationship between the variables) is negative implying that the lower the percentage of the vessels in this species the denser the wood, percentage of rays also has 30 % influence on the density but the relationship is inverse since the B coefficient is negative which also implies that the lower the percentage of rays the denser the species. The same goes for the axial parenchyma which account for 14 % of the density of the wood. The percentage of double fibre wall thickness in *Albizia ferruginea* accounts for 13.6 % of the density of this species with a positive B coefficient implying that the more the double wall fibre the denser the wood. In *Blighia sapida*, the percentage vessels can be used to predict about 51.4 % of the density of the species and since the B coefficient is negative, it implies that the less vessels the denser the wood. Percentage fibres accounts for 26 % of the density of the wood species and double fibre wall thickness accounts for 32.8 % of the density of the wood, and so if the B coefficient is negative it means that the wood is less dense. In explaining this phenomenon, Wiendenhoeft and Miller (2005) stated that in hardwoods density was not only dependent on fiber wall thickness, but also on the amount of void space occupied by the vessels and parenchyma. The percentage fibres in *Sterculia rhinopetala* account for 44.6 % of the density of this species, meaning the more the fibres, the denser the wood. Double fibre wall thickness accounts for 21 % of the density with axial parenchyma and rays following with 30 % and vessels 15 %.

CHAPTER SIX

CONCLUSION

6.1 Natural Durability Investigations

There were differences in the natural durability of the ten lesser utilised species. *Albizia ferruginea* was found to be very durable; *Blighia sapida* was rated moderately durable whilst *Antiaris toxicaria* and *Canarium schweinfurthii* were found to be non-durable. Some of these less utilised species such as *Blighia sapida* K. D. Koenig could be useful substitutes for some of the primary species like *Heritiera utilis* (Sprague) Sprague. Some of the wood species which were not durable for example, *Antiaris toxicaria*, could be impregnated under pressure with preservatives. Four out of the ten species tested were significantly more durable than the others. The differences in natural durability of sapwood and heartwood of most of the wood species were statistically significant.

6.2 Anatomical Study

Anatomical features and structures studied helped explain the results of the properties of the wood species. It was possible to make certain predictions about wood properties from careful anatomical examinations. Accordingly woods with many thick-walled cells would be stronger, heavier and stiffer than wood with thin-walled elements. Some anatomical features like fibre wall thickness have effect on the bending strength of the species. Narrow vessels in *Sterculia rhinopetala* also affected water uptake and therefore made the wood species less permeable. Some inclusions which may include extractives found in *Albizia ferruginea* and *Sterculia rhinopetala* could be responsible for their natural durability. These extractives could be isolated and analysed to determine the various component and be able to discuss properly what their function was and how far they influence the utilization of the woods. The use of scanning microscopy to examine the anatomical and ultra-structural aspects of wood has been found to be a useful approach to a clearer understanding of the features and structures found in wood. Even though these species have been identified macroscopically. The microscopic and SEM investigations carried out in this study helped to identify some of the features that were not visible macroscopically. Some of these features such as the presence of crystals in *Blighia sapida* and the thick-walled fibers of *Steruclia rhinopetala* and the absence of axial parenchyma *in Blighia sapida* had enabled these species to be better understood. It therefore goes to buttress the fact that where more positive identification was required, a laboratory investigation must be made of the microscopic anatomy of the wood.

6.3 Sorption Properties

Albizia ferruginea, Canarium schweinfurthii, and *Sterculia oblonga* were found to have high water uptakes. On the other hand, *Sterculia rhinopetala, Tectona grandis, Blighia sapida* and *Amphimas pterocarpoides* were found to have lower water uptakes. The European species were found to have higher water uptakes than the 10 tropical timbers. Generally the EMC of the sapwoods of the wood species were higher than the EMC of the heartwoods ranging from 19.8 to 18.4 and that of heartwoods ranging from 18.3 to 16.1. *Sterculia rhinopetala* had the lowest EMC with sapwood value of 11.0 and heartwood value of 9.6. The absorption and adsorption tests saw *Sterculia rhinopetala* having low water/moisture uptake and *Albizia ferruginea* having the highest uptakes. A relationship between water uptake and the microstructure of wood was observed. Generally the denser the species the less water/moisture it takes up and the more durable it was.

6.4 Bending Strength

Sterculia rhinopetala was found to have a high bending strength. Its strength was slightly higher than European Beech. *Antiaris toxicaria* was found to have a bending strength comparable to *Ceiba Pentandra.* At 12 % moisture content the bending strengths of all the wood species were higher than when green.

6.5 Interrelationships

In principle the bending strength property of timber correlate with density and it was precisely in this respect that some lesser-used timber species have an advantage over the primary species. There is a strong correlation between density and bending strength of most of the wood species. Even though for hardwood basic density, it does not only depend on fibre wall thickness but also involves the volume ratio of fibres to vessels. There was also a good correlation between density and water sorption and durability which gives the indication that the denser the wood species, the less water/moisture it will take up and therefore the more durable it will be even though there were exceptions. There was a negative correlation between density and durability. Density correlates with fibre wall thickness but does not with fibre length. Predicting the density of a wood species without determining it can be done by knowing the varoius percentages of the tissues in the wood. In conclusion efficient utilization dictates that species should be matched to end-use requirements through an understanding of their properties and the interrelationships that govern them.

RECOMMENDATION

- Further investigation on the extractives of *Sterculia rhinopetala* will be worthwhile to understand the factors involved in the high resistance against bio- deterioration. This is because sound understanding of the influences of extractives in wood facilitates competitiveness and intelligent use of wood as a material. Research should be aimed at separation and characterisation of extracts to understand their chemical composition and to enhance the use of the right wood for the right purpose. In addition, a comparative anatomical study between *Sterculia rhinopetala* and *Sterculia oblonga* should be conducted to better explain the differences in durability.
- In addition, research could be conducted to evaluate the role of wood extractives on the wettability and sorption properties of the woods.
- A complete study of the sorption characteristics could be done to better explain the hysteresis that will result in order to fully understand the behaviour of these woods in contact with water.
- Furthermore, the Hailwood –Horrobin sorption model could be acquired to help estimate the fibre saturation point of the wood species.
- Even though most of the studied wood species were found to be non-durable, most of them had high national stocking levels which could be harnessed to help stop the over dependence on the so-called durable species. This could be done by enhancing their durability through preservative treatment.

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