UNIVERSITY OF EDUCATION, WINNEBA
COLLEGE OF TECHNOLOGY EDUCATION, KUMASI

LOGGING RESIDUES QUANTITIES, AND SOME PROPERTIES OF SOLID AND FINGER-JOINTED LUMBER OF STEM (OFF-CUTS) AND BRANCH WOOD OF SOME GHANAIAN TROPICAL HARDWOODS.

PETER KESSELS DADZIE
(91010780003)
MSc. WOOD TECHNOLOGY AND INDUSTRIAL MGT.
BEd. (Hons.) TECHNOLOGY EDUCATION (WOOD OPTION)

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DECLARATION

STUDENT"S DECLARATION

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

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SUPERVISORS" DECLARATION:

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

NAME OF 1ST. SUPERVISOR: --

SIGNATURE: --

DATE: ---

NAME OF 2ND SUPERVISOR: --

SIGNATURE: --

DATE: ---

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	MEANINGS
KD	Kiln-dried
AD	Air-dried

TIDD	Timber Industries Development Division
FPI	Forest Products Industry
WPI	Wood Products Industry
GHGE	Green House Gas Emissions
MLNR	Ministry of Lands and Natural Resources
LRs	logging residues
GDP	Gross Domestic Products
FAO	Food and Agricultural Organization
IIED	International Institute for Environment and Development
AAC	annual allowable cut
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
FJ	Finger-Joint (ing)
FSP	Fibre Saturation Point
NAFI	National Association of Forest Industries
ISO	International Standard Organization
ASTM	American Standard for Testing and Materials
PRF	Phenol Resorcinol Formaldehyde
PVAs	Polyvinyl Acetate Adhesives
LLL	Logs and Lumber Ltd
MSD-SE	Moist Semi-Deciduous (South-East type
MSD-NW	Moist Semi-Deciduous North-West forest
ME	Moist Evergreen
FORIG	Forestry Research Institute of Ghana
TUCs	Timber Utilization Contracts
TMRV	Total Merchantable Residue Volume

TMWV	Total Merchantable Wood Volume
ELV	Extracted Log Volume
DBH	Diameter at Breast Height
WD	Wood Density
MC	Moisture Content
%WL	Percentage Weight Loss
IAWA	International Association of Wood Anatomists

ABSTRACT

The purpose of this study was four-fold: First, to estimate merchantable logging residues left in the forest after logging; second, to investigate the natural durability of stem and branch wood of five species; third, to compare the bending strength of solid and finger-jointed lumber; and finally to investigate the influence of anatomical properties on natural durability and mechanical properties of wood. The five wood species were *Entandrophragma cylindricum (*sapele), *Entandrophragma angolense* (edinam), *Khaya ivorensis* (mahogany), *Terminalia superba* (ofram), and *Pterygota* *macrocarpa* (koto/kyere). Forest residues were quantified with Smalian‟s equation, natural durability test was measured on percentage weight loss in accordance with EN 252-1989, whereas bending strengths of solid and finger-jointed lumber (produced with PVA adhesive) were evaluated in accordance with BS 373-1957, and the anatomical properties assessed using IAWA Committee protocol and using ImageJ software. Results showed 25% of merchantable logging residues of felled trees were left in the forest unextracted. Unlike branchwood of mahogany, ofram and koto whose natural durability were comparable to their stemwood, branchwood of sapele and edinam dried to 9±3%MC were significantly ($p<0.05$) better than their stemwood counterparts. Bending test showed significant ($p<0.05$) MOE differences from 9.4% to 23.5% higher in solid branchwood of edinam, mahogany and ofram, whereas MOR differences were from 16.5% to 23.5% higher in branchwood of edinam and mahogany compared to their stemwood counterparts with MC and wood type having significant effect ($p=0.000$). Branchwood finger-jointed lumber combinations produced joint efficiencies in MOE ranging from 59% to 110%, and those in MOR ranged from 30% to 68%. Expectedly, finger-joint efficiencies in MOE and MOR correlated inversely with wood density. But unlike the MOEs, MORs of all finger-jointed combinations were significantly lower ($p<0.05$) than those of stemwood of their respective species. As a characteristic of hardwoods, sizes and quantities of some wood cells were either significantly ($p<0.05$) more or less in stemwood than in branchwood. As expected, fibre and parenchyma proportions respectively correlated inversely and positively with percentage weight loss. Also, fibre and vessel proportions correlated positively and inversely respectively with MOE and MOR. In conclusion, wood residues are of substantial quantities, and solid wood or finger-jointed lumber of branches are not inferior to those of stemwood of the same species and therefore branches could be extracted for use to supplement stemwood so as to help in addressing the challenge being posed by timber shortages to industry and also help in reducing the depletion rate of Ghana‟s forest cover.

CHAPTER ONE

INTRODUCTION

1.1: General Introduction

The forest products industry (FPI), including the wood products industries (WPIs) are confronted with several challenges relating to technological diversification to production of quality wood products (Cionca, Badescu, Zelenivc & Olaresui, 2006). However, the most recent and pronounced challenge in the WPIs is the shortage of raw material (timber) due to the continuous dwindling of the world‟s wood resources, and Ghana is no exception (Cionca et al., 2006; Hawthorne & Abu-Juam, 1995). Several reasons and causes have been ascribed to the continuous depletion of wood resources. The causes include increase in demand for wood and wood products, inefficient logging, logging damages, mining activities, inefficient processing practices, urbanization, agricultural expansion, forest fires, and misuse of wood residues like branches and off-cuts (Ayarkwa, Hirashima, & Sasaki,. 2000a, 2000b; Hawthorne & Abu-Juam,1995; Okai, 2002). Again the dwindling or depletion trend is much more being increased by increases in population and its associated expansion of the construction sector leading to a much higher demand for wood and wood products (EarthTrends, 2003; Agyarko, 2001). Ghana‟s tropical forests depletion stands at a mean rate of 2% per annum (Ministry of Lands and Natural Resources-MLNR, 2012a) which is measured as 750km^2 per year and also translates into about €877,346.903 loss annually (Murray, 1993).

The dwindling of the forest resources and its associated shortage of wood raw materials for the wood related industries are negatively affecting the WPIs‟ operations, the economic lives of Ghana as a country and that of the citizenry in general. It is reported that the timber products of Ghana are major economic resources that contribute substantially to the Gross Domestic Product (GDP) of the country, and also provide both direct and indirect employment to the citizenry. Timber export is the third foreign exchange earner after cocoa and minerals and contributed about 8% to the GDP of the country, a decade ago, but this contribution has fallen to a current level of 4% and the situation is partly attributed to the dwindling trend of the wood resources (MLNR., 2012a). Again, besides the national GDP, wood products manufacturing also provides direct employment to over 100,000 people (Ghana Statistical services, 2007) and together with indirect employments, the forests provide livelihood to nearly 15% of the Ghanaian population (MLNR., 2012a). Again, it is reported that the deforestation situation and the deficit of about 1,500,000m^3 per annum between wood mills installed capacity as against Annual Allowable Cut (AAC), among other factors, have caused some wood processing industries to either fold-up or not to operate at full capacity, due to lack of wood raw materials (Food and Agricultural Organization-FAO, 2009; 2012; Oten-Amoako et al., 2008). These have subsequently led to job losses and which have in turn affected the economic lives of otherwise employed people in the WPIs and their dependants. It has therefore been realized by most WPIs that the industry can no longer continue to expand to meet demand for wood and wood products, achieve economic growth and offer employment, simply by extracting more tree stems (Asumadu, 2004).

It is also worthy of emphasis that beyond the economic consequences of forest depletion and degradation, there are critical functions of the forests that cannot be underestimated and which are being threatened by the depletion trends. The forest is responsible for the protection and preservation of the ecosystem and climate, including water bodies and the soil (Ministry of Lands and Natural Resources-MLNR, 2012b). It is therefore reported that deforestation and degradation of forests account for around 20% of global greenhouse gas (GHG) emissions, which are widely believed to drive climate change (Gorte & Sheikh, 2010; Peskette, Huberman, Bowen-Jones, Edwards, & Brown, 2008) and negatively affecting water bodies and the entire ecosystem. Hence, the carbon sequestration responsibility of the forests is vital and critical for environmental safety. In line with this, it is reported that carbon sequestration capacity of Ghana"s 38,000 sq. km protected forest area is about 16% and Ghana produced GHGE of about 24 metric tonnes of CO_2 equivalent in 2006 (MLNR, 2012a). In the face of increase in oil exploration and production in Ghana, CO_2 emissions are forecasted to grow above the 2006 levels and if steps are not taken to address deforestation and forest degradation in order to play its role of carbon sequestration effectively, the emissions will gradually put the climatic structure and the environment in danger for all living organisms, including man (MLNR, 2012a). Consequently, reducing tropical deforestation is critical to controlling the levels of carbon emissions (Amazon Institute for Environmental Research, 2005; Van-der-Werf et al., 2009). Moreover, and more importantly in this regard, tropical forests, and adolescent and matured trees rather than young ones, are the major source of carbon sink (Houghton, 2005; Oregon Forest Resource Institute, 2011; Peskette et al., 2008). Therefore, such trees need to be preserved, protected and used efficiently.

The most disturbing aspect of the depletion of Ghana"s forests is the drastic extinction of the commercial timber species used for furniture and other value-added products, and which have much value especially in the export markets (Dadzie, 2011). According to the International Institute for Environment and Development (IIED), supplies of the traditional (premium and commercial) hardwood timber species including *Entrandophragma angolense* (edinam), *Entrandophragma cylindricum* (sapele), *Millicia excels*a (Iroko/odum) and *Terminalia superba* (emire), among others could fall by a further 50% within five years (Acquah & Whyte, 1998). The manifestation of this predicted trend of depletion could lead to further shortage of timber to feed the furniture, construction and other wood related industries and which could lead to eventual collapse of additional number of such industries. Therefore, it stands to be only a necessity that cogent steps are taken to find alternatives or supplements to stemwood to ensure continuous operations of the WPIs while safeguarding the environment and climate. One readily available means of obtaining alternatives or supplementing is to use almost all parts of felled trees (whole tree utilization concept) especially, logging residues like branches and off-cuts (Shmulsky & Jones, 2011).

It is however important to report that several institutional and policy reforms have been introduced by the government of Ghana since the 1990"s to reduce the depletion rate of the forests. These reforms include placement of limitations on the flow of some premium and commercial tree species to the processing mills and exploitation and promotion of lesser-utilised timber species. All these sought to encourage the forest and wood processing sector to lay much emphasis on more efficient use of harvested timber by possibly adopting the whole tree utilization concept in value addition chains of wood products manufacturing (Quisheng, Shenzue, & Youngyu, 2002). These already stated policies and reforms, though have made some impacts, the demand for wood continues to increase due to increasing population and its associated human activities (like housing, farming, opencast mining etc.), all of which continue to aid depletion of the forests. In Ghana, annual population growth rate is 3.0% and is estimated to require additional land area of about 33ha per unit percentage (totalling 99ha. per annum) for additional housing infrastructure and other social services, besides farming, mining and others (Agyarko, 2001).

Therefore, finding alternative or supplementary sources of wood by adopting the whole tree utilization concept is still relevant and continues to generate interest. The concept of whole tree utilization advocates for the use of logging residues (LRs) like tree tops, limbs/branches, stumps and roots (Shmulsky & Jones, 2011), all of which can serve as supplements or alternatives to stemwood in wood products manufacturing. But for silvicultural reasons of those parts providing soil nutrients for tree growth, people are either prevented or discouraged in using the residues (Walmsley, Jones, Reynolds, Price & Healey, 2009). However, it is also important to note that one potential benefit from whole-tree utilization to forest operations is that, it can make forest site preparations in the subsequent timber rotations easier and faster, which in turn reduces logging cost (Westbrook, Greene & Izlar, 2007). Again, it is also reported that the whole tree utilization concept is found to increase yield by about 60% over and above the traditional method of harvesting- where only the stem log is extracted (Shmulsky & Jones, 2011).

Meanwhile, the LRs left in Ghana"s tropical forests have been reported to be relatively high and of good quality. Amoah (2008) and Amoah and Becker (2009) reported that, there is about 25% of merchantable wood residues, in the form of branches, stumps and stem off-cuts left as LRs in the forests which translates into the preservation of at least 6.0ha of forest and which are of good quality to be processed for use. It is evident therefore that wood residues are of substantial quantity and quality to serve as a potential source of wood supply to supplement stemwood, make site preparations easier and less costly in future operations, and above all, contribute substantially towards reducing depletion of the forests.

In spite of the above benefits of utilizing LRs, there are concerns about the nature or quality of branchwood materials, in terms of mechanical and other properties that make people disinterested in their use. It is reported that the properties of branchwood differ from wood of the main stem, and so manufacturing processes may have to be modified to accommodate these variable components (Shmulsky & Jones, 2011). Again, from the utilization point of view, branches have much higher proportion of bark especially those with diameters of less than 2.5cm and could also possess too many knots, all of which could reduce its strength (Shmulsky & Jones, 2011). Also, branchwood itself differs from the wood of the main bole due to possible presence of reaction and juvenile wood contents, which make branchwood utilization difficult. The presence of reaction and juvenile wood produces wolly and fuzzy surfaces, and also makes wood shrink excessively and develops drying stresses in the wood (Shmulsky & Jones, 2011). However, hardwood branchwood is generally higher in specific gravity than stem wood (Amoah, Appiah-Yeboahand & Okai, 2012; Okai, Frimpong-Mensah, & Yeboah, 2004). In general, high specific gravity wood usually has high natural durability and mechanical strength (Antwi-Boasiako, & Pitman, 2009; Antwi-Boasiako & Atta-Obeng, 2009), which suggest that branchwood could possibly have high natural durability and mechanical strength. Also the variation between stemwood and branchwood density among species appears rather unpredictable (Ayarkwa, 1998), and normal branchwood (having diameter of 50mm and above) of some species have similar compressive strength parallel to the grain and similar shock resistance but have even greater plasticity compared to normal stemwood (Gurau, Cionca, Mansfield-Williams, Sawyer, & Zeleniuc, 2008; Shmulsky & Jones, 2011). As a result of the prooven reliability of branchwood, those of one species (*Aningeria robusta*- asanfena) have been used alone to produce furniture in Ghana (Okai, 2003) and in a mix with normal stemwood for hardboards production elsewhere (Gurau et al., 2008).

If attributes of some species‟ branchwood make it good enough to be used either alone or in a mix with normal stemwood for the manufacture of some wood products, then it is equally necessary to seek to find the suitability of branchwood of additional species to be used either alone or in a mix with stemwood off-cuts, as components of furniture parts (like seat slats, backrest slats and side rails) and non-structural and light structural finger-jointed lumber productions (e.g. wooden T and J ceiling panels, table tops, laminated doors and cabinets). Meanwhile finger-jointing offers the best technique of dealing with the problems of knots in branchwoods. This is because, it has the advantage of getting rid of strength reducing defects like knots, among others, from otherwise discarded wood by cutting the wood into short sections after which they are jointed with adhesive to produce lumber of any desirable length (Bustos, Beauregard, Mohammad, & Hernández, 2003a).

1.2: Statement of the Problem

Ghanaian tropical forests resources are of great environmental and economic importance to the nation and the citizenry but the tropical forest resources are declining at an alarming rate which pose a threat to both the environment, survival of WPIs and human life in general. There have therefore been calls for efficient wood resources utilization in the country to at least reduce the rate of the resources‟ decline (Amoah, 2008; Ayarkwa et al., 2000a; 2000b; Oten-Amoako et al., 2008; Okai, 2003; 2002). Meanwhile, Amoah (2008) and Ayarkwa et al. (2000 a, 2000b) assert that wood residues, including wood branches, represent about 25-32% of the total harvested wood. It is estimated that at least, approximately 10% of this can be recovered by redirecting them technologically to become an alternative or supplementary resource to stemwood in wood products manufacturing (Gurau, Cionca, Timar, & Olarescu, 2010). However, unfortunately in Ghana, most of the residues are used for charcoal production as firewood or left in the forest to rot. Although those uses as sources of energy (fuelwood) for the citizenry is not out of place, such uses also have environmental consequences since they add to the total greenhouse gas emissions in the country, and therefore need to be discouraged. Again, the value of such wood when supplied for use as those sources of energy is lower than when supplied for finger-jointed lumber production (Meng, Delahunty, & Chui, 2009).

Again, the deficit between the processing capacity of the WPIs and the annual allowable cut (AAC) in Ghana has widened from 1,500,000m^3 per annum (Antwi, 1999) to about 2,400,000m^3 (Hansen, Lund, & Treue, 2009; FAO, 2009). The obvious question is, how can this deficit be catered for without alternatives and supplements to stemwood which has been the wood material resource in use and which is dwindling over the years? In view of the decreasing raw material supply and environmental concerns about the depletion of Ghana‟s forests, one way of meeting the raw material supply to the industries and the demand for wood products is through the reduction of waste in timber harvesting and processing. In this regard, the whole-tree concept, which advocates the utilization of other merchantable parts of trees in addition to the stem may be useful (Okai, 2002) for making the LRs such as branch, stump and buttress logs more valuable. Meanwhile, increasing the value of branches implies finding alternative uses other than firewood, charcoal and or particleboard (Gurau et al., (2008).

Alternative utilization and possible commercialization of wood residues have been investigated by some researchers (Amoah, 2008; Amoah & Becker, 2009; Okai, 2002; Amoah et al., 2012; Okai, et al., 2004). However, these studies have centred on only about three (3) Ghanaian tropical hardwood species (*Terminalia ivorensis* – emire, *Aningeria robusta* –asanfena, and *Milicia excelsa* – odum), but so far no study has dealt with the "redwood species" which are of higher value in the international market, especially when used for furniture production (Dadzie, 2011). Meanwhile the utilization of branchwood will, to a large extent, depend on their availability, natural durability, availability of equipment for their conversions, mechanical properties, anatomical properties, identification of some value-addition technology (such as finger-jointing), among others. However, besides mechanical properties, studies on other properties such as natural durability and anatomical properties have not been sighted. Also, finger-jointing of branchwood either alone, or in a mix with stemwood appears either not or less studied since it has not yet been sighted in literature. In the light of these, further research on branchwood especially in respect of the "redwood species" to cover the natural durability, anatomical properties and their use in finger-jointing technology need to be conducted. This will widen the data base on branchwood which will in turn enhance and promote efficient utilization of such species in particular and wood in general.

1.3: Purpose of the Study

The main purpose of this study was to provide additional and current information on logging residues (i.e above-stump stem off-cuts and branchwoods) to aid their utilization as supplementary materials for furniture and finger-jointed lumber production.

1.4: Specific objectives of the study

The specific objectives of this study were four-fold, namely, to:

1. Estimate above-stump merchantable logging residues quantity and current logging efficiency, and their differences among species and ecological zones/sites.
2. Investigate and compare the natural durability and service lives of stemwood off-cuts and branchwood and how they are influenced by moisture levels, density and wood type (stem and branch), for five selected tropical hardwoods.
3. Determine and compare bending strength properties (MOEs and MORs) of solid and finger-jointed lumber of stem off-cuts and branchwood (for non-

structural and light structural applications) and how they are influenced by moisture levels, density and wood type, for five selected tropical hardwoods.

4. Compare five anatomical features and assess their influence on wood density, natural durability and bending strength properties of stemwood and branchwood of the five selected tropical hardwoods.

From the enumerated specific objectives, the statement of the problem is expanded to cover each of them as follows;

1.4.1: Above-stump merchantable wood quantity and logging efficiency

Efforts to promote the utilization of branchwood and off-cuts trigger the questions of „what is the current merchantable quantity of the materials left in the forests after logging operations by the concessioners, and how much contribution can that make in reducing depletion of the forests?" On what constitutes merchantable residue, Heiligmann and Bratkovich (2010) assert that, portions of tree trunk or entire trunks that are hollow, excessively crooked, rotten, etc., are not merchantable for lumber production and therefore should not be measured for any calculation of volume of potential lumber. Thus merchantable above-stump residues will include portions of tree branches and off-cuts that can be used to produce lumber but exclude hollow, excessively crooked and rotten ones.

Some studies have been conducted on the availability and quality of merchantable logging residues in Ghanaian forests. Previous study in three ecological zones indicated logging efficiency of 75% and availability of about 25% of merchantable wood in the form of branches and stem off-cuts (Amoah, 2008). Again, Amoah and Becker (2009) also found out that the total merchantable volume of logging residues that have Small-End Diameter (SED) averaging 31 cm and 60cm with varied lengths of between 3.0 to 8.5m from 135 trees felled was about 25% of the total merchantable volumes of the trees. This study however recommended that regular studies need to be conducted to ascertain the current quantity of residues. Meanwhile, normal branchwood are those with diameters of equal or larger than 5cm (Gurau et al., 2008) and therefore there appear to be some normal branchwood that were not measured in the studies of Amoah (2008), and Amoah and Becker (2009). In other studies, Ofori, Adam and Ofosu-Asiedu (1993), and Nketiah (1992) estimated above-ground total tree volumes down to 10cm and 20cm branch diameter limits respectively. However, these studies were on small sample sizes of 30 to 40 trees and took place in only the Moist Semi-deciduous and the Dry Semi-deciduous forest types of the Ashanti and the Brong-Ahafo Regions respectively. Again, Eshun (2000) also estimated logging efficiency to be 68% and quantity of logging residues to be 32% by using two ecological zones within only the Western Region of Ghana. The dimensions observed in the previous studies were beyond the 5cm diameter described by Shmulsky and Jones (2011) and Gurau et al. (2008) as normal branchwood. This suggested a possibility that during those studies, some normal branchwoods which could also be used to produce small dimension stock (e.g. scantlings, shorts, squares, narrows and strips) that could be used for some furniture parts and finger-jointed products were not covered. Again, trees differ in anatomical properties through physical properties to mechanical properties as a result of genetic, systematic, site soils and climatic or environmental conditions (Ofori, Brentuo, Mansah, Mohammed, & Boamah-Tawiah, 2009; Shmulsky & Jones, 2011). It is therefore possible that there can be significant variations in quantity of branchwood and off-cuts among species and site (ecological zone), but this has either not been established, limited or dated.

It is therefore still important for branchwoods and off-cuts left after logging operations to be quantified by covering more than one ecological zone while at the same time using a relatively large sample size to provide information on the current status of residues and logging efficiency in Ghana. Again, such information will also aid current conclusion on how far the extraction of the residues for commercial processing and subsequent utilization can help reduce depletion of Ghana"s forests and protect the environment, especially when stumps are not considered. The call to exclude stumps is based on the report that stump harvesting has detrimental effects like disturbing the soil structure, increasing the risk of soil erosion, and depleting soil nutrient and carbon capital (Moffat, Nisbet, & Nicoll, 2011). All these, in turn, adversely affect woodland biodiversity and tree health which consequently pose risk to sustainable forest management (Moffat, Nisbet, & Nicoll, 2011). It is upon this basis that this aspect of this study does not consider stumps as part of the logging residues.

1.4.2: Natural durability of wood

Natural durability of wood is the natural resistance that wood offers to damage by biological agents like termites, fungi and other micro-organisms. It is therefore an inherent ability of timber (Building Research Establishment-BRE, 1998) to withstand attack by wood destroying organisms, when the wood is without preservative treatment (Ncube, 2010; BS EN 350-1, 1994). Natural durability therefore determines the service life of wood when put into use without preservative treatment (National Association of Forest Industries-NAFI, 2003; Ncube, 2010). Therefore, natural durability assessment is of vital importance because, any wood material in value-added production will only be accepted provided the properties of such materials are known and understood (Gurau et al., 2008), and one of such properties that could supply stakeholders in the wood products manufacturing industry, with added-value information towards addressing the most appropriate use of the material, is natural durability. To this end, in the quest to encourage the utilization of branchwoods towards efficient utilization of timber resources, both producers and consumers of wood products will be interested to know the service life (natural durability) of the material.

Previous studies contend that assessing the potential durability of timber is assisted by relating the timber‟s required performance standards with historical and test data (NAFI, 2003). Moreover, natural durability testing can be done either under laboratory conditions or on the field. But to make a meaningful comparison of tests to ensure consistency is a major challenge in natural durability studies, especially when results have been obtained by different researchers with different test methods, and at different sites (Brischke et al., 2011; New Zealand Forest research Institute, 1997). Other previous studies of natural durability of wood have confirmed this challenge (Cookson, 2004; Quartey, Zurcher, & Frimpong-Mensah, 2008).

Some previous studies on natural durability of some Ghanaian hardwood species include; the influence of density and natural durability (Antwi-Boasiako & Pitman, 2009), differences between sapwood and heartwoods durability (Quartey et al., 2008), vessel-fibre ratio, specific gravity and durability (Antwi-Boasiako & Atta-Obeng, 2009) and anatomy, natural durability, and treatability of two lesser-utilised and two related Ghanaian tropical species (Antwi-Boasiako, 2004). Again, Pleydell (1994) has also reported on the natural durability of about 68 different tropical Ghanaian hardwoods, including those selected for this study. However, it appears that there is either limited or no study on the natural durability of branchwood of any Ghanaian tropical hardwood has been conducted and therefore none has been sighted. To fill this gap in literature is the reason why this aspect (i.e. natural durability) of this study is of utmost importance.

1.4.3: Static bending strength of solid and finger-jointed lumber

Among the reasons usually given for the non-extraction of timber from the crown area of tress is the lack of knowledge on the wood quality, including density and mechanical properties (Ayarkwa, 1998). Mechanical strength, especially bending strength is of much importance in measuring the stiffness (MOE) and the maximum load (MOR) of beams (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). Furniture items like chairs and tables have parts that act like beams (e.g. seat slats, backrest slats, armrest, side rails and table tops) and are therefore subjected to bending stresses when loaded (Dinwoodie 2010).

Meanwhile, the mechanical (bending) properties of wood can be affected by some factors including moisture content, type of wood/species, specific gravity/density, and other natural defects such as knots, among others (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). However, finger-jointing (FJ) is one major wood processing technology that can be employed to deal with strength reducing factors that are difficult to control like knots, since the wood can be cut into short pieces to take off the knots before jointing. Finger-jointing technology is therefore reported to have the advantage of getting rid of strength reducing defects or factors and make otherwise discarded wood valuable (Bostus et al., 2003a; Shmulsky & Jones, 2011; Wengert, 1998). Therefore, the use of FJ technology becomes more important in the quest to promoting residues, especially branchwood utilization since knots are sometimes difficult to control and they can be many on branchwood.

Moreover, FJ technique has been found to be the most economically available alternative in terms of wood utilization and joining wood end grain to end grain. This, according to Ayarkwa et al. (2000a), is because low-graded short pieces of wood in the range of 1.2m to 3m (4ft to 10ft) and which generally command low price, can be redirected and used to produce high-quality lumber of any length, and or other products including profiled boards and engineered wood components like trusses and I-joists. Additional advantage of FJ technique is that, besides the adhesive used to bond the parts, no additional fastener is needed to hold the joints since it avails several side grains for better bonding that provide strong end-joint (Beaulieu, Verreault, Gosme, & Samson, 1987). It is reported that the decline in wood resource influences a rise in interest in FJ of wood for many lumber products (Gene, 2010).

Considering the rate of depletion of Ghana‟s forest and their consequential effects on the economy and environment, there should be a major rise in interest in FJ of wood, especially regarding the premium commercial wood species which have higher economic value and also used for furniture and FJ products manufacturing for both local and export markets. Some of such commercial and premium species, used for furniture and FJ products in Ghana include; iroko/odum (*Milicia excelsa)*, edinam (*Entandrophragma angolense)*, sapele (*Entandrophragma cylindricum*), essa (*Celtis mildbraedii*), koto (*Pterygota macrocarpa)*, mahogany (*Khaya spp*.), wawa (*Triplochiton scleroxylon*, ofram (*Terminlia superba*) among others. In fact, some of the WPIs in Ghana have already adopted FJ technology using many of these species for the production of doors, table tops, chair seat slats, T & J ceiling panels, laminated beams, among others.

Researchers have conducted some studies on bending strength of both unjointed and finger-jointed lumber of some Ghanaian tropical hardwood species. However, whereas some of these previous studies on bending strength of unjointed lumber have covered both stem and branch woods (Amoah et al., 2012; Ayarkwa, 1998; Ayarkwa, 2000; Okai, 2002; 2003), those on bending strength of finger-jointed lumber have only covered stemwood off-cuts (Ayarkwa et al., 2000a, 2000b; Ayarkwa, 2010) and none has been sighted on Ghanaian hardwood branchwoods.

Moreover, in the sighted literature on finger-jointing works on Ghanaian hardwood stem off-cuts, the jointings were done after the wood were kiln-dried and none was done in the green state, although it has been made possible elsewhere (Mantanis, Karasteriou, & Barboutis, 2010; United Soybean Board, 2006). Meanwhile, FJ of green wood is also considered as an economically and environmentally attractive means of increasing the yield of high-grade lumber and increasing the value of low-grade wood (Lang & Hassler, 2007; United Soybean Board, 2006). FJ green wood is economical because there is no need to dry waste at a cost. It speeds up production by reducing idle time of workers to meet delivery time, and the exact cut lengths after FJ before drying help good stacking which prevent drying defects due to stacking and also reduce energy consumption of drying fans which inturn reduce drying cost (Källander, 2008). Environmentally, FJ green wood ensures that the cut offs are not dried and can therefore be used for pulp & paper, particle boards and other products and which will reduce the quantity of waste to be disposed off to affect the environment (Källander, 2008). Also, since no energy is burnt to release environmentally unfriendly gases, before joining the wood, FJ green wood poses limited threat to the environment. Additionally, although the export market normally demand kiln-dried products in Ghana, many local furniture producers do not own kiln driers to be able to dry wood far below the FSP before using them. Additionally, accessing kiln-driers of the large-scale timber firms is costly and will swell-up their production costs. Hence the success of finger-jointing green wood will be a relief to such industrialists.

From the foregoing, all the available and sighted literature on finger-jointing of Ghanaian hardwoods used only stemwood off-cuts which were all kiln-dried before jointing. As a result, no information on finger-jointing of branchwood either separately or in combination with stem wood off-cuts, either at the green or kiln-dried moisture content states have been sighted and therefore such studies appear to be non-existing. Again, none of the unjointed branchwood strength in previous studies was also determined at moisture contents higher than 12%MC and up to the fibre saturation point within which local furniture producers and other wood users in Ghanaian use wood (Quartey, 2009). It is for these reasons that this aspect of this study was done to investigate the static bending strength of both solid stem off-cuts and branchwood, and their finger-jointed lumber combinations at both air-dried MCs (above 13% but below 25%) and kiln-dried MCs (between 6% and 13.5%) for non-structural and light structual applications.

1.4.4: Anatomical study

The anatomical properties of wood play important roles in selecting the appropriate wood for specific use as they affect the density, strength properties, appearance, resistance to preservative treatment, and resistance to decay. The pattern and arrangement of the various cells in wood determines its structure and density which also give wood majority of its properties (Shmulsky & Jones, 2011; Wiedenhoeft, 2010). These cells perform three main functions of conduction of water, providing mechanical supports and storage of biochemicals or photosyntates in the living tree, and these functions translate into the physical, mechanical, chemical and technological properties of wood from the trees. In this wise, understanding the interrelationships between form and function of these cells in wood aids better insight into the realm of wood as an engineering material, its strength and limitations (Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005).

Branchwoods of same trees can be different from stemwood. Some kinds of cells are more abundant or less in wood from branches than wood from the main bole (Shmulsky & Jones, 2011). These differences, if significant could pose utilization challenges in an effort to use wood from the branches either alone or in combination with wood from the main stem. However, currently, no literature on Ghanaian tropical hardwood branchwood anatomy has been sighted, at least, regarding the species sampled for this study. Such data is either limited or absent. However, anatomical data on the stemwood of the species are available (Duvall, 2011; Forest Products Laboratory, 2010; Kimpouni, 2009; Lemmens, 2008; Richter & Dallwitz, 2000; Tchinda, 2008). A more recent work of macroscopic identification of 100 Ghanaian hardwoods has also been done by Oteng-Amoako, Zurcher, Agyakumhene, Ebanyele and Rogenmoser (2006), yet, it appears no anatomical study has been done on branchwood. It was in this light that this aspect of this study was to ascertain any qualitative and quantitative differences in the cells in wood from the main stem and that from branches.

1.5: Research Questions

The following questions were formulated to guide the study;

1. What is the current logging efficiency and quantity of merchantable above-stump residue left in the forest after logging operations?
2. How does extracted log volume relate with merchantable residue volume and total merchantable wood volume?
3. How comparable is the natural durability of branchwood and stemwood off-cuts of same wood species to warrant branchwood as supplement to stemwood for some components of outdoor furniture and finger-jointed products?
4. What is the relationship between natural durability, and density and moisture content of stem and branch wood?

5. Are the bending strength properties (MOEs and MORs) of solid/unjointed branchwood and stem off-cuts of same species comparable to recommend branchwood use to supplement stemwood for some furniture components?
6. How comparable are the MOE and MOR of finger-jointed lumber of stemwood, branchwood, and mixture of stem and branch wood with those of solid stemwood of same wood species?
7. Are the MOE and MOR of same species" stem & stem finger-jointed lumber combination comparable with those of either stem & branch or branch & branch wood combinations?
8. How do MOE and MOR of both solid and finger-jointed lumber relate with moisture content and density?
9. How do finger-joint efficiencies in MOE and MOR with unjointed lumber relate with wood density?
10. Are the anatomical features of stemwood significantly different from those of branchwood of same species?
11. What are the relationships between anatomical properties and density, natural durability, and bending strength (MOE and MOR) of stem off-cuts and branchwood?
12. Qualitatively, are the anatomical features of stem (off-cuts) and branch wood different?

1.6: Scope of the Study

The study estimated the current quantity of above-stump logging residues left in the forest, evaluated natural durability, bending strength of unjointed and finger-jointed lumber (i.e. non-structural and light structural), and the anatomical properties of stem off-cuts and branchwood of five tropical hardwoods from Moist-

Semideciduous and Moist Evergreen zones in Ghana. It also examined how logging residue volume relates with extracted log volume, and how moisture content, density and anatomical features relate with natural durability and bending strength properties.

The wood species studied were; *Entandrophragma cylindricum* (sapele), *Entandrophragma angolense* (edinam), *Khaya ivorensis* (mahogany), *Terminalia superba* (ofram) and *Pterygota macrocarpa* (koto). However, *Ceiba pentandria* (onyina) stemwood was used as control for the natural durability test.

1.7: Significance of the Study

This study will have both theoretical and practical relevance by adding to the scientific data on branchwood and stem off-cuts on the selected species and also encourage branchwood utilization to promote overall efficient wood utilization. The study will provide additional theoretical knowledge about stem and branch wood of the same species in terms of their natural durability, bending strength and anatomical properties variabilities. Practically, the study will reduce uncertainties about branchwood properties which appear to be hampering its utilization and also create confidence in wood users to use branchwood to supplement stemwood in finger-jointing and manufacturing of other wood products.

CHAPTER TWO

LITERATURE REVIEW

2.1: Quantifying Above-Stump Merchantable Wood Volume

Generally, deforestation and degradation rate of Ghana"s forest estate has been accelerating and a more recent assessment indicates a combined lost rate of 1.9% for both primary and secondary forest over 25years (1980-2011) (MLNR, 2012). But, over the last 11 years from the year 2000 to 2011, forests have been lost at a rate of 2.3% (MLNR, 2012). As timber resource continues to diminish in quantity, one of the objectives of forest management has been to continuously evaluate and predict the volume of merchantable wood in order to control the flow of wood, minimise losses and put realistic monetary value on wood resources (Amoah & Becker, 2009). Volume quantification is also done to provide information for the development of management strategies, estate planning, tax basis and litigation settlements (Henning & Mercker, 2009).

According to Magnusson and Reed (2004), volume is the most widely used measure of wood quantity and it is always estimated for the assessment of timber economic value or commercial utilization potential. The wood volume of a tree comprises the stem, branches, stumps and roots. For standing trees, above ground volume production is usually based on stem wood volume for softwoods but may include branches for hardwoods. However, depending on measurement objectives and local traditions, measurements or predictions of wood volume may refer to total stem volume, total tree volume (stem and branches) or volume above a certain merchantable limit. Moreover, volume may or may not include bark (Magnusson & Reed, 2004).

2.1.1: Requirements for determining wood volume

To determine the volume of trees (which are viewed as cylinders), two pieces of information are needed: diameter and length. As a result, standing and harvested trees diameters and heights or lengths are important in their inventories (Henning & Mercker, 2009; Magnusson & Reed, 2004). These parameters are however, substituted in a number of formulae including the Smalian‟s formula, to determine the volume/quantity of wood material in logs or trees in cubic meters.

It is however argued that, Smalian‟s formula assumes that logs have paraboloid shapes and this makes the formula bias leading to overestimation, especially for butt logs. (Briggs, 1994; Forest Products Management Development Institution, 1998). This is confirmed by Patterson, Doruske, Hartley and Hurd (2007) that Smalian‟s formula overestimates butt logs by 6% but it is very accurate for upper logs. However, according to the Ministry of Forests, Lands and Natural Resource Operations-MFLNRO (2011), from the inception of cubic scaling, the Smalian formula has been adopted as the cubic scale rule as its accuracy is relatively the best. It is however important to note that the accuracy of all cubic volume formulae decreases as log lengths increases. Hence it is helpful to segment logs into shorter lengths for measurements to ensure accuracy (Briggs, 1994; Forest Products Management Development Institute, 1989).

2.1.2: Studies on logging residues conducted in Ghanaian forests

In Ghana, inventories have been done on forest trees and residues by some researchers (Amoah, 2008; Eshun, 2000; Nketiah, 1992; Ofori et. al., 1993). In a more recent and comprehensive study, Amoah and Becker (2009) quantified logging residues left in Ghanaian forests to be about 25% of total tree volume, and for that matter, established logging efficiency in Ghana to be about 75%. This efficiency was viewed as relatively high and was attributed to the scarcity of timber in recent times which might have raised consciousness among logging firms to extract more merchantable stemwood to meet their timber processing requirements/capacity. Previously, the logging efficiency has been reported to be as low as 50% (Acquah & White, 1998; Adam, Ofosu-Asiedu, Dei-Amoah, & Asante-Asiamah, 1993). Amoah and Becker (2009) also found that the diameters (which ranged from 41cm to 60cm) and lengths (that ranged from 4.2m to 8.0m) of main bole off-cuts and branch logs were of sufficient quality to warrant their extraction and utilization. The study by Amoah and Becker (2009) also indicated that the 25% logging residue translates into the conservation of about 6.8 hectares of forested land, if the branches and off-cuts were extracted and used. The study also found positive correlations between extracted log and total merchantable wood volumes with regression coefficient (R^2) values ranging from 0.55 to 0.86 for individual species and an overall R^2 value as high as 0.89. However, they recommended strongly that periodically, fresh data should be taken to assess current situations. It is therefore important to note that, timber inventory establishes two key pieces of information: 1) the number of trees per acre (tpa) on a forested tract and, 2) the volume per acre of wood that could be extracted from the trees obtained (Henning & Mercker, 2009).

2.1.3: Equipment for sawing/converting logging residues and conversion efficiency.

Logging residues, especially branches could mostly consist of small-diameter logs and this appear to suggest that the sawing equipment used for sawing stem logs may not be applicable in converting branch logs. However, findings have proven otherwise that the bandmills used to convert large stem logs and other small mobile bandmills could be used to convert branch logs into usable lumber. For instance, Okai (2002) used a universal mobile bandmill (called woodmizer) to convert branch logs of diameters ranging from 10cm to 25cm into lumber. It is also heartwarming to note that Dadzie and Amoah (2013) used the same bandmill (called BOSTKA) for converting stem logs to also convert branch logs of diameters ranging from 26cm to 52cm at Lumber and Logs Ltd. (a timber firm in Kumasi). Also, Eldred (2000) has indicated that various mobile bandmills (such as the Multitek 2025- Figure 2.1) as well as firewood processors and woodchippers are all good equipment that could be used in converting small-diameter logs but the choice depends on the diameter of the materials and the requirements of the end products. The multitek 2025 mobile bandmill model could saw small-diameter logs down to diameters of 50mm while some firewood processors can saw logs down to 20mm (Eldred, 2000).

Figure 2.1. Multitek 2025- a mobile bandmill used in sawing small-diameter logs.
Source: http://www.forestryjournal.co.uk

Additionally, according to Eldred (2000), and Wiedenbeck, Blankenhorn, Scholl and Stover (2004), many of the small bandmills are mostly mobile and not too heavy and therefore could easily be transported and used on-site (in the forests) to avoid huge transport costs of conveying small diameter logs from forests to the mills.

Moreover, it is reported that the sawing efficiency or recovery of small-diameter logs correlates positively with the diameter of the logs (Eldred, 2000; Wiedenbeck et al., 2004). However, small-diameter logs can produce a yield of between 30 and 40 percent of number 1 common or better grade lumber with varied percentage of the other lumber grades (Wiedenbeck et al., 2004). In Ghana, however, conversion efficiency of small diameter branch logs has been found not to be affected by the sawing technique (i.e. either quarter sawing or through-and-through methods) (Okai, 2002). However, the mean yield for first and second (FAS) grade boards for *Aningeria robusta* (asanfena) and *Terminalia ivorensis* (emire) branch logs (with diameters of 10cm to 25cm) was 25% and 20% respectively whereas the mean volume yield (i.e. including other grades) were 40% and 32% respectively upon using the woodmizer mobile bandmill (Okai, 2002). Comparing this to the logging recovery rates for the main stem logs of 50–75% in Ghanaian sawmills (Amoah 2008; Amoah and Becker 2009), the conversion efficiencies for the 10cm to 15cm branch logs could be deemed as appreciable.

2.2: Natural Durability of Wood

Durability is a broad term and it is defined as the resistance of wood against biotic factors (e.g., fungi, insects and bacteria) and abiotic factors such as UV radiations (BRE, 1998; BS EN 350-1, 1994; Ncube, 2010). The resistance against the biotic factors is generally referred to as the natural durability of wood which is defined as the inherent resistance of timber species to decay and insect attack under favourable conditions for such attack. Natural durability is therefore also referred to as biological durability (National Association of Forest Industries- NAFI, 2003). These biotic and abiotic external factors may cause degradation of appearance, structure and chemical composition of wood, thereby limiting its use and greatly shortening the service life of the wood (NAFI, 2003; Shmulsky & Jones, 2011). Hence, natural durability test is used to also predict the service life of wood (Brischke, 2007; Brischke et al., 2011).

Additionally, Oteng-Amoako (2006) asserts that, natural durability of wood is due to some specific inherent chemicals in the heartwoods that serve as poison to wood destroying organisms. Natural durability of wood is therefore viewed as species dependant due to the fact that the anatomical and chemical make-up of wood differs from species to species. However, wood is a unique material in which the chemical composition, anatomical features, physical and mechanical properties, and natural durability are interrelated (Ali, 2011). Wood deterioration therefore encompasses all effects or activities of any kind that adversely affect the physical, chemical and mechanical properties of wood thereby reducing its service life (Shmulsky & Jones, 2011;Wolgang, Nadine & Jan-Willem, 2012).

Moreover, it is reported that the burden of knowing whether or not wood species will have sufficient durability for the intended application falls largely on the user or purchaser. But unfortunately, most users of wood products do not have the expertise to evaluate any evidence of durability (Morris, Laks & Lebow, 2011a). This situation, coupled with the depletion of many premium and commercial timbers leading to the quest to promote the utilization of other timber species and tree parts whose natural durabilities are not well known, have all compelled users of wood to resort to the use of preservatives to improve the service lives of the timbers. In fact, one of the factors that prompted the development of wood preservatives was the depletion of the naturally durable wood resources (Morris, Ingram, Larkin & Laks, 2011b). However, due to environmental concerns about the chemicals used to make non-durable wood durable, interest in natural durability of wood is much growing across the world (Cookson, 2004).

Meanwhile, out of the two main ways that wood deteriorates (biological and non-biological), the biological deterioration is the major cause of wood degradation though it has its importance of ensuring decay to provide nitrogen to the soil to facilitate growth of young trees. Hence, for the purpose of this study, biological deterioration due to fungi and wood destroying animals (wood borers and termites) are considered.

2.2.1: Deterioration by fungi

Fungi are simple plants that do not have chlorophyll and as a result, are unable to produce their own food by photosynthesis and thereby obtaining their nutrients by using the fungal cells. In wood, the carbohydrates and lignin components provide food for the fungi and hence the organisms attack wood cells where these „foods" are (NAFI, 2003; Shmulsky & Jones, 2011). Generally, for fungi to be able to use wood components (cellulose, hemicelluloses, or lignin) as food, it must be able to break down these cells" constituents into simple molecules that can be metabolized. This causes biochemical changes accomplished by the catalytic action of enzymes produced by the hyphae of the fungi (Brischke et al., 2011; Shmulsky & Jones, 2011). It is important to note however that two main fungi types exist, namely; stain and decay fungi, but the decay fungi is the most important factor that affect the durability of wood (Tsoumis, 1991).

Some symptoms and effects of fungal attack on wood include weight loss, weight gain, strength loss, increased permeability, reduced calorific value, increased electrical conductivity, discolouration, reduced pulp quality, reduced mechanical strength, reduced density, hygroscopicity increases among others (Brischke et al., 2011; Ncube, 2010; Nzokou, Wehner & Kandem, 2005; Shmulsky & Jones, 2011). These symptoms and characteristics depend on the type of fungi that caused the defect. Three main kinds of fungal decay exist, namely; brown rot, white rot, and soft rot. These terminologies relate to the appearance of the decayed wood. The fungi species are also grouped according to these modes of decay (Dinwoodie, 2010; NAFI, 2003S; Ncube, 2010; Shmulsky & Jones, 2011).

The fungi species that cause brown rot are the brown rot fungi which include *Coniophora cerebella (Caniophora pateana), Lenzites trabeum*, *Meruluis lacrymans (Serpula lacrymans),* and *poria vaillantii (Firoporia vaillantii)*. These fungi consume mainly the carbohydrates (cellulose and hemicelluloses) and do not consume lignin but change lignin"s solubility. Their attack on wood splits the wood longitudinally and across the grain forming large cubes which are usually brownish in colour at the surface of the wood. Again, brown rot attack and remove different cell-wall layers at the same time (Dinwoodie, 2010; NAFI, 2003).

White rot is a fibrous form of decay where the attack is well advanced. White rot means the degradation of cellulose, hemicelluloses, and lignin. White rots are classified by macroscopic characteristics into white-pocket, white-mottled, and white-stingy, depending on the fungal species, wood species and ecological conditions. White rot also attacks standing trees and may be in wood when not well seasoned or not sterilized, and they attack hardwoods more than softwoods. With white rot, carbohydrates and lignin are almost uniformly degraded at the same time and at almost a similar rate throughout all the decay stages. Typical fungi with such similar and uniform white rot are *Fomes fomentarius, Phellinus igniarius, Phellinus robustus, and Trametes versicolor* in standing tree and hardwoods stored (Dinwoodie, 2010; Ncube, 2010; Shmulsky & Jones, 2011). One major difference between white and brown rot fungi is that, unlike the brown rots, the white rots remove cell layers progressively (Tsoumis, 1991).

Soft rot decay are of less importance and the fungi that cause such decay are; ascomycetes and deuteromycetes or *Fungi Imperfecti*. Their decay is similar to that of brown rot fungi, in terms of chemical action. The wood becomes superficially soft, darker with progressive attack, and when dried its surface layers become checked (as in brown rot) and brittle. The underlying wood however is firm and sound. Soft rot occurs in wood exposed to very high moisture, in water (including sea water) or in contact with moist soil (Tsuomis, 1991). Some common species of fungi that cause soft rot include *Chaetomium globosum* and other *Chaetomium spp*. (Forti & Poliquin- as cited in Quartey, 2009).

2.2.2: Deterioration by wood destroying animals

In addition to fungi (which are plants), animals that destroy wood are generally insects and they are of three (3) main groups, namely; wood boring beetles, termites and marine borers. Most of these rely on micro-fungi for their nutrition through symbiotic practices (Dinwoodie, 2010; Ofori, n.d). For the purpose of this study, marine borers are not inclusive since the study was not done along the seashores or in the sea.

2.2.2.1: Wood boring beetles

Wood boring beetles are insects that have the normal life cycle of egg, larva, pupa and adult. However, the major damage to wood is done by the larvae, which actively tunnel in the timber to derive nourishment, while the only damage caused by most adult beetles is cutting a flight or passage way through the surface of the timber as they escape from it. The damage by larvae desiccate the wood and make frass called bore-dust (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011). Beetles attack wood throughout its life, namely; from the forests (as standing trees), freshly felled trees, seasoning wood, and wood in service. Thus, there are about four (4) different groups of beetles that attack wood and they include; Standing tree beetles called bark borers (*Scolytidae*) which bore into the barks lay their eggs beneath it and sometimes introduce fungal diseases into the tree which can even kill the tree (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011). There are also the freshly felled tree beetles also called *Platypodae* (pinhole borers or ambrosia beetles) of which the males make tunnels in unseasoned wood, attract the females, and both enter the wood and mate to lay eggs. These tunnels or pinholes degrade the wood and affect strength properties and economic value of the wood (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011).

The Seasoning wood beetles also called *Lyctidae* (e.g. powder post beetle) attack timber and reduce it to fine flour-like powder. The Lyctids, though are the most troublesome pests of sawmills, timber yards and manufacturing premises globally, only attack the sapwood of susceptible hardwoods and almost all softwoods are immune from their attack (NAFI, 2003). However, (Ofori, n.d); asserts that these beetles attack only hardwoods that have larger vessels to accept the slender egg-laying tubes (ovipositor) of the adult female. The attack of the powder post beetle is limited to only sapwood due to the high starch content (NAFI, 2003). The Furniture beetles also called *Anobiids* (common one being *Anobium* furniture beetle), may attack all softwoods and some hardwoods and they prefer old, well seasoned timbers. The damage from their attacks is sufficient to cause floorboards and old furniture to collapse. Old furniture like pianos and cup-boards are seriously affected by the activities of these beetles and their actions are manifested by surface holes with digested wood as granular powder (NAFI, 2003; Ofori, n.d).

2.2.2.2: Termites

Termites, as social insects, live in colonies in the ground and, almost exclusively, in total darkness. It is reported that there are many different species of termites. However, those that attack timber and are of economic importance to users of wood and foresters are grouped into three (3) main categories as; subterranean (soil inhabiting termites), dry wood, and damp wood termites with the dry wood and dump wood types being non-subterranean but wood dwelling (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011). However, only 8 of these termites are found to be destructive to timber (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011). Again, the damage by termites is by far, more serious than all the biological agents as it causes great financial loss due to the extent of damage (Dinwoodie, 2010; Shmulsky & Jones, 2011). According to NAFI (2003), and Ofori (n.d), termites invade wood for two main reasons; firstly to obtain shelter and, secondly to secure food (the cellulose in wood cells). However, Dinwoodie (2010), and Shmulsky and Jones (2011) assert that the three main categories of termites attack wood differently but they are more attracted to wood already degraded by fungi since such wood are sometimes soft and penetration is easier.

The subterranean (soil inhabiting/earth-dwelling) termites includes forest pests that attack living trees as well as building members, poles, pests, bridge timber, and furniture parts etc. that have contact with the ground. Subterranean termites are by far, the biggest of the three groups and they are responsible for most of the termite damage to wood structures and cause the greatest structural weakening to wood in contact with the ground (Dinwoodie, 2010; NAFI, 2003; Ofori, n.d; Shmulsky & Jones, 2011;). These termites usually enter and attack wood from the ground, use the wood as shelter in order to avoid exposure to outside environment, and to also obtain food (cellulose) from the wood. They live entirely within the wood once they enter and establish a colony and hence, such wood do not show any sign of condition of attack until failure occurs. However, for these termites to be able to extend their infestation and destruction, they must maintain a reasonably high level of moisture which they obtain from the ground and send to their sealed colony – the wood (Dinwoodie, 2010; Shmulsky & Jones, 2011).

The dampwood termites, on the other hand, are the group that operate in damp or moist conditions and therefore prefer wet wood that is already decaying or have been infested by fungi and bacteria. These termites enter wood directly from the air during swarming and have no contact with the ground (Ofori, n.d; Oteng-Amoako, 2006). They cause damage to wood in bathrooms, kitchens, laundries, and other wood components exposed to source of moisture and a subsequent infestation by fungi. However, these termites are of less economic importance as compared to the subterranean and the dry wood termites (Dinwoodie, 2010; NAFI, 2003; Shmulsky & Jones, 2011).

Moreover, drywood termites also require no contact with the ground or soil but they are attracted by light and enter wood directly from the air during swarming. They attack relatively dry and sound timber (MC of 10%) and are most troublesome than the subterranean because they are difficult to control (Dinwoodie, 2010; Shmulsky & Jones, 2011). Some of these termites also live in holes in the dead wood of living trees as well as some dump wood. The species in this group, that is of great known economic importance is the powder-post termites (NAFI, 2003; Ofori, n.d). However, Oten-Amoako (2006) reports that, the action of these termites can result in significant reduction in the strength of the wood, leading to complete destruction. The destruction by dry wood termites is identified by clean galleries with no soil particles but loose faecal pellets.

2.2.3: Factors that influence natural durability of wood

Natural durability of wood is influenced by factors such as density, cell wall thickness, wood permeability, extractives and inorganic materials, leachability of extractives, moisture content, and also the content, type and proportion of lignin (Brischke et al., 2011; Cookson, 2004; NAFI, 2003; Ncube, 2010; Wolgang et al., 2012). However, for the purpose of this study, species/wood type (in this case, stem or branch woods of the 5 selected species), density and moisture content were considered.

2.2.3.1: Density and natural durability

Density gives a measure of how much actual substance (cellular) is inside a specific sample of wood, and greater density means more structural material, which tend to make the wood stronger, harder and durable (Skadsen, 2007). Density of wood is also a measure of the amount of cell wall per unit volume or the proportion of the void volume which makes it directly related to it porosity (Dinwoodie, 2010; Shmulsky & Jones, 2011). In view of all these, high density timbers have small void volumes and thicker cell walls, a situation believed to reduce diffusion of gases through the wood and consequently likely to reduce the rate of fungal attack or decay (Shmulsky & Jones, 2011). Moreover, density varies considerably within a given specimen and even among different zones within the same tree (Antwi-Boasiako & Pitman, 2009; Dinwoodie, 2010; Ofori et al., 2009; Ofori & Obese-Jecty, 2001; Quartey et al., 2008; Shmulsky & Jones, 2011;). According to Ncube (2010), denser wood normally has thicker cell substance which implies much material to be decayed and that enables denser wood to have longer service life than light (less dense) woods. Additionally, extremely dense timber tends to be durable because diffusion of gasses is slower and growth of fungi is retarded on account of diminished supply of

O_2 and accumulation of CO_2 around the hyphae (Shrivastava 2000). Again, Schultz, Nilson and Nicholas (2000) are of the view that thick cell walls are more effective in retarding the enzymes of fungi from penetrating and degrading wood.

However, according to Dinwoodie (2010), and Shmulsky & Jones (2011), individual trees of the same species may vary in their decay resistance due to genetic factors and possibly silvicultural systems. These silvicultural systems or treatments given to wood to either slowdown or accelerate its growth etc., could lead to differences in density of the wood (Dinwoodie, 2010; Shmulsky & Jones, 2011; Skadsen, 2007). But Zabel and Morrel (1992) reported in contrast that some low – density timbers including Western Red Cedar and *Cedrella spp.* are highly resistant to biological deterioration (e.g. fungal decay) than some high density varieties like *Quercus spp.* Akhter and Hale (2002) have also found that the density of Douglas fir (seudotsuga menziesii) is not positively correlated with its durability against fungi. These findings thus generate argument as to whether or not density of wood species alone could influence durability against fungi and other bio-degrading agents.

2.2.3.2: Wood species/types and natural durability

Different wood species have different contents (chemically, cellular etc) and these have influence on different wood species‟ natural durability. The unique anatomical characteristics coupled with the irregular content of pigmented extractives throughout heartwood is what gives wood its distinctive figure (Eero, 1993; Shmulsky & Jones, 2011; Skadsen, 2007). These extractives {which are huge deposits of organic substances in wood and which are either soluble in neutral organic compounds (lipophilic type) or water (hydropholic types)}, occupy various morphological sites in the wood structure. For instance, resin acids are in resin canals, whereas fats and waxes are in ray parenchyma cells (Dinwoodie, 2010;

Shmulsky & Jones, 2011; Skadsen, 2007). According to Dinwoodie (2010), Shmulsky and Jones (2011), and Skadsen (2007), extractive content in wood is about between 10% and 40% of dry wood weight and varies by wood species, position of wood, the season in which the tree was felled, and the conditions under which it grew. The content also varies in the various parts of a particular tree (i.e. stem, branches, roots, barks and needles differ markedly in respect of both their amount and composition or type). However, due to their different tastes and colour, they provide different levels of protection against insects, pathogenic, or fungal attacks and are also responsible for differences in some characteristics such as colour, taste or odour of various wood species. However, Eero (1993) contends that some extractives (like fats) are not necessarily for protection against biological agents but as a source of energy for the wood cells.

Another content of wood species that can cause variability in wood properties is lignin. According to Dinwoodie (2010); Shmulsky and Jones (2011), and Skadsen (2007), lignin occurs between individual cells and within the cell walls performing varied functions. Between the cells, it serves as a binding agent to hold the cells together whereas within the cell walls it is intimately associated with cellulose and hemicelluloses and gives rigidity to the cell. As a results of these functions, lignin is credited with reducing dimensional change with moisture content fluctuations and also adds to the wood toxicity and makes wood resistant to decay and insect attack (Eero, 1993; Skadsen, 2007). Additionally, according to Panshin and De zeeuw (1980), and Zabel and Morrell (1992), lignin in wood renders some portions of the cell wall, such as the primary cell wall and middle lamella, more resistant to microbial attack by presenting a physical barrier to enzymatic attack on the polysaccharides, except for white rot fungi that have some enzymes capable of degrading lignified tissue. However, though all wood species have lignin because they are of various kinds and contents and their distributions within and among cells in wood also vary, their contributions to durability of wood also subsequently vary. For instance, Blanchette, (1995) and Eaton and Hale, (1993) have asserted that, Guacyl (G) type lignin is more resistant to degradation and as such, the ratio of Syringyl (S) to (G) type lignin has considerable influence on decay resistance of wood. Typical ratio for hardwoods is 80:20 (less durable) to 40:60 (more durable) with the least content of the (G) units being responsible for non-durability of some hardwoods (Ncube, 2010). Hence high content of G type lignin in some hardwoods renders them more durable than others.

Some studies have been conducted on the contribution of density and species" content on natural durability of wood. Some of the findings are that, density of wood is not entirely dependent on the cell wall thickness but other factors like the content of the extraneous materials (extractives) and chemical compositions, all of which contribute to the density and consequent durability of the wood (Dinwoodie, 2010; Shmulsky & Jones, 2011). Moreover, besides decay resistance, extractive content also affects wood properties such as hardness, density, compression strength, flammability, and level of hygroscopicity (permeability) of the wood. Thus, the amount of extractives in heartwood can affect how quickly wood gains or loses moisture (Skadsen, 2007).

In Ghana, the contribution of extractives to natural durability of wood has been studied by Antwi-Boasiako and Pitman (2009). These authors upon studying the natural durability difference between two groups of samples of same species (one group with all chemicals intact and another group with some extractive content removed) found that extractives are by far a more important factor than density as regards their contributions toward wood resistance against biodeterogens or decay. Thus, the authors suggested that density in itself is a poor determinant of durability for some tropical hardwoods. Again, Antwi-Boasiako and Atta-Obeng (2009) studied the relationship between wood specific gravity (SG), vessel-fibre ratio (VF ratio) and natural durability. The study concludes that higher SG means lower VF ratio and higher durability, whereas higher VF-ratio implies low SG and lower natural durability.

2.2.3.3: Moisture content/drying method and natural durability

According to Dinwoodie (2010) and Shmulsky and Jones (2011), water is a natural constituent of all parts of a living tree. In the xylem portion of the stem, water commonly makes up over half the total weight. Due to this, many properties of wood, including resistance to biodeterioration and dimensional stability are affected by the amount of water present. As a result, the risk of decay in wood products can vary widely with moisture availability, soil condition and climate. Another assertion of Shmulsky and Jones (2011) is that, high moisture in wood means much sap (food) to attract biological agents for feeding on them and thereby destroying the wood. The moisture also softens the wood cells and therefore makes it easier for the wood destroying agents to penetrate into the wood for quicker and easier destruction. However, it is reported that wood dried below 20%MC have a leverage over those that have higher moisture content in terms of fungal infestation and subsequent attack by other biological agents and wood dried below 15%MC does not rot (Eaton & Hale, 1993; NAFI, 2003; Tsoumis, 1991). However, white-rot fungi need the least water to attack, brown rot fungi require more and soft-rot fungi require the highest water content, but all of them require moisture at or near the fibre saturation point. It is however important to note that, though theoretically dry wood does not rot, termites attack dry wood by bringing their own moisture to the wood to enhance their enzymatic actions (Rowell, 2005).

The foregoing indicate that moisture content in wood needs to be reduced through drying to enhance natural durability of the wood. However, wood is dried either naturally (air-drying) or artificially (kiln-drying) and kiln-drying method has some advantages over air-drying method (Dinwoodie, 2010; Shmulsky & Jones, 2011). The heating of the wood during kiln-drying process kills eggs, larvae and adult borers and those of other biodeterogens that may be present in the wood prior to drying (Dinwoodie, 2010; Shmulsky & Jones, 2011). Therefore, although kiln-drying does not prevent reinfestation of the wood by biological wood destroying agents, by killing the already existing ones, the drying method has the tendency of prolonging the service life of the wood compared to air-dried ones of which all infestations may be intact as the wood is used. Again, it is also reported that in kiln-drying, the temperature and hot air in the kiln sterilize the wood to ensure that test specimens are clear by destroying or killing all contaminations such as microorganisms that might have already infested the wood (Dinwoodie, 2010; Ncube, 2010; Shmulsky & Jones, 2011).

In another development, it is reported that upon heat application to some wood, fatty acids in the lignin change, harden and cannot be altered from that more rigid state by any amount of moisture absorbed during use of the wood (Shepherd, 2009). Moreover, some wood species could contain some resins or inclusions (Forest Products Laboratory, 2010) that can get hardened once kiln-dried (Dinwoodie, 2010; Townsley, 2010). These occlusions/inclusions may block wood natural flow paths to reduce or disallow leaching of toxic substances from wood as well as impede the admission of some level of moisture into wood, thereby reducing/delaying biodeterioration (Antwi-Boasiako & Atta-Obeng, 2009; Ncube, 2010). Thus, kiln-drying can improve the durability of wood relative to air-drying. Therefore, natural durability can vary for the same species at different MCs and dried with different drying methods, as well as severity of hazards in the locations of use/application (Scheffer & Morrell, 1998). In view of this, it is reported that air-drying could sufficiently decrease the resistance of some wood species to the extent that it could compel reclassification of wood from a highly durable class to a durable class (Guangxi Universities Forestry College, 2007a).

2.2.4: Evaluating natural durability of wood

There exist two main test types for determining the durability of wood, namely; laboratory tests and field tests. However, besides these tests, knowledge about natural durability can also be obtained through practical experience of the end users (Ali, 2011). Each of these types of tests has various procedures spelt out in various standards and when they are followed, the results obtained are used to predict the service life of wood, either when chemically treated or not. However, the choice of laboratory or field test depends on a number of factors.

In the first place, it must always be remembered that, wood species vary widely in their resistance to attack by the various biodegrading agents. Hence, according to Scheffer and Morrell (1998), some naturally durable wood species can resist attack by insects and marine borers while others can resist fungal attack but will have little or no protection against other organisms. Further to these, some wood species might be resistant to one group of termites but susceptible to others. However, these authors contend that, considering the high cost of evaluating natural durability of wood species to cover all hazard conditions one after the other, a preliminary evaluation of untested species by a laboratory accelerated testing is nearly always warranted. But to confirm performance under the intended exposure conditions, wood species should be evaluated against the hazards (field) to which they will be exposed in the country of their use (Brischke et al., 2011; Scheffer & Morrell, 1998).

Field tests expose specimens to real service or hazard conditions but take a longer time and also result from different sites are not easily comparable due to possible different exposure conditions. Although accelerated laboratory test provides alternatively short time results, by using isolated fungus cultures, it presents a problem in predicting natural durability of timber in use, since natural conditions are not reproducible in the laboratory (Cavalcante, Lopez, Montagna, & Fosco-Mucer, 1985; Ncube, 2010). There is therefore a wide disparity between results from laboratory test and field test which is attributed to the fact that, while laboratory test uses one organism at a time, the field test exposes the wood to almost all organisms responsible for decay and degradation at the same time (Brischke et al., 2011).

In another development, Scheffer and Morrell (1998) have asserted that, though field tests expose the wood to many biological agents at a time, because the soil, temperature and rainfall conditions vary widely from site to site, the test type makes comparison of results difficult. The authors also state that laboratory test results, however, produces a more uniform result since temperature and moisture conditions can be more closely controlled, but even with this, variations in decay organisms used and laboratory techniques can also influence results. Moreover, Bischke et. al. (2011) have discovered that some fungi (e.g. Hypholoma fasciculare and its likes) are rarely used for laboratory decay tests but are sometimes responsible for massive decay of wood in-ground during field (graveyard) test. Thus these authors conclude that field or graveyard test gives the true picture of the natural durability of wood in its real use environment, and for that matter, aids a better prediction of the service life of wood. Therefore, field test methods should be preferred, in any case, to laboratory ones. As a result, it is a requirement in ISO

15686 – 2 (2002) that laboratory natural durability test results should have to be validated through comparison with field test results.

From the foregoing, Eaton and Hale (1993) are also of the view that field trials have two main advantages over laboratory tests: (1) it enables large sizes of wood samples to be exposed to the biodeteriorating agents; (2) it allows the samples to be tested under conditions similar to the end use situation. These advantages among others make field test a better option for generalization than laboratory tests.

2.2.5: Durability classifications and service life of wood

Assigning natural durability or decay resistance classes to wood species entails the use of several criteria but it is based on results of a laboratory test and or field/ in-service tests. However, in examining any of these performance test results to assign resistance ratings that are presumed to be appropriate for any exposure conditions, often involves some subjective decisions concerning the severity of attack from a specific test and appropriate ratings (Scheffer & Morell, 1998).

Some of the criteria used for assessing wood resistance to biodegrading agents include weight losses, times for nominal or complete failures and relative conditions of specimens after a set number of weeks, months or years (Ncube, 2010; Scheffer & Morrell, 1998; Wolgang et al., 2012). However, the rating that applies to the relative condition of specimen due to the severity of attack by biodeterogens is identified to be very subjective compared to the weight losses and times for nominal or complete failures due to attack (Scheffer and Morrell, 1998; Wolgang et al., 2012). Hence, the European Standard EN 252 (1989) recommends that, the criteria for rating and classifying the natural durability of wood due to the severity of attack, should be done by more than one person. In the light of the subjectivity of decisions on service life prediction and durability classification of wood, there has been a concern for a generally acceptable concept that will meet the end use requirements or hazard conditions. Hence, a test method to be used for any classification or assessment should be closely related to the intended use situation (Brischke et. al., 2011).

Following the identification of hazard class that wood can be exposed to in a specific environment, NAFI (2003) and Cooksen (2004) have reported and provided the service lives for four main natural durability classes, namely; **class 1** (highly durable), **class 2** (durable), **class 3** (moderately durable) and **class 4** (non-durable). It must, however, be noted that species rated class 4 would require preservative treatment for any in-ground structural use. These durability classes correspond to various service life of wood and their hazard conditions (Table 2.1).

Table 2.1: Guide to service life for the various durability classes.

Durability Class	**Heartwood Service Life (years)**		
	H5 In-ground	**H3 Above ground**	**H1 Covered or Protected**
Class 1. (Highly Durable)	25 +	40 +	40 +
Class 2. (Durable)	15 –25	15- 40	40 +
Class 3. (Moderately Durable)	5 – 15	7- 15	40 +
Class 4. (Non Durable)	0 - < 5	0 -7	40 +

Sources: Cookson (2004) and National Association of Forest Industries –NAFI (2003).

2.2.6: Natural durability studies on Ghanaian hardwood species

Available literature indicates that some information exists on the natural durability of some Ghanaian tropical hardwood species. Among the sighted published studies on natural durability of Ghanaian wood species include Ocloo (as cited in Quartey, 2009)-on natural resistance of *Terminalia ivorensis* to fungi and termites and Usher and Ocloo (as cited in Quartey, 2009)- on the resistance of 85 Ghanaian wood species to damage by subterranean termites. Others include Kumi-Woode (1996) who worked on 14 less-utilized species, while Gyimah-Boadi (as cited in Quartey, 2009) worked on the treatability and durability of some less utilized species. Again, Pleydell (1994) has also studied the natural durability among other properties of 68 different species. The more recent ones which relate to the objectives of this study are Antwi-Boasiako and Atta-Obeng (2009) and Antwi-Boasiako and Pitman (2009). Antwi-Boasiako and Atta-Obeng (2009) studied the relationship between wood specific gravity (SG), vessel-fibre ratio (VF ratio) and natural durability. Some of their conclusions are that higher SG means lower VF ratio and higher durability, whereas higher VF-ratio implies low SG and lower natural durability. Hence, much vessels in wood make the SG low and result in low natural durability, whereas lower VF ratio (implying relatively more fibres) makes the SG of wood higher and tends to also make the natural durability higher. On the other hand, Antwi-Boasiako and Pitman (2009) studied the influence of wood density on natural durability. The study found that generally, density correlates positively with natural durability. However, they also generally concluded that, extractives are by far a more important factor than density in respect of their contributions towards wood natural durability or decay resistance. Thus, the authors suggested that density in itself is a poor determinant of durability for some tropical hardwoods. They moreover concluded that, although extractive content influences durability, extractive type is an important determinant factor to consider.

However, there are no sighted published works on the natural durability of any Ghanaian tropical hardwood branchwood either alone or in comparison with their stemwood.

2.3: Bending Strength of Unjointed and Finger-Jointed Lumber

According to Dinwoodie (2010) and Shmulsky and Jones (2011), mechanical properties (strength) requirements of wood are of different kinds and they relate to the specific use of the material. Hence, wood that is relatively strong with respect to one strength or mechanical property may rank lower in a different property. Therefore, the type of mechanical property most critical to any application is determined by the type of loading to which that product will be subjected. For example, to find out the extent that a material will bend under load, and for that matter, how solid or stiff the material will be measuring or testing its modules of elasticity (MOE) is very necessary and appropriate. Hence, for materials to be used for table-tops, chair seat and backrest slats, chair and table side rails, shelves or cabinet dividers etc. (which normally act as beams) bending strength (MOR) and modulus of elasticity (MOE) are of much importance.

Again, for end jointed lumber like finger-jointed ones, according to ASTM D 7469-(2012), the various mechanical tests needed to investigate the effect of joint parameters (such as joint profile, adhesive type, moisture content, temperature, among other strength-reducing characteristics in the assembly) that may influence the structural capacity and integrity of an end-joint include Axial Tension, Bending, Cyclic Delamination, Tension Proofload, and Bending proofload.

In this study, however, the bending (static) test is the focus, since targeted products or materials are to act as beams to carry loads and in such structural members bending strength (MOR) and modulus of elasticity (MOE) are the most necessary. Additionally, according to Guangxi University Forestry College (2007b), bending stress is a combination of all the three primary stresses (compressive, tensile, and shear) and so to some appreciable extent, bending test also tests the wood in compression, tension and shear. Because static bending test combines all the three primary stresses, they act together to cause flexure or bending in the wood (Guangxi University Forestry College, 2007b), and for that matter, the differences between the tensile strength and the crushing strength of wood during such tests determines the characteristics behaviour of a wood beam in bending (Dinwoodie, 2010; Shmulsky & Jones, 2011). It is for this reason that, the concept of stress and strain is quite simple in tension and compression but much more complex in a beam (bending members). When a beam such as shelves in bookshelves, seat slats etc. is bent, the topmost portion is compressed (shortened in dimension) and the bottom half is stressed in tension (increased in dimension), whereas the central portion (neutral axis) neither experiences tension nor compression (Guangxi University Forestry College, 2007b). This situation results in the bending of the beam due to the corresponding compressive and tensile strains induced into the wood at various sides or sections (Dinwoodie, 2010; Shmulsky & Jones, 2011). However, according to (Dinwoodie, 2010; Guangxi University Forestry College, 2007b; Shmulsky & Jones, 2011), the degree of bending at the midpoint of the beam is the deflection. This deflection depends on the location and magnitude of the applied load, the length and size of the beam and the MOE of the material (the higher the MOE of a material, the lesser the deflection under load).

2.3.1: Factors that influence bending strength of solid/unjointed and finger-jointed wood

The various mechanical properties including bending strength of both unjointed and jointed (in this case, finger-jointed) lumber are affected by some variables or factors.

The bending strength of unjointed lumber is affected by moisture content, density, chemical components, wood structure, decay, wood species concerned, among others (Dinwoodie, 2010; Forest Products Laboratory, 1999; Forest Products Laboratory, 2010; Guangxi University Forestry College, 2007b; Richter & Dallwitz, 2000; Shmulsky & Jones, 2011). The bending strength of finger-jointed lumber is, however, also affected by the wood species involved, adhesive type, finger-joint orientation and configuration, finger profile, end pressure, duration of pressure application, moisture content (or drying state) of wood, density of wood, curing time of adhesive, and machining parameters used in preparing the wood for jointing (Ayarkwa et. al., 2000b; Bustos, Hernández, Beauregard, & Mohammad, 2004; Bustos et al., 2003a; Bustos, Mohammad, Hernández, & Beauregard, 2003b; Castro & Paganini,1997; Forintek Canada Corp., 2003; He, Fu, Lin, Cao, 2012; Hoffmeyer & Thógersen, 1993; Hwang & Hisiung, 2001; International Development Researrch Centre -IDRC, 1997; Jokerst, 1981; Meng et at., 2009; St. Pierre, Beauregard, Mohammad, & Bustos, 2005; Vrazel & Sellers, 2004).

According to Ayarkwa et al. (2000b), Meng et al. (2009), and Jokerst (1981) finger profile or geometry has been proven to be the governing factor and most critical variable that determines finger joint strength among wood density, adhesive, finger-joint profile and end pressure. However, there are four (4) interdependent variables that form the finger-joint profile or geometry. These variables are pitch (P), length (L), slope (angle of slope = θ) and width of fingertips (t) (Ayarkwa et. al, 2000b; Bustos et al., 2003a; Castro & Paganini, 1997; Jokerst, 1981; Vrazel & Sellers, 2004). However, Meng et al. (2009) are also of the view that space or gap between fingers (s) is also an important parameter. Again, Bustos et al. (2003a) and Jokerst (1981) are also of the opinion that these four elements of the profile are so related that changing any one element automatically changes another. Thus, this interrelationship of the elements of a finger-joint profile complicates investigating the effect on strength of any one element since each of them can influence the performance of end-joints.

In finger-jointing therefore, the finger geometry is very important and a considerable number of studies on the interrelationships among the finger geometric parameters and their effect on finger-joint strength have been sighted. These include works done by Ayarkwa et al. (2000b), Bustos et al. (2003a), Castro and Paganini (1997), Meng et al. (2009), Jokerst (1981), Wengert (1998), and. However, there are some agreements in findings by these authors that it is always important to keep finger tips as thin as practicable to obtain maximum strength. Two primary reasons assigned for this are; **(1)** blunt tips are butt joints incapable of transmitting stresses, and **(2)** finger tips introduce abrupt changes in section that cause stress concentrations and which in turn results in lower than expected loads at failure (Jokerst, 1981). Moreover, Wengert (1998) asserts that, three main variables or elements of the geometry that combine to yield sufficient area on the fingers for a good, strong joint are the slope (angle), the tip and the pitch (also called base or root width). According to this author, best strength performance seem to be achieved with a slope of 1 to 12 with a thin tip of 0.01in (0.25mm), and a pitch of 0.3in (7.5mm). The specific roles played by each element or variable in the finger geometry in contributing to either the strength or weaknesses of finger-joints have extensively been studied by Ayarkwa et al. (2000b). However, naturally the wood species and the basic strength of the wood itself around the joint are also important in determining the final strength of finger-jointed lumber.

In this study however, the variables being considered for study on their influence on both unjointed and finger-joint lumber strength are species/wood type (i.e. stem off-cut and branch), density, and moisture content (state of dryness or wetness).

2.3.1.1: Species/type of wood

The species of wood, their various parts, and their quality affect the strength properties of both unjointed and finger-jointed lumber produced from them. Rate of growth accounts for about 15% of variation in strength properties among wood species and regional or site differences are also factors that can affect the strength of wood species (Forest Products Laboratory, 2010). Again, age and cell wall thickness can also lead to variations in strength (Dinwoodie, 2010; Shmulsky & Jones, 2011). Additionally, wood species/parts characterised by many knots, spiral/sloppy grains appear to have lower bending strengths relative to its unknotty portions (Dinwoodie, 2010; Forest Products Laboratory, 2010, Guangxi University Forestry College, 2007b; Shmulsky & Jones, 2011). In view of these, most failures during bending test of wood appear to occur at areas of grain deviations than at the finger-joints (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). Also, species or parts of wood with coarse grains normally have low stiffness and bending strength than those with medium grain texture (Jokerst, 1981). It has also been reported that fuzzy grains (suggesting presence of tension wood) in some wood species/type tend to affect the mechanical strengths of the wood (Okai, 2002).

In finger-jointing, the efficiency of the joint strength in relation to unjointed timber of same species also vary among species (Ayarkwa et al*.,* 2003a; Jokerst, 1981). It must however, be noted that many of the factors that affect unjointed wood bending strength can also affect that of finger-jointed lumber. For instance, wood species or parts that have many knots are also likely to have less bending strength in both finger-jointed and unjointed members of the species (Jokerst, 1981). As a confirmation, the strength reduction from finger-joint is about equal to that caused by an 18.75mm diameter knot. Therefore, if the finger-joint itself additionally contains knots, then the decreased strength value may be near a double figure (Jokerst 1981).

It has also been reported that some species or wood parts contain either juvenile or reaction wood and these turn to lower their mechanical strength values when used as either unjointed lumber or components of finger-jointed lumber

(Dinwoodie, 2010; Guangxi University Forestry College, 2007b; Okai, 2002 Shmulsky & Jones, 2011). Similarly, it is found that, wood species have influence on the final strength of finger-jointed lumber made from them (He et al., 2012; Vrazel & Sellers, 2004; IDRC, 1997), but these differences among species are attributable to the presence of extractives (IDRC, 1997). According to the finding of IDRC (1997), the bending strength between two species (Albezia and Masson pine) was quite low. However, upon chemically treating the finger surfaces of the species to possibly remove some of the extractives, the joint strength was improved remarkably. Hence, the weakness in the strength was attributed to the presence of extractives in the hardwood (Albizia) that affected adhesion due to a possible extractive seepage on the finger surfaces to be joined.

2.3.1.2: Density/specific gravity

Density is one of the most important physical properties of wood and it is influenced to a large extent by the structural arrangement of the wood cells (Dinwoodie, 2010; Shmulsky & Jones, 2011). For instance, wood with higher proportions of early wood than late wood will have lesser density and vice versa. This is to say that density of wood increases or is higher in wood species with high proportions of cells with thick cell walls. Also, the amount of space occupied by voids (vessels), parenchyma and fibres also determine the density of a wood species (Dinwoodie, 2010; Guangxi University Forestry College, 2007b; Shmulsky & Jones, 2011).

In respect of the effect of density on the mechanical properties of wood, Castro and Paganini (1997) studied the influence of density on the strength of finger-jointed popular wood and concluded that the influence of density on the performance of jointed specimens were almost similar to that shown in solid wood. This therefore implies that density affects the strength of both solid and finger jointed lumber of species almost equally. Again, it has been asserted that, density and specific gravity of wood affect the mechanical strength of both solid and finger-jointed lumber (Bustos et al., 2003a; Meng et al., 2009; Jokerst, 1981). In other developments, Jokerst (1981) reports that, density or specific gravity below the average density or specific gravity for wood species will exhibit less finger-joint strength than the same joint in the same species with average or higher density. However, low density wood species are the ones with SG of 0.42 (density = 420kg/m^3) or less and those beyond are classed as high density species (Vrazel & Sellers, 2004). Additionally, Meng et al. (2009) are of the opinion that, species or group of samples that show no significant difference in overall density among them is an indication that all of them have similar wood quality and as such, there will not be any significant effect of raw material on the finger-jointed or solid lumber strength properties.

Some of the conclusions of the aforementioned studies appear to have either been corroborated or affirmed by some findings on some Ghanaian hardwood species. Ayarkwa et al. (2000a) concluded that density affects the strength of finger-jointed lumber and that, gluing hardwoods of densities in excess of 700kg/m^3 can produce inconsistent results, while finger-joints in hardwoods of densities below 700kg/m^3 appear to perform better as expected. However, Ayarkwa et al. (2000b) also found that it was also possible to obtain high bending strength from a low density wood like *Triplochiton scleroxylon* (Obeche) with some type of resorcinol formaldehyde adhesive.

2.3.1.3: Moisture content (MC)

According to Meng et al. (2009), moisture content (MC) affects the density of wood samples, thereby affecting the mechanical strength properties. Thus samples at different MC, though same species, may have different density and strength properties. For this reason, when densities of wood are determined, the MC at the time should also be necessarily indicated (Dinwoodie, 2010; Forest Products Laboratory, 2010; Guangxi University Forestry College, 2007b; Meng et al., 2009; Shmulsky & Jones, 2011). It is reported that MC has negative correlation with bending strength after the fibre saturation point (FSP) of wood and therfore bending strength increases as MC decreases (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). However, reports indicate that, change in bending strength with change in MC is non-linear, and that the percent increase in strength per unit reduction in MC percent is greater at low compared to high MC levels (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011;). For instance, the MOE of Douglas fir wood at MC range of 6 to 10% increased by 0.21% while MOR increased by 4.74%. However, the same wood at MC range of 12 to 16% had the MOE increased by 0.18% whereas the MOR increased by 3.62% (Dinwoodie, 2010; Shmulsky & Jones, 2011). It is however important to note that, a full explanation of the effect of MC on strength properties of wood is still not available, but it is generally accepted that the overall increase in strength with reduction in moisture is due to the shortening and consequent strengthening of the hydrogen bonds linking together the microfibrils in wood (Dinwoodie, 2010; Shmulsky & Jones, 2011).

Moreover, in finger-jointing, Biechele, Chui and Meng (2010), and Bustos et al.(2003a), have also pointed out that to use wood more efficiently in the development of finger-jointed products, specific process parameters like the moisture content must be taken into account. This is because, according to the authors, the moisture content affects the gluing or adhesion process of the glue/adhesives and consequently affects the stiffness strength of joints formed. Results from a study by

St-.Pierre et al. (2005) on the effect of MC and temperature on tension strength of black spruce lumber attested to this. These authors found that the mean ultimate tensile strength increases with decreasing MC of wood.

In view of the effects of MC on finger-joint adhesion and subsequent strength, most of the sighted extensive previous studies on finger-jointed lumber have all been on dried (mostly kiln-dried) components/members, whose MCs were reduce to ≤ 15% before jointing (He et al., 2012; Biechele et al., 2010; Ayarkwa, 2010; Meng et al., 2009; Vrazel & Sellers 2004; Bustos et al., 2004; Bustos et al., 2003a; Ayarkwa et al., 2000a; Ayarkwa et al., 2000b; Bustos et al., 2003b; Reeb, Karchesy, Foster, & Krahmer, 1998; Castro & Paganini, 1997; Beaulieu et al., 1997).

However, Finger-jointing of wood in either green or elevated moisture contents state have less been studied. Meanwhile, according to IDRC (1997), finger-jointed lumber made from green wood can obtain bending strengths close to those of air-dried finger-jointed lumber. However, this report also enumerates some limitations of green wood finger-jointing technology to include the fact that: **1)** The MC of lumber used for production by industry is expected to lie at 12 – 15%, **2)** The jointed green wood often have to be re-dried after jointing, at which time deformation could occur during the process, especially in some hardwoods if not well stacked, **3)** The deformation may not be able to be corrected completely and thus can lead to increased machining works. However, notwithstanding these limitations of green lumber finger-jointing technology, it has some economic and environmental benefits (Källander, 2008). Economically, there is no need to dry waste at a cost, and it speeds up production by reducing idle time of workers to meet delivery times. Also, after jointing, the exact cut lengths help to reduce drying cost and prevent drying defects that would have arisen from stacking uneven lengths of unjointed off-cuts for drying before jointing (Källander, 2008). Environmentally, the cut-offs from green jointed lumber are not dried and therefore can be used for pulp and paper, particle boards and other products, which in turn, reduce wastes that should have been disposed off to affect the environment negatively (Källander, 2008). However, the decision to either join wood in the green or dry state depends on the wood species, uses of the end products, and the local production and technical conditions (IDRC, 1997). According to Jokerst (1981) if wood MC is too high, the adhesive is absorbed by the wood and result in starved joints. Also, if heat is used for curing such joints, the heat heats the water instead of the glue and results in undercured gluelines. However, the report was of the opinion that wood species of good stability (those that shrink relatively less) will produce joint of relatively high strength or efficiency when jointed green, compared to the relatively unstable wood species (those that shrink relatively high).

Meanwhile, green finger-jointing has been done successfully elsewhere. It is reported by Mantannis et al. (2010) that, producing finger-jointed lumber from wood species like *Pinus nigra* using green-gluing technology produced good bending strength efficiencies (i.e., joint efficiencies ranged from 68.13% to 87.30 for MOR and from 89.52% to 100% for MOE) . However, in that study, phenol resorcinol formaldehyde (PRF) and an HRP 55 type hardener in the ratio of 1:5 were used, while Amonia solution (25% concentration) was also applied on one side of the joint to act as accelerator. Mantannis et al. (2010) also reports that previous researchers (Curier, 1960; Murphey & Nearn,1956; Strickler, 1970; Raknes,1967; Troughton & Chow,1980) have also successfully finger-jointed green softwoods. However, in those studies, phenol resorcinol formaldehyde (PRF) glue was used while heat was applied to pre-dry ends of green wood and to also accelerate curing of the adhesive. In a similar development, continuous research on green lumber finger-jointing led to the development of new glue types, namely; Greenweld (consisting PRF + Hardner + Ammonia). Besides this, according to Mantannis et al. (2010), a two component adhesive called SoyBond, based on hydrolysed soy protein and conventional PRF has also been successfully used to produce finger-jointed lumber from green wood. In another perspective, Lang and Hassler (2007) points out that, the obvious problem with green end jointing is the high MC of the materials. This is because, upon the application of glue and pressure, the free and bond water in the wood dilutes the chemical concentration of the synthetic resins, resulting in significant increases in curing time and subsequent low strength development.

In the light of the aforementioned issues, researchers have approached the problems with green finger-jointing in different ways. One procedure according to Lang and Hassler (2007), was the local drying of the mating surfaces. Other researchers also improved the technology by introducing a second drying procedure and using overheated steam to achieve the desired MC level in the fingers. Another approach was also to combine the available glues (usually phenol resorcinol formaldehyde-PRF resins) with additives that either accelerate the curing or prevent dilution and over-penetration. Some of the proposed additives include soy-based hydrolyzate, tannin and M-Aminophenol (Lang & Hassler, 2007). However, costs and technological considerations or challenges prevented rapid acceptance of these technologies, since their combined effect defeats the main idea of gluing green wood, which is to reduce overall cost (Lang & Hassler, 2007). All these appear to discourage finger-jointing wood in the green state. But Lang and Hasler (2007), and Jokerst (1981) concluded in support of Källander (2008) (who enumerated some economic and environmental advantages of the technology and stated earlier) that in spite of any limitations of finger-jointing green or high MC wood, the technology is much more economically attractive than when wood is dried before jointing, due to drying cost.

In Ghana, however, Amoah, Kwarteng and Dadzie (2014) have found joint efficiencies of green finger-jointed lumber to range from 49% to 55% in MOE and 13% to 40% in MOR, whereas their counterparts jointed in the dried state registered efficiencies ranging from 58% to 89% in MOE and from 15% to 51% in MOR for some low and medium density tropical hardwoods. However, no finger-jointing of branchwood, either alone or in combination with stemwood whether in the green or dried state has been sighted.

2.3.2: Determination of bending strength

Bending test measures modulus of rupture (MOR-bending strength) in addition to the MOE (modulus of elasticity) to determine the load resistance of wood (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). While MOE is a measure of the stiffness of a body, MOR is related to the maximum load that can be resisted by the beam (i.e. maximum strength of the wood). According to Dinwoodie (2010), and Shmulsky and Jones (2011), the test procedures for determining bending strength properties of wood are specified by several standards such as the American Society for Testing and Materials Standard ASTM 143-52. The British Standard BS 373 (1957) however, provides for specimen dimensions of 20×20×300mm which is to be supported over a span of 280mm. Another standard is the German Standard Specification DIN 52185 (1976) that permits any cross section from 2cm × 2cm to 4cm × 4cm and the length ≤ 18h, where „h‟ is the height of the specimen (Kollmann & Côté, 1968). However, these authors have indicated that, the modulus of rupture for small clear wood beams with cross-sections from 2cm × 2cm up to about 6cm × 6cm is practically equal. Therefore the dimensions of test specimens to be used for any mechanical test is normally determined by the information needed, the standard test procedure being adopted and the specifications on the testing machine (which is influenced by the standard upon which it was designed).

2.3.3: Some related issues about finger-jointing technology

Wood exhibits its greatest strength parallel to the grain and the development of end joints that can transmit a significant proportion of this strength has been challenging and at times difficult (Jokerst, 1981). The problem, according to Jokerst (1981), is that wood cannot be bonded sufficiently well end-grain to end-grain with existing adhesives and techniques (butt and scarf jointing) to make the end product be of any practical importance. However, wood can be bonded quite effectively with most adhesives side-grain to side-grain and generally quite easily, and this is what finger-jointing provides (Jokerst, 1981; Wengert, 1998). This is because, NZWood (2007) asserts that the end grain of wood is so porous that no good joint can be produced from end-grain gluing or jointing without having much exposed side or edge grain. But these side grains are made available through finger jointing technique for better gluing and eventual stronger joints.

Finger joint involves the process of gluing short pieces of wood end to end or longitudinally by the use of fingered or tapered ends to produce a joint (IDRC 1998). Finger-joints are used to join pieces of various lengths end-grain to end grain and also to join short lengths of materials into lengths long enough to be useful, after the defects in the members have been removed (Wengert, 1998). As a result, it is one effective method of salvaging residual wood, from mills and logging operations, that otherwise would have been wasted (IDRC, 1998; Wengert, 1998).

2.3.3.1: Advantages of finger-jointing technology

Finger-jointing technique has both economic and technical advantages besides the main one of salvaging waste wood. According to IDRC (1998), economically, the technique has the potential of boosting a country"s production of lumber while recycling waste material and providing part-time income to rural people who supply wood thinning from their farms and community woodlots (as is in the case of China). It is reported that people make more money by selling small diameter woods to the finger-jointing mills than selling it for firewood (IDRC, 1998; Jokerst, 1981). This eventually increases the economic value of the wood and stimulates farmers" interest in planting trees, which contributes substantially towards dealing with deforestation. Again, finger joints may also be used to upgrade lumber by removing defects that limits the grade of the lumber, since after jointing, the lumber becomes defect-free whole length (Jokerst, 1981; Lang and Hassler, 2007) which will attract higher value.

Meng et al. (2009), and NZwood (2007) report that technically finger-jointed lumber also possesses some desirable properties like straightness, dimensional stability, interchangeability with unjointed lumber and unlimited length. These advantages make finger-joined lumber a common component in engineered wood products and in some sectors (like prefabricated homes) a preferred component to unjointed lumber (Brink Forest Products Ltd., 2012).

2.3.3.2: Challenges of finger-jointing technology

Although finger-jointing technique has proven economic and technical benefits, there are also some challenges associated with it. According to Wengert (1998), the process requires some capital investment, adhesives, and labour, all of which can swell-up production cost. Again, the reduced waste can also eliminate an energy source, though as energy, the value of such wood is less than when supplied to be used for finger- jointing (Meng et al., 2009). Moreover, some wood users have perceived the joint itself as being unattractive and consequently, considering the end product from it as being inferior to solid wood. But these have been proven not to be the case as the joint can possess bending strength of about between 75% and 85% of the strength of clear solid/unjointed lumber (Ayarkwa et al., 2000a; Wengert, 1998).

2.3.3.3: Uses or applications of finger-jointing

Finger joints are used for both non-structural and structural applications. These use classifications are based on the strength requirements which in turn depend on the geometry (or profile) of the fingers (Jokerst, 1981).

The non-structural finger-jointed lumber is the type that appearance quality, other than strength, is the primary concern. On the other hand, structural finger-jointed lumber is made with emphasis on mechanical or strength rather than appearance quality (He et al., 2012; Reeb et. al., 1998). The differences in appearance between structural and non-structural joints lie in the geometry of the fingers. Non-structural finger-joints generally, have short fingers with blunt tips (ends) whereas the structural joints have relatively longer fingers and sharp tips (Jokerst, 1981). Again, the non-structural finger-joints primarily find applications in moulding stocks, trims, siding, facia boards, door stiles and rails, window frames, light flooring, door jambs, table tops etc., whereas the structural finger-joints are used in structural dimension lumber and for end jointing laminate used for large laminated beams in which the length of the beam may exceed the length of the available unjointed lumber by several times (Reeb et al., 1998). The structural finger-jointed lumber finds applications in staircases, garden bench, garden chairs and has been accepted by various international building regulatory bodies as good materials for use in various components of building structures like trusses, I-joists, open-web joist, beams, columns etc. However, this acceptance is subject to adhering to the specifications of structural lumber end-joint certification and quality control practices. In view of these, structural FJ lumber is also referred to as engineered lumber (Bustos et al., 2003a; Reeb et al., 1998).

2.3.3.4: Finger-joint profile orientations

According to Jokerst (1981), a factor that can affect finger-joint performance is its orientation relative to width and thickness of the pieces to be jointed. There are three (3) main finger-joint profile orientations existing for both structural and non-structural finger-joints, namely; vertical, horizontal and inclined (Figure 2.2; A, B and C respectively). Findings reported by Jokerst (1981) indicate that vertical finger-joints to be stressed in bending are said to perform better than horizontal finger joints. The reason being that, with the profile of the joint on the edge (for the horizontal type), the two outer fingers carry most of the load and their integrity is very critical to the performance of the joint. However, with the profile on the wide face (for the vertical type), the stresses are more evenly distributed across all of the fingers of the joint and therefore make them capable of carrying much load.

Again, it is also not uncommon in finger jointing to apply only end pressure without any lateral pressure. If this occurs, the outer fingers of the horizontal type tend to spread out and result in thick gluelines and low-strength joints at face or edge (where these outer fingers are). As these weak joints appear on the outer surfaces of the edges or faces, they result in areas of high stress concentrations, and the reduction in strength is greater than would be expected. These also make the horizontal type weaker than the vertical type (Jokers, 1981). However, if both end and lateral pressures are applied at the same time to bonding/jointing, this problem of weakening of outer fingers can be dealt with and that can result in no significant differences in the strength of joints due to orientations.

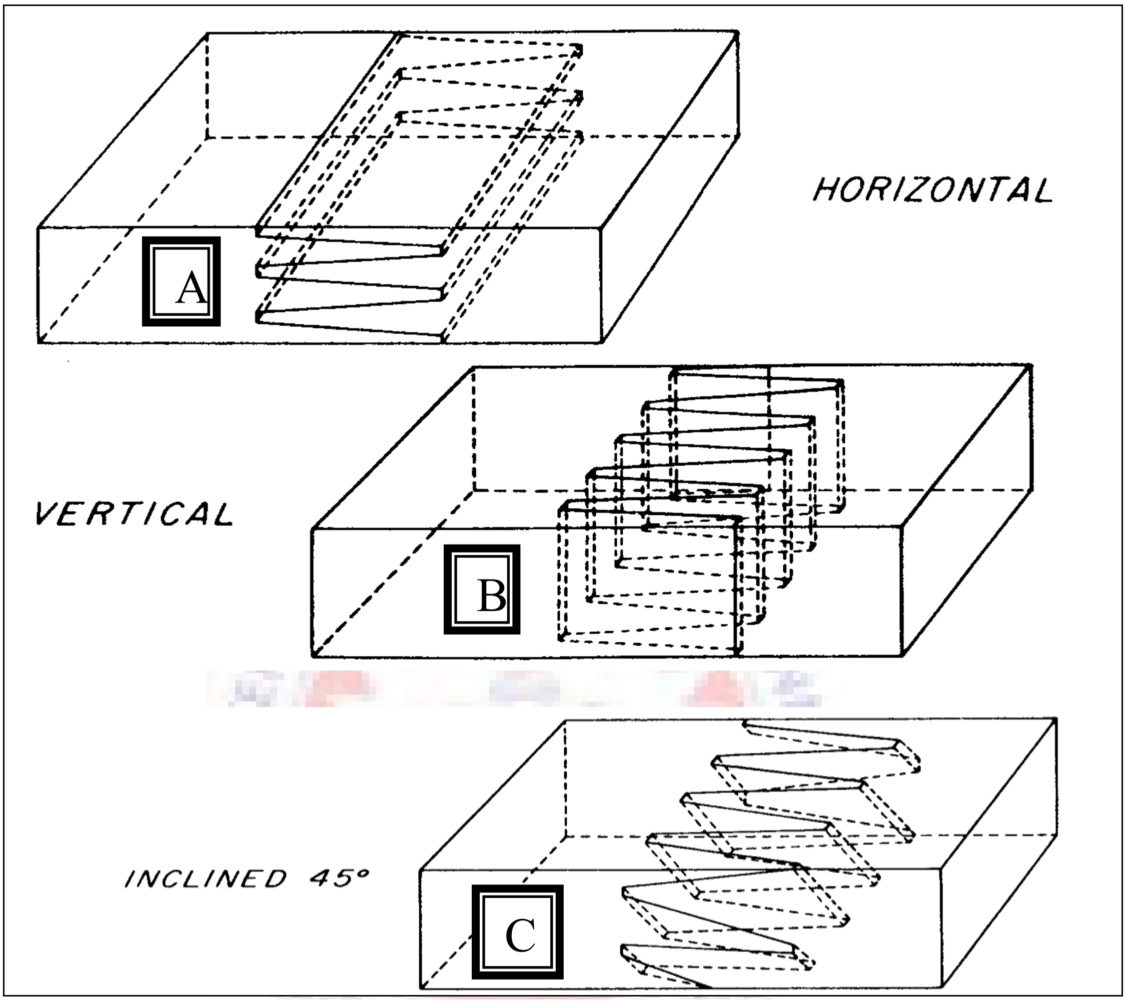


Figure 2.2: Finger-joint profile orientations. Source; Jokerst (1981).

Moreover, another intervention that deals with the strength reduction due to outer fingers is the finger orientation cut at an angle of 45° to the plane of the board (Figure 2.2C). With this, there are no thin, flexible fingers at the surfaces and therefore, all fingers are sufficiently rigid to resist load spreading, leading to strong bonds throughout the joint without applying lateral pressure. These joints perform significantly better in bending and similarly in tension relative to vertical or horizontal joints (Bustos et al., 2003a).

2.3.3.5: Economics of finger-jointing

Finger-jointing operations, according to Jokerst (1981), differ from one firm to the other and the extent to which the operation will be profitable depends on the type and cost of machinery in use, rate at which the machine is used, amount of preparation needed on the material, type and cost of auxiliary equipment used with the machine(s), among others. As a result, the profitability of finger-jointing operations cannot be generalized but each particular operation must be evaluated and determined on its own merit. However, it is reported that, with the increasing value and decreasing volumes of high-grade raw material availability, finger-jointing has become an economic necessity (Tze, 1964).

Meanwhile, one cannot afford just to assume that finger-jointing will be profitable, without making detailed analysis on the percentage of short length lumber that can be salvaged, and the alternative value of those materials as chips or as fuels. This value of the materials (as fuels or chips) should then be compared to the value of the appropriate grade of finger-jointed lumber to be obtained, minus the cost of manufacturing (Equipment cost, operating cost, direct cost, waste cost) in order to ascertain the final profit to be accrued. This profit or otherwise will determine if the operation is economically feasible or not (Jokerst, 1981; Tillman, 1985).

In terms of short length lumber availability in Ghana, sawmill off-cuts are readily available in appreciably larger quantities. It is reported that sawmill recovery in Ghana is between 40% and 50%, (Ayarkwa et al., 2000b). These authors further asserted that, sawmill off-cuts in Kumasi city alone suitable for finger-jointed lumber is over 70,000m^3, and well over 50% of this volume of off-cuts is used as fuelwood for boilers in the sawmills and also for bread baking. Hence materials are available in appreciable quantity in Ghana for finger-jointing. Again, IDRC (1998) reports that, people who supply raw materials (branches from thinning etc.) to finger-jointing facilities make more money than selling the materials as firewood. Thus, it is likely that, when branchwoods together with off-cuts (either from mill or forest) are directed towards the production of finger-jointed lumber, either alone or in a mix with sawmill off-cuts, the process will be profitable and attractive to individuals than selling such materials as firewood.

Also, regarding returns on investment on the industrial front, Jokerst (1981) reports that, finger-jointing operation is likely to yield 50% return on investment even at a capital investment of $1 million. Additionally, Tze (1964) studied the feasibility of establishing finger-jointing operation and drew 2 conclusions. One conclusion was that, there is a profit potential of $50 per day and an equipment payout period of two (2) years for finger-jointing operations that produce about 9.3m^3 of finger-jointed lumber (with dimensions of 50 × 100 × 4880mm or 2 × 4 ×192 inches) per day. This could be realised when a low volume machine that has a speed of 6000 linear feet per 8hrs (i.e., total working hours per day) is used to salvage wood waste in a prefabricated house and mobile home plant. The second finding was that, a profit potential of $175 per day and an equipment payout period of 1.6 years for an operation that utilizes a high-volume finger-joint unit to upgrade lumber to customer specifications. This is when production level was about 57.50m^3 of finger-jointed lumber (with dimensions of 150 x 100 x 73,200mm or 2 x 4 x 240 inches) per day of 8hrs, using a high volume machine with a speed of 30,000 linear feet per 8hrs. In another development, IDRC (1998) also assert that, to set up a finger jointed lumber mill with an annual output of 3,000m^3 (i.e. 12m^3 per day for 250 days a year – Tze 1964) will approximately employ between 80 – 100 workers.

The foregoing indicate that besides the profits to the firms, there will also be substantial increase in employment capacity of the wood industry due to expansion or addition of new production line when finger-jointing technology is adapted or enhanced. Observations of the operations of some wood industries in Ghana (i.e. LLL and FABI timbers – all located in Kumasi) appear to confirm this. Such increase in employment have positive economic and social implications for the country and the citizenry. Hence, it is important to recognize that even though finger-joint strength (particularly MOR) does not equal that of clear unjointed wood, it is convincingly the best and economically feasible method of salvaging waste in sawmills and forests, while at the same time making higher returns on investment as well as generating employment for socio-economic development of the country.

2.3.3.6: Adhesives for finger-jointing

Generally, any adhesive suitable for bonding wood technically could also be used for bonding finger joints. However, there are certain factors that limit choices of the various adhesives. Some of such factors include intended use of products, mechanical and physical properties, rate of bonding, curing method available, cost, and colour of adhesive. Moreover, in each situation, not all the factors are considered, but there is always a factor(s) that overrides the others (Jokerst, 1981). Meanwhile, the performance (strength) of any adhesive is determined by the adhesion of the polymers to wood and the cohesive strength of the polymers (Lijun & Allan, 2001). Choice of adhesive for finger-jointing can therefore be made from a number of adhesives that are being used to bond wood for various purposes. These include; resorcinol resins, phenol-resorcinol resins, melamine resins, melamine area resins, polyvnyl resins emulsions, and thermosetting polyvinyl emulsions (General Technical Report FPL-GTR-190; Jokerst 1981; Lijin & Allan, 2001). However, Jokerst (1981) contends that, usually if there is one limiting overriding factor, the choice becomes automatic.

However, the adhesives commonly used in finger-jointing wood products are phenol-resorcinol, resorcinol, melamine, melamine urea, urea and both thermosetting and thermoplastic polyvinyl acetate adhesives (PVAs) (Jokerst 1981; Lijun & Allan 2001). But the melamine-urea, urea and the PVAs are used only in non-structural applications. These adhesives are synthetic resins and are divided into two categories – thermosetting and thermoplastics. The thermoplastic ones never harden permanently but soften or melt at high temperatures and harden again when cooled, but the reversible process is without any chemical reaction. The thermosetting resins however, undergo irreversible chemical reactions either at room or at elevated temperatures to develop their strength and weather durability. Hence, after this reaction has occurred, the resin cannot be dissolved or again melted without degradation (General Technical Report FPL-GTR – 190; Jokerst 1981, Lijun & Allan 2001). Moreover, in finger-jointing green wood, Green Weld and Soy Bond could also be used (Mantanis et al., 2010).

Meanwhile, in Ghana (Kumasi city in particular), observations made in some finger-jointing facilities indicate that the most commonly used adhesive is the Polyvinyl Acetate types (PVA‟s).

2.3.3.6.1: Types and behaviour of polyvinyl acetate adhesives (PVAs).

Two major groups of the PVAs exist, namely; polyvinyl resin emulsion and thermosetting polyvinyl (also called cross-linked polyvinyl acetate) emulsion (Lijun & Allan, 2001).

The polyvinyl acetate (PVA) emulsion is one of the non-structural types used most commonly in furniture, flush doors, plastic laminates, panellized floor and wall systems in manufactured housing and other wood products manufacturing (Lijun & Allan, 2001). It is described as general purpose interior glue. This glue has several advantages, including; low cost, ease of use, simplicity of application and minimal harmful environmental effects (Lijun & Allan, 2001). These advantages notwithstanding, the structural characteristics of PVAs give rise to inherent weaknesses like poor heat and creep resistance. The acetyl groups can be partially hydrolysed to hydroxyl groups relatively easily in water or a high humidity environment. When applied to wood, the acetyl and hydroxyl groups do not form covalent links to the component of timber but their interaction is through secondary forces. This shortcoming allows water molecules to easily penetrate into the wood-PVA interface through the adhesive layer and through the wood, leading to softening of the adhesive and reduced adhesive and cohesive strengths (General Technical Report FPL-GTR – 190; Lijun & Allan, 2001).

The thermosetting (cross-linked) polyvinyl acetate emulsion, on the other hand, is also identified as catalyzed PVA emulsions, and they are modified types that include copolymers capable of cross-linking with a separate catalyst which is also white to tan in colour and forms colourless bondline. This type of PVA cures at room temperature or elevated temperature in hot and radio-frequency presses (Lijun & Allan, 2001). However, room temperature cure of these adhesives does not always develop their full potential for resistance to creep, heat and moisture but they perform better than the ordinary PVAs particularly long-term performance in moist environment. As a result, they perform well in most non-structural interior and protected exterior uses like doors, mouldings and architectural woodworks (General Technical Report-FPL-GTR – 190; Lijun & Allan, 2001)

2.3.4: Manufacturing finger-jointed lumber.

According to Jokerst (1981), and Wengert (1998), five (5) basic steps exist in manufacturing finger-jointed lumber, namely; **1)** Selection and preparation of materials, **2)** Formation or cutting of joint profile, **3)** Application of adhesive, **4)** Assembling of joints, and **5)** Curing of the adhesive. However, according to the authors, there can be variations within these steps depending on the manufacturing system being used, but all are necessary and controllable in producing good joints. It is however, necessary to note that even under the most favourable conditions, strength of finger-joint will be lower than strength of clear wood, and therefore attention should be paid to such controllable factors throughout the processes. This is necessary to preventing additional unnecessary strength losses, or equally important, higher than expected variability in strength between joints (Jokerst, 1981).

2.3.4.1: Selection and preparation of materials

Developing quality finger-joints necessarily begins with selection and preparation of material to be end-jointed. It must be noted that no adhesive joint can be stronger than the wood being bonded and therefore only materials with potential to develop needed strength should be selected (Jokerst, 1981). As a result, joint profiles must be in normal, clear, and straight –grained wood of average or high density and at a moisture content (MC) between 6-17%, but depending on the adhesive type, this lower and upper limits of MC can be varied (Wengert, 1998; Jokerst, 1981).

2.3.4.2: Formation/cutting of finger-joint profiles

This stage involves the sizing of, at least, one edge of the wood components to serve as a reference surface/plane. The ends to be jointed should be squared by a trimming saw before the woods are passed on to the profile cutter heads to cut the finger profiles. But in the trimming and profile cutting processes, the wood should be well clamped in position to avoid wabbling which can affect the profile and the subsequent strength of the joint (Wengert, 1998; Jokerst, 1981). Meanwhile, according to Jokerst (1981), there are essentially three methods used to form finger-joint profiles and they include the use of; cutting tools, dies, and both cutting tools and dies. However, the use of cutting tools is the most common method.

2.3.4.3: Application of adhesives

According to Jokerst (1981), several methods exist for the application of adhesives onto the surfaces to be jointed. These methods include; spraying, brushing, use of extruder nozzle, dipping, and use of mechanical applicator (a common type which is a revolving metal drum with the same surface shapes as the cut fingers or profiles). In sighted literature, (Ayarkwa et al., 2000b; Mantanis et al., 2010; Vrazel & Sellers, 2004) have used brush method in their studies of finger-jointed lumber strength, where as Bustos et al. (2003a), Bustos et al. (2003b) and Bustos et al. (2004) also used mechanical applicators. Moreover, He et al. (2012) used the spraying method. It is however necessary to note that none of these systems or methods of adhesives applications is completely satisfactory (Jokerst, 1981).

2.3.4.4: Finger-joints assembly

Assembly of the joints is the alignment of the joints‟ component members and applying mating or end pressure to fix the joint. Meanwhile, the process of applying pressure in finger-jointing, according to Jokerst (1981), involves several available systems or methods. The methods include; **1)** the crowder system where pressure is applied by having the in-feed mechanism in the bonding or curing area moving at a faster rate than the out-feed end of the line. This system is often used if materials being joined continue to move as they pass through a heating system (Radio frequency – RF – curing tunnel), **2)** Another system is the stop - and – go system where there is one stationary clamp and one movable clamp. The stationary clamp grabs onto a piece on one side of the joint and holds it in place while the movable clamp grips the piece on the opposite side of the joint and moves forward, forcing the two halves together. The author however, asserts that regardless of how pressure is applied, it is important to keep it at sufficient magnitude to force the two halves tightly together, and the pieces guided to be properly aligned while the adhesive cures.

The required magnitude of pressure, according to Jokerst (1981), depends on the viscosity of the glue and the quality of fitting of the fingers. The pressure level also depends on; the density of the wood species concern, the finger profile and whether the species are soft or hardwoods. For instance, the German standard DIN 68 – 140 (1971) provides minimum pressures for finger length of 10mm to be 120kg/cm^2 , finger length of 60mm to be 20kg/cm^2 but states that in no case should the end pressure be less than 10kg/cm^2. However, Jokerst (1981) states that information in literature on amount and duration of pressure required to form strong well-bonded joints is confusing and at times contradictory, possibly due to the numerous determining factors. These findings appear to be corroborated by Bustos et al. (2003b) who worked on black spruce wood and found that the end pressure affects joint strength and the suitable pressure for the species is 3.43Mpa (498Psi), while Bustos et al. (2004) re-affirmed this. Castro and Paganini (1997) worked on finger-jointed *Poplar* wood species and also concluded that pressure affects joints strength, and the optimum assembly pressure was found to be lower than what was spelt out in German standard DIN 68-140 (1971) by about one-third (⅓), and hence concluded that, higher pressures results in poor mechanical performance of the joint.

In Ghana, however, the effects of end pressure has also been studied. Ayarkwa et al. (2000b) worked on the effects of end-pressure on finger-jointed lumber of three Ghanaian hardwood species but found that, it has no significant effect on the MOE and MOR of the finger-jointed lumber. This finding seems somehow contradictory to that of Castro and Paganini (1997), thereby affirming the position of Jokerst, (1981) that the effect of the amount and duration of end-pressure on finger-jointed lumber performance seems confusing and indeed, contradictory.

2.3.4.5: Curing the adhesive

Adhesive curing, which is the final stage in manufacturing finger-joint, may occur at room temperature or may need some amount of heat, depending on the type of adhesive used and the end use requirement of the product (Jokerst, 1981; Tsoumis 1991). The heat application greatly reduces the curing time of the adhesive. However, not all the systems used for finger-jointing involve a heating system (Jokerst, 1981). For instance, the mini-joint system and also in a situation where a high pressure is used, for 2 to 3 seconds, the frictional forces developed in the joint are high enough to hold the two halves together well enough for machining even as the adhesive continue to cure.

The heating system of curing adhesives in finger-jointing can be applied either; before gluing (also called residual or stored heat gluing), or after application of the glue/adhesive. However, it should be noted that, applying heat before gluing limits time of pressure application and can also reduce some limitations associated with wood MC at time of gluing (Jokerst, 1981). However, Jokerst (1981), asserts that applying heat to a joint after gluing is more flexible than the stored heat method but the equipment for it is expensive to buy, operate and maintain. Meanwhile, regarding curing time, Jokerst (1981) recommended a minimum of 8hrs stockpiling (stacking) of formed joints before use. However, according to the author, this duration is dependent on the adhesive type. These findings and recommendations appear to be consistent with other ones. For instance, Ayarkwa (2000a) used over 48hrs in line with the glue manufacturer‟s instructions to cure adhesive at 30^0C. Also, Lang and Hassler (2007) used a maximum of 24hrs, whereas Mantanis et al. (2010) used 8 weeks due to the moisture levels (MCs) of the wood components involved and the glue type. Hence, enough time is needed to cure the adhesive before machining or use, but the duration is dependent on the adhesive type and MC levels.

2.3.5: Structure of Ghana's wood products industries and finger-jointing

Ghana‟s wood products industries (WPIs) are dominated by sawn wood, manufactured boards and profiled and machined timber (including finger-jointed timber). However, in 2003, four main product groups, namely sawn timber, veneer, plywood and further processed lumber (which include finger-jointed lumber mouldings) were exported. While sawn lumber exports stood at 45%, plywood stood at 15% and veneer stood at 24%, the processed lumber had 9% with others (such as furniture, dowel, broom stick etc.) obtaining 7% of total quantity of wood products exported from Ghana within the year (Asumadu, 2004; Sools et al., 2003). However, it is reported that there has been the realization within the industry that, they cannot expand by simply extracting more trees owing to the diminishing resource base (Asumadu, 2004). Meanwhile, expansion could be achieved through efficient use of harvested wood by minimizing waste and utilizing off-cuts in further processing to provide shaped and machined mouldings, flooring, furniture components, dowels and similar value-added products for exports (Asumadu, 2004; Sools et al., 2003). This realization could possibly be the reason for the increase in the number of WPIs engaged in further processing of wood to profiled and machined lumber from 37, out of 200 in 2002 to 41 out of the 200 in 2005 (Asumadu 2004; Timber Industry Development Division -TIDD 2002). Unfortunately by 2010, the number of companies that engages in further processed wood manufacturing has reduced to 27 (TIDD, 2006; 2007; 2008; 2009; 2010), possibly due to lack of raw materials (timber) resulting from the dwindling timber resource base.

In the face of the dwindling wood raw material resource supply, it is heart warming and encouraging to note from Pleydell (1994) that the over 25 wood processing firms engaged in the production and export of processed lumber and mouldings have the capacity to produce a wide variety of mouldings and profiled boards. These machined wood products are reported to be made from very wide range of about 28 – 36 wood species (TIDD, 2005-2010). The notable species, in general, include mixed redwoods, wawa, koto/kyere, ofram, niangon, essa, odum, sapele, denya, papao etc. (Pleydell, 1994).

2.4: Anatomical Structures/Characteristics of Wood

According to Shmulsky and Jones (2011), during wood formation, numerous factors, inside and outside the tree lead to variations in the type, number, size, shape, physical structure and chemical composition of the wood elements. Thus, wood quality is the arbitrary classification of these variations in the wood elements when they are counted, measured, weighed, analyzed or evaluated for some specific purpose. The beauty and complexity of wood are found in the interrelationship between these different cells. As a result, these cells provide all the macroscopic properties of wood such as density, hardness, bending strength among others (Desch & Dinwoodie, 1996). Moreover, the interrelationship between the cells and the macroscopic properties are based on both chemical and anatomical details of wood structure (Wiedenhoeft & Miller, 2005).

Meanwhile, due to genetic, systematic, environmental factors and presence of defects, there are variabilities in both the chemical and anatomical details of wood within same tree (horizontal and vertical variations), among trees of same species, and among different species (Dinwoodie, 2010; Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005). Therefore, according to Desch and Dinwoodie (1996), in the utilization of timber, possibly one single most important factor detracting from its outstanding performance as a material is its variability. In view of this, in all applications of timber, whether in furniture production, housing construction among others, some quantities and species of wood are rejected on grounds that they are different in appearance, behave differently during machining, or behave differently under load.

Moreover, between stem and branches, it is reported that, wood of the main stems also varies from wood of the branches (Dinwoodie, 2010; Shmulsky & Jones, 2011). Unlike softwoods, the branchwood of hardwoods generally have higher density than stemwood of same species, but could also range from lesser in some species to the same or higher in other species (Shmulsky & Jones, 2011). Additionally, there are many vessels and rays but less fibres in branchwood than in stemwood. The lumen diameter of braanchwood vessels and fibres are smaller than those of stemwood arising from the relatively slower rate of growth of branches than the main stem of trees. Additionally, vessel elements and fibre lengths are generally shorter and narrower in branchwood than in stemwood of same species (Dinwoodie, 2010; Shmulsky & Jones, 2011). Again, it is important to note that, in some wood species, branchwood fibre length can increase from the base to a certain point, and then decrease gradually towards the top where it is generally at the minimum (Tsoumis, 1991). It is also reported that, essentially, the anatomical details of stem and branch woods of same species are species dependent (Desch & Dinwoodie, 1996; Shmulsky & Jones, 2011).

It is worthy to acknowledge that the anatomy of the stemwood of the species selected for this study has been well investigated. *Entandrophragma cylindricum* has been found to have vessel density of 5-20 per mm^2 cross sectional area, vessel lumen diameter of 90-200µm, fibre length of 690-2005µm, and rays to be 4-12 per tangential mm (Kémeuzé, 2008; Richter & Dallwitz, 2000). *Entandrophragma angolense* also has vessel density of 2-20 per mm^2 cross sectional area, vessel lumen diameter of 45-220µm, fibre length of 960-2225µm, and 2-12 rays per tangential mm (Richter & Dallwitz, 2000; Tchinda, 2008). *Khaya ivorensis* also possesses vessel density of 2-20 per mm^2 cross sectional area, vessel lumen diameter of 80-245µm, fibre length of 90-1650µm, and 4-12 rays per tangential mm (Lemmens, 2008; Richter & Dallwitz, 2000). *Terminalia superba* has vessel density of 3-20 per mm^2 cross sectional area, vessel lumen diameter of 70-300µm, fibre length of 550-1998µm, and 4-15rays per tangential mm (Kimpouni, 2009; Richter & Dallwitz, 2000). Finally, *Pterygota macrocarpa* also possesses vessel density of 1-20 per mm^2 cross sectional area, vessel lumen diameter of 95-240µm, fibre length of 1265-2780µm, and 3-12 rays per tangential mm (Oyen, 2008; Richter & Dallwitz, 2000).

Meanwhile, no literature on any Ghanaian hardwood branchwood anatomy has been sighted. It could be for this reason that Okai (2002) recommended for some anatomical studies to be conducted on hardwood branchwoods in comparison with their stemwood counterparts. In the light of these, and in seeking to promote efficient utilization of wood (while focusing on branchwood and stem off-cuts utilization), it is only essential that knowledge of some anatomical features and their relationships with density, natural durability and bending strength are established. This will not only add to existing knowledge but will also provide current knowledge on stem (off-cuts) anatomy and new knowledge on branchwood of the selected Ghanaian tropical hardwoods, as well as how those anatomical features relate with some properties of the wood.

2.4.1: Wood anatomical characteristics and wood natural durability

The natural flow paths (vessels, resin canals, pits etc.), inorganic mineral deposits and presence or absence of tyloses in wood influence the permeability and consequently contribute to wood durability (Ncube, 2010; Shmulsky & Jones, 2011; Skadsen, 2007). This is because, biodegrading agents of wood usually colonise wood through the natural flow paths (Eaton & Hale, 1993; Ncube, 2010), but presence of tyloses and mineral deposits (especially silica) may render wood impermeable (Panshin & de Zeeuw, 1980). This is because the tyloses block the pits to disallow moisture flow, while the minerals also occupy a sizeable portion of the lumen and cell walls, thereby preventing easy diffusion of gases or moisture (which are needed for respiration and growth of biodeterogens) through the cell walls (Ncube, 2010). These situations therefore make it uneasy for most microorganisms to get into the wood to cause decay since the moisture in wood will continue to be relatively low and therefore presents an unconducive atmosphere for growth and other activities of the organisms that cause decay. For example, closure of pits and pores by tyloses in white oaks (e.g. *Quercus robur*) renders the species impermeable, and silica content of 0.5% or more can impart decay resistance e.g. as in woods like Dialum Spp. (Eaton & Hale, 1993). The silica deposits alter wood moisture holding capacity which impedes wetting and consequently make the wood resistant to microorganism‟s colonization and activities since low moisture contents is generally unsuitable for decay (Eaton & Hale, 1993).

In Ghana, however, some correlations of anatomical features and density, and natural durability have been found. Antwi-Boasiako and Atta-Obeng (2009) found that higher proportion of fibres in wood (lower vessel-fibre ratio) leads to higher density and higher natural durability of wood. In another way, higher vessel-fibre ratio which implies more vessels in wood lead to lower density and lower natural durability.

2.4.2: Wood anatomical characteristics and wood density

It is reported that wood structure determines its density. Thus, density increases as the proportion of cells with thick cell walls increases. However, in hardwoods, density does not only depend on fibre wall thickness but also on the amount of void spaces occupied by vessels and parenchyma cells. Therefore, when vessels are of large diameter and there is abundance of axial and ray parenchyma with thin walled fibres, density is low (Shmulsky & Jones, 2011). But when fibres are thick walled and are in abundance relative to vessels and parenchyma, density is high (Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005). In view of this, density can be used to estimate the proportion of void volume in the wood since they are directly related (Shmulsky & Jones, 2011). Since the void volume is also related to leachability of toxic compounds (extractives) in wood, density also correlates with natural durability of wood (Shmulsky & Jones, 2011).

In Ghana, the most current and sighted study on the relationship of density and natural durability is that of Antwi-Boasiako and Pitman (2009). In this study, the authors found that density correlates positively with natural durability of the species studied. Thus the author concluded that generally, high density woods are durable and vice versa.

2.4.3: Wood anatomical characteristics and bending strength

According to Tsoumis (1991), in hardwoods generally, the latewood are of relatively higher mechanical strength than the earlywood. However, the author assertes that, cellular characteristics are the fundamental factors that affect wood mechanical properties, but an admission was also made to the effect that the correlations of cellular features and mechanical or strength properties are rare in literature. Meanwhile, it is reported that, bending strength is related to proportion of fibres, distribution of soft elements, and the aggregation of vessels (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011;). Moreover, the ultrastructure of wood has also been found to play very essential role in determining the mechanical strength of wood. For instance, large microfibril angle of the S_2 layer is reported to cause low strength of wood (Dinwoodie, 2010; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011).

In Ghana, however, it appears some correlation of anatomical features and bending strength have been found. Antwi-Boasiako and Atta-Obeng (2009) found that higher proportion of fibres in wood (lower vesse-fibre ratio) leads to higher density. However, generally, high density woods are relatively strong, and therefore, it could be inferred that there is a positive correlation between vessel-fibre ratio and strength properties of wood. This thereby affirms that higher proportion of cells with thick walls like fibres, make wood dense and provides for the wood higher mechanical strengths, including bending –MOE and MOR (Shmulsky & Jones, 2011; Skadsen, 2007; Wiedenhoeft & Miller, 2005).

CHAPTER THREE

MATERIALS AND METHODS

3.1: Materials

Branch and stem (off-cuts) materials of five **(5)** Ghanaian hardwood species, namely; *Entandrophragma angolense* (edinam), *Khaya ivorensis* (mahogany), *Entandrophragma cylindricum* (sapele), *Terminalia superba* (ofram), and *Pterygota macrocarpa* (koto/kyere) were used for this study. Selection of the species was based on the threat of their extinction and their use for furniture and mouldings (including finger-jointed lumber) production in Ghana (Amoah et al., 2012; Asumadu, 2004; TIDD, 2005; 2006; 2007; 2008; 2009; 2010).

Two trees of each species were sampled and used for this study with one tree each taken from a different forest reserve lying in a different ecological zone. The number of sites (ecological zones) and the selection of the sites themselves as well as the particular trees of the five species were dictated by the firm from whose concessions the materials were obtained (Logs and Lumber Ltd.). From each of the two trees of each species, two sound branch logs without any visible defects were taken from first (main branch) and the third branch (counting from the main branch) of felled trees. Sampling of branch logs at different positions on each tree, and from different forest reserves was done to ensure that test results will represent the species to some general extent by minimizing undue disparities arising from ecological or climatic (sites) conditions as well as diameter differences as has been reported by many authors (Antwi-Boasiako & Pitman 2009; Cookson, 2004; Morris et al., 2011a, 2011b; Ncube, 2010; Shmulsky and Jones 2011). Therefore, four branch logs of each species totalling 20 branch logs (i.e. 4 logs x 5 species) were extracted from the forests, converted and used for the various tests in this study.

The diameters of the branch logs ranged from 26cm to 52cm with lengths ranging from 2m to 2.5m. The Diameter at Breast Height (DBH) of the trees from which branch logs were extracted averaged; 120cm for sapele, 108cm for edinam, 112cm for mahogany, 96cm for ofram and 76 for koto. The sampling of these reserves and zones were however influenced by the study company-Logs and Lumber Ltd"s (LLL) forest section management since entry into the reserves was based on their agreement and work schedules. However, the main criteria for inclusion of a particular branch, on a tree, in the sample were straightness, absence of dead knots, and absence of any obvious or visible decay.

3.1.1: Materials collection sites (study areas)

In all, logging residue samples (i.e. stem off-cuts and branch logs) were extracted from four (4) forest reserves which are lying in three (3) different ecological zones in Ghana. Figure 3.1 indicates the four reserves (arrowed) in Ghana that were used as the study sites/areas and from where the logging residues used for this study were extracted. Data on merchantable residues left in the forest were also collected from these same sites/reserves.

These four forest reserves (arrowed in Figure 3.1) included: Asukawkaw reserve (arrowed as 1), located at Nkawkaw in the Eastern Region and which is a Moist Semi-Deciduous (South-East type- MSD-SE) forest and lying within the boundaries of longitude 1^0 0^0 and 0^0 0^0 W, and latitude 6^0 0^0 and 7^0 0^0 N; Abonyere, and Bosambepo reserves (arrowed as 2a and 2b respectively) which are all located at Akordie in the Brong-Ahafo Region, and are Moist Semi-Deciduous North-West forest types (MSD-NW) lying within the boundaries of longitude 2^0 0^0 and 3^0 0^0 W, and latitude 7^0 0^0 and 8^0 0^0 N.

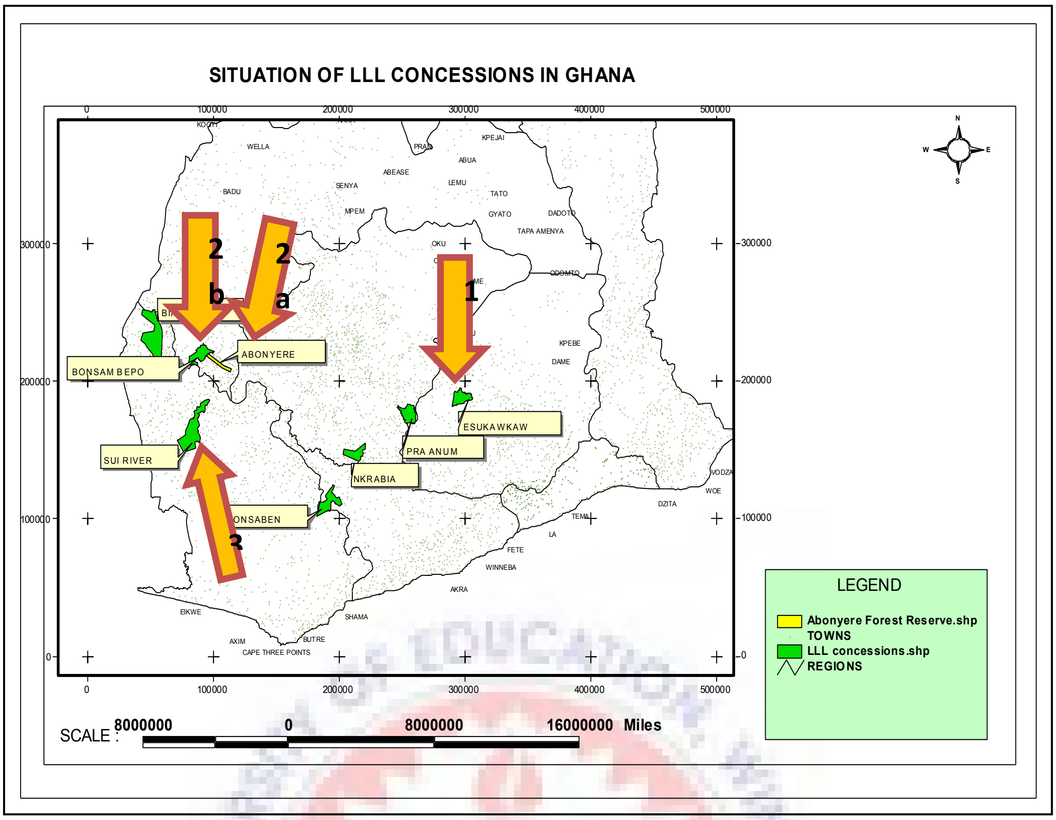


Figure 3.1: **A section of Ghana map indicating the study areas/sites,** (**1**=Esukawkaw, **2a**=Abonyere, **2b**=Bonsambepo, and **3**= Sui river). **Source:** Abeney et al. (2012-unpublished).

The final reserve was Suii river (arrowed as 3) located at Sefwi Wiawso in the Western Region – a Moist Evergreen (ME) zone forest lying within the boundaries of longitude 2^0 0^0 and 3^0 0^0 W and latitude 6^0 0^0 and 7^0 0^0 N (MLNR, 2012; Abeney et. al., 2012). The range of annual temperature and precipitation of the 3 sites were 23.9-26.9°C and 1200-1400mm; 24.3-27.8°C and 1400-1600mm; and 24.5-28.2°C and 1600-1800mm respectively for site 1, 2 and 3 (Logah, Obuobie, Ofori, Kankam-Yeboah, 2013). However, the ecological zones where the forest reserves are located are arrowed in an ecological map of Ghana (Appendix 1). These reserves were all concessions of the study company-LLL. Moreover, the 4 reserves are located in three (3) administrative regions, namely Eastern, Western and Brong-Ahafo Regions which form about 60% of the 5 main regions that have forest reserves and they also possess about 71.62% of total forest estate of Ghana (Antwi, 1999).

3.1.2: Materials preparation sites and procedures

All the extracted branch logs were conveyed to LLL factory for conversion. The same bandmills (called BOSTKA) used for stem logs conversions in the company were used for the conversion of the branch logs. Figure 3.2 shows a branch log being converted on one of the bandmills at LLL.

The logs were initially processed into rough lumber boards of 65mm thickness with varied widths and to the lengths of the logs. Both through- and-through and quarter sawn methods were employed during the conversion. Okai (2002) used a horizontal mobile bandmill (woodmizer) for converting branch logs into boards.

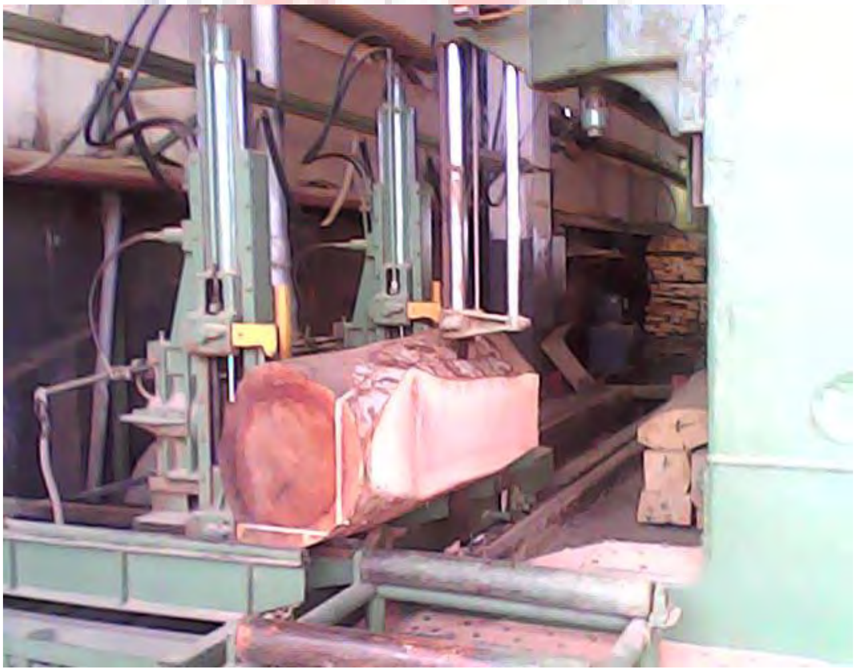
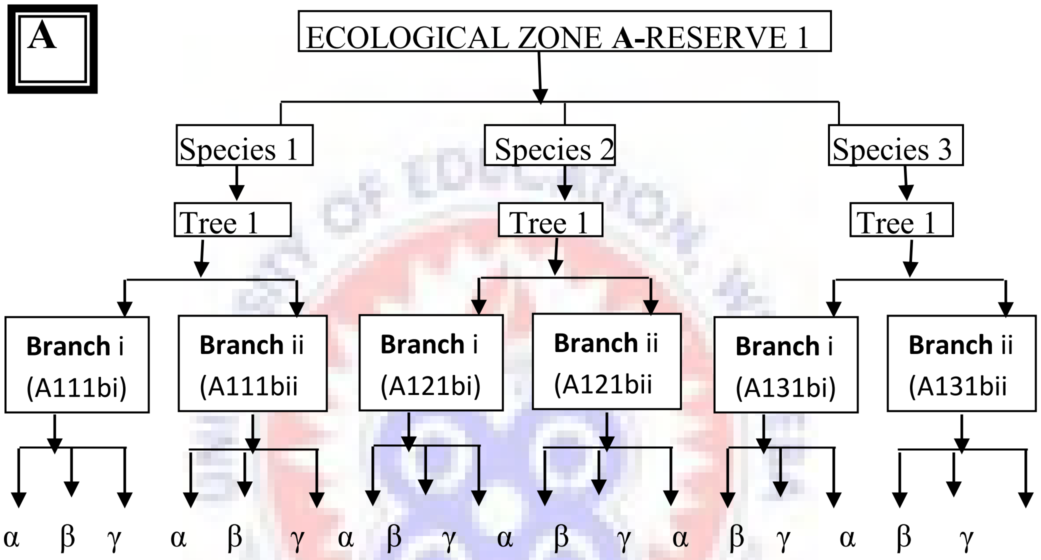
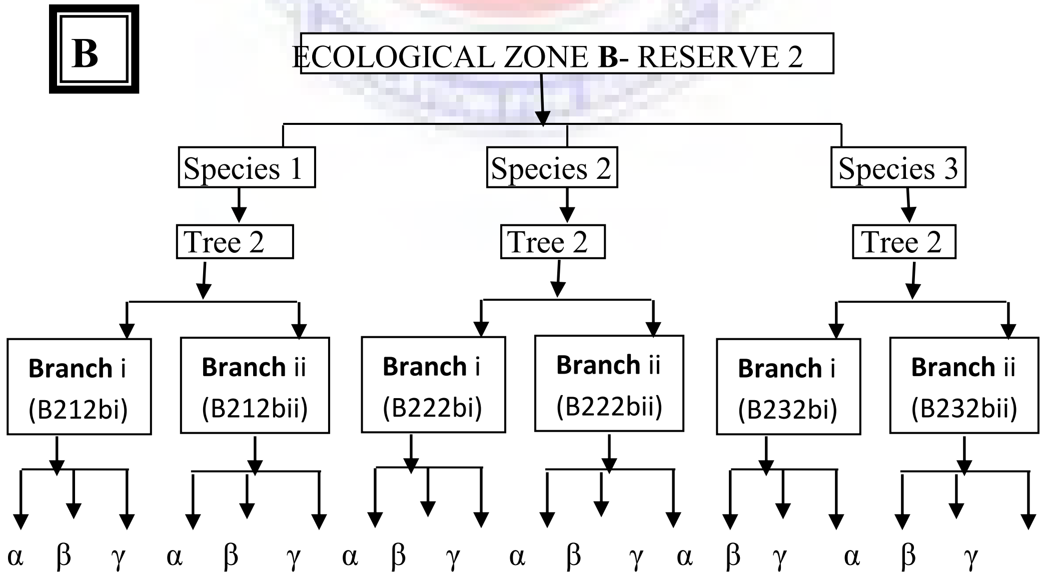


Figure 3.2: Branch log being converted to lumber boards on a bandmill at LLL.

After the conversion of logs, both branch and stem wood boards were resawn and crosscut to dimensions of 65mm x 65mm cross section and 420mm long after which they were grouped and provided with identification marks according to species, wood type (i.e. stem or branch) and the reserves from which they were obtained. Then after, clear defect-free samples among them were selected and randomly grouped according to the various tests (objectives) of this study. All wood detected to have fuzzy grains/surface (which is an evidence of reaction/tension wood- Desch & Dinwoodie, 1996) were rejected. Figure 3.3 (**A-D**) show how the branch and stem woods from the various reserves and species were grouped (i.e. **A** and **B** representing sapele, edinam, and mahogany, whereas **C** and **D** are for koto and ofram).





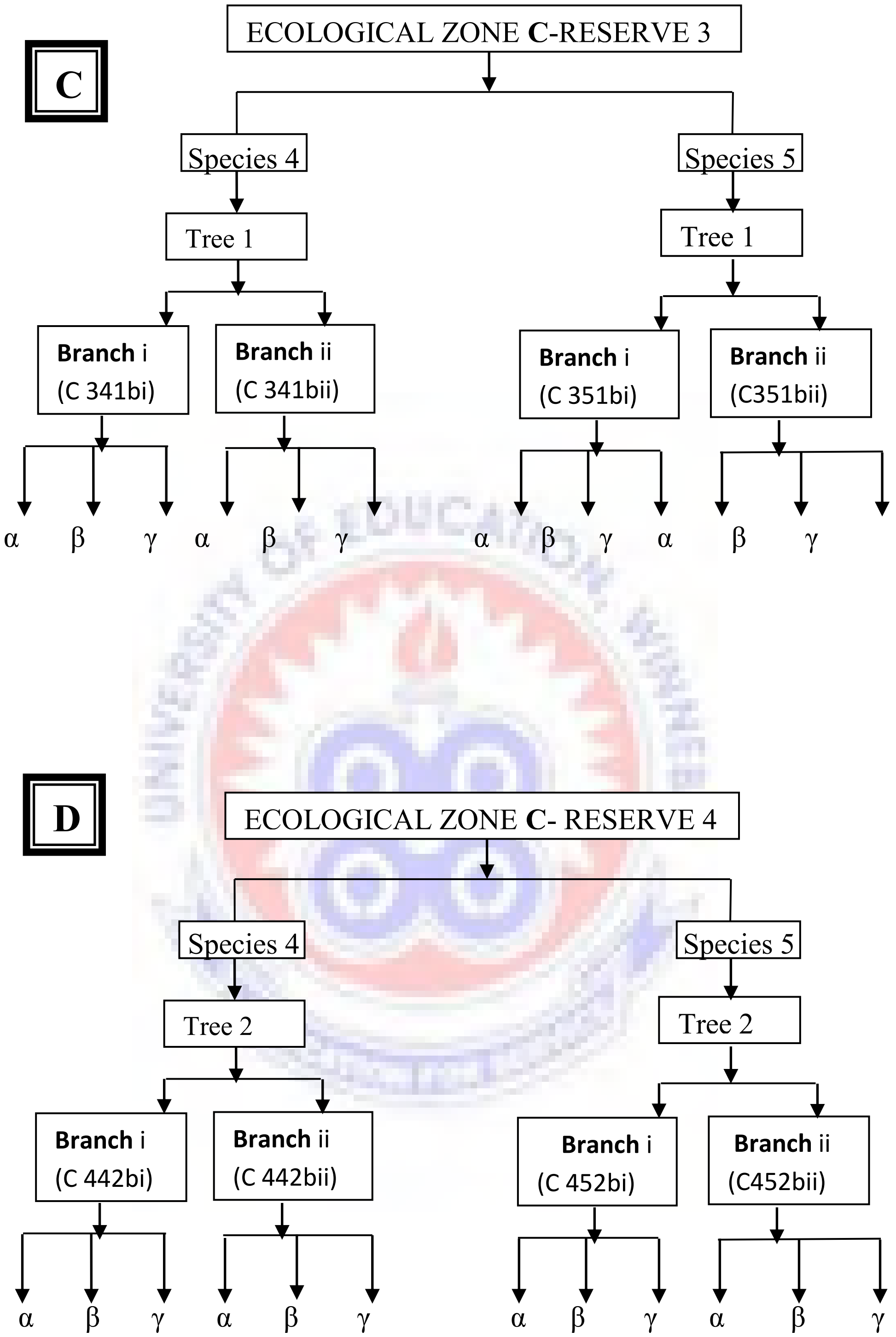


Figure 3.3: Groupings of branch and stem woods from the various reserves for the various tests. **A** and **B** were for sapele, edinam, and mahogany, and **C** and **D** were for koto and ofram.

NOTE: From Figure 3.3; Sample group **α** represents those used for natural durability test, **β** represents those used for bending strength tests (both unjointed and finger-jointing lumber), and **γ** represents those samples used for anatomical features studies.

3.1.3: Final test samples' preparation site

After convertion and initial preparations, all sample groups were conveyed from LLL to Kumasi Polytechnic for processing and subsequent commencement of the various tests. Each sample group was prepared to different dimensions in accordance with specifications in the standard or protocol used for each particular test. This final sample preparation took place at the workshops of the Department of Interior Architecture and Furniture Production of Kumasi Polytechnic. This department has adequate machinery that enabled accurate preparations of the final specimens.

3.1.4: Natural durability test site

The site (i.e. the graveyard) for field testing of natural durability of the stem and branch woods was a demarcated termites prone area in the farms of Kwame Nkrumah University of Science and Technology in Kumasi. It is a site used for such studies by students and staff of the University.

Meanwhile, it is reported that Kumasi is located in the transitional forest zone (moist semi-deciduous South-East Ecological Zone) and within latitude $6.35^0 – 6.40^0$ N and longitude $1.30^0 – 1.35^0$ E, and has an elevation ranging from 250 – 300 metres above sea level. Temperature ranges from 21.5°c to 30.7°c, with humidity of about 84.16% at 0900 GMT and 60% at 1500 GMT. The city has a double maximum rainfall regime (214.3mm in June and 165.2mm in September) which has direct effect on soil organisms" activities and agriculture (Ministry of Local Government and Rural Development and Maks Publications & Media Services, 2006; Ministry of Food and Agriculture, 2013). Kumi-woode (1996) also asserts that, Kumasi generally has a high decay index with a very high decay hazard and the author describes the soil of the test area as that of medium to fine texture with pore spaces varying from 40 – 60% and which is a home to a lot of termitarian mounts.

Before the conduct of the test at this site, the site was a farm scrub that has previously been cultivated and abandoned making it easy for access and preparation for the test. Figure 3.4 shows a map of KNUST indicating the test site.

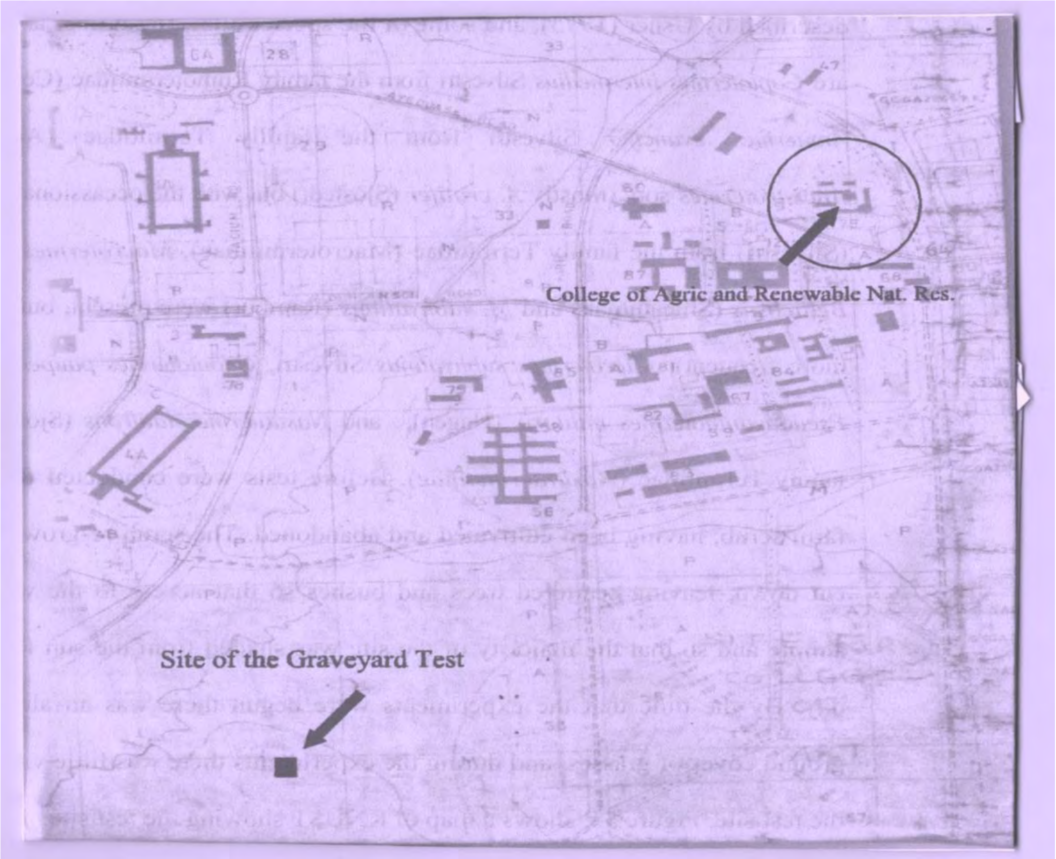


Figure 3.4: Site map of KNUST indicating the location of the graveyard test site. Source: University master plan G.50 in Quartey (2009).

3.1.5: Anatomical study and bending strength tests sites

The anatomical study and bending strength tests were carried out at the Forestry Research Instittute of Ghana (FORIG), Fumesua-Kumasi, specifically at the Wood Anatomy and Timber Engineering Laboratories respectively. FORIG has some standard machinery and equipment, namely; microtome for sectioning and microscopes with software that aided the microscopic study of some anatomical details of stem and branch wood. It also has INSTRON TCM Universal testing machine which has a computerised system to record all data about test conditions (i.e. temperature, relative humidity, crosshead speed etc.) and about the test sample and test results (i.e. sample dimensions, deflection, maximum load, moduli of elasticity and rupture etc.) and can be used for testing mechanical properties of materials.

3.1.6: Site for finger-jointed lumber production

The Finger-jointed lumber of various combinations of stem off-cuts and branch wood were produced in the company used for this study (i.e. Logs and Lumber Ltd.-LLL The company is located at Asokwa (a suburb of Kumasi) off Lake Bosomtwi road and directly opposite CONSAR‟s main office which is close to the new Asokwa interchange. LLL is a Private Limited Liability Company incorporated on 17th June 1967 as a Free Zone Enterprise and is currently one of the leading timber logging and processing companies in Ghana and the West African Sub-Region (Web4uGhana Design, 2010). The company draws its strength from the significantly adequate machinery and equipment and it is also one of the leading producers of finger-jointed lumber in Ghana. Since 2007, the company has been the leader in the production and export of processed lumber or mouldings, including finger-jointed ones (TIDD, 2007; 2008; 2009; 2010).

3.2: Methods

3.2.1: Above-stump merchantable wood quantities/volumes.

Above stump total merchantable residues (TMR) were classified into 3 groups as stem butt-end off-cuts (sbt), crown-end off-cuts (scr) and branches (bch). The stem butt-end (sbt) and stem crown-end off-cuts (scr) were put together as stem off-cuts (sof) . Hence TMR = (sof+bch).

Data was collected on only the stem off-cuts and branch logs of matured, felled and hauled trees that were considered merchantable for lumber production. Shmulsky and Jones (2011) and Gurau et al. (2008) described branches with 5cm diameter as normal branchwood. In Ghana, Amoah and Becker (2009) defined merchantable branch log as defect-free and straight log with diameter ≥ 20cm and length ≥100cm. But also in Ghana, Okai (2002) used branchwood of between 10cm and 25cm for studying the milling and strength properties of some tropical hardwood branchwood. Hence in this study, merchantable off-cuts and branches were considered to be any part of matured felled tree that has been left after normal commercial logging operations (i.e., after main stem has been extracted) and which has diameter ≥15cm and capable of being used for lumber production (at least for the local market and finger-jointed products). Sampling trees to acquire data on their stem off-cuts and branches were done randomly. Walks were taken along hauling paths and other routes in the forests to identify the trees through sighting of their stumps and their branches, and sometimes guided by the loggers to possibly get access to the trees‟ parts for measurements and data collection.

In all, a total of one hundred and fifty-four (**154**) trees comprising 20 species formed the total sample. Since this aspect of this study followed normal commercial logging operations, the species composition in the sample was influenced by the loggers‟ choice of species during felling. However, the loggers‟ choice of species were also dependent on their contractual obligations to buyers at the time. Pillsbury and Pryor (1989) have indicated that a sample size of 40 trees is normally satisfactory for estimating volumes of tree stems and their branches, and even for testing the adequacy of developed equations. Dean (2003) also used three (3) trees to calculate wood volume and stem taper of both stem and branch woods of *Eucalyptus regnans* species. In Ghanaian tropical forests, Eshun (2000) found that a total of 56 trees (with error of ± 10% at 95% confidence level) is adequate for quantifying logging residues. Also, Amoah and Becker (2009) used 135 timber trees (comprising 9 species) to acceptable predict stumpage volume of commercial species in Ghana.

The species covered in this aspect of this present study included: dahoma (*Piptadeniastrum africanum*), chenchen (*Antiaris toxicaria*), wawa (*Triplochiton scleroxylon*), essa (*Celtis mildbraedii*), edinam (*Entandrophragma angolense*), mahogany (*Khaya spp.*), sapele (*Entandrophragma cylindricum*), ofram (*Terminalia superba*), yaya (*Amphimas pterocarpoides*), onyina (*Ceiba pentandra*), danta (*Nesogordonia papaverifera*), denya (*Cylicodiscus gabunensis*), koto/kyere (*Pterygota macrocarpa*), Utile *(Entandrophragma utile)*, Albizia *(Albizia ferruginea)*, Iroko/odum *(Milicia excelsa),* Guarea *(Guarea spp.)*, Hyedua *(Guibortia ehie)*, Baku *(Terminalia heckelii)*, and Asanfena *(Anangera robuster)*. These species covered in this present study though included those covered by the previous studies (i.e. Amoah & Becker, 2009; Eshun, 2000) the only difference is that, this present study considered 3 different ecological/vegetation zones within 3 administrative units of Ghana and which were different from sites of the previous studies.

For each of the species covered, a total of from 2 to 26 trees were captured. This happened because some species are either scarce or virtually absent in some ecological zones as were also recorded in the previous studies (Amoah & Becker, 2009; Eshun, 2000). For instance, Amoah and Becker (2009) used for each species, from 1 to 57 trees in their study. Every available, identified and accessible merchantable stem off-cuts and branchwoods were measured. The branches that were identified but it became difficult to measure all of their parts due to the volume of foliage on them, those branches had their measurements estimated.

In this study, Diameter at Breast Height (DBH) was not of interest because, in the previous study by Amoah and Becker (2009), DBH was found to be a poor predictor variable for predicting total merchantable wood volume compared to using extracted log volume as the predictor variable. Altogether, extracted log volume was the variable of interest in this study. Therefore, DBHs were not taken for all the trees whose logging residues were quantified except for those whose branch logs and stem off-cuts were extracted for the various tests in this study.

3.2.2: Above-stump total merchantable wood volumes (TMWV) estimation

In this study, total merchantable wood volume (TMWV) refers to extracted log volume (ELV) plus total merchantable residue volume (TMRV). Hence *TMWV= TMRV+ ELV.*

In measuring the dimensions of branch and stem off-cut logs, two straight sticks of between 200cm and 240cm in length/height and a tape measure (measuring tape) were used for diameter and length measurements of all residues. Figure 3.5 shows pictures of how the measurements (i.e diameter over back, and length) were done. Lengths were measured at one side from just beneath one branch fork to the next with the tape measure (Figure 3.5 A). The two sticks were placed at two different opposite sides of each end of each identified merchantable off-cut or branch (Figure 3.5 B). The distances between these two sticks as they touch the two sides of the logs were measured and represented the diameter (over bark) of the logs. All diameters and lengths were measured to the nearest 0.1cm.

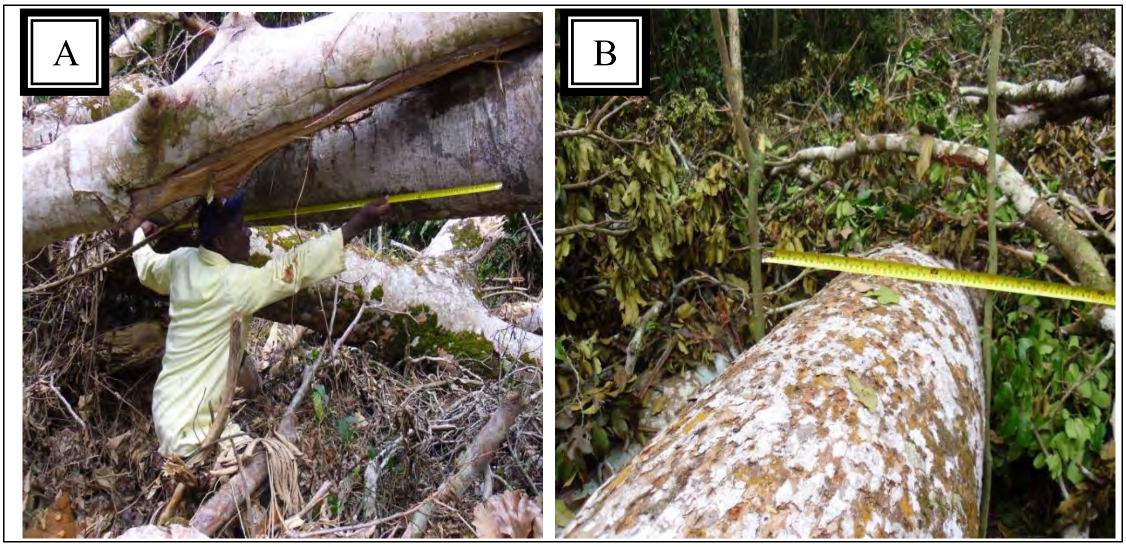


Figure 3.5: Pictures showing how diameters and lengths of branch and off-cuts were measured in the forests. (A and B = length and diameter measurement respectively).

Buttress protrusions were not considered as being merchantable for the production of lumber and finger-jointed lumber products as proposed by Eshun (2000), and therefore they were disregarded in the estimation of butt-end off-cuts‟‟ volumes. Consequently, butt-end off-cuts were considered to be of similar shape as the shapes of extracted main stem.

Smalian‟s equation/formula, **$V= (A_S + A_B) L/2$** was used to estimate the volumes of all residues. Where **V** = volume in cubic meters of log; **L** = length of log in meters; **A_B** = cross-sectional area of log at the large or base end in cm^2; **As** = Cross-sectional area of the log at the small end in cm^2, and **A** (in general) = **πr^2** (Briggs, 1994; Forest Products Management Development Institute, 1998). Smalian‟s formula has acceptably been used to estimate volume of all tree sections (except stumps) (Eshun, 2000). Though Smalian‟s formula overestimate stem logs by about 6%, it is considered relatively accurate among cubic scaling formulae (Patterson et al., 2007; Forest Products Management Development Institute, 1998).

1. Total Merchantable residue volume (TMRV)

TMRV of each tree and species comprised; 1) Total volume of stem off-cuts (TV_{sof}) which also consisted of volume of stem butt-end off-cuts (V_{sbt}) and volume of stem crown-end off-cuts (V_{scr}), and 2) Volume of branch logs (V_{bch}), of trees and species. i.e. **TMRV = TVsof + TVbch**

a. Volume of stem off-cuts (V_{sof})

For each tree, V_{sof} was determined by adding/combining the volume of stem butt-end off-cut (V_{sbt}) and volume of stem crown-end off-cuts (V_{scr}), **i.e.** $\mathbf{V_{sof} = V_{sbt}}$ + $\mathbf{V_{scr}}$**.** For both $\mathbf{V_{sbt}}$ and $\mathbf{V_{scr}}$, two diameters (at near right-angles to each other) were measured at the top end (where the first log was cut), and at the base end (where the tree was felled off the stump). The distance between the two ends was measured as the total length of each. Mean diameters for each end and the lengths were substituted into Smalian‟s formula to determine the volume for each tree. The total for each species was found as the sum of the volumes of each tree within the species. At instances where two diameters (at near right-angles to each other) at each end were not possible, one of that end‟s diameters was estimated and added as proposed by Dean (2003).

b. Volume of merchantable branchwood (Vbch)

Merchantable branch logs, in terms of suitability for lumber production, were considered to be branches without sweeps or crooks and also excluding the basal portions of branch forks (which are basically knots). As a result, measurements on branches were done in segments (short lengths or billets) for easy measurements and to avoid major natural defects (like curvature, sweeps, crooks etc. that can have influence on measurements) as done by Pillsbury and Pryor (1989).

For each tree within the sample, all merchantable branches with diameters equal to or greater than 15cm were measured. However, branches which were crushed due to movement and impact of falling of hauling equipment, were considered damaged and therefore not measured for volume estimation. Where necessary, for each branch segment, two diameter measurements (at near right-angles to each other) were taken at the base of the branch just above the fork and at the top, just before the next branching. The distances between these two points where diameters were taken, were measured as the length of the branch segment. All visible branches on each tree were measured, but in some cases, there were identified branches which were not accessible for measurements of two diameters at each end or full length owing to their locations and the volume of foliage that covered them. For such branches, those measurements were estimated and added as proposed by Dean (2003). The mean diameters at each end of each segment and the segments‟ lengths were then substituted into Smalian‟s formula to determine their volumes. Afterwards, volumes of all segments were tallied together as the volume of branchwood (**V_{bch}**) for the tree. The total branch volume (TV_{bch}) for each species was found as the sum of the volume of all trees within the species.

Although Pillsbury and Pryor (1989) measured branch segments to include the basal area of branch forks, because such areas are basically knots, they were not considered in this study as being part of merchantable branch log for lumber production. This is also because, knots reduce strength properties of wood and can also pose sawing difficulties like blunting of saws etc. (Shmulsky & Jones, 2011).

2. Volume of extracted log (main bole) -ELV

The utilised/extracted logs of almost all the trees whose branch logs and stem off-cuts were measured had already been conveyed from the forest to the factory site in Kumasi at the time of data collection. In view of this, among other difficulties, extracted log volume (**ELV**) for each tree was obtained from the company"s log loading yard records (otherwise called felling records) of the respective logging sites (reserves). This was done by using the stock survey numbers and species names recorded on the stumps of the trees to trace the trees and their volumes in the felling records. As a result, these volumes were the exact volumes of logs actually extracted by the company from the sampled trees and which were of much interest in this study. Only trees whose branches were accessible for measurements were traced for their respective extracted log volumes for analyses in this study. The ELV for each species was also found as the sum of the volumes of all trees within the species.

3.2.3: Merchantable wood data analyses

All the 154 sampled trees were used for analyses of TMRV (branchwood and stem off-cuts) and ELV from the three (3) sites/ecological zones. All the trees were also used in assessing wood harvesting efficiencies among the various timber species and among the 3 sites. Wood harvesting/logging efficiency was calculated as the ratio of the ELV to TMWV expressed in percentage {i.e. (ELV/TMWV) x 100%}-(Amoah & Becker, 2009; Shmulsky & Jones, 2011).

Both descriptive and inferential statistical analyses (comprising means, percentages and analysis of variance-ANOVA) using MS-excel 2003 and 2007 and SPSS 16.0 softwares were done to compare group means, determine significant differences among obtained values/results by sites and by species. Linear regression analyses were also done to establish the relationships between ELV and TMWV and

ELV and TMRV for individual species (species specific model) for the various ecological zones or study sites (site specific model), and for all species and sites together (mixed species and site model) to predict TMWV and TMRV using ELV as an indirect predictor variable. In these cases, the TMWV and TMRV per tree are directly proportional to the ELV per tree at the different sites, for the different species and also for all species. Equations 3.1 and 3.2 depict the relationship between ELV and TMWV, and ELV and TMRV respectively.

$$TMWV = \alpha\, ELV + C \qquad \text{---} \qquad 3.1$$

$$TMRV = \alpha\, ELV + C \qquad \text{---} \qquad 3.2$$

Where **α** indicates the quantum of increase/decrease in either TMWV or TMRV per $1m^3$ rise/fall in ELV and C is a constant { i.e. intercept indicating the value of TMWV or TMRV at situations where ELV is zero (0)}.

3.3: Natural Durability Test

It is recommended that field or graveyard test provides the true picture of the natural durability of wood in its real use environment and for that matter, aids a better prediction of the service life of wood (Brischke et.al., 2011). Hence, European Standard EN 252 -1989 with status of British standard (BS7282, 1990) in combination with percentage weight loss (Eaton & Hale, 1993; Nzokou et al., 2005) were adapted for the field test (i.e. soil block test) of natural durability of stemwood and branchwood of the five selected wood species. EN 252 provides for qualitative assessment of natural durability by visually rating the extent of attack or destruction of samples and it is measured on a 5-point visual rating scale as: 0=No attack; 1= Slight attack, 2=Moderate attack, 3=Severe attack and 4=Failure (completely destroyed). Percentage weight loss, on the other hand, is a quantitative assessment of natural durability based on the percentage difference between weight of samples before test and their weights after the test expressed in percentage and measured on a 4-point percentage scale as: 0–5 % loss = very durable, 6–10 % loss= durable, 11–40 % loss = moderately durable, and 41–100 % loss = non-durable (Nzokou et al., 2005; Eaton and Hale 1993). Thus, this study measured natural durability in two ways (i.e. percentage weight loss – quantitative approach, and visual rating of attack-qualitative approach).

It should be noted that the standard EN 252 is designed for determining the relative protective effectiveness of a wood preservative in ground contact and also for in-ground durability test for heartwood and sapwoods. Moreover, this standard has been recommended for use for natural durability test of wood and has acceptably been used by some researchers including Meyer, Brischke, & Pilgard (2012), Brischke et al. (2011), and Quartey (2009) for in-ground natural durability testing of wood.

3.3.1: Samples preparation for natural durability test

The rough sawn and selected clear wood samples of each of the two wood types of the five species under study (i.e branchwood and stem off-cut of the **α** groups in Figure 3.3) were prepared for the natural durability test. Samples for each species were regrouped into four groups using their identification marks (i.e. 2 groups of stem off-cuts and 2 groups of branchwood representing the two reserves/sites where they were extracted from). This was done to ensure that, for each specie, each sample group (stem off-cut and branchwood) has materials representing each site/forest reserve. The stem and branch woods representing each forest reserve were then regrouped into two (2) each, using their identification marks.

Following this, one group each of stem off-cuts and branch woods was allowed to air-dry to moisture content level of 14±2%MC (i.e. moisture content specified in EN 252-1989) and tagged as MC1 samples. The other one group each of stem off-cuts and brachwoods was kiln-dried in the kiln-dryers of LLL (at temperature and relative humidity conditions set and used by the company to dry its wood) to moisture content level of 9±3%MC (i.e. MC level used for kiln-dried and finger-jointed lumber production in Ghana) and tagged MC2 samples. Upon attainment of these MC levels, each of these groups of samples (MC1 and MC2 for both stem and branch woods) was finally prepared to dimensions of 250mm x 25mm x 12.5mm at Kumasi Polytechnic. Though the standard (EN 252, 1989) specifies sample dimensions of {(500 ± 1)mm x (50 ± 0.3)mm x (25 ± 0.3)mm} when measured at 14±2%MC and to be tested over a period of between 5 to 10 years, it also recommends and accepts modifications of the specifications.

For each of the groupings, 160 samples were used {(16 replicates of branchwood x 5 species) + (16 replicates of stemwood x 5 species)}. Thus for the 2 MC levels/drying types, a total of 320 study samples were used (i.e. 16 MC1 replicates and 16 MC2 ones for stem off-cuts for each of 5 species, and another 16 MC1 replicates and 16 MC2 ones for branchwood for each of the 5 species). Additional 32 samples of *Ceiba pentandra* (onyina) stemwood (i.e. 16 MC1 replicates and 16 MC2 ones), prepared to similar dimensions like the study samples, were used as reference materials. The standard (EN 252, 1989) specify ten (10) replicates of study samples, and so the 16 samples for each group as used in this present study was a modification which the standard recommends and accepts. This modification was done in order to have more samples to cover a relatively wider plot. Hence, an overall total of Three Hundred and Fifty-two (352) samples were used for this natural durability study which adapted EN 252 (1989) and percentage weight loss (Eaton & Hale, 1993; Nzokou et al., 2005).

However, it is important to note that, besides the fact that the standard (EN 252- 1989) used in this study recommends and accepts modifications, standard modifications have been acceptably done by previous researchers including Feuntes-Talavera et al., (2011) who modified EN 350-1 (CEN 1994) so as to use more samples with reduced dimensions (i.e. dimensions from standard of 2.5cm x 1.5cm x 5.0cm was modified to 2.5cm x 2.5cm x 1.0cm). Other researchers who have done similar modifications include Quartey (2009) and Quartey et al. (2008) who also modified this same standard (EN252) to similar dimensions as used in this current study and used 15 samples for each test group instead of 10 samples specified in the standard. The use of *Ceiba spp*.(onyina) as reference material has also been acceptably used by Balsundaran et al. (1985).

Again, the introduction of KD/MC2 (9±3%MC) samples instead of only AD/MC1 (14±2%MC) samples is also a modification which is a novelty since the standard recommends only AD samples. This KD/MC2 (9±3%MC) was included because in Ghana, neither green nor air-dried finger-jointing is being produced. So this inclusion of kiln-dried samples was to ascertain whether or not kiln-drying could improve the natural durability of branchwood to warrant their use for finger-jointed lumber production.

Meanwhile, it could also be argued that the MCs of all sample groups (MC1 and MC2) may equilibrate on the field and as such the inclusion of the KD/MC2 samples may not make any difference. However, it is reported that equilibrium moisture content (EMC) is dynamic and differs from one species to the other at same climatic conditions and it is also affected by the method of drying since the hygroscopicity of some wood species could be reduced permanently after some method of drying (Rowell, 2005; Tsoumis, 1991; Aker Woods company, n.d). Additionally, the temperature and hot air in the kiln sterilize wood and kill all microorganisms that might have already infested the wood, a situation that could delay the decay of such wood and thereby improving the wood‟s durability (Dinwoodie, 2010; Ncube, 2010; Shmulsky & Jones, 2011). In affirmation of the foregoing, according to Guangxi Universities Forestry College (2007a) air-drying have sufficiently decreased the resistance of *red cedar* wood from a highly durable class to just a durable class. Hence, introducing KD samples as a modification of the standard was not inappropriate.

3.3.2: Natural durability data collection

All test samples were first weighed, given identification tagging and reweighed using an electronic balance with accuracy of 0.01g. The tagging was done using different geometric shapes (triangle, rectangle, parallelogram, and trapezium) and colours (red, yellow, blue, white and ash) to identify specimen groups in each species, each wood type, and each MC level or drying type.

Densities of all samples were computed as ratios of their masses and volumes (volumes were determined by using their dimensions after measuring them with digital callipers with accuracy of 0.01mm) in accordance with ISO 3131 (1975). Shmulsky and Jones (2011) recommend this method of volume determination, especially for dried wood samples, because in the authors‟ view, the displacement method using water can wet the wood through penetration and subsequently produce erroneous volume values. Also, the use of high surface tension non-wetting fluids also present safety hazards.

On the field, the samples were planted to half of their lengths, in holes made with earth chisels, and at distances of 300mm between replicates and between samples of same drying type (or moisture content ranges) and same species, but at 600mm between different drying types (moisture content ranges) and different wood species. Also, allowances of 600mm were left between the samples and bushes around the cleared area. As a result, the soil block test covered a space of 960cm x 570cm (area of 547,200cm^2) on the demarcated termite prone site. Figure 3.6 shows some pictures on the natural durability test.

According to Eaton and Hale (1993) and EN 252 (1989), regular inspection of stakes should normally be done every 6 or 12 months. But all recommend that this period can be modified depending on the country and the geographical area. In the light of this, in this study, the stakes (specimen) were inspected, at least once each two months to ascertain their states, in terms of level of attack by biodeterogens. Meanwhile, Quartey (2009) acceptably adopted this same inspection period in a similar study.

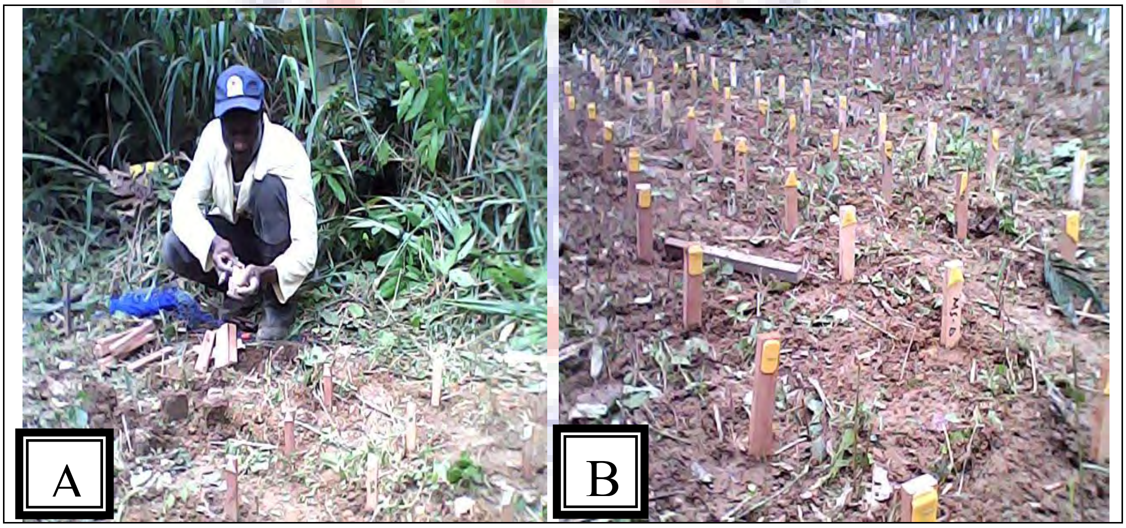


Figure 3.6 Some pictures on the natural durability testing. A= specimen being planted on the field; **B** = a section of the planted specimen on the field.

During these inspections, the 25mm wide faces were given light blows with a piece of wood (20 x 20 x 150mm) as the stakes were in the ground to ascertain whether their strengths have been reduced so much that they can break. Those that did not break were gently removed and examined for their levels of attack indicated by reduction of size, presence of fungi mycelium etc. as recommended in EN 252 (1989). After inspection, the stakes were carefully planted back into their positions.

The study samples were on the field for a period of one (1) year (from 8th March, 2012 to 26th February, 2013) before they were harvested. At this time of removal, all sample groups/categories of one test species (*Pterygota marcrocarpa*) had failed completely (destroyed). Again, at this time, the reference material (*Ceiba pentandria*) had also been replaced once and again, all had failed for a second time. The standard (EN 252) is used to test the protective effectiveness of wood preservative over a period of 5 to 10 years, but since it recommends and accepts modifications to suit the kind of test, it has acceptably been applied for a 6 months period by Quartey (2009) and Quartey et al. (2008) to test the natural durability of heart and sapwood of some lesser utilized tropical hardwoods in Ghana.

After harvesting, all the specimens were gently but thoroughly cleaned with brush as done by Quartey (2009). Also, all fungi mycelium were removed carefully with a razor blade as done by Ncube (2010) while ensuring that no wood was removed with the mycelium. Thereafter, all the samples were conditioned to assume a mean MC levels corresponding to their condition before the experiment. In view of this, the A.D/MC1 specimens were air-dried for about 48 hours, while the K.D/MC2 ones were conditioned in an oven set at a temperature of 102 ± 2^0C for some 3 to 4 hours while checking their MCs each hour. The MCs of all samples were measured with a resistance type moisture meter that has accuracy of ±1.5% upon validation with oven-dry method using some 30 samples drawn from stem and branch woods of the species {(3 stem samples x 5 species) + (3 branchwood samples x 5 species)}. Some researchers including Amoah et al. (2012), Ayarkwa, et al. (2000a), and Beaulieu et al. (1997) have acceptably used moisture meters in wood property studies. The final weights/masses of all specimen were measured with the same electronic balance as used before the experiment and with an accuracy of 0.01g.

Following these final measurements, percentage weight loss of each specimen was determined using Equation 3.3.

$$\textit{Percentage weight Loss} = [(W_1 - W_2)/W_1] \times 100\% \text{ ----------------------------- } 3.3$$

Where $\mathbf{W_1}$ =Initial weight and $\mathbf{W_2}$ = Final weight (Nzokou *et. al.,* 2005; Ncube, 2010).

3.3.3: Natural durability test data analyses

Descriptive and inferential statistical analyses (comprising means, percentages and analysis of variance-ANOVA, multiple comparison test) using MS-excel 2003 and 2007, and SPSS 16.0 software were done to compare group means, determine significant differences among obtained values/results by species/type of wood (branch or stem), and moisture content on quantitative data. Qualitative assessments based on visual ratings of attack as directed in the standard used were also done to grade the wood types and species into various durability classes, for prediction of their likely or expected service lives. Regression analyses were also done to establish the relationships among moisture content (MC), wood density (WD) and percentage weight loss (%WL) or natural durability and to predict the percentage weight losses/natural durability of species with MC alone, WD alone, and MC and WD combined. In these cases, MC and WD were used as indirect predictor variables for percentage weight loss. The regression equations of the relationships are as presented in Equations 3.4, 3.5 and 3.6.

$$\%WL = \alpha\, MC + C \qquad \text{---} \qquad 3.4$$

$$\%WL = \beta\, WD + C \qquad \text{--} \qquad 3.5$$

$$\%WL= \alpha\, MC +\beta\, WD + C \qquad \text{--} \qquad 3.6$$

Where **α** and **β** indicate the quantum of increase/decrease in %WL per 1 unit rise/fall in MC and WD respectively, whereas C is a constant { i.e intercept and indicating the value of %WL at situations where MC or WD or both MC and WD happen to be zero (0)}.

3.4: Static Bending Strength (MOE and MOR) of Solid and Finger-Jointed Lumber

Stem and branch wood sample groups (i.e. **β** groups in Figure 3.3- with dimensions of 65mm x 65mm x 420mm) earmarked for static bending test of both unjointed and finger-jointed lumber were divided into four groups (i.e. stemwood into 2 groups and branchwood also into 2 groups) while ensuring that each group has samples from each tree and forest reserve. For one group each of stem and branch woods, some samples of each of the 5 species were sampled and finger-jointed in the green state (MC range of 48 to 67%) and allowed to air-dry under room temperature and relative humidity before testing for static bending strength. The remaining samples in this same group were tested as unjointed/solid timber after air-drying. Green lumber finger-jointing technology was adapte because of its economic and environmental benefits of reducing drying costs and eventual reduction of waste that will be disposed off into the environement (Källander, 2008) and as provided in detailes in section **2.3.1.3** of this present study. Both the unjointed and finger-jointed samples in this group were tested at 17±3%MC (i.e. air-dried MC and referred to as MC1 group samples). The other one group each of stem and branch woods of each of the 5 species were kiln-dried to MC range of 6-11%MC in the study company"s kilns together with the company‟s lumber and according to the kiln-schedules being used for drying the various species in the company.

After the kiln-drying, some samples were randomly sampled and prepared as unjointed/solid timber specimens for bending test whereas the rest were finger-jointed before testing. Both the solid and finger-jointed samples in this group (i.e. those kiln-dried) were finally tested at 10±4%MC (referred to as MC2 group). All MCs were measured with moisture meter with accuracy of ±1.5% upon validation by oven-dry method on some 30 samples drawn from stem and branch woods of the species {(3 stem samples x 5 species) + (3 branchwood samples from 5 species)}. Some researchers including Amoah et al. (2012) and Ayarkwa et al. 2000a, Beaulieu et al. (1997) have used moisture meter method in measuring MC in wood properties studies.

3.4.1: Finger-jointed lumber production

All the prepared samples of both stem off-cuts and branch woods of the five species belonging to each MC group were jointed separately. The profile cuttings, application of adhesive and joint assembly were all done continuously in a universal finger-jointing machine at LLL factory (Model ES-SK10/520). This machine has a head and a table. The head consists of a trimming saw, the profile cutter, and a mechanical adhesive applicator (a metal drum with the same surface shapes as the fingers and which is in continuous rotation as it spreads the adhesive). The machine also consists of a long joint assembling table that operates on the stop-and-go system (as described by Jokerst, 1981). The machine also operates with pneumatics or air pressure for the application of end pressure. The following steps were followed in producing the finger-jointed lumber, both at the green and kiln-dried states.

3.4.1.1: Pairing/arrangement of stem and branch woods for finger-jointing

Figure 3.7 presents the pairing/arrangements of the samples for finger-jointing. Before samples were fed into the machine for the profile to be cut for jointing, they were arranged in a specific pattern or order and numbered according to their identifications as either branchwood or stemwood to form a number of groups to be jointed separately. Each group to be jointed separately comprised 4 members (i.e. 2 stemwood and 2 branchwood) so as to ensure better pairings of stem and branch woods of each species to satisfy the objectives of this aspect of this study. Besides satisfying the objectives of this study, the pairings or arrangements (Figure 3.7) were also to obtain an appreciable or minimum length that will not adversely affect the proper functioning of the finger-jointing machine available for use (the minimum length for proper functioning of the finger-jointed machine as specified by manufacturers and inscribed on it was 1m).

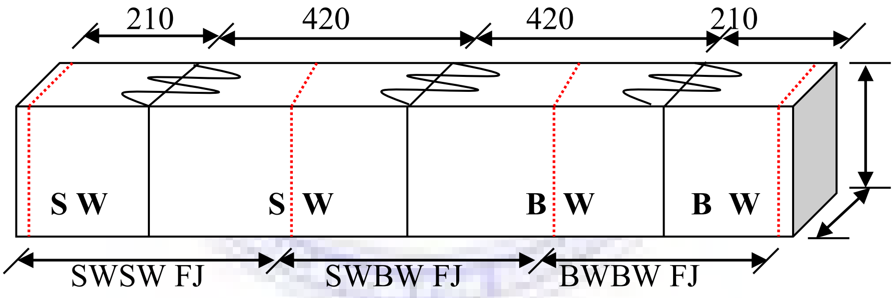


Figure 3.7. Pairings/arrangements of stem and branch woods for finger-jointing. (All dimensions are in **mm**).

Where: **SW** = Stemwood (off-cuts) of the species, **BW** = Branchwood of the Species; **SWSW FJ**= stem & stem FJ, **SWBW FJ**= stem & branch FJ, and **BWBW FJ** = branch & branch FJ combinations.

For each species, 8 of the paired/arranged stem and branch woods lumber (Figure 3.7) were produced for each of the 2 MC ranges. Hence, a total of **80** finger-jointed lumber in the form of Figure 3.7 were produced in this study (i.e. 8 paired lumber x 2 MC ranges x 5species) before finally prepared to the dimensions recommended in BS 373 (1957) as was done for the solid/unjointed samples of the species.

3.4.1.2: Finger profile and adhesive used

The finger-joint geometry being used in the company for all finger-jointed products manufacturing was also used for this study. The parameters of the finger-joint geometry/profile used in this study are as presented in Figure 3.8. However, this geometry is reported to be the vertical feather type, which is found to produce better joint strength (Bustos et al. 2003a; Jokerst, 1981).

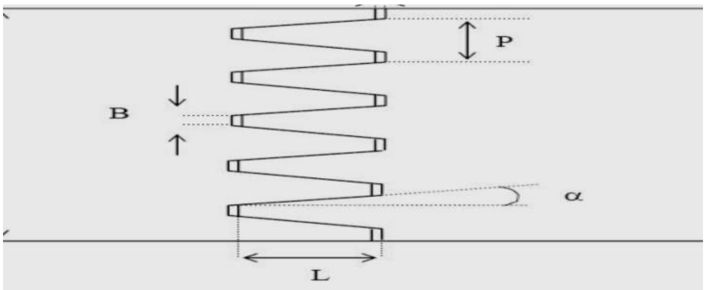


Figure 3.8: Finger-Jointing profile used in this study.

Where: L (finger length) = 10.18mm; B (tip thickness) = 0.72mm; P (pitch) = 3.80mm; α (slope) = 15^0.

Cross-link (also called thermosetting) type Polyvinyl Acetate (PVA) adhesive being used by LLL Company for light structural and non-structural finger-jointed lumber products manufacturing was used in this study. The adhesive called Jowacell 102.272-KD4-liem is a 2 component D4 glue with viscosity of ≅ 5,000 MPas. and made by Jowart Klebstoffe in Germany. The finger-jointing machine settings and operations were all done by personnel of the company who operate and or work on the finger-jointing machine. Adhesive application was done by a mechanical applicator (revolving plastic or metal drum with the same surface shapes as the finger-joint profiles) and attached to the universal finger-jointing machine. Hence, all samples fed into the machine received adhesive, upon activating the revolving drum, before they come out to be assembled or arranged for pressing to subsequently form the finger-jointed lumber.

3.4.1.3: End pressure and joint assembling

Assembling/pressing pressure of 45 kg/cm^2 (pressure used by the factory for jointing the species studied) was used for pressing the finger-jointed lumber. This end pressure was used for both the green and the kiln-dried samples and they were applied according to the operational method (stop-and-go method) of the finger-jointing machine used. The pressing time was found to average 22 ± 2s for the „redwood‟ species and 16 ± 2s for the „whitewood‟ species.

Finger-jointed lumber assembling were done in batches according to species and moisture level. Jointing of one spcies and each moisture level group was completed before others followed. This was done to ensure that neither wood of different species nor wood of same species but at different moisture levels do not mix-up. Hence, each species was jointed separately. However, because each individual sample in a particular batch was identified with a permanent marker, after the jointing, all species were properly stacked with stickers on same pallets and kept at a secured position and area. After 24hrs. on the pallets, by which time the adhesive was expected to have been fully cured (manufacturers of the adhesive specifies curing time of 12 hrs.), all samples were conveyed to Kumasi Polytechnic where they were wrapped in black polythene rubber to control absorption of moisture, in the case of the kiln-dried ones. The green finger-jointed specimen were however, allowed to air-dry in a room under prevailing room temperature and relative humidity until the MCs of samples reached between 20% and 25%MC before controlling the MC by wrapping them in black polythene rubber to prevent excessive drying. This control continued even as the final specimens were being prepared. This procedure of finger-jointing green wood and testing it in air-dried MC has been acceptably done by Lang and Hassler (2007). Also, it is reported that wood kept under such natural environmental conditions of control can absorb moisture at a rate of 1% per month in an open shed and 0.3% when kept in a closed and roofed sheds if their MCs are higher than the equilibrium moisture content (EMC) (Forest Products Laboratory, 2010). Thus the control environment was not inappropriate.

3.4.2: Preparation of test samples (solid/unjointed and finger-jointed) for bending test.

All test samples (both unjointed and finger-jointed and at both MC levels) were prepared according to the specifications of British Standard BS 373; 1957. All samples were sawn, planed and carefully examined for any visible defects. The samples were all prepared to final dimensions of 20mm x 20mm cross sections and 300mm lengths as specified in BS 373; 1957, and used by Amoah et al. (2012), Dinwoodie (2010) and Gurau et. al. (2008).

The actual samples dimensions were measured with digital callipers (with accuracy of 0.01mm) as recommended in ISO 3131 (1975) for volume and eventual density determinations. The use of digital callipers for final research sample dimension measurements had also been acceptably done by some researchers, including Amoah et al. (2012) and Gurau et al. (2008). The masses of all samples (both unjointed and finger–jointed) were measured after testing with an electronic balance whch had an accuracy of 0.01g after which density of samples were determined as the ratio of the mass and the volume (volumes were from the dimensions determined at calliper accuracy of 0.01mm) as recommended in ISO 3131 (1957).

In all, a total of 32 test specimens were prepared for each MC level of the three finger-jointed combinations (Figure 3.7) of each species, but results from 30 test samples each were used for analyses. The extra 2 samples were added to take care of any unforeseen circumstance that could lead to the destruction of some samples. Hence, a total of 960 FJ samples were prepared (i.e. 32 replicates x 3 combinations x 2MC levels x 5 species), but results on about 900 (i.e. 30 replicates x 3 combinations x 2MC levels x 5 species) were used for analyses. Also a total of 22 test samples were prepared for each MC level of unjointed stem off-cuts and branch woods for each species, but results of 20 test samples each were used in the analyses. The extra 2 samples were added to take care of any unforeseen circumstance that could lead to destruction of some samples. Hence, a total of 440 samples were prepared (i.e; 22 replicates x 2 wood types x 2MC levels x 5 species) but results on about 400 (20 replicates x 2 wood types x 2MC levels x 5 species) were used in the analyses. In related studies, various sample sizes which are mostly below what is used in this study has been acceptably used for similar tests. For instance, Ayarkwa et al. (2000b), and Ayarkwa (2010) used between 10 and 13 structural size sample replicates for each treatment combinations in studying the effects of end pressure and finger geometry on flexural strength of finger-jointed lumber. Also, Bustos et al. (2003b) used from 12 to 16 replicates of small clear samples (with dimensions off 64mm x 38mm x 305mm) to study the effects of curing time and end pressure on finger-jointed lumbers strength. Again, Bustos et al. (2004), used between 25 and 34 replicates of small clear samples (of dimensions 38mm x 64mm x 20-91mm), with Castro and Paganini (1997), using as less as 10 replicates of small clear samples (dimensions of 23mm x 50mm x 300mm) in studying bending strength of finger-jointed lumber. Additionally, in studying the bending strength properties of finger-jointed lumber jointed in the green state, Mantanis et al. (2010) used 30 small clear test samples of dimensions; 20mm x 20mm x 360mm.

3.4.3: Testing solid/unjointed and finger-jointed lumber for bending strength (MOE and MOR).

All unjointed and finger-jointed samples were conveyed to the wood/timber Engineering Laboratory of the Forestry Research Institute of Ghana (FORIG) for static bending testing (MOE and MOR). The Test (three-point flexure) followed British Standard BS 373 (1957) using an INSTRON TCM Universal Testing Machine model 4482 with crosshead speed of 6.6mm/min. This machine operates with a three-point flexural testing device and have a computerised data acquisition system that captures all the relevant information of the test and test sample. Figure 3.9 shows some of the samples under test in the INSTRON TCM testing machine.

Figure 3.9: Bending strength test set-up for testing both solid/unjointed and finger-jointed lumber in the INSTRON machine showing some of the samples under test.

After testing each batch of sample groups, the MC of each sample within all the samples groups were estimated with the moisture meter with an accuracy of ±1.5% based on oven-dry calibration tests. These MCs were taken close to failure zones of the samples and the next close region of the other member (i.e. in the case of

Finger-jointed lumber) as specified in the standard used (BS 373-1957). However, at each failure zone of the samples, 2 MC readings were taken at 2 different sides. The averages of these two readings were taken as the MC of the sample at test. The density of all the specimens were also determined as a ratio of their masses (by weighing them in an electronic balance with accuracy of 0.01g) to their volumes (ISO 3131 -1975).

3.4.4: Bending test data analyses

Both descriptive and inferential statistics (consisting of means, percentages, analysis of variance-ANOVA – both one and two-way) were employed to evaluate the bending strength (MOR and MOE) values of both solid and finger-jointed (FJ) lumber using MS-excel 2003 and 2007, and SPSS 16.0 software. Mean MOE and MOR of groups were compared while significant differences among species/type of wood (branch or stem) and moisture content were also determined. Tuckey multiple comparison tests were used to compare MOE and MOR of FJ lumber combinations in each MC level with solid stem off-cuts (controls) of the respective species that were in the same moisture conditions as the FJ lumber.

Moreover, joint efficiencies in MOE and MOR (in terms of strength gained) for all FJ combinations of all species within both 2 MC levels were determined using only the MC2 (KD) groups of solid stem off-cuts and of respective species as references/controls. This was done because KD/MC2 (10±4%MC) groups generally had higher strength than AD/MC1 (17±3%MC) groups and so using the KD/MC2 as reference for all will be a better option. Another reason was also because, currently all finger-jointing in Ghana are done with KD/MC2 wood. The joint efficiencies (in both MOE and MOR) were therefore found as a ratio of the strength of FJ lumber to that of solid/unjointed stemwood of the same species and expressed as a percentage (Ayarkwa et al., 2000a; Jokerst, 1981)-Equation 3.7.

$$Joint\ Efficiency\ in\ MOE\ or\ MOR = \frac{\text{FJ lumber strength}}{\text{Unjointed lumber strength}} \text{ x } 100\% \text{ ------- } \mathbf{3.7}$$

Additionally, for both solid and FJ lumber, regression analyses were also used to assess the relationships among moisture content (MC), wood density (WD), MOE and MOR. Also, regression analyses were done to predict MOE and MOR of various solid stem and branch wood of the species at both 2 MC levels using MC alone, WD alone, and MC and WD combined as predictor variables. However, in predicting the MOE and MOR of FJ lumber, only the model that combined both MC and WD as predictor variables was used. In all these cases, MC and WD were in effect used as indirect predictor variables for MOE and MOR of solid and FJ lumber. Again, MOE was used to predict MOR of solid stem off-cuts and branch wood (i.e. for stemwood and branchwood of all species together and for individual species). The regression equations of the relationships are as presented in Equations 3.8 to 3.11.

$$\text{MOR or MOE} = \alpha \text{ MC} + \text{C} \quad \text{---------------------------} \quad 3.8$$

$$\text{MOR or MOE} = \beta \text{ WD} + \text{C} \quad \text{----------------------------} \quad 3.9$$

$$\text{MOR or MOE} = \alpha \text{ MC} + \beta \text{ WD} + \text{C} \quad \text{----------------------------} \quad 3.10$$

$$\text{MOR} = \gamma \text{ MOE} + \text{C} \quad \text{---------------------------} \quad 3.11$$

Where **α**, **β** and **γ** indicated the degree of increase/decrease in MOE or MOR per 1 unit rise/fall in MC, WD and MOE respectively, whereas C is a constant {i.e; intercept indicating the value of MOR or MOE at situations where MC, WD, or both or MOE is zero (0) respectively in the 4 equations}.

3.5: Anatomical Study of Wood

In the anatomical studies, two processes were used, namely; sectioning and maceration. The sectioning was done to ascertain fibre, vessels and parenchyma tissue proportions as well as vessel lumen diameter of each wood type. Maceration was however conducted to separate the wood fibres in order to measure fibre lengths of stem and branch woods of the species.

3.5.1: Sectioning process

Samples of both stem and branch woods (from each site/forest reserve) of the wood species in the **‘γ’** group of rough lumber (Figure 3.3) were finally prepared to 20mm cubes in accordance with IAWA Committee (1989) protocol. Three (3) samples were prepared for each wood type and species from each site/forest reserve totalling 60 cubes (i.e. 3 replicates x 2 wood types x 5 species x 2 sites). As part of the softening process, the samples were first placed in water for 21 days until saturation (indicated by complete submerging of all samples in the water). This was to remove air in the woods. Following this, the samples were soaked in a mixture of ethanol and glycerol in a ratio of 1:1, for an average period of 21 to 30 days, in containers labelled with the names of the species, wood type and forest reserves. Thin sections of 20-30µm thick produced from transverse surfaces of the samples using a sliding microtome were first washed in water and then stained in 1% safranin in 50% ethanol solution for about 10 to 15 minutes. Afterwards, the sections were rewashed in water and dehydrated in increasing concentration of ethanol; from 30, 50, 70, 80, 90 and 100% for 5 to 10 minutes for dehydration (Figure 3.10 A). They were then immersed in xylene to remove little traces of water. The sections were then mounted permanently in Canada balsam after which the slides were dried in an oven at 60^0C overnight.

3.5.2: Maceration process

Maceration process was also done in accordance with IAWA Committee (1989) protocol. After the initial softening process with water for 21 days, one sample of each wood type/species from each site was taken and 2 match-stick sized specimens were plucked from them for maceration. These were then placed in separate labelled containers and immersed in a mixture of acetic acid and hydrogen peroxide (6%) prepared in a ratio of 1:1. The specimens in the solution were placed in an oven and heated at 60^0C for a period of 24 to 48hrs. till maceration (Figure 3.10 B).

Figure 3.10: Some photographs on the anatomical studies. (**A** = sectioned specimens in the 6 different concentrations of ethanol, and **B** = macerates in containers).

Upon removal from the oven, all the chemical solutions were poured away, specimens were rinsed in distilled water after which portions were carefully taken and teased in glycerol before mounting them on microscope for measurements of fibre lengths.

3.5.3: Qualitative anatomy of wood

Micrographs taken from the sections and macerates were used to describe and make qualitative comparison of the anatomical features of stem and branch woods of same species by following the terminologies in IAWA committee"s recommendations (IAWA Committee, 1989).

3.5.4: Quantitative anatomical data collection

The slides of both sectioning and maceration specimens were examined and micrographs taken separately using 40**x** magnitication in a light microscope (micromaster premier) connected through its software (Micron USB 2) into a computer (Figure 3.11).

Figure 3.11: Photomicrographs being taken from a microscope.

The photomicrographs obtained were then analysed with ImageJ software that enabled the tissues/cells to be counted and measured. For each wood type or species, vessel lumen diameter and fibre length were obtained by taking 50 measurements for each and finding the averages (i.e; 25 from specimen from each site/forest reserve). Also, for each wood type or species, proportions of the 3 main tissues [vessel, fibres, parenchyma (ray and axial)] were estimated using a total of 50 micrographs each (25 micrographs each of specimens from each forest reserve) in line with IAWA committee‟s recommendations of using at least 25 micrographs (IAWA Committee, 1989). The grid system in ImageJ was used to count the number of points of each tissue in the grid after which these numbers were expressed in percentage terms to estimate the average quantity (%) of a particular tissue found within 1mm^2 cross-sectional area of the wood type.

3.5.5: Anatomical data analyses

Descriptive and inferential statistical analyses (consisting of means, percentages, analysis of variance-ANOVA, Tuckey-multiple comparison test and independent sample T-Test) were employed to evaluate the quantitative anatomical data on the tissues of both stem and branch woods of the species. MS-excel 2003 and 2007, and SPSS 16.0 software to compare group means and determine significant differences among obtained values/results by species/type of wood (branch or stem). Regression analyses were also performed to ascertain the relationship among the mean quantitative data for the tissues, wood density, MOE and MOR of unjointed lumber of the species/wood types.

CHAPTER FOUR

RESULTS

4.1: Above-Stump Merchantable Wood Quantities/Volumes

Above stump total merchantable residue volume - TMRV (branchwood and main bole off-cuts) were quantified from a total of 154 randomly sampled trees. The 154 randomly sampled trees consisted of 20 different species and their distribution across the 3 ecological zones (study sites) are: zone 1=11, zone 2= 10 and zone 3=19 species with only 7 species being common to all the 3 sites (Table 4.1.1). The 11 species from ecological zone 1 provided the highest mean extracted log volume (ELV) of 15.51m^3 per tree (i.e. harvesting efficiency/ recovery per tree) but a mean total merchantable residue volume (TMRV) of 4.85m^3 per tree, whereas the 10 species from ecological zone 2 provided the least mean ELV of 13.40m^3 per tree and a mean TMRV of 4.34m^3 per tree. However, the 19 species from ecological zone 3 produced the highest TMRV of 5.13m^3 per tree.

For the individual species, (in Table 4.4.1) *Triplochiton scleroxylon* outnumbered the other species across the ecological zones and occupied about 23.4% of the total sample size. The ELV for the various species ranged from the highest of 33.91m^3/tree for *Ceiba pentandra* from econlogical zone 1 to the lowest of 6.74m^3/tree for *Celtis mildbraedii* from ecological zone 2. However, the TMRV ranged from the highest of 14.2/tree for *Entandrophragma angolense* from zone 3 to the lowest of 1.32m^3/tree for *Nesorgodonia papaverifera* (danta) also from zone 3.

Table 4.1.1. Summary of Data Collected from the three Forest Study Sites.

Wood Species	N	Extracted log volume (ELV) per tree (M^3)			Total merchantable residue volume (TMRV) per tree (M^3)		
		Ecological Zone 1	Ecological Zone 2	Ecological Zone 3	Ecological Zone 1	Ecological Zone 2	Ecological Zone 3
P. africanum (dahoma)	24	13.39 ±7.46	23.89±5.70	9.60±2.26	6.03±3.71	7.69 ±0.77	4.37 ±1.03
A. toxicaria (kyenkyen)	11	20.92±10.12	17.37	17.77±1.35	5.47±3.05	4.61	7.26±0.55
T. scleroxylon (Wawa)	36	15.26 ±4.59	14.91±4.19	14.89±4.00	3.07±1.36	4.19±3.25	5.18±1.39
C. mildbraedii (Esa)	11	12.52 ±3.84	6.74 ±1.87	7.20	1.68 ±1.02	3.45±4.10	2.34
E. angolense (edinam)	7	19.56 ±6.69	-	13.95±3.76	6.78 ±2.75	-	14.20±3.44
Khaya spp. (mahogany)	6	10.71 ±7.55	16.61	12.87 ±3.70	8.03±4.61	9.00	7.53±2.16
E. cylindricum (sapele)	14	14.25 ±3.27	-	15.06 ±4.35	4.15 ±1.78	-	3.73±0.94
T. superba (ofram)	15	9.23 ±1.91	10.6 ±1.35	13.99±3.78	4.46 ±2.04	3.33±4.39	4.13±1.18
A. pterocarpoides (yaya)	2	18.19 ±4.67	-	-	8.98 ±6.56	-	-
C. pentandra (onyina)	6	33.91±0.85	14.82	16.79	4.48±1.03	4.92	6.06
N. papaverifera (danta)	3	9.25	10.58	8.00	4.13	5.04	1.32
C. gabunensis (denya)	3	-	18.09 ±0.46	12.96	-	7.74±3.28	4.26
P. macrocarpa (koto/kyere)	7	-	7.08 ±1.03	8.32 ±2.21	-	0.77 ±0.34	1.92±0.61
E. utile (utile)	1	-	-	20.56	-	-	5.34
A. ferruginea (albizia)	2	-	-	13.87±5.56	-	-	2.27±0.91
Milicia excelsa (Iroko/odum)	1	-	-	19.83	-	-	0.59
Guarea spp. (guarea)	1	-	-	7.70	-	-	3.10
G. ehie (hyedua)	1	-	-	7.50	-	-	1.34
T. heckelii (Baku)	1	-	-	20.90	-	-	7.05
A. robusta (Asanfena)	2	-	-	8.47±4.18	-	-	3.13 ±1.55
TOTAL	**154**	**15.51±7.85**	**13.40±6.78**	**13.64±4.57**	**4.85±3.14**	**4.34 ±3.52**	**5.13±3.45**

NOTE: Ecological Zone 1= MSD-SE; Asukawkaw (Nkawkaw), Eastern Region**; Ecological Zone 2 -Reserves 2 & 3 = MSD-NW**; Bonsambepo & Abonyere (Akordie), B. Ahafo Region: **Ecological Zone 3 –Reserve 4 = ME**; Sui river (Sefwi-Wiawso), Western Region.

The merchantable wood quantities among the various timber tree species covered are as presented in Table 4.1.2. From this table, the total merchantable wood volume (TMWV) of the sampled timber trees was about 2,964m^3 and ELV was about 2,221.41m^3. The ELV thus averaged 75.31% of the TMWV and represented the general average logging efficiency of the 3 sites/ecological zones in this study. On the average, harvesting efficiencies of the various wood species found in all 3 ecological zones however, ranged from the highest of about 83.66% for *Ceiba* *pentandra* (onyina) to the lowest of 59.54% for *Khaya ivorensis* (mahogany). The general TMRV (stem off-cuts = 186.56 + branchwoods = 556.01) was found to be 742.57m^3 representing approximately 25% of the TMWV (Table 4.1.2).

Table 4.1.2. Merchantable Wood Quantities and Logging Efficiencies among various Wood Species.

Species		Extracted log volume –ELV (m^3)	Merchantable residue volume- MRV			Total merchantable wood-TMWV (m^3)
Names	N		Branchwoods (m^3)	Stem off-cuts (m^3)	Total –TMRV (m^3)	
P. africanum (dahoma)	24	345.17 (67.76)	132.40(29.31)	13.94(2.93)	146.35(32.24)	491.52
A. toxicaria (kyenkyen)	11	213.98(76.04)	43.37 (15.70)	23.16(8.26)	66.52(23.96)	280.50
T. scleroxylon (wawa)	36	540.67 (78.27)	90.83 (13.51)	58.56(8.21)	149.39 (21.72)	690.06
C. mildbraedii (esa)	11	109.28 (81.92)	22.30 (14.98)	3.92 (3.10)	26.21(18.08)	135.50
Khaya spp. (Mahogany)	6	74.48 (59.54)	34.39 (29.25)	13.76(11.20)	48.15(40.45)	122.64
T. superba (ofram)	15	162.69 (76.07)	34.09 (13.98)	23.89 (9.95)	57.97(23.93)	220.66
C. pentandra (onyina)	6	167.24 (83.66)	14.03 (7.94)	14.88 (8.40)	28.90(16.34)	196.14
Total of 7species common to 3sites	109	1613.51(75.06)	371.41(17.98)	152.09(6.95)	523.50 (24.93)	2137.01
Total of other species	45	607.90 (74.97)	184.59 (19.23)	34.47 (4.87)	219.07 (24.09)	826.97
Total of all species	154	2221.41(75.31)	556.01(18.35)	186.56(6.34)	742.57 (24.69)	2963.98

Note: Numbers in parentheses are volume in relation to TMWV expressed in percentages (efficiencies)(%)

4.1.1. Merchantable branchwood, stem (off-cuts) and logging efficiencies among species and ecological zones

Analyses of variance (ANOVA) as presented in Tables 4.1.3, 4.1.4, 4.1.5 and 4.1.6, indicated significant differences ($P<0.5$ and $P<0.01$) in % branchwood and % stem off-cuts among the various wood species and the ecological zones/study sites. From the tables, ANOVA indicated significant differences at 95% confidence level in branchwoods among the various wood species ($P = 0.000$; Table 4.1.3) and the ecological zones ($P= 0.013$; Table 4.1.4). Moreover, there were also significant differences in quantity of stem off-cuts among the various wood species ($P = 0.004$; Table 4.1.5) and among the ecological zones ($P= 0.000$; Table 4.1.6) all at 95% confidence level.

Also, wood species explained 24% (Table 4.1.3) and 14% (Table 4.1.5) respectively of the variations in percentage of branchwood and stem off-cuts in total merchantable wood volume. Additionally, sites/ecological zones also explained 4.4% (Table 4.1.4) and 40% (Table 4.1.6) respectively of the variations in percentage of branchwood and stem off-cuts in total merchantable wood volume.

Table 4.1.3. ANOVA of % Merchantable Branchwood in total Merchantable Wood Volume among Species.

Source	Type III Sum of Squares	df	Mean Square	F- Value	P-Value
Corrected Model	9730.221^a	19	512.117	3.487	.000***
Intercept	14898.219	1	14898.219	101.439	.000***
Wood Species	9730.221	19	512.117	3.487	.000***
Error	19680.449	134	146.869		
Total	81245.048	154			
Corrected Total	29410.670	153			

a. R Squared = .331 (Adjusted R Squared = .236). Significant ** * P< 0.01

Table 4.1.4. ANOVA of % Merchantable Branchwood in Total Merchantable Wood Volume among Ecological Zones

Source	Type III Sum of Squares	df	Mean Square	F-Value	P-Value
Corrected Model	1654.699^a	2	827.350	4.501	.013**
Intercept	46219.727	1	46219.727	251.448	.000***
Ecological zones	1654.699	2	827.350	4.501	.013**
Error	27755.971	151	183.814		
Total	81245.048	154			
Corrected Total	29410.670	153			

a. R Squared = .056 (Adjusted R Squared = .044). Significant *** P< 0.01; ** P< 0.05

Table 4.1.5. ANOVA of % Off-Cuts In Total Merchantable Wood Volume among Species.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1448.450^a	19	76.234	2.276	.004***
Intercept	1811.105	1	1811.105	54.078	.000***
Wood Species	1448.450	19	76.234	2.276	.004***
Error	4487.772	134	33.491		
Total	11994.268	154			
Corrected Total	5936.222	153			

a. R Squared = .244 (Adjusted R Squared = .137). Significant *** P< 0.01

Table 4.1.6. ANOVA of % Off-cuts in Total Merchantable Tree Volume among Ecological Zones

Source	Type III Sum of Squares	df	Mean Square	F-Value	P-Value
Corrected Model	2407.514[a]	2	1203.757	51.511	.000***
Intercept	5647.571	1	5647.571	241.670	.000***
Ecological zones	2407.514	2	1203.757	51.511	.000***
Error	3528.707	151	23.369		
Total	11994.268	154			
Corrected Total	5936.222	153			

a. R Squared = .406 (Adjusted R Squared = .398). Significant *** P< 0.01

Analyses of variance also indicated significant difference (P= 0.000; Table 4.1.7) in logging efficiencies among the species but not among the study sites (P = 0.435; Table 4.1.8) and wood species explained 29% of the variation in logging efficiencies.

Table 4.1.7. ANOVA of Logging Efficiencies among the Wood Species.

Source	Type III Sum of Squares	Df	Mean Square	F-Value	P-Value
Corrected Model	7646.085[a]	19	402.426	2.910	.000***
Intercept	285817.412	1	285817.412	2066.850	.000***
Wood Species	7646.085	19	402.426	2.910	.000***
Error	18530.385	134	138.286		
Total	899585.443	154			
Corrected Total	26176.470	153			

a. R Squared = .292 (Adjusted R Squared = .192). Significant *** P< 0.01

Table 4.1.8. ANOVA of Logging Efficiencies among the Ecological Zones/Study Sites

Source	Type III Sum of Squares	Df	Mean Square	F-Value	P-Value
Corrected Model	286.834[a]	2	143.417	.836	.435^{ns}
Intercept	815794.179	1	815794.179	4758.079	.000***
Ecological zones	286.834	2	143.417	.836	.435^{ns}
Error	25889.636	151	171.455		
Total	899585.443	154			
Corrected Total	26176.470	153			

a. R Squared = .011 (Adjusted R Squared = .002). Non-Significant ^{ns} P> 0.1; Significant *** P< 0.01

4.1.2: Predicting total merchantable wood volume (TMWV) and total merchantable residue volume (TMRV) from extracted log volume (ELV).

Linear regression analyses were performed to ascertain the viability in using ELV to predict TMWV and TMRV.

4.1.2.1: Predicting TMWV and TMRV from ELV among ecological zones

The relationships between ELV, TMWV and TMRV were analyzed for the 3 ecological zones (Figure 4.1.1). The relationships sought to predict the TMWV and TMRV from ELV without having to spend money, energy and time to go to the forest for measurements.

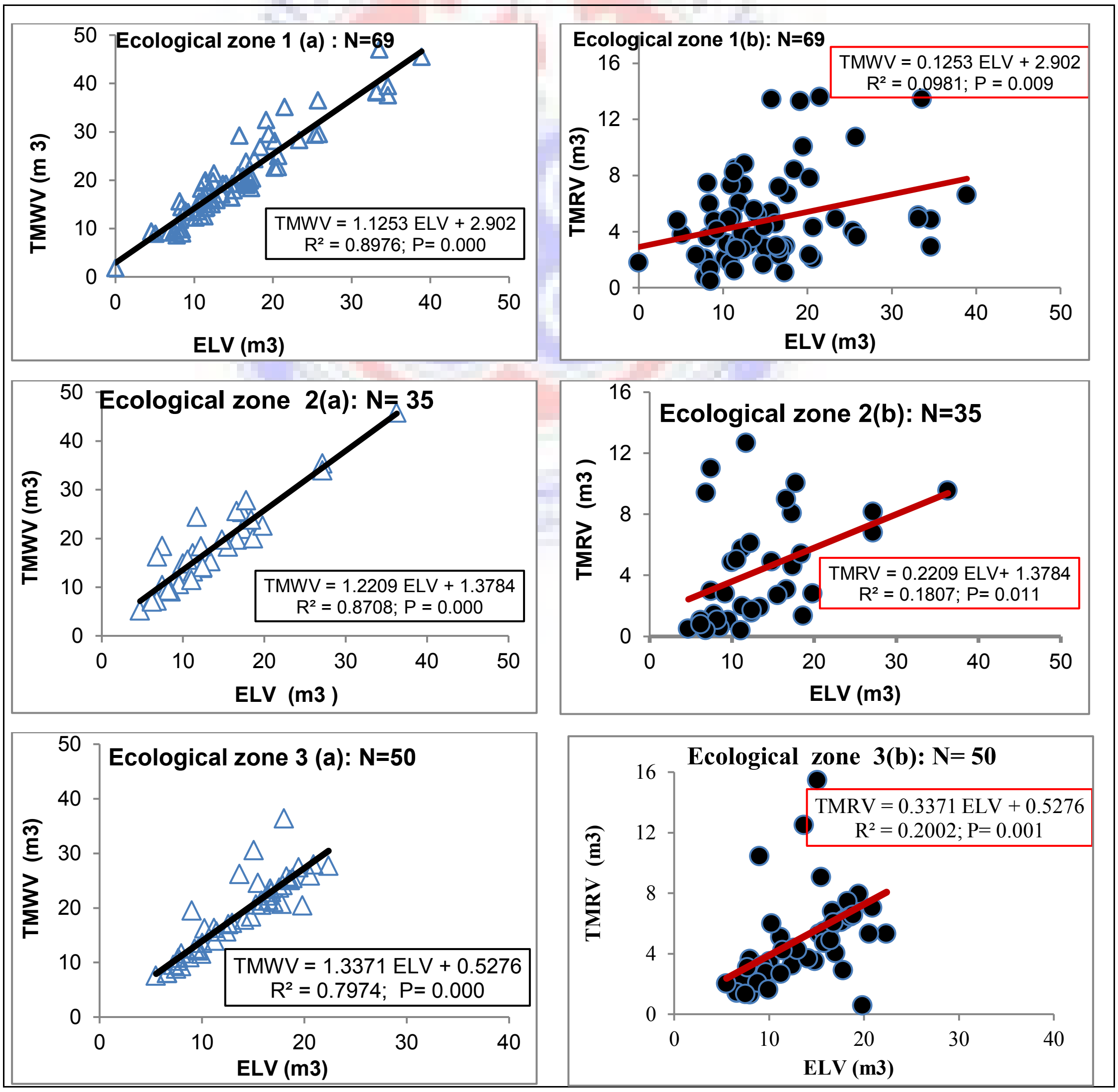


Figure 4.1.1. Predicting Total Merchantable Wood (TMWV) and Total Merchantable Residue (TMRV) from Extracted Log Volume (ELV) among Ecological Zones (site specific models).

From Figure 4.1.1, the R^2 values of the relationships indicated that ELV can predict TMWV more accurately than as it can predict TMRV in all the 3 ecological zones . The R^2 values of the relationships between ELV and TMWV ranged from the highest of 0.897 to the lowest of 0.797 for ecological zone 1 (MSD-SE forest) and ecological zone 3 (ME forest) respectively, suggesting strong relationships. The R^2 values of the relation between TMRV and ELV, however ranged from the highest of 0.20 to the lowest of 0.098 for all species from ecological zones 3 and 1 respectively which suggest weak relationships.

4.1.2.2: Predicting TMWV and TMRV from ELV for selected species (species specific model)

The relationships between TMWV and ELV, and TMRV and ELV for 10 individual tree species (those with N ≥ 6) out of the 20 species covered are as presented in Table 4.1.9. These relationships for individual species also suggest that ELV of each species is a better predictor of the TMWV than for TMRV of that species.

Table 4.1.9. Relationship between ELVand TMWV, and TMRV of Selected Species.

Species	N	Total merchantable wood vol. (TMWV)			Total merchantable residue Vol. (TMRV)		
		Regression Equation	R^2	P-Value	Regression Equation	R^2	P-Value
P. africanuum	24	$TMWV = 1.308\ ELV + 1.654$	0.95	0.000	$TMRV = 0.284\ ELV + 1.425$	0.48	0.000
A. toxicaria	11	$TMWV = 1.072\ ELV + 4.642$	0.92	0.000	$TMRV = 0.044\ ELV + 3.075$	0.02	0.510
T. scleroxylon	36	$TMWV = 1.121\ ELV + 2.324$	0.89	0.000	$TMRV = 0\ .043\ ELV + 1.875$	0.02	0.079
C. mildbraedii	11	$TMWV = 0.948\ ELV + 2.892$	0.71	0.001	$TMRV = -0.065\ ELV + 2.681$	0.01	0.804
E. angolense	7	$TMWV = 0.636\ ELV + 16.96$	0. 38	0.227	$TMRV = -0.302\ ELV + 15.01$	0.14	0.302
Khaya spp.	6	$TMWV = 1.522\ ELV + 1.539$	0. 98	0.000	$TMRV = 0.414\ ELV + 0.584$	0.30	0.007
E. cylindricum	14	$TMWV = 1.081\ ELV + 2.781$	0.88	0.000	$TMRV = 0.062\ ELV + 2.642$	0.02	0.005
T. superba	15	$TMWV = 1.189\ ELV + 1.806$	0.50	0.003	$TMRV = 0.151\ ELV + 3.916$	0.02	0.572
C. pentandra	6	$TMWV = 0.943\ ELV + 6.392$	0.99	0.000	$TMRV = -0.015\ ELV + 2.774$	0.001	0.289
p. marcrocarpa	7	$TMWV = 1.354\ ELV + 1.336$	0.97	0.000	$TMRV = 0.108\ ELV - 0.31$	0.45	0.023

From Table 4.1.9, the R^2 values for the TMWV and ELV ranged from the lowest of 0.384 for *Entandrophragma angolense* to the highest of 0.990 for *Ceiba pentandra* (onyina), whereas those of the TMRV and ELV ranged from the lowest of 0.001 for *Ceiba pentandra* to the highest of 0.48 for *Piptadeniastrum africanum* (dahoma).

4.1.2.3: Predicting TMWV and TMRV from ELV for all species and ecological zones combined.

Figure 4.1.2 also presents the regression analyses of the relationships between TMWV and ELV, and between TMRV and ELV, for all the 20 species together (154 trees in all) from the 3 ecological zones. These relationships are also found to be positive in both cases with R^2 values of 0.87 and 0.13 respectively for TMWV and ELV, and TMRV and ELV. These R^2 values suggest that whereas ELV is a weak predictor variable for TMRV, it is a strong predictor variable for TMWV.

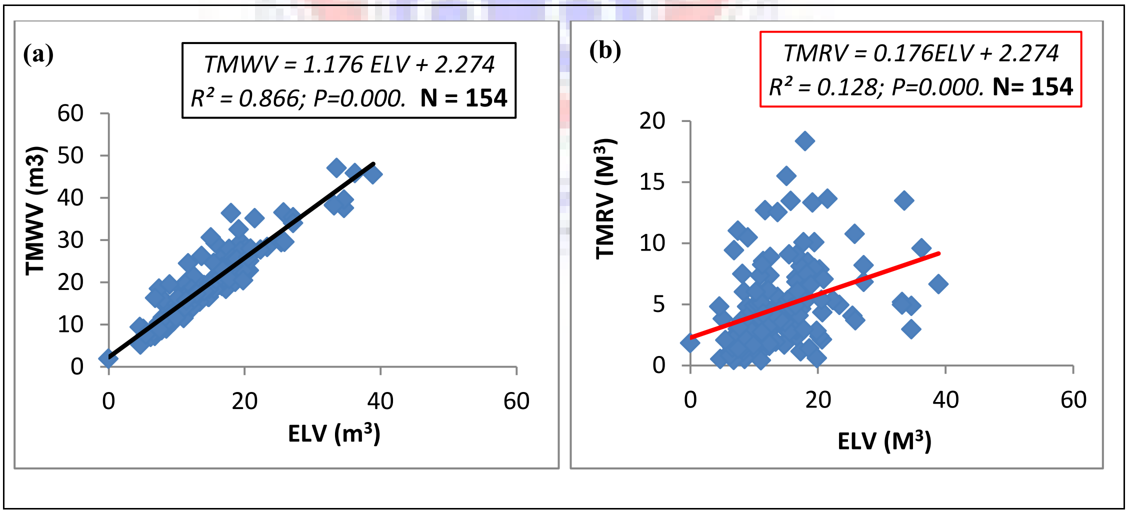


Figure 4.1.2. Relationship between TMWV and ELV (a), and TMRV and ELV (b) for all species (154 Trees) from all 3 ecological zones altogether

4.2: Natural Durability of Wood

Natural durability of stem and branch wood of the studied species (*Entandrophragma cylindricum*-sapele, *Entandrophragma angolense*-edinam, *Khaya ivorensis*-mahogany, *Terminalia superba*-ofram and *Pterygota macrocarpa*-koto) were assessed in two directions namely; quantitative and qualitative. The quantitative assessement was based on percentage weight losses whereas the qualitative assessement was based on visual rating of the extent of attack or destruction of the wood samples by biological agents. Detailed experimental results on the natural durability test is presented in Appendix 2.

4.2.1 Visual rating of extent of attack/destruction of wood by biological agents (qualitative assessement of natural durability)

Assessement of visual rating of the extent of attack of wood by biological agents is done to estimate or predict the service life of wood**.** Figure 4.2.1 shows the mean visual ratings obtained by stem and branch woods of the studied species tested at 2 moisture levels (14±2%-air-dried MC and 9±3%-kiln-dried MC).

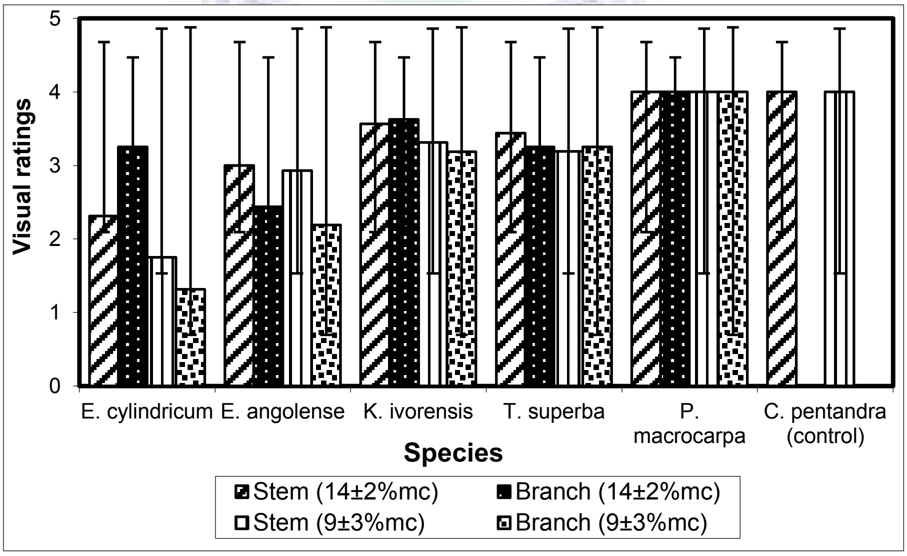


Figure 4.2.1. Visual Ratings of Extent of Destruction of Stem and Branch Woods Tested for Natural Durability at Two Moisture Levels; N= 16; Error bars = SD

The ratings were qualitatively obtained upon assessing the appearances of the samples (Figure 4.2.2) after the test and in accordance with the five-point rating in the standard used-EN 252 (1989) (i.e. 0=no attack, 1= slight attack, 2= moderate attack, 3= severe attack and 4= failure). From Figure 4.2.1 and Appendix 2 in general, both stem and branch woods dried to 9±3%MC which had lower ratings than their counterparts dried to 14±2%MC. The visual ratings of samples dried to 9±3%MC were from 3.313-*Khaya ivorensis* (mahogany) stem to 1.313-*Entandrophragma cylindricum* (sapele) branch, whereas those dried to 14±2%MC ranged from 3.625-mahogany branchwood to 2.312-sapele stemwood.

From Figure 4.2.2, all samples of koto within the 2 moisture content ranges obtained the highest similar mean visual ratings of 4.0 and equivalent to that of the control (onyina stemwood). But because onyina specimens were replaced once before the end of the test period (1year) and at that time there were some survival koto specimens, koto stem and branch woods can be said to resist destruction by biological agents relatively better than onyina stemwood. Since higher ratings imply much destruction to wood, the results generally suggest that, except for koto, high moisture content resulted in much destruction of the wood samples. Therefore moisture content appeared to to have influenced the extent of destruction of wood by biodegrading agents, and therefore can affect the service life of wood.

Moreover, generally, branch and stem woods of same species at same moisture range had different resistance to destruction. However, it appeared that branchwood had better resistance than their stemwood counterpart, especially when dried to relatively lower moisture content. For instance, at 14±2%MC, sapele had ratings of 3.25 and 2.31 respectively for its branchwoods (Figure 4.2.2; 1c) and stemwood (Figure 4.2.2; 1a), but at 9±3%MC, the species had ratings of 1.75 and 1.313 respectively for the stemwood (Figure 4.2.2; 1b) and branchwood (Figure

4.2.2; 1d). Similar patterns were also obsereved for edinam and mahogany. These suggested that besides moisture content, wood type (i.e. being stem or branch) could also affect the degree of destruction of wood by biological agents and it could lead to different service lives for stem and branch woods of same species.

Figure 4.2.2. Appearances of the remains of Stem and Branch Wood `samples after Durability Test {1= *E. cylindricum*; **2=***E. angolense*; **3=** *K. ivorensis*; **4=** *T. superba*; **and 5=** *P.macrocarpa*); ***a*** = stemwoods *(MC1)*, ***b*** = Stemwoods *(MC2)*, ***c*** = Branchwoods *(MC1), and* **d**= branchwoods *(MC2) of the various species*}. The control specimens ***(C. pentandria)*** were not tagged and all were destroyed.

Table 4.2.1 presents a Two-way ANOVA to give further evidence of the effect of moisture content and wood type/species on the extent of destruction of wood by biodeterogens. From Table 4.2.1, wood type (i.e. stem or branch) had siginificant effect (F = 27.643, p = 0.000), moisture levels also had significant effect (F= 17.386, p = 0.000) and the interaction between the two variables also had significant effect (F= 4.317, p=0.000), all at 1% level of signigicance on the visual ratings of destruction of wood. Also it was found that wood type and moisture levels, however, explained 47% of the variations in the visual ratings of attack on the wood types/species (Table 4.2.1).

Table 4.2.1.Two-Way ANOVA of the effect of MC and Wood Type on Visual Rating of Extent of Destruction of Stem and Branch Woods Tested at Two Moisture Levels

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	198.239a	21	9.440	16.047	.000
Intercept	3563.636	1	3563.636	6.058E3	.000
Wood Type/Species	162.614	10	16.261	27.643	.000
Moisture Levels	10.227	1	10.227	17.386	.000
Wood Type/Species * Moisture Levels	25.398	10	2.540	4.317	.000
Error	194.125	330	.588		
Total	3956.000	352			
Corrected Total	392.364	351			

a. R Squared = .505 (Adjusted R Squared = .474)

4.2.2: Percentage weight losses of wood (quantitative assessment of natural durability)

Natural durability in terms of percentage weight losses (%WL) is a 4 point quantitative assessement scale used to describe wood as; very durable =0-5%WL, durable = 6-10%WL, moderately durable = 11-40%WL, and non-durable = 41-100%WL as adapted from Nzokou et al. (2005) and Eaton and Hale (1993). The percentage weight losses by stem and branch woods in this study are graphically presented in Figure 4.2.3. Table 4.2.2 however, presents the summary descriptive statistics and one-way ANOVA of the percentage weight losses of stem and branch woods of studied species in relation to the control species. From Figure 4.2.3 and Table 4.2.2, results appeared to suggest again that moisture content have effect on percentage weight loss too. Generally, the sample groups (both stem and branch woods) dried to 14±2%MC had relatively higher percentage weight losses (suggesting less durability) than their counterparts dried to 9±3%MC levels (suggesting relatively better durability).

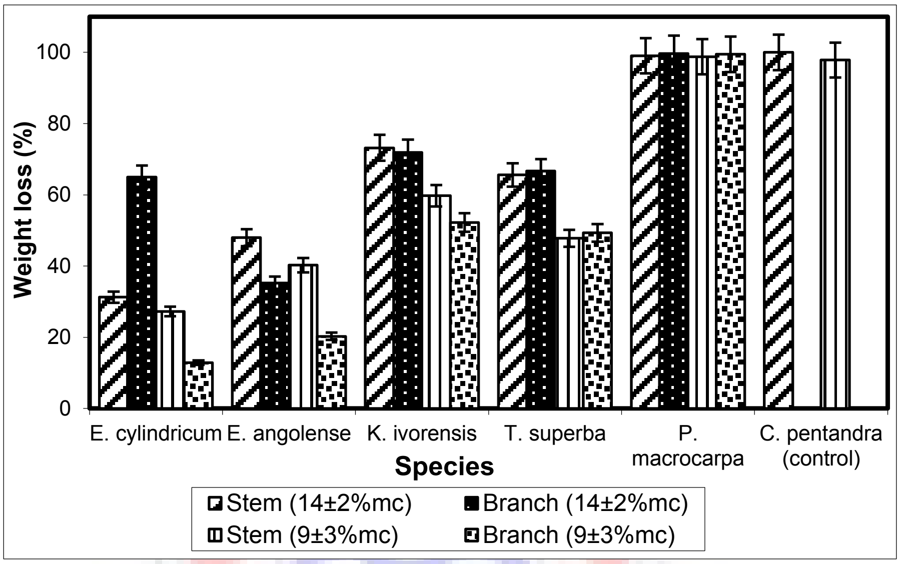


Figure 4.2.3. Mean percentage Weight Losses of Stem and Branch Wood tested for Natural Durability at Two Moisture Levels; N= 16, Error bars = percentages.

The percentage weight losses of samples tested at 14±2%MC ranged from 31.255% (for *E. cylindricum* stemwood) to 99.700% (for *P. macrocarpa* branchwood) and those dried to 9±3%MC had percentage weight losses ranging from 27.24% (*E. cylindricum* stemwood) to 99.46% (*P. macrocarpa* branchwood). As expected of a perishable species the reference material (*C. pentandra* stemwood) had the highest weight losses at both 2 moisture content ranges and these, at 95% confidence level, were significantly different from the weight losses obtained by stem and branch woods of all species at both moisture levels, except *Pterygota macrocarpa*-koto (Table 4.2.2).

Table 4.2.2: Summary descriptive statistics and One-Way ANOVA of percentage Weight Losses of Stem and Branch wood tested at Two Moisture Levels.

Species	Moisture level (%)	Wood Type	% Weight Loss Mean (SD)	F- value	P-value
Entandrophragma cylindricum (sapele)	14±2	*Ceiba* stem (control)	100.00 (0.00) ^{ab}	20.358	.000***
		Stemwood	31.255 (33.03)^{ac}		
		Branch	64.980 (41.17)^{bc}		
	6±3	*Ceiba* stem (control)	97.843 (9.39)^{ab}	453.133	.000***
		Stemwood	27.242 (12.37)^{ac}		
		Branch	12.850 (6.04)^{bc}		
Entandrophragma angolense (edinam)	14±2	*Ceiba* stem (control)	100.00 (0.00)^{ab}	21.881	.000***
		Stemwood	47.970 (37.60)^{a}		
		Branch	35.260 (34.17)^{b}		
	6±3	*Ceiba* stem (control)	97.843 (9.39)^{ab}	58.643	.000***
		Stemwood	40.230 (32.07)^{ac}		
		Branch	20.251 (16.44)^{bc}		
Khaya ivorensis (mahogany)	14±2	*Ceiba* stem (control)	100.00 (0.00)^{ab}	8.785	.001***
		Stemwood	73.188 (27.60)^{a}		
		Branch	71.877 (24.79)^{b}		
	6±3	*Ceiba* stem (control)	97.843 (9.39)^{ab}	22.792	.000***
		Stemwood	59.733 (24.45)^{a}		
		Branch	52.187 (25.18)^{b}		
Terminalia superba (ofram)	14±2	*Ceiba* stem (control)	100.00 (0.00) ^{ab}	13.173	.000***
		Stemwood	65.603 (32.75) ^{a}		
		Branch	66.692 (17.89) ^{b}		
	6±3	*Ceiba* stem (control)	97.843 (9.39) ^{ab}	28.672	.000***
		Stemwood	47.813 (27.05) ^{a}		
		Branch	49.318 (24.38) ^{b}		
Pterygota macrocarpa (koto)	14±2	*Ceiba* stem (control)	100.00 (0.00)	.713	.496^{ns}
		Stemwood	99.049 (3.81)		
		Branch	99.700 (1.20)		
	6±3	*Ceiba* stem (control)	97.843 (9.39)	.543	.585^{ns}
		Stemwood	98.770 (4.92)		
		Branch	99.464 (2.14)		

Note: mean values with the same letters indicate significant difference at 95% confidence level; ***=significant at p≤ 0.01; ns=non-significant (p>0.1).

Again, from Figure 4.2.3 and Table 4.2.2, the percentage weigth loss (%WL) of branchwood relative to stemwood of same species at same moisture content or level appeared to be species dependent. But generally at 9±3%MC level, some branchwood lost less weight (suggesting improved durability) relative to their stemwood counterparts. This could be due to factors from chemical content to anatomical structural differentials between wood of the stem and that of the branch.

At 9±3%MC, stemwood had percentage weight losses in the range of 27.269% (sapele) to 77.416% (mahogany) while branchwood registered weight losses in the range of 12.854% (sapele) to 71.878% (mahogany). The reverse of this trend is the case for koto and ofram with which branchwood rather lost much weight than their stemwood counterparts. These also appear to indicate that stem and branch woods of same species at same moisture content can have different natural durability status.

Hence, from Figure 4.2.3 and Table 4.2.2, whereas stemwood tested at 14±2%MC were described as moderately durable for only sapele and non-durable for edinam, mahogany, ofram and koto, their branchwood counterparts were described as moderately durable for only edinam and non-durable for sapele, mahogany, ofram and koto (Appendix 2). But for samples tested at 9±3%MC, the stemwood were moderately durable for sapele and edinam and non-durable for those of mahogany, ofram and koto, but their branchwood counterparts happened to be moderately durable for sapele and edinam, and non-durable for mahogany, ofram and koto. However, besides sapele and edinam, the difference in percentage weight losses of stemwood and branchwood was not statistically significant at 5% confidence level (Table 4.2.2). Thus, whereas the natural durability of branchwood of sapele and edinam appeared generally better than their stemwood, branchwood of the other species were comparable to their stemwood in terms of natural durability.

A Two-Way ANOVA (Table 4.2.3) established the effect of moisture levels and wood type/species on percentage weight loss of wood. Results showed that at 1% significant level, wood type/species had significant effect (F=41.928, p=0.000), moisture level also had significant effect (F=29.318, p=0.000) and the interaction between these two variables also had significant effect (F=3.114, p=0.001) on the percentage weight losses of stem and branch woods of the species. Also, moisture level and wood type/species explained 57% of the variation in percentage weight losses (Table 4.2.3).

Table 4.2.3: Two-Way ANOVA of the effect of MC and Wood Type on the percentage Weight Loss by Stem and Branch Woods Tested at Two Moisture Levels

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	267289.487[a]	21	12728.071	22.845	.000
Intercept	1347692.569	1	1347692.569	2.419E3	.000
Wood type/Species	233605.024	10	23360.502	41.928	.000
Moisture Levels	16334.645	1	16334.645	29.318	.000
Type of wood/Species * Moisture_Levels	17349.819	10	1734.982	3.114	.001
Error	183860.123	330	557.152		
Total	1798842.179	352			
Corrected Total	451149.610	351			

a. R Squared = .592 (Adjusted R Squared = .567)

4.2.2.1: Predicting percentage weight loss from moisture content and wood density as single predictor variables.

Regression analyses of the relationships between percentage weight losses (%WL) and moisture contents (MC), and also between %WL and wood density (WD) of stem and branch wood of the species are as presented in Figures 4.2.4 and 4.2.5 respectively. These relationships are necessary because, they offer a non-destructive and relatively less stressful method of determining the natural durability of the wood types.

From Figure 4.2.4, positive correlations were found between MC and %WL for both branch and stem woods for the two moisture levels. However, it appeared from the R^2 values that, there were generally strong associations between %WL and MC of both stem and branch woods within the 9±3%MC range relative to those in the 14±2%MC level. The R^2 values of stemwood samples tested at 14±2%MC ranged from the lowest of 0.210(koto) to the highest of 0.677(edinam), and those of branchwood ranged from the lowest of 0.038(mahogany) to the highest of 0.591(sapele). Meanwhile, the R^2 values for samples tested within 9±3%MC ranged from the lowest of 0.183(sapele) to the highest of 0.50 (mahogany) for stemwoods while those of branchwoods ranged from the lowest of 0.151 (sapele) to the highest of 0.715 (edinam) (From Figure 4.2.4). Thus, it appeared that MC can predict %WL accurately when wood is dried to a relatively lower MC than at a higher MC.

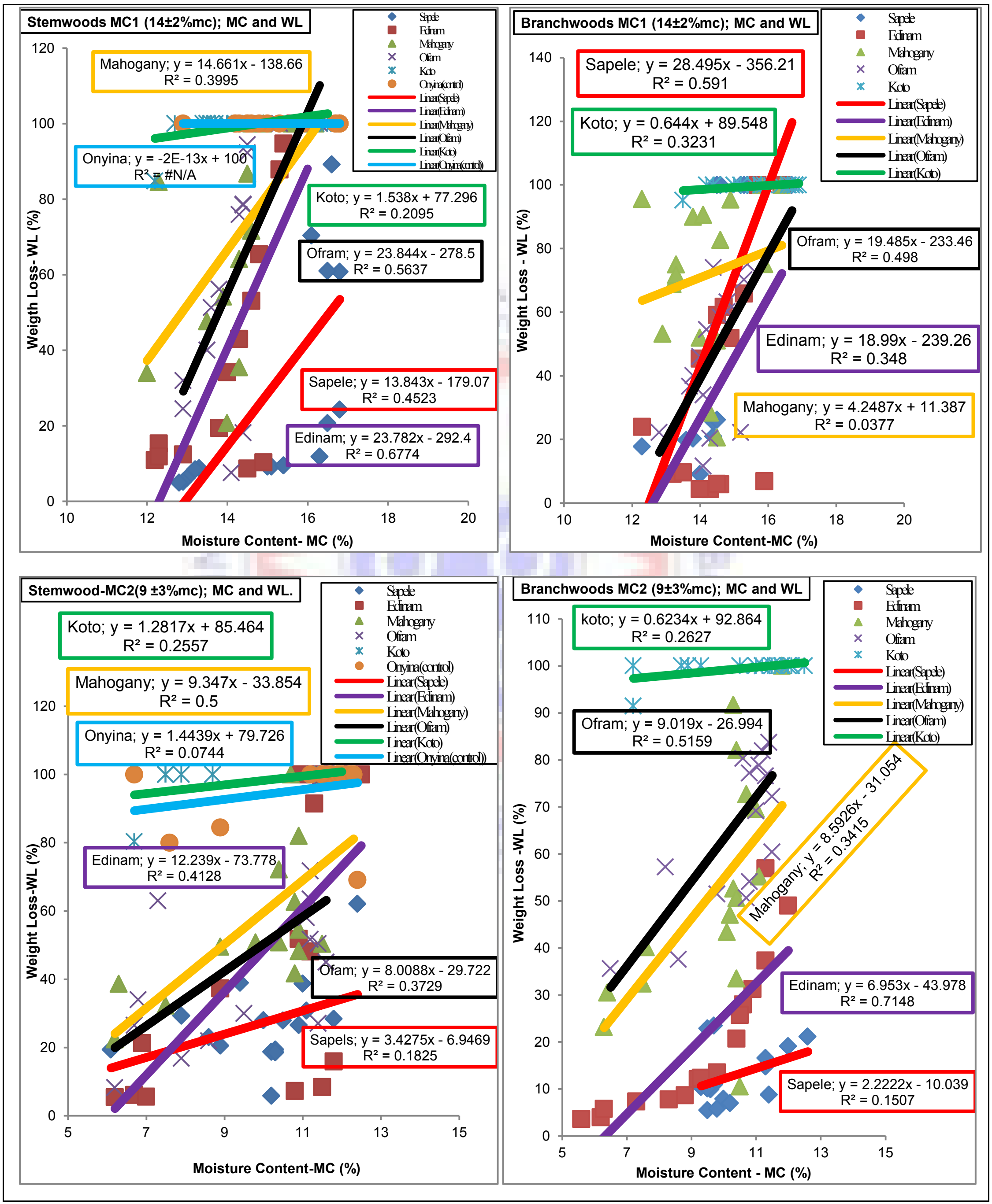


Figure.4.2.4. Relationship between Moisture Content and percentage Weight Loss of Stem and Branch Wood at Two Moisture Levels; N= 16.

Also, the coefficients of MC (**α** – equation 3.4) in the regression equations (Figure 4.2.4), generally appeared to be rather relatively higher for samples tested at

14±2%MC than those tested within 9±3%MC, suggesting that the rate of percentage weight loss due to 1% change in MC is higher when wood has much moisture than when it has less moisture. The **α** coefficients were also lower in stemwood than branchwood at 14±2%MC but the reverse was the case at 9±3%MC. For stemwood at 14±2%MC, 1% change in MC leads to %WL ranging from 23.84% (ofram) to 1.538%(koto), whereas at 9±3%MC, 1% change in MC could lead to %WL ranging from 12.24%(edinam) to 1.28%(koto). For branchwood, however, at 14±2%MC, 1% change in MC leads to %WL ranging from 28.50%(sapele) to 0.64%(koto) whereas at 9±3%MC, 1% change in MC could lead to %WL ranging from 9.02%(ofram) to 0.62%(koto). Thus, for stem and branch woods of same species, at high MC level, 1% change in MC leads to relatively higher %WL than at a lower MC level. Moisture content effect on %WL is relatively higher for stemwood than branchwood at high MC level, and the opposite is the case when stem and branch woods are at a lower MC level.

Figure 4.2.5 shows negative or inverse correlations between %WL (natural durability) and wood density (WD) of stem and branch woods of the studied species. Generally results presented in Figure 4.2.5 indicated that, at the same moisture content range, except for *P. macrocarpa* (koto), branchwood had relatively higher density than their corresponding stemwood samples.

From Figure 4.2.5 and appendix 2, mean stemwood density ranged from the highest of 658.936kg/m^3 for *E. cylindricum* (sapele) at 14±2%MC to the lowest of 491.920kg/m^3 at 9±3% for *K. ivorensis* (mahogany), whereas the branchwoods had mean densities from the highest of 688.616kg/m^3 for *T. superba* at 14±2%MC, to the lowest of 547.672kg/m^3 for *K. ivorensis* at 9±3% MC. These generally suggest that except for *P. macrocarpa*, branchwood of the studied species had higher density than their stemwood counterpart at the same MC range.

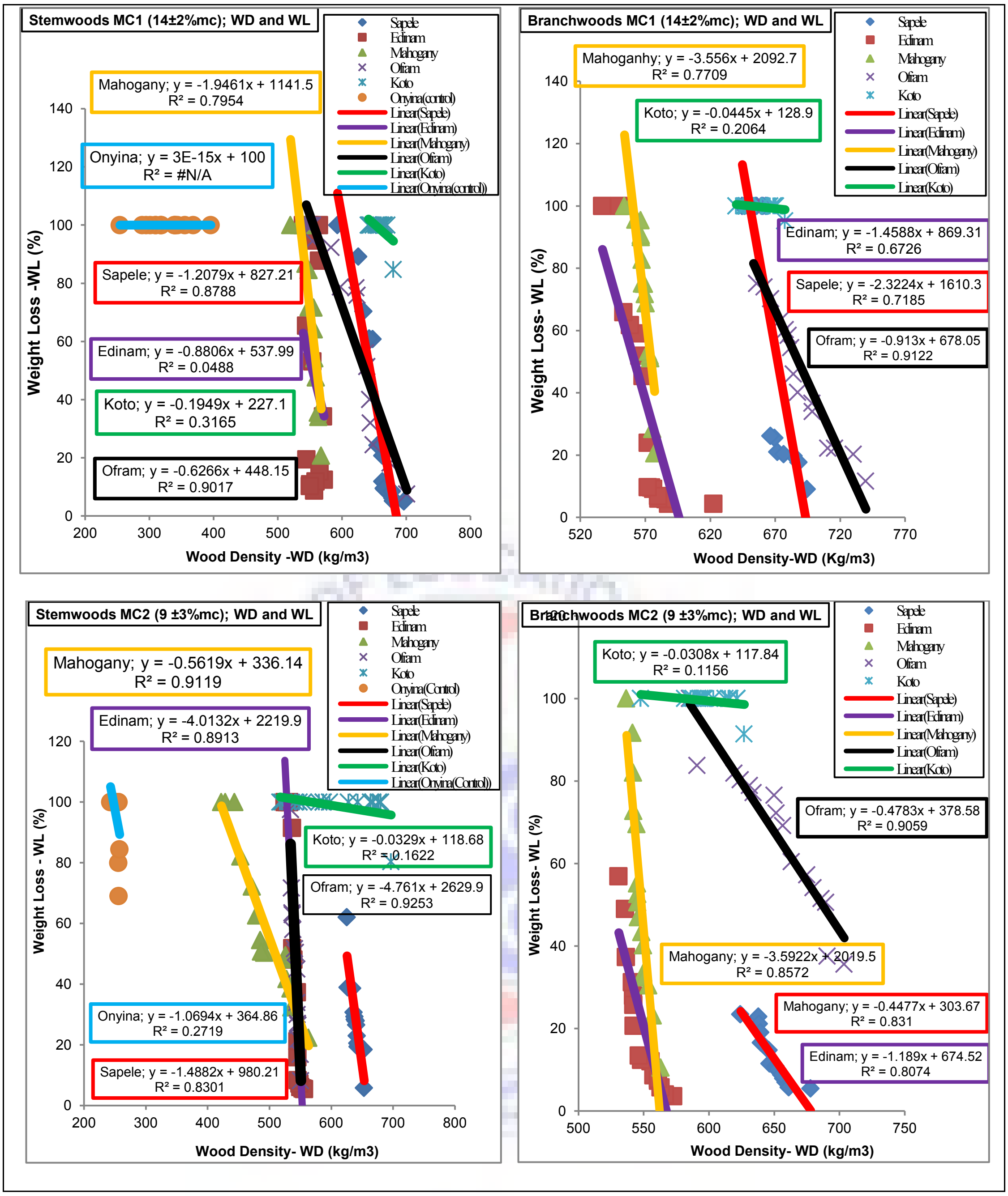


Figure.4.2.5. Relationship between percentage Weight Losses and Wood Density of Stem and Branch wood at Two Moisture Levels; N= 16.

Moreover, from Figure 4.2.5, the strengths of the relationships (R^2 values) suggested that within similar moisture content range, density can predict %WL (natural durability) of both stem and brach wood to about 90% level of accuracy. The R^2 values for stemwood samples tested at 14±2%MC ranged from 0.317(Koto) to 0.925 (ofram) and those of branchwoods were from 0.116 (koto) to 0.912 (ofram) for the branchwood. For samples at 9±3%MC, the R^2 values of stemwoods (besides the reference species) ranged from 0.162 (koto) to 0.925 (ofram), while those of the branchwoods ranged from 0.116 (koto) to 0.906 (ofram).

The coefficient of density (**β** – Equation 3.5) suggested that density affects the natural durability of both branch and stem woods of the species but the effect is also influenced by moisture content. Hence generally, density appeared to have higher effect on %WL of samples dried to 9±3%MC than those dried to 14±2%MC, and this effect appears to favour branchwood than stemwood, since higher %WL implies less durability of the wood. At 14±2%MC level, **β** was generally higher for branchwoods (from 0.045-ofram to 3.556-mahogany) than stemwoods (from 0.195-koto to 1.946-mahogany). This trend however reversed for samples in 9±3%MC range and stemwood had relatively higher coefficients (from 0.033-koto to 4.761-ofram) than their branchwood counterpart (from 0.031-koto to 3.592-mahogany).

4.2.2.2: Predicting percentage weight loss of stem and branch wood from moisture content and wood density as combined predictor variable

Table 4.2.4 presents the regression relationship between moisture content (MC) combined with wood density (WD) as one predictor variable for percentage weight loss (%WL) of stem and branch woods of the studied species. The R^2 values suggest that MC and WD combined can predict %WL (natural durability) a little more accurately than using MC or WD alone and the p-values indicated that density has significant influences ($p<0.01$; $p<0.05$ and $p<0.1$) on %WL than moisture content.

Table 4.2.4. Moisture Content and Wood Density as Combined Predictor Variables for Percentage Weight Losses (Natural Durability) of Wood.

				Unstandardized coefficients		Standardized coefficients			
Wood Type /Species & Moisture Content	**N**	**Equation**	**Symbol**	**B**	**Std. Error**	**Beta**	**t-Value**	**P-Value**	**R^2 Ad.**
Sapele Stemwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	906.942	160.825		5.639	.000***	0.864
			α	1.720	2.996	.084	.574	.576ns	
			β	-1.289	.188	-1.001	-6.873	.000***	
MC2 (9±3% mc)	16		c	906.977	107.431		8.442	.000***	0.857
			α	1.772	.807	.221	2.195	.047*	
			β	-1.401	.164	-.858	-8.530	.000***	
Sapele Branchwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	1686.280	844.416		1.997	.067*	0.675
			α	1.272	13.408	.034	.095	.926ns	
			β	-2.408	.991	-.879	-2.430	.030**	
MC2 (9±3% mc)	16		c	286.229	39.884		7.177	.000***	0.817
			α	.621	.667	.109	.932	.368sn	
			β	-.431	.057	-.877	-7.530	.000***	
Edinam Stemwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	1256.863	259.430		4.845	.000***	0.902
			α	12.244	3.023	.424	4.051	.001***	
			β	-2.490	.414	-.630	-6.023	.000***	
MC 2 (9±3% mc)	16		c	2463.476	321.849		7.654	.000***	0.883
			α	2.445	2.507	.128	.975	.347^{ns}	
			β	-4.418	.560	-1.039	-7.895	.000***	
Edinam Branchwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	611.326	205.466		2.975	.011**	0.696
			α	9.062	5.116	.282	1.771	.100^{ns}	
			β	-1.237	.283	-.695	-4.375	.001***	
MC2 (9±3%mc)	16		c	905.988	361.915		2.503	.026**	0.785
			α	2.447	3.713	.298	.659	.521^{ns}	
			β	-1.569	.597	-1.185	-2.626	.021**	
Mahogany Stemwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	981.524	215.051		4.564	.001***	0.781
			α	3.523	3.502	.152	1.006	.333^{ns}	
			β	-1.747	.329	-.801	-5.304	.000***	
MC2 (9±3% mc)	16		c	361.946	51.195		7.070	.000***	0.901
			α	.959	1.689	.073	-.568	.580^{ns}	
			β	-.595	.075	-1.011	-7.914	.000***	
Ma‟gan Branchwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	2375.378	327.206		7.260	.000***	0.781
			α	4.794	2.923	.219	1.640	.125^{ns}	
			β	-3.933	.541	-.971	-7.273	.000***	
MC 2 (9±3% mc)	16		c	1916.249	279.833		6.848	.000***	0.840
			α	1.110	1.862	.075	.596	.561^{ns}	
			β	-3.423	.491	-.882	-6.969	.000***	

Table 4.2.4 (Continuation)

Wood Type /Species & Moisture Content	N	Equation	Symbol	Unstandardized Coefficients		Standardized Coefficients	t-Value	P-Value	R^2 Adj.
				B	Std. Error	Beta			
Ofram Stemwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	398.780	107.682		3.703	.003***	0.889
			α	2.049	4.228	.065	.485	.636^{ns}	
			β	-.594	.088	-.900	-6.763	.000***	
MC2 (9±3% mc)	16		c	2519.728	254.912		9.885	.000***	0.917
			α	.843	1.211	.064	.696	.499^{ns}	
			β	-4.573	.457	-.924	-10.008	.000***	
Ofram Branchwood		WL = C + αMC + βWD							
MC1 (14±2%mc)	16		c	478.606	61.845		7.739	.000***	0.954
			α	7.244	1.818	.262	3.985	.002***	
			β	-.776	.063	-.812	-12.331	.000***	
MC2 (9±3% mc)	16		c	310.586	39.369		7.889	.000***	0.920
			α	2.548	1.172	.203	2.174	.049*	
			β	-.415	.047	-.825	-8.841	.000***	
Koto Stemwood		WL = C + αMC + βWD							
MC1 (14+/-2%mc)	16		c	254.666	122.687		2.076	.058*	0.215
			α	-.379	1.528	-.113	-.248	.808^{ns}	
			β	-.229	.158	-.660	-1.451	.170^{ns}	
MC2 (9±3% mx)	16		c	91.809	23.671		3.878	.002***	0.146
			α	1.115	.850	.440	1.312	.212^{ns}	
			β	-.008	.027	-.093	-.278	.785ns	
Koto Branchwood		WL = C + αMC + βWD							
MC1 (14+/-2%mc)	16		c	36.653	51.318		.714	.488ns	0.278
			α	1.338	.715	1.181	1.870	.084*	
			β	.064	.062	.653	1.034	.320^{ns}	
MC2 (9±3% mc)	16		c	104.504	14.487		7.214	.000***	0.191
			α	.548	.297	.450	1.845	.088*	
			β	-.018	.022	-.201	-.822	.426^{ns}	
Onyina Stemwood		WL = C + αMC + βWD							
MC2 (9±3% mc)	16		c	340.424	120.469		2.826	.014**	0.218
			α	1.189	1.215	.225	.979	.346^{ns}	
			β	-1.025	.471	-.500	-2.178	.048*	

NOTE: The statistical analyses are significant at 95% confidence level. ***p < 0.01; **p < 0.05; *p <0.1; and non-significant, ^{ns}p > 0.1; N; number of samples, WD: wood density (kg/m^3); MC: moisture content of wood (%); WL: weight loss (%).

Generally, from Table 4.2.4 MC and WD combined resulted in some marginal increases in the values of the coefficient of determination (R^2) for some species relative to those obtained when MC and WD were used as single predictor variables (Figures 4.2.4 and 4.2.5). The highest R^2 value with MC as a single predictor variable was 0.677 (edinam at 14±2%MC range) for stemwood and 0.715 (edinam at 9±3%MC range) for branchwood, whereas with WD as a single variable, the highest R^2 value was 0.925 (ofram at 9±3%MC range) for stemwood and 0.912 (ofram at 14±2%MC) for branchwood. However, with MC and WD as combined predictor variable, the highest R^2 values were 0.917 (ofram at 9±3%MC range) for stemwood and 0.954 (ofram at 14±2%MC range) for branchwood.

Moreover, generally, for both stem and branch woods, the **α** and **β** unstandardised coefficients for moisture content and wood density respectively (Equation 3.6), were higher for samples with higher moisture levels (i.e. 14±2%MC range) than their counterparts with relatively lower moisture (i.e. 9±3%MC range). This indicates that weight loss of both stem and branch woods as influenced by moisture content and density is higher when the MC level is high than when the MC is low. This also show that the resistance of both stem and branch wood and for that matter their natural durability is improved when the moisture level is relatively low.

4.3: Static Bending Strength of Solid/Unjointed and Finger-Jointed Lumber

Static bending strength of both solid and finger-jointed lumber from stem and branch woods were evaluated under two moisture conditions (17±3%-air-dried MC level and 10±4%-kiln-dried MC level).

4.3.1: Static bending strength of solid stem and branch wood

Modulus of elasticity (MOE) and modulus of rupture (MOR) of stem and branch wood were assesed at the two MC levels. The detailed experimental results on solid stem and branch wood are presented in Appendix 3.

4.3.1.1: Modulus of Elasticity (MOE) of solid wood

Figure 4.3.1 shows the graphical presentation whereas Table 4.3.1 shows the summary descriptive statistics and one-way ANOVA of the mean modulus of elasticity (MOE) of solid stem and branch wood tested at 2 moisture conditions.

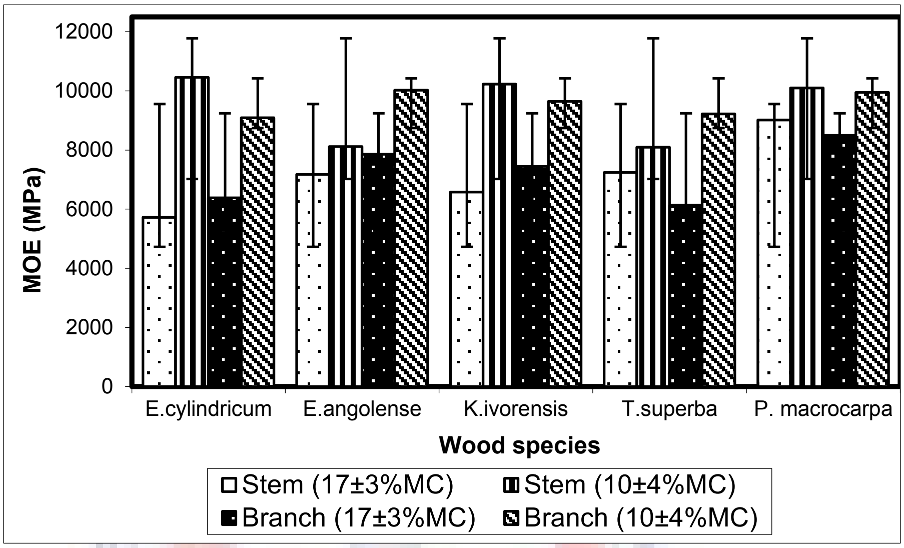


Figure 4.3.1: Mean Modulus of Elasticity of Solid Stem and Branch Woods Tested at Two Moisture Conditions; N=20, Error bars = SD.

From Figure 4.3.1 and Table 4.3.1, generally, both stem and branch woods of all the species dried to 10±4%MC exhibited higher MOE than their counterparts dried to 17±3%MC. This indicates that the known fact that MC affects MOE of stemwood is also applicable to branchwood. The MOE for the stemwood dried to 10±4%MC were 10.46GPa, 8.12GPa, 10.23GPa, 8.10GPa, and 10.10GPa. respectively for sapele, edinam, mahogany, ofram and koto. But the stemwood of the species tested at 17±3%-%MC obtained decreases in MOE of 45.3%, 11.6%, 33.8%, 10.6% and 10.8% respectively. Moreover, branchwood dried to 10±4%MC obtained MOE of 9.09GPa, 10.03GPa, 9.64GPa, 9.22GPa, and 9.95GPa. respectively for sapele, edinam, mahogany, ofram and koto. But branchwood of the species dried to 17±3%MC exhibited 29.8%, 21.7%, 22.8%, 33.5% and 14.7% reduction in MOE respectively.

Table 4.3.1. Summary Descriptive Statistics and One-Way ANOVA of MOE Values of Solid Stem and Branch Wood of Species Tested at Two Moisture Levels.

Species	Moisture level (%)	Wood Type	MOE (MPa)	F- value	P-value
			Mean (SD)		
Entandrophragma cylindricum (sapele)	17±3	Stemwood	5719.75 (1451.80)	2.753	.105
		Branch	6385.10 (1052.90)		
	10±4	Stemwood	10461.00 (3213.20)	2.752	.106
		Branch	9094.50 (1638.80)		
Entandrophragma angolense (edinam)	17±3	Stemwood	7177.30 (983.54) ^{a}	3.713	.062*
		Branch	7853.90 (1224.39) ^{a}		
	10±4	Stemwood	8119.75 (842.09)^{b}	22.999	.000***
		Branch	10025.50(1565.00)^{b}		
Khaya ivorensis (mahogany)	17±3	Stemwood	6576.75 (1021.81)^{a}	10.703	.002***
		Branch	7448.70 (613.65)^{a}		
	10±4	Stemwood	10233.10 (721.39)	1.909	.175
		Branch	9642.80 (1768.87)		
Terminalia superba (ofram)	17±3	Stemwood	7238.30 (1333.00)^{a}	6.910	.012**
		Branch	6135.55 (1320.13)^{a}		
	10±4	Stemwood	8100.55(1124.54)^{b}	7.173	.011**
		Branch	9221.68 (1474.66)^{b}		
Pterygota macrocarpa (koto)	17±3	Stemwood	9011.40 (946.56)	1.257	.269
		Branch	8490.90 (1847.87)		
	10±4	Stemwood	10102.10 (1261.68)	.103	.652
		Branch	9952.15 (1669.99)		

Note: Mean values with the same letters indicate significant difference at 95% confidence level. *significant at $p \leq 0.1$; **significant at $p \leq 0.05$ and ***$p \leq 0.01$.

Again, from the results (Figure 4.3.1 and Table 4.3.1), whereas stemwood of some species exhibited higher MOE than their branchwood counterpart dried to similar moisture content range, other species had their stemwood exhibiting lower MOE. For instance, whereas the MOE of branchwood dried to 10±4%MC of edinam and ofram respectively attained 23.5%, and 13.8% increases in MOE over their stemwood counterparts, branchwood of sapele, mahogany and koto exhibited reductions in MOE of 13.06%, 5.77%, 10.25% respectively relative to their respective stemwood. However, generally, at both two moisture conditions the differences in MOEs of branchwood of edinam and ofram were significantly higher than their stemwood counterparts, whereas the differences between stem and branch woods of sapele and koto were not statistically significant at 95% significance level

(Table 4.3.1). These appear to indicate that, in terms of MOE, branchwood of the species could safely and even perform better as supplementary materials to their respective stemwood.

The two-way ANOVA (Table 4.3.2) provided further evidence of the influence of moisture level and wood type/species on MOE. Results from Table 4.3.2 indicated that moisture level had significant effect (F=245.593, p= 0.000), wood type also had significant effect (F= 9.256,p=0.000), and also the interaction of moisture level and wood type had significant effect (F= 9.256, p= 0.000) on the MOE at 1% significant levels. Additionally, from the table, moisture level of wood and wood type explained 49% of the variation in MOE. Thus, moisture content significantly affected the MOE of wood.

Table 4.3.2. Two-way ANOVA of the effect of MC and Wood Type on MOE of Stem and Branch Wood tested at Two Moisture Levels.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8.487E8[a]	19	4.467E7	21.001	.000
Intercept	2.774E10	1	2.774E10	1.304E4	.000
Wood Types/specie	1.772E8	9	1.969E7	9.256	.000
Moisture Levels	5.224E8	1	5.224E8	245.593	.000
Wood Types/species * Moisture_Levels	1.467E8	9	1.630E7	7.661	.000
Error	8.040E8	378	2126950.413		
Total	2.937E10	398			
Corrected Total	1.653E9	397			

a. R Squared = .514 (Adjusted R Squared = .489)

4.3.1.2: Modulus of Rupture (MOR) of solid wood

Figure 4.3.2 and Table 4.3.3 also present the bending strength (modulus of rupture-MOR) of solid stem and branch wood of the studied species tested at 2 moisture conditions. From the results generally, like the MOE, both stem and branch wood dried to 10±4%MC exhibited higher MOR than their counterparts dried to 17±3%MC, implying that moisture content affected MOR. The stemwood dried to 10±4%MC obtained MOR of 101.49MPa, 78.57MPa, 85.48MPa, 76.44MPa and

86.87MPa respectively for sapele, edinam, mahogany, ofram and koto, whereas their counterparts dried to 17±3%MC had 34.4%, 19.6%, 33.1%, 22.7%, and 16.8% decreases in MOR respectively.

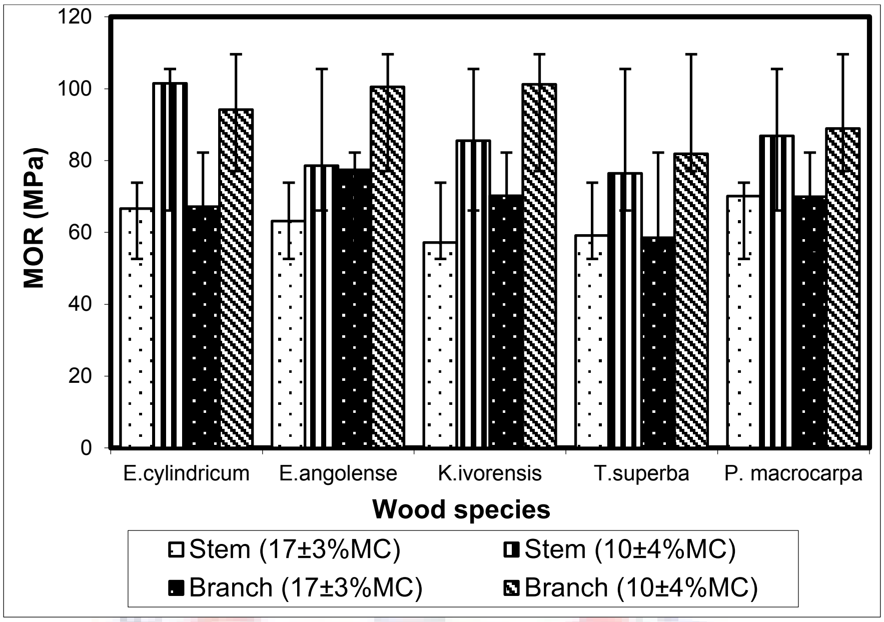


Figure 4.3.2. Mean modulus of rupture of solid stem and branch wood tested at two moisture conditions; N=20, Error bars = SD

Also from the results, branchwood dried to 10±4%MC had MOR of 94.13MPa, 100.52MPa, 101.24MPa, 81.88MPa, and 88.92MPa respectively for sapele, edinam, mahogany, ofram and koto, but their counterparts dried to 17±3% MC respectively showed 28.6%, 23.0%, 30.7%, 28.5%, 21.4% reduction in MOR (Figure 4.3.2, Table 4.3.3). These appeared to suggest that moisture content affected the MOR of both stem and branch woods but the level of the effect is species dependent.

Additonally, though the results presented in Figure 4.3.2 and Table 4.3.3 indicated that some stemwood exhibited either lower or higher MOR than their branchwood counterpart, the results appeared to generally suggest that branchwood exhibited higher MOR than their counterpart stemwood at similar moisture content range. Stemwood of sapele, edinam and mahogany dried to 17±3% MC exhibited reduction of 0.9%, 18.4% and 18.5% respectively in MOR, but ofram and koto respectively registered 0.9%, and 0.2% increases in MOR compared to their branchwood counterparts. Moreover, compared to their branchwood, the MOR of stemwood of edinam, mahogany, ofram and koto dried to 10±4% MC showed 21.8%, 15.6%, 6.6% and 2.3% reductions respectively but sapele exhibited 7.8% increase in MOR.

Table 4.3.3: Summary Descriptive Statistics and One-Way ANOVA of MOR values of Solid Stem and Branch Wood of Species Tested at Two Moisture Levels.

Species	Moisture level (%)	Wood Type	MOR (MPa) Mean (SD)	F- value	P-value
Entandrophragma cylindricum (sapele)	17±3	Stemwood	66.60 (13.36)	.025	.875
		Branch	67.17 (8.88)		
	10±4	Stemwood	101.49 (35.37)	.726	.400
		Branch	94.13 (13.12)		
Entandrophragma angolense (edinam)	17±3	Stemwood	63.15 (5.64) ^{a}	41.376	.000***
		Branch	77.37 (8.12) ^{a}		
	10±4	Stemwood	78.57 (7.80) ^{a}	29.180	.000***
		Branch	100.52 (16.42) ^{a}		
Khaya ivorensis (mahogany)	17±3	Stemwood	57.19 (11.36) ^{a}	18.596	.000***
		Branch	70.16 (7.19) ^{a}		
	10±4	Stemwood	85.48 (10.76)^{a}	15.628	.000***
		Branch	101.24 (14.23)^{a}		
Terminalia superba (ofram)	17±3	Stemwood	59.09 (15.64)	.012	.914
		Branch	58.54 (16.80)		
	10±4	Stemwood	76.44 (14.99)	1.114	.298
		Branch	81.88 (17.17)		
Pterygota macrocarpa (koto)	17±3	Stemwood	70.11 (11.99)	.001	.269
		Branch	69.94 (16.80)		
	10±4	Stemwood	86.87 (14.76)	.207	.652
		Branch	88.92 (13.79)		

Note: Mean values with the same letters indicate significant difference at 95% confidence level. *significant at $p \leq 0.1$; **significant at $p \leq 0.05$ and ***$p \leq 0.01$.

Hence, it could be said that wood type also have effect on the MOR. However, from Table 4.3.3, the MOR of branchwood of edinam and mahogany at both 2 MC levels were significantly higher ($p<0.01$) than their stemwood counterparts whereas the differences in MOR between stemwood and branchwood of sapele, ofram and koto were not statistically significant at 95% significance level. Therefore, in terms of applications where MOR is of interest, edinam and mahogany branchwood could perform even better than their stemwood counterparts whereas branchwood of sapele, ofram and koto could all be covenient supplements to their respective stemwood at similar moisture levels.

Moreover, a two-way ANOVA (Table 4.3.4) was performed to provide further information on the effect of moisture level and wood type on MOR.

Table 4.3.4. Two-way ANOVA of the effect of MC and Wood Type on the MOR of Solid Stem and Branch wood tested at Two Moisture Levels

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	78834.415[a]	19	4149.180	18.493	.000
Intercept	2404915.231	1	2404915.231	1.072E4	.000
Wood Types/species	19336.419	9	2148.491	9.576	.000
Moisture_Levels	55513.642	1	55513.642	247.423	.000
Wood Types/species * Moisture_Levels	3909.112	9	434.346	1.936	.046
Error	84810.995	378	224.368		
Total	2565939.853	398			
Corrected Total	163645.410	397			

a. R Squared = .482 (Adjusted R Squared = .456)

From Table 4.3.4, moisture level had significant effect (F=247.423, p= 0.000), wood type/species also had significant effect (F= 9.576, p= 0.000) both at 1% significance level whereas the interaction between moisture level and wood type had significant effect (F= 1.936, p= 0.046) but at 5% significance level on MOR of solid stem and branch woods. Moreover, results from the Table indicated that moisture level of wood and wood types explained 46% of the variability in MOR.

From all the findings in this section, it could generally be concluded that: moisture content affected both the MOE and MOR of both stem and branch wood, and the differences in MOE and MOR of stem and branch wood at same moisture levels were species dependent but not statistically significant (p>0.1).

4.3.1.3: Predicting bending strength of solid wood from density and moisture content

The relationships between wood density, MOE and MOR, and moisture content, MOE and MOR were determined to assess any difference in the relationships for stem and branch woods of same species. These relationships could also serve as a possible non-destructive method of determining MOE and MOR of stem and branch woods. In view of these, density and moisture content were used as single predictor variables and combined predictor variable for both MOE and MOR. Meanwhile, generally, the density of both stem and branch woods of all species tested at 17±3% MC were higher than their counterparts tested at 10±4% MC (Figure 4.3.3).

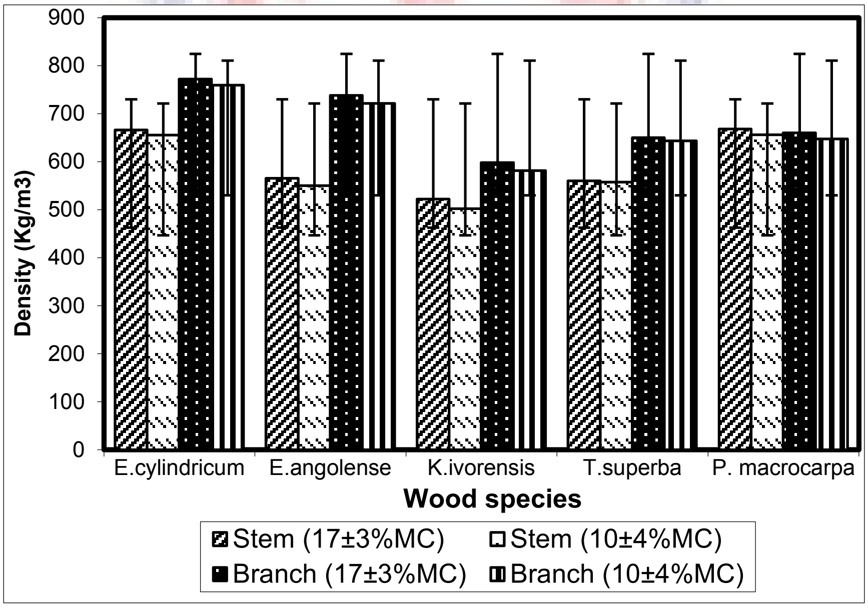


Figure 4.3.3. Mean Density of Solid Stem and Branch Wood Determined at Two Moisture Conditions; N=20, Error Bars= SD

From Figure 4.3.3 and Appendix 3, generally, at each moisture range, except for *Pterygota macrocarpa*, branchwood exhibited higher density than their stemwood counterparts of the same species. The stemwood dried to 17±3% MC had density of 666kg/m^3, 565kg/m^3, 522kg/m^3, 560kg/m^3 and 668kg/m^3 for *Entandrophragma cylindricum*-sapele, *Entandrophragma angolense*-edinam, *Khaya ivorensis*-

mahogany, *Terminalia superba*-ofram, and *Pterygota macrocarpa*-koto respectively. However, stemwood of the respective species dried to 10±4%MC and recorded reductions of 1.7%, 2.7%, 3.8%, 0.5%, 1.8% respectively. Meanwhile, compared to their stemwood counterparts, the branchwood dried to 17±3%MC also registered increases of 15.9%, 30.6%, 14.6%, 16.7% respectively for sapele, edinam, mahogany and ofram, but koto branchwood exhibited a decrease of 1.2%. Also, branchwood of sapele, edinam, mahogany and ofram dried to 10±4%MC obtained increases of 15.9%, 31.1%, 15.7%,15.4% respectively in density compared to their stemwood counterparts, but koto had a decrease of 1.4% relative to its stemwood. These observed trends in density between stem and branch woods of the species as well as the deviation of koto from the observed trend could be due to genetical, anatomical or chemical differences between stem and branch woods of the species.

4.3.1.3.1: Predicting bending strength of solid wood from density

Density of stem and branch wood were found to be positively correlated with their MOE and MOR as presented in Figures 4.3.4 and 4.3.5 respectively. From Figure 4.3.4, the R^2 values for density and MOE for wood at 17±3%MC levels ranged from 0.686(edinam) to 0.797(koto) for stemwoods, and from 0.794(ofram) to 0.948(edinam) for branchwoods. At 10±4%MC, the R^2 values of stemwoods were in the range of 0.524(sapele) to 0.923(ofram), and those of branchwoods ranged from 0.367(mahogany) to 0.915 (sapele). These mean that at 17±3%MC, density can predict branchwood MOE to a relatively higher accuracy (from 79% to 95%) than as it will predict stemwood MOE (from 69% to 80%) but the prediction accuracies appear to be similar for both stem and branch woods at 10±4%MC.

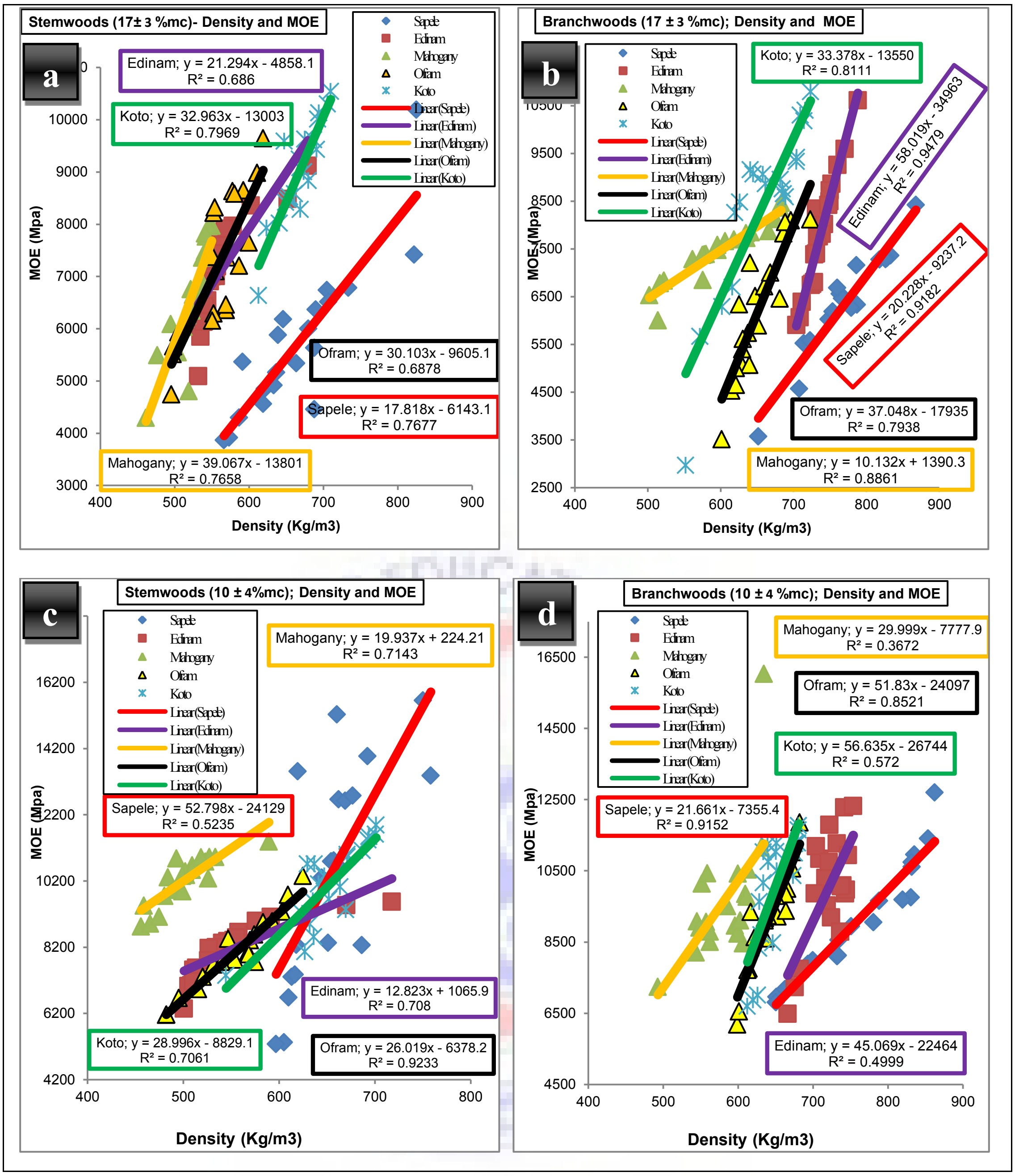


Figure 4.3.4. Relationships between Density and MOE of Stem and Branch Woods tested at two Moisture Levels; N= 20.

Again generally, the regression coefficients of wood density (**β** -Equation 3.9) for MOE were found to be generally higher for branchwoods than stemwoods of the various species studied at the two MC levels. However, for stemwood, those at 17±3% MC had higher coefficients than their counterparts at 10±4%MC while the reverse was the case for branchwoods. For stemwood, at 17±3% MC 1kg/m^3 change in density could result in a change in MOE of between 17.81MPa (sapele) and

39.1MPa (mahogany), and at 10±4% MC, 1kg/m^3 change in density could result in a change in MOE of between 12.8MPa (edinam) and 52.8MPa (sapele). However, for branchwood, at 17±3% MC 1kg/m^3 change in density could result in a change in MOE of between 10.1MPa (mahogany) and 58.0MPa (edinam), and at 10±4% MC, 1kg/m^3 change in density could result in a change in MOE of between 21.7MPa (sapele) and 56.6MPa (koto). These suggest that the strength of the relation and the rate of change of MOE per 1kg/m^3 change in density of stem and branch woods are moisture content and species dependent. However, from the R^2 values, density can predict the MOE of both stem and branch woods to accuracies from 37% (mahogany branchwood at 10±4%MC) to about 95% (edinam branchwood at 17±3%MC) for others, though the influence of density appeared to be higher on branchwood MOE than stemwood MOE (Figure 4.3.4).

From Figure 4.3.5, density and MOR at 17±3%MC produced R^2 values in the range of 0.599(edinam) to 0.893(mahogany) for stemwoods, and from 0.790(koto) to 0.915(edinam) for branchwoods. However, at 10±4%MC, stemwoods had R^2 values in the range of 0.685(edinam) to 0.920(mahogany) whereas branchwoods had from 0.729(mahogany) to 0.880(ofram). These suggested that at a relatively higher MC (17±3%), stemwood density had stronger relationship with MOR than branchwood density, but at a relatively lower MC (10±4%), the strengths of the relationships between stemwood density and branchwood density with MOR were about the same.

Again from Figure 4.3.5, the regression coefficients of wood density (**β**) for MOR were generally higher at relatively lower MC (10±4%MC) than higher MC (17±3%MC) for both stem and branch woods, though considering the individual species, branchwood appeared to have marginal leverage over stemwood at both 2 MC levels. For stemwood, 1kg/m^3 change in density could result in between 0.11MPa (edinam) and 0.47MPa (mahogany) change in MOR at 17±3%MC, and between 0.12MPa(edinam) and 0.71MPa (sapele) in MOR at 10±4%MC. However, for branchwood, 1kg/m^3 change in density could result in between 0.12MPa (mahogany) and 0.47MPa (ofram) change in MOR at 17±3%MC, and between 0.12MPa(sapele) and 0.61MPa (ofram) in MOR at 10±4%MC.

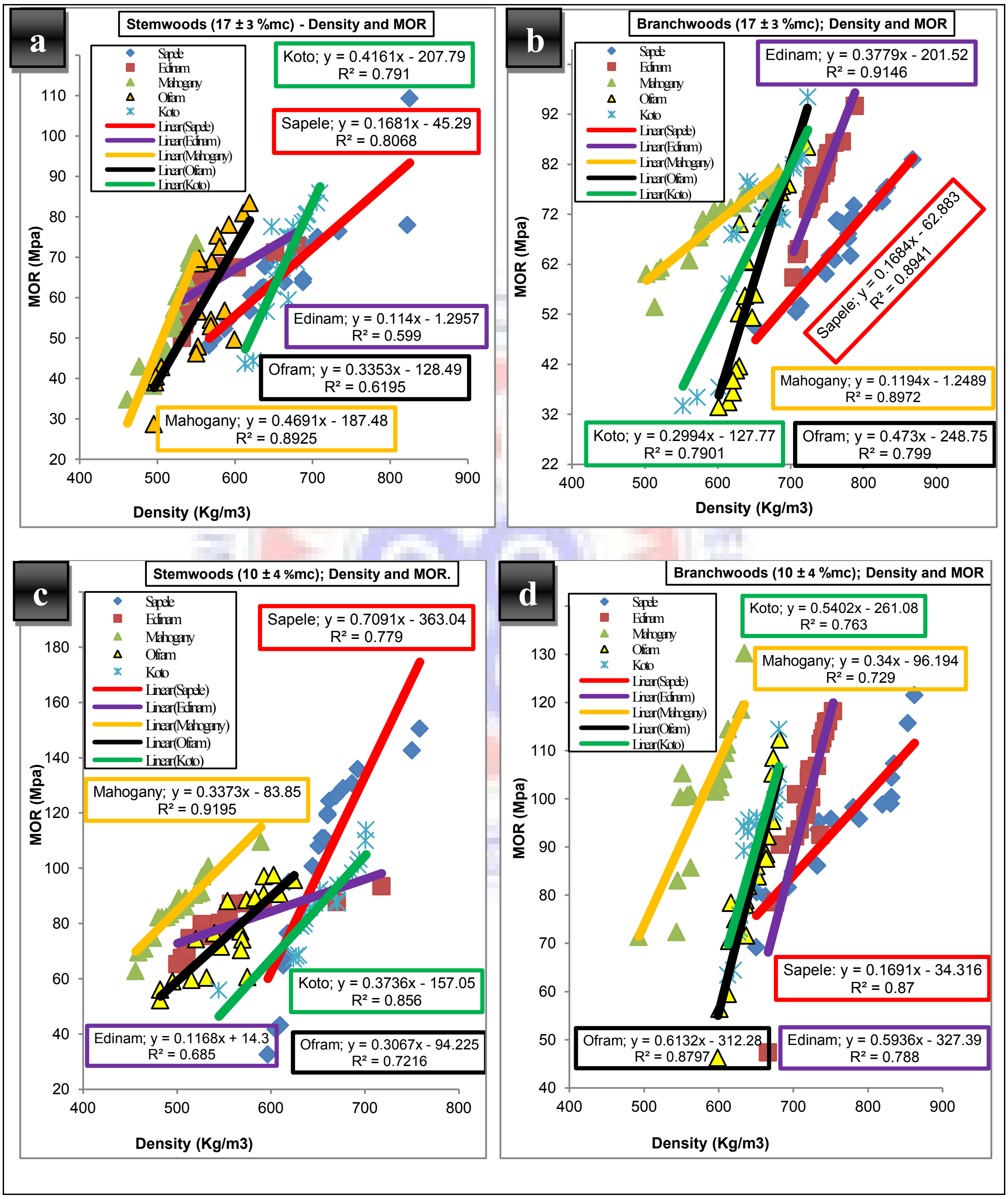


Figure 4.3.5. Relationships between Density and MORs of Wood tested at Two Moisture Levels; N=20.

These R^2 and **β** values appeared to suggest general strong relationships of density of both stem and branch woods with their MOR, but both the relationships and the effect of change in density on MOR are moisture content denpendent. Additionally, the R^2 values indicated that density can predict MOR of both stem and branch wood to accuracies of between 60% (edinam stemwood at 17%MC) and 92% (edinam branchwood at 10%MC and Mahogany stemwood at 10%MC).

4.3.1.3.2. Predicting bending strength of solid wood from moisture content

Figures 4.3.6 and 4.3.7 respectively presents the relationships between moisture content and MOE, and MOR of stem and branch wood. Moisture content correlated negatively with MOE of both stem and branch woods. The strength of the relationship (R^2 values) appeared higher for branchwood than stemwood. Stemwood samples tested at 17±3%MC had R^2 values ranging from 0.345(edinam) to 0.760(ofram) whereas those of branchwood ranged from 0.460(koto) to 0.900(mahogany). Also, stemwoood samples tested at 10±4%MC had R^2 values from 0.269(koto) to 0.742(mahogany) whereas branchwood counterparts had 0.254(ofram) to 0.815(mahogany). (Figure 4.3.6).

The coefficient of MC (**α** – Equation 3.8) were also found to be generally higher for branchwood than stemwood at both two MC levels, however for both branchwood and stemwood, the values of **α** were generally higher for the samples tested at 10±4%MC than those tested at 17±3%MC. From the R^2 and **α** values, MC can predict MOE of stem and branch wood to about 76% and 90% levels of accuracy respectively, but the rate of increases in MOE of both stem and branch wood per 1% change in MC is higher for samples at a lower MC range than those at a relatively higher MC range.

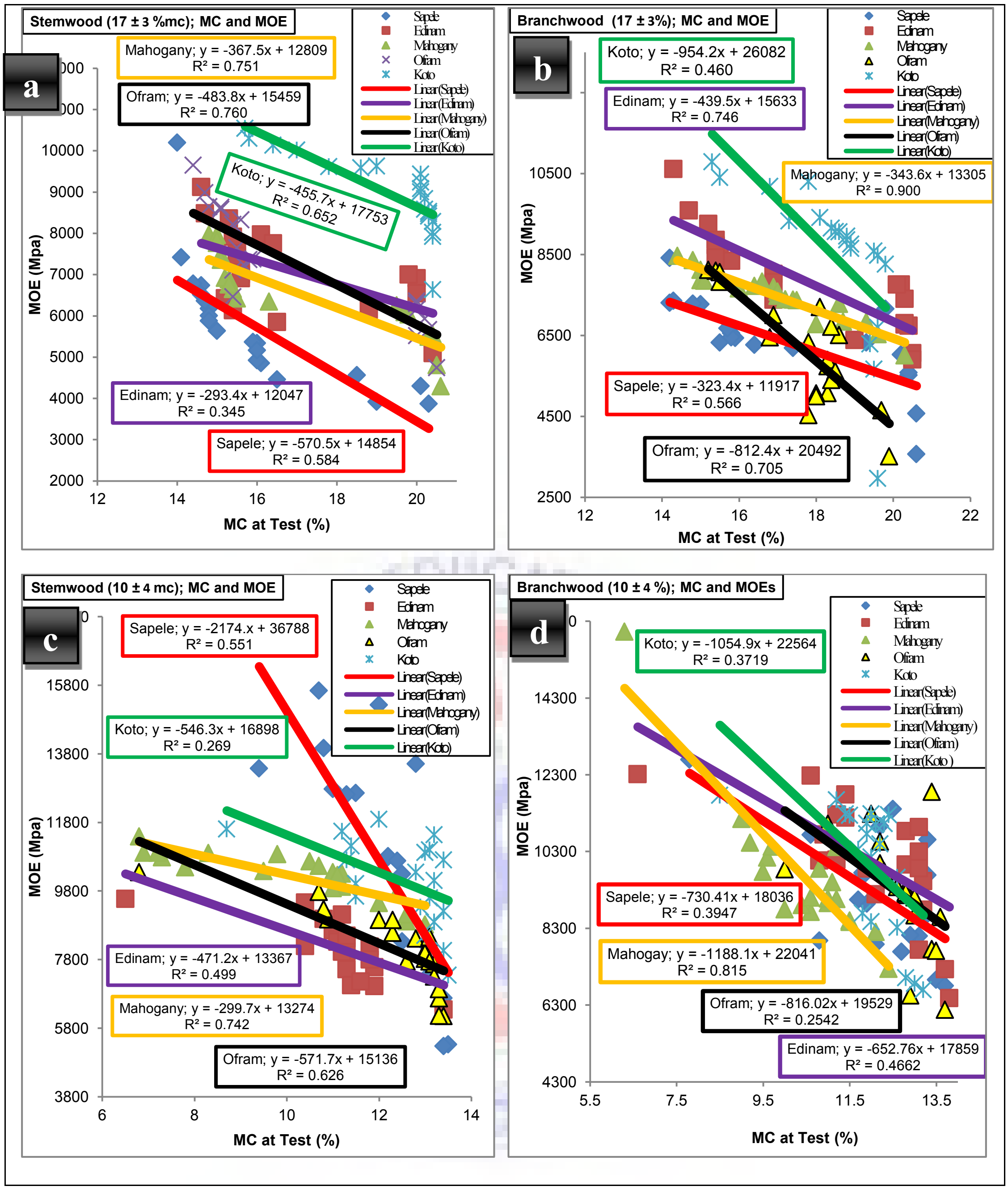


Figure 4.3.6. Relationship between Moisture Content and MOEs of Stem and Branch Woods Tested at Two Moisture Levels; N=20.

Figure 4.3.7 also shows negative correlation of moisture content and modulus of rupture (MOR) of wood. Implying that as wood dries (decreases in MC) its MOR increases. The R^2 values however suggested moderate to strong relationships between MOR and MC for branchwood than for stemwood. The R^2 values for stemwood samples tested at 17±3%MC ranged from 0.262(edinam) to 0.769(mahogany) while those of branchwood were in the range of 0.483(koto) and

0.878(mahogany). Moreover, samples tested at 10±4%MC had the R^2 values of MC and MOR ranging from 0.442(koto) to 0.769(mahogany) for stemwood whereas the branchwood had R^2 values in the range of 0.279(ofram) to 0.660(mahogany). The R^2 values suggested that moisture content could predict MOR to varied levels of accuracies of between 26% and 77% for stemwood, and between 48% and 88% for branchwoods.

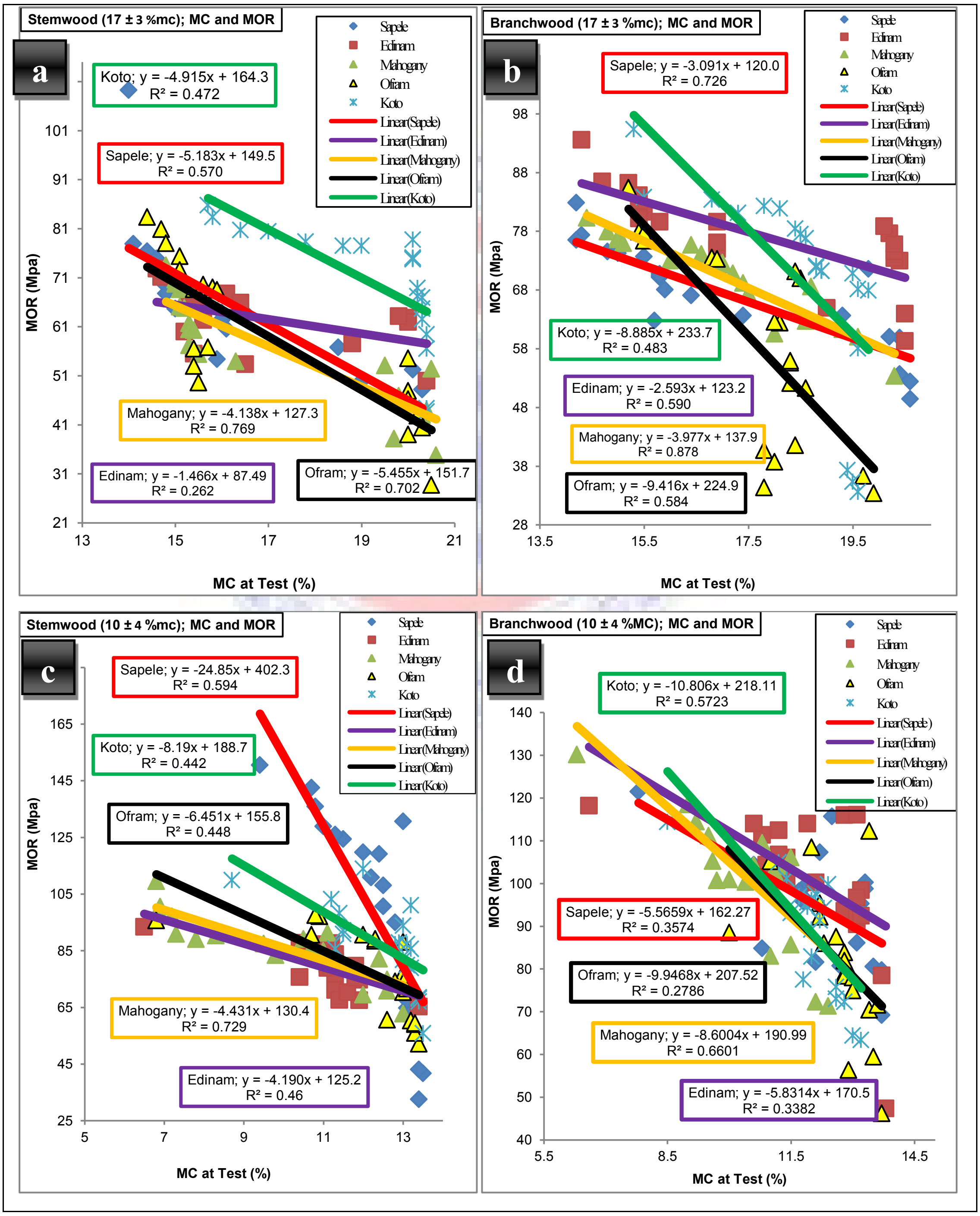


Figure 4.3.7. Relationship between moisture content and MOR of Stem and Branch Wood tested at two Moisture Levelsl; N=20.

Additionally from Figure 4.3.7, the coefficients of MC (**α)** were also found to be generally higher for branchwood than stemwood for samples tested at both 17±3%MC and 10±4%MC. The trend of the **α** values meant that the rate of increases in MOR of both stem and branch woods per 1% change in MC is higher for samples at a lower MC range than those at a relatively higher MC range. For stemwood, 1% change in MC resulted in between 1.5MPa. (edinam) and 5.5MPa. (ofram) in MOR at 17±3%MC but the change was between 4.2MPa. (edinam) and 24.9MPa. (sapele) in MOR at 10±4%MC. For branchwood, 1% change in MC resulted in between 2.6MPa. (edinam) and 9.4MPa. (ofram) in MOR at 17±3%MC but the change was between 5.6MPa. (sapele) and 10.8MPa. (koto) in MOR at 10±4%MC.

4.3.1.3.3:Predicting bending strength of solid wood from moisture content and wood density as combined predictor variables

Tables 4.3.5 and 4.3.6 respectively present the relationship between moisture content and wood density as combined predictor variables for MOE and MOR in multiple linear regression models. Generally, this model that combined moisture level and density resulted in marginal increase in the R^2 values for all sample groups compared with when the variables were used separately as single predictors. These R^2 values for MOE of stemwood ranged from 0.542 (sapele- tested at 10±4%MC) to 0.933 (ofram-tested at 10±4%MC), whereas those of branchwoods ranged from 0.552 (koto-tested at 10±4%MC) to 0.961 (edinam-tested at 17±3%MC). Hence, MC and WD (wood density) combined can predict MOE to accuracies of up to 93% for stemwood and 96% for branchwood and they are improvements over the 92% prediction accuracy by WD alone for both stem and branch wood (Figures 4.3.4), and the 76% and 90% accuracies respectively for stem and branch woods by MC alone (Figure 4.3.6).

Table 4.3.5: Relationship of Wood Density and Moisture Content combined and MOE of Solid Stem and Branch Wood tested at Two Moisture Levels.

			Coefficients						
Wood Species/Type & MC	**N**	**Equation**	**Symbol**	**Unstandardized B/Value**	**Std. Error**	**Standardized B/Value**	**t**	**P-Value**	**R^2 Adj.**
Sapele Stemwood 17±3%MC	20	MOE= c-αMC+βWD	c	-749.802	3988.499		-.188	.853ns	.769
			α	-181.920	124.656	-.244	-1.459	.163ns	
			β	14.092	3.397	.693	4.148	.001***	
10±4%MC	20	MOE= c-αMC+βWD	c	10024.605	21852.082		.459	.652ns	.542
			α	-1335.992	803.724	-.456	-1.662	.115ns	
			β	25.351	20.026	.347	1.266	.223ns	
Sapele Branchwood 17±3%MC	20	MOE= c-αMC+βWD	c	-9909.338	2595.244		-3.818	.001***	.909
			α	-14.191	49.327	-.033	-.288	.777ns	
			β	20.784	2.422	.985	8.580	.000***	
10±4%MC	19	MOE= c-αMC+βWD	c	-2681.350	1801.886		-1.488	.156ns	.940
			α	-239.033	76.896	-.206	-3.109	.007**	
			β	19.359	1.498	.855	12.926	.000***	
Edinam Stemwood 17±3%MC	20	MOE= c-αMC+βWD	c	-1068.263	2831.607		-.377	.711ns	.703
			α	-124.311	71.101	-.249	-1.748	.098*	
			β	18.239	3.661	.709	4.982	.000***	
17±4%MC	20	MOE= c-αMC+βWD	c	1301.530	3595.920		.362	.722ns	.674
			α	-10.902	158.328	-.016	-.069	.946ns	
			β	12.615	3.618	.828	3.487	.003***	
Edinam Branchwood 17±3%MC	20	MOE= c-αMC+βWD	c	-25125.860	3991.715		-6.295	.000***	.961
			α	-112.300	39.411	-.221	-2.849	.011**	
			β	47.383	4.615	.795	10.266	.000***	
10±4%MC	20	MOE= c-αMC+βWD	c	-6899.832	9645.950		-.715	.484ns	.574
			α	-398.771	173.103	-.417	-2.304	.034**	
			β	30.116	11.542	.472	2.609	.018**	
Mahogany Stemwood 17±3%MC	20	MOE= c-αMC+βWD	c	-1840.686	5127.862		-.359	.724ns	.813
			α	-192.725	73.760	-.454	-2.613	.018**	
			β	22.402	7.764	.502	2.885	.010**	
10±4%MC	20	MOE= c-αMC+βWD	c	7006.607	2754.856		2.543	.021**	.780
			α	-179.094	64.476	-.515	-2.778	.013**	
			β	10.046	4.372	.426	2.298	.035**	
Mahogany Branchwood 17±3%MC	20	MOE= c-αMC+βWD	c	8151.573	2525.466		3.228	.005**	.911
			α	-200.177	73.617	-.553	-2.719	.015**	
			β	4.529	2.188	.421	2.070	.054*	
10±4%MC	20	MOE= c-αMC+βWD	c	17696.332	4822.958		3.669	.002***	.804
			α	-1097.139	165.040	-.834	-6.648	.000***	
			β	5.846	6.208	.118	.942	.360ns	
Ofram Stemwood 17±3%MC	20	MOE= c-αMC+βWD	c	5009.295	4760.182		1.052	.307ns	.794
			α	-319.669	93.223	-.576	-3.429	.003***	
			β	13.691	6.100	.377	2.244	.038**	
10±4%MC	20	MOE= c-αMC+βWD	c	-2600.370	1954.486		-1.330	.201ns	.933
			α	-137.027	62.979	-.190	-2.176	.044*	
			β	22.260	2.360	.822	9.431	.000***	

Table 4.3.5: (Continuation)

			Coefficients						
Wood Species/Type & MC	N	Equation	Symbol	Unstandardized B/Value	Std. Error	Standardized B/Value	t	P-Value	R^2 Adj.
Ofram Branchwood 17±3%MC	19	MOE= c-αMC+βWD	c	-8170.407	9785.498		-.835	.415ns	.783
			α	-230.595	220.803	-.238	-1.044	.311ns	
			β	28.290	9.488	.680	2.982	.008**	
10±4%MC	20	MOE= c-αMC+βWD	c	-25472.539	5914.008		-4.307	.001***	.834
			α	54.263	189.026	.034	.287	.778ns	
			β	52.905	6.557	.942	8.068	.000***	
Koto Stemwoood 17±3%MC	20	MOE= c-αMC+βWD	c	-3210.414	4457.367		-.720	.481ns	.836
			α	-193.355	75.488	-.343	-2.561	.020**	
			β	23.853	4.940	.646	4.828	.000***	
10±4%MC	20	MOE= c-αMC+βWD	c	-6649.403	4925.995		-1.350	.195ns	.677
			α	-90.291	163.704	-.086	-.552	.588ns	
			β	27.378	5.370	.793	5.099	.000***	
Koto Branchwood 17±3%MC	20	MOE= c-αMC+βWD	c	-11588.962	7215.104		-1.606	.127ns	.790
			α	-62.976	216.415	-.045	-.291	.775ns	
			β	32.167	5.702	.868	5.642	.000***	
10±4%MC	20	MOE= c-αMC+βWD	c	-15672.338	12720.415		-1.232	.235ns	.552
			α	-370.715	345.118	-.214	-1.074	.298ns	
			β	46.387	14.941	.619	3.105	.006**	

NOTE: The statistical analyses are significant at 95% confidence level. ***$p < 0.01$; **$p < 0.05$; *$p <0.1$; and non-significant, nsP > 0.1; N; number of samples, WD: wood density (kg/m^3); MC: moisture content of wood (%).

Moreover, generally, for both stem and branch woods, the coefficient of MC (**α** –Equation 3.10) with MOE for samples at 10±4%MC were higher than those at 17±3%MC. Also, whereas the coefficient of WD (**β** – Equation 3.10) with MOE for stemwood samples tested at 17±3%MC were larger than those at 10±4%MC, branchwood **β** coefficients behaved in the opposite. However, these **β** coefficients of WD and MOE were significant ($P < 0.01$; $P < 0.05$ or $P < 0.1$) for most stem and branch wood than the **α** coefficients of MC and MOE. Also, between stem and branch wood MOE, at same MC range, **α** coefficients for stemwood were found to be higher than those of their counterpart branchwood. However, at same MC range, **β** coefficients of WD and MOE for branchwood were rather found to be generally higher than those of their stemwood counterparts. The **α** values suggested that 1% change in MC led to a higher change in the MOE at lower MC than at higher MC and also for stemwood than branchwood, and **β** values also indicated that 1kg/m^3 change in density led to a higher change in the MOE of branchwood than of stemwood. Practically, these also suggest that if MC and density are combined the effect of 1 unit change in MC and WD on MOE of stem and branch woods are not the same.

Table 4.3.6 also presents the relationship between moisture content (MC) and wood density (WD) combined, and MOR. From Table 4.3.6, the R^2 values for MOR ranged from 0.582 (edinam tested at 17±3%MC) to 0.928 (mahogany-10±4%MC) for stemwoods, whereas those of branchwoods ranged from 0.770 (koto-17±3%MC) to 0.911 (sapele-at 17±3%MC).

Table 4.3.6 : Relationship of Wood Densityand Moisture Content Combined and MOR of Solid Stem and Branch Wood Tested at Two Moisture Levels.

			Coefficients						
Wood Species/Type & MC	**N**	**Equation**	**Symbol**	**Unstandardized B/Value**	**Std. Error**	**Standardized B/Value**	**t**	**P-Value**	**R^2 Adj.**
Sapele Stemwood 17±3%MC	20	$MOR = c - \alpha MC + \beta WD$	c	-7.839	34.114		-.230	.821ns	.801
			α	-1.263	1.066	-.184	-1.185	.252ns	
			β	.142	.029	.760	4.893	.000***	
10±4%MC	20	$MOR = c - \alpha MC + \beta WD$	c	-252.043	174.309		-1.446	.166ns	.759
			α	-4.342	6.411	-.135	-.677	.507ns	
			β	.620	.160	.772	3.880	.001***	
Sapele Branchwood 17±3%MC	20	$MOR = c - \alpha MC + \beta WD$	c	-16.550	21.635		-.765	.455ns	.911
			α	-.978	.411	-.270	-2.379	.029**	
			β	.130	.020	.730	6.441	.000***	
10±4%MC	19	$MOR = c - \alpha MC + \beta WD$	c	-1.377	20.357		-.068	.947ns	.882
			α	-1.685	.869	-.181	-1.939	.070*	
			β	.153	.017	.843	9.038	.000***	
Edinam Stemwood 17±3%MC	20	$MOR = c - \alpha MC + \beta WD$	c	14.878	19.248		.773	.450*	.582
			α	-.531	.483	-.185	-1.098	.288ns	
			β	.101	.025	.685	4.058	.001***	
10±4%MC	20	$MOR = c - \alpha MC + \beta WD$	c	9.126	34.573		.264	.795ns	.648
			α	-.239	1.522	-.039	-.157	.877ns	
			β	.121	.035	.860	3.490	.003***	
Edinam Branchwood 17±3%MC	20	$MOR = c - \alpha MC + \beta WD$	c	-205.693	41.152		-4.998	.000***	.905
			α	-.048	.406	-.014	-.117	.908ns	
			β	.382	.048	.968	8.037	.000***	
10±4%MC	20	$MOR = c - \alpha MC + \beta WD$	c	-280.268	73.676		-3.804	.001***	.774
			α	-1.207	1.322	-.120	-.913	.374ns	
			β	.548	.088	.820	6.219	.000***	

Table 4.3.6: (Continuation)

Wood Species/Type & MC	N	Equation	Symbol	Coefficients			t	P-Value	R^2 Adj.
				Unstandardized B/Value	Std. Error	Standardized B/Value			
Mahogany Stemwood 17±3%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-96.403	38.465		-2.506	.023**	.915
			α	-1.467	.553	-.311	-2.652	.017**	
			β	.342	.058	.689	5.875	.000***	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-41.156	23.557		-1.747	.099*	.928
			α	-1.627	.561	-.317	-2.745	.057*	
			β	.275	.037	.782	7.357	.000***	
Mahogany Branchwood 17±3%MC	20	$MOR= c-\alpha MC+\beta WD$	c	56.379	30.521		1.847	.082*	.906
			α	-1.706	.890	-.402	-1.918	.072*	
			β	.072	.026	.568	2.710	.015**	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	20.722	32.347		.641	.530ns	.863
			α	-5.035	1.107	-.476	-4.549	.000***	
			β	.229	.042	.575	5.503	.000***	
Ofram Stemwood 17±3%MC	20	$MOR= c-\alpha MC+\beta WD$	c	42.240	65.533		.645	.528ns	.716
			α	-3.735	1.283	-.574	-2.910	.010**	
			β	.144	.084	.337	1.709	.106ns	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-66.778	55.643		-1.200	.247ns	.694
			α	-.996	1.793	-.103	-.555	.586ns	
			β	.279	.067	.774	4.158	.001***	
Ofram Branchwood 17±3%MC	19	$MOR= c-\alpha MC+\beta WD$	c	-308.985	125.906		-2.454	.025**	.779.
			α	-1.422	2.841	-.116	-.501	.623ns	
			β	.527	.122	.996	4.317	.000***	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-317.543	62.238		-5.102	.000***	.865
			α	-.207	1.989	-.011	-.104	.918ns	
			β	.617	.069	.944	8.945	.000***	
Koto Stemwoood 17±3%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-172.196	66.690		-2.582	.019**	.772
			α	-.703	1.129	-.098	-.622	.542ns	
			β	.383	.074	.819	5.181	.000***	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-89.348	35.187		-2.539	.021**	.880
			α	-2.804	1.169	-.228	-2.398	.028**	
			β	.323	.038	.801	8.430	.000***	
Koto Branchwood 17±3%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-88.473	68.549		-1.291	.214**	.770
			α	-1.262	2.056	-.099	-.614	.547ns	
			β	.275	.054	.817	5.079	.000***	
10±4%MC	20	$MOR= c-\alpha MC+\beta WD$	c	-117.935	68.467		-1.723	.103ns	.810
			α	-4.793	1.858	-.336	-2.580	.019**	
			β	.408	.080	.659	5.070	.000***	

NOTE: The statistical analyses are significant at 95% confidence level. ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$; and non-significant, nsP> 0.1; N; number of samples, WD: wood density (kg/m^3); MC: moisture content of wood (%).

A comparison of these R^2 values with those of WD alone (from 0.60 to 0.92 for stemwood and 0.73 to 0.92 for branchwood-Figure 4.3.5) and MC alone (from 0.26 to 0.77 for stemwood and from 0.28 to 0.88 for branchwood-Figure 4.3.7) suggested that the two variables combined had better predictive power for MOR than when the variables acted as single predictors, and MC may not be a good predictor of MOR of both stemwood and branchwood.

Also, generally, from Table 4.3.6, it was found that for both stem and branch wood samples, the coefficient of MC with MOR (**α** - Equation 3.10) for samples tested at 10±4%MC were higher than those tested at 17±3%MC. But whereas the coefficient of WD with MOR (**β** – Equation 3.10) for stemwood samples tested at 17±3%MC were larger than those tested at 10±4%MC, branchwood **β** coefficients behaved in the opposite. However, these **β** coefficients of WD and MOR were significant ($P < 0.01$; $P < 0.05$ or $P < 0.1$) for most stem and branch wood than the **α** coefficients of MC and MOR. Also, at 17±3%MC, the **α** and **β** coefficients were found to be generally higher for stemwood samples than their counterpart branchwood, but at 10±4%MC these coefficients tend to be generally higher for branchwood than stemwood. These imply that the combined effect of MC and WD appeared to be greater on branchwood than stemwood at a lower MC (10±4%) but it turned to be greater on stemwood than branchwood at a relatively higher MC level (17±3%). All these appear to suggest that the consituents of densities (i.e. chemical, anatomical etc.) of stem and branch woods of the species could be different and such constituents may also be influenced differently by moisture levels and drying.

Therefore, from all the results on MC and WD relationships with bending strength, it appeared generally that the effect of moisture content and density on the bending strength properties (MOE and MOR) changes are not the same for stem and branch woods as they dry from relatively higher moisture levels to lower ones. Additonally, it is proven that the effect of 1 unit change in MC and WD on bending strength properties of wood below 12%MC is higher than those wood above 12%MC and beyond the fibre saturation point but there are differences in these in respect of stem and branch woods of same species.

4.3.1.4: Predicting MOR of solid wood from their MOE.

Figure 4.3.8 presents the regression analyses of the relationships between MOE and MOR of stemwood and branchwood sample groups tested at the two moisture levels (i.e. for all species together). Generally, positive relationships were observed between MOE and MOR of both stem and branch woods at the two MC levels (i.e. 17±3%and 10±4%).

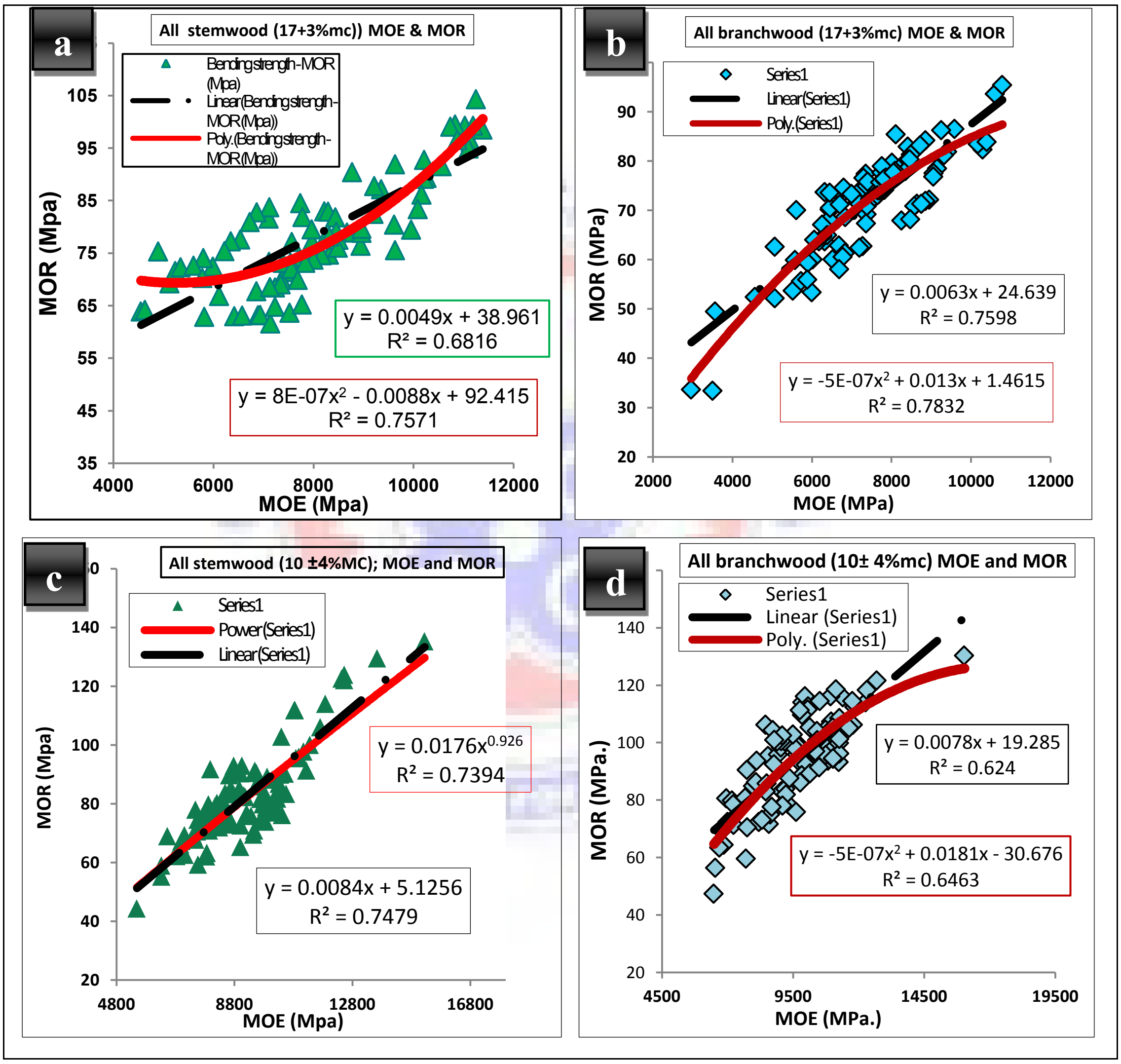


Figure 4.3.8: Relationship between MOEs and MORs of Stem and Branch Woods of all species together and tested at Two Moisture Levels; N= 100.

From figure 4.3.8, generally, it appeared that both linear and second degree polynomial functions ($p< 0.001$, R^2= 0.65-0.76) and linear functions ($p< 0.001$, R^2= 0.62-0.76) provided the best fits in predicting MORs of both stemwood and branchwood of all the species as functions of their MOEs. For predicting the MORs of stemwood of the species at 17±3%MC based on their MOEs, a polynomial function proved to be the best fit and accounted for 76% of the variation whereas linear function best predicted the MORs at 10±4%MC (R^2 = 0.76; Figure 4.3.8c). Moreover, in predicting the MORs of branchwood from their MOEs polynomial functions appeared to be the best fit and accounted for 78% and 65% of the variations at 17±3%MC and 10±4%MC respectively. These mean that whereas in stemwood the MOE and MOR relationships at both 17±3%MC and 10±4%MC appeared not to be generally different, in branchwood, the relationships at the two moisture levels differed. Thus moisture level appeared to affect the MOE and MOR relationships in branchwood but not in stemwood of the studied species.

Additionally, from figure 4.3.8, the coefficient of MOE (**γ-** Equation 3.11) at 17±3%MC levels were generally lower for stemwood (i.e. 0.0049) than for branchwood (i.e. 0.0063). However, at 10±4MC%, the coefficient was higher (i.e. 0.0087) for stemwood than branchwood (i.e. 0.0078). These values indicated that the rate of change in MOR per 1 unit change in MOE was higher for branchwood at 17±3%MC but it tend to higher for stemwood than branchwood at 10±4%MC.

Figure 4.3.9 also presents linear regression analyses of the relationships between MOE and MOR of stemwood and branchwood sample groups tested at the two moisture levels (i.e. for the various species studied). Comparing the linear functions, the R^2 values of either stemwood and branchwood of some individual species either fell below or above the R^2 for all species together at either moisture levels. The stemwood of all species obtained R^2 values of 0.68 and 0.75 at 17±3%MC and 10±4%MC respectively whereas the branchwoods obtained R^2 values of 076 and 0.62 at 17±3%MC and 10±4%MC respectively (figure 4.3.8 a). However, mahogany generally belonged to the species with lower R^2 values. The R^2 values of mahogany stemwood (0.62 at 17±3%MC and 0.47 at 10±4%MC) were the least among the species (figure 4.3.9 a and c). The species‟ branchwood also had the least R^2 value of 0.22 at 10%MC(figure 4.3.9 d). However, sapele stemwood had the highest R^2 values of 0.89 at 17±3%MC and 0.95 at 10±4%MC, whereas koto branchwood had the highest R^2 values of 0.86 at 17±3%MC and 0.90 at 10±4%MC. These findings affirms those in figure 4.3.8 that the relationship existing between MOE and MOR is affected by species/wood type and also moisture levels.

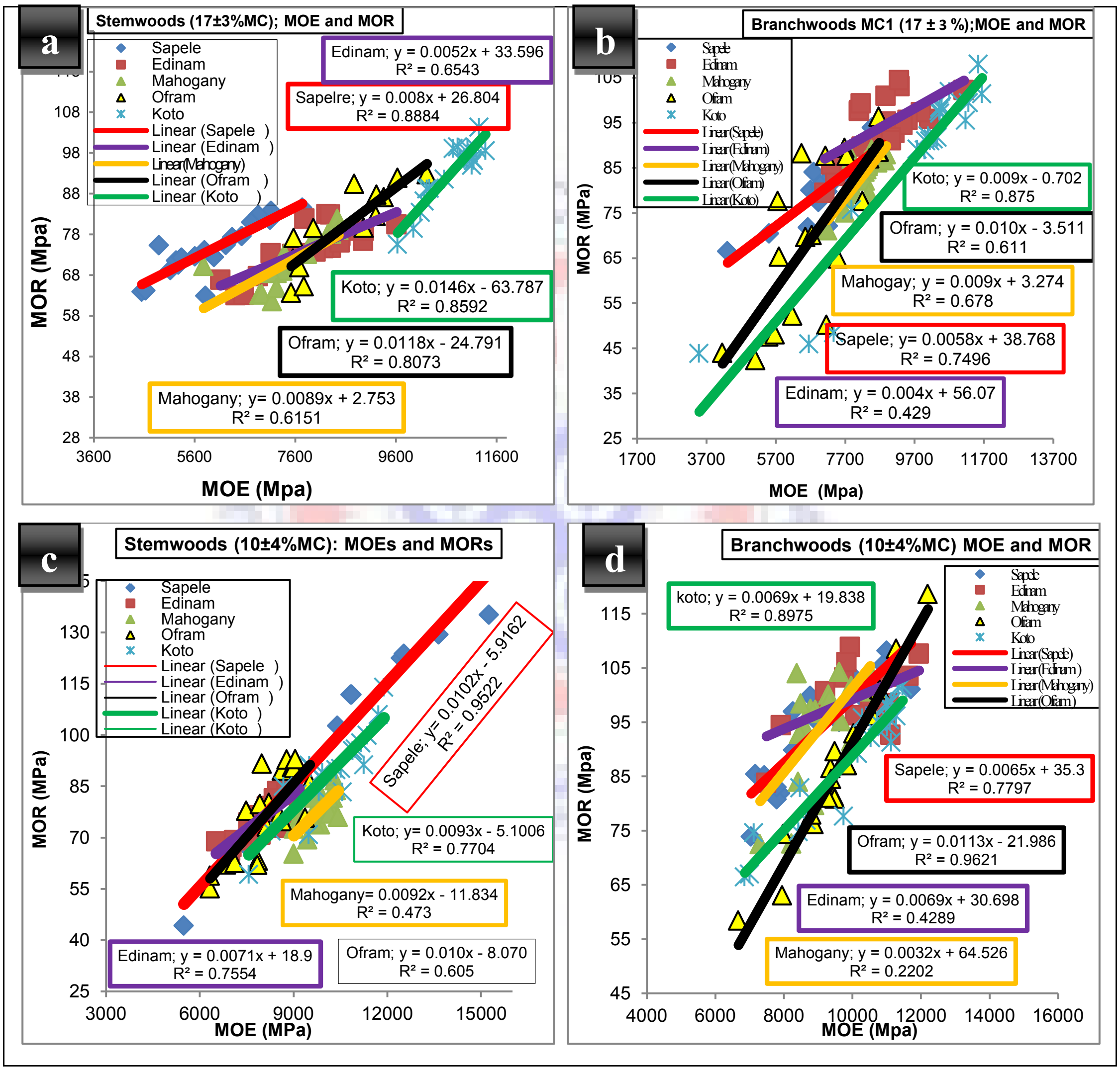


Figure 4.3.9: Relationship between MOEs and MORs of Stem and Branch Woods of individual species tested at Two Moisture Levels; N= 20.

4.3.2: Bending strength of finger-jointed lumber combinations

Stem (off-cuts) and branch wood of the studied species were finger-jointed in both green and dried moisture conditions and tested for static bending strength at the two moisture levels (MC1=17±3% and MC2=10±4%). This was done to ascertain whether or not branchwood, besides recording both comparable and significantly higher MOE and MOR values in the solid form than their solid stemwood counterparts (Table 4.3.3), branchwood can also produce finger-jointed (FJ) lumber of a comparable joint efficiency as the stem & stem (the status-quo) FJ lumber, to warrant their use as supplementary material to stemwood for finger-jointing. Appendix 4 presents the detailed experimental data on moisture content, density and static bending strength properties (Modulus of Rupture – MOR and Modulus of Elasticity-MOE) obtained for the 3 finger-jointed lumber combinations from stem (off-cuts) and branch woods (stem & stem FJ, stem & branch FJ, and branch & branch FJ combinations) at the two moisture conditions. Summaries of the results are presented in Figures 4.3.9 and 4.3.10 and Table 4.3.7. However, MOE and MOR of solid stemwood of each species also dried to 17±3% and 10±4% moisture conditions and taken from Appendix 3 were used as control samples for the FJ lumber at the 2 MC levels.

4.3.2.1: Modulus of Elasticity (MOE) of finger-jointed lumber combinations.

Figure 4.3.10 shows the relationship between the MOE of the 3 finger-jointed (FJ) lumber combinations with their species" solid stem controls, whereas Table 4.3.7 presents summary descriptive statistics and one-way ANOVA of their MOE at the 2 moisture conditions. Finger-jointed lumber dried before jointing and their controls tested at 10±4%MC exhibited higher MOE values than their counterparts jointed in the green state and tested at 17±3%MC on possible account of moisture in the green wood impeding adhesion of the members forming the joints. The results presented in Figure 4.3.10 also showed that some finger-jointed lumber of stem and branch combinations jointed in either green or dried state exhibited higher MOE than their species" solid stemwood tested at similar moisture condition."

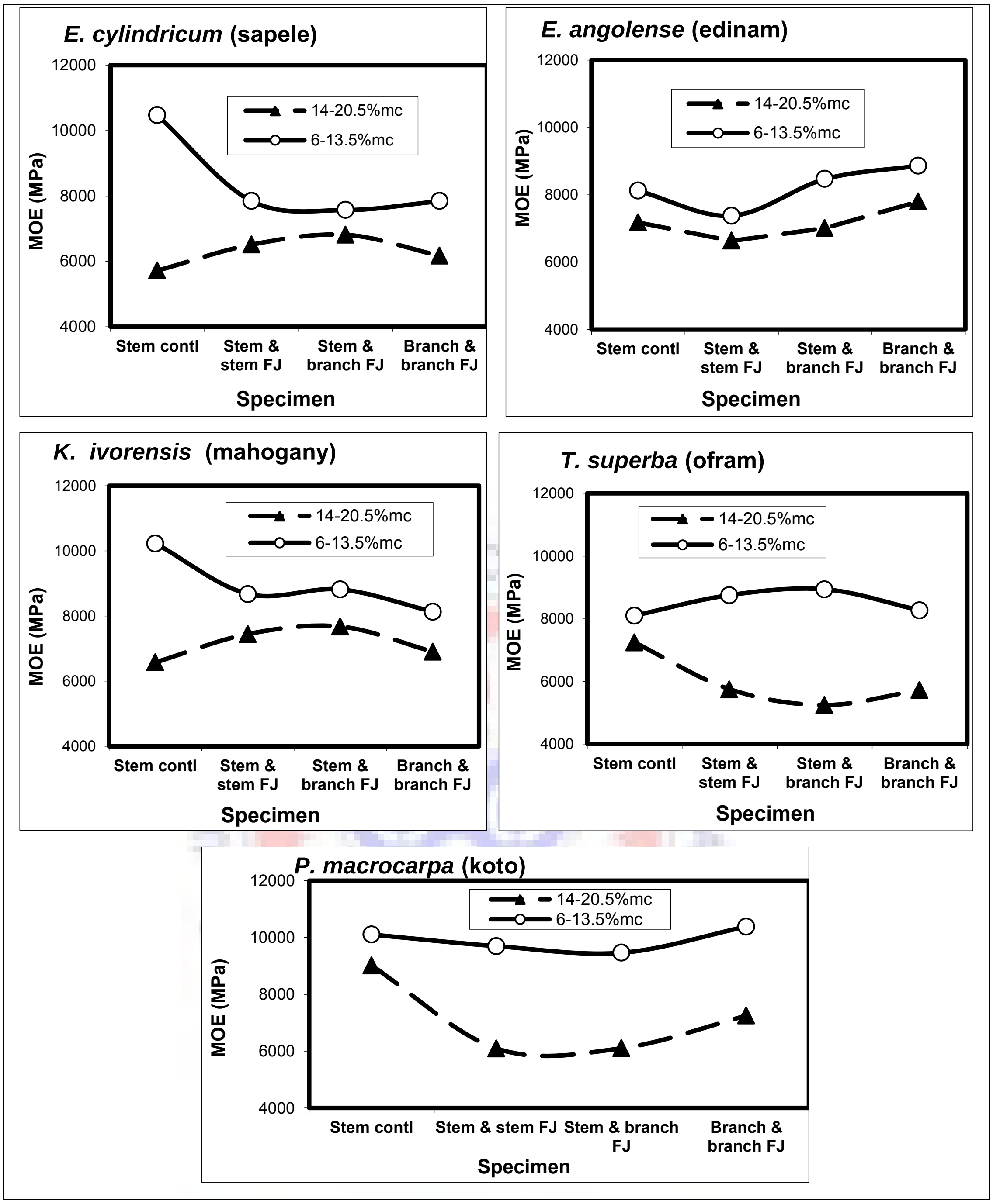


Figure 4.3.10. Mean Modulus of Elasticity of Solid Stemwood and Finger-Jointed Lumber combinations produced in Green and Dried States. N = 30.

The MOE (stiffness strength) of the groups tested at 10±4%MC for solid stem control, stem & stem FJ, stem & branch FJ, and branch & branch FJ were respectively: 10.46GPa, 7.84GPa, 7.57GPa, 7.84GPa for those of sapele; 8.12GPa, 7.38GPa, 8.47GPa, 8.87GPa for those of edinam; 10.23GPa, 8.68GPa, 8.82GPa, 8.13GPa for those of mahogany; 8.10GPa, 8.75GPa, 8.94GPa, 8.27GPa for those of ofram; and 10.10GPa, 9.70GPa, 9.46GPa, 10.38GPa for those of koto (Figure 4.3.10 and Table 4.3.7). For the groups tested at 17±3%MC, the results indicated reduction in MOE relative to their counterparts tested at 10±4%MC for the solid stem control, stem & stem FJ, stem & branch FJ, and branch & branch FJ in respective order of 45.32%, 17.0%, 10.0% and 21.3% for sapele, 11.6%, 10.1%, 17.2% and 12.0% for edinam, 35.7%, 14.2%, 12.9% and 15.1% for mahogany, 10.6%, 34.7%, 41.4%, and 30.8% for ofram, and 10.8%, 37.2%, 35.5%, and 30.2% for koto.

Moreover, from Figure 4.3.10 and Table 4.3.7, whereas some finger-jointed lumber combinations of some species had higher MOE, others had lower MOE relative to their respective solid stem controls at each of the two moisture conditions. This could be characteristic differences of stem and branch woods of the species. The groups tested at 10±4%MC had differences (positive = increases and negative =decreases) in MOE for stem & stem FJ, stem & branch FJ, and branch & branch FJ, relative to their respective stem controls in respective order of: -25.0%, -27.7% and -25.1% for those of sapele; -9.1%, +4.3%, and +9.2% for those of edinam; -15.2%, -13.8%, -20.5% for those of mahogany; +8.1%, +10.3%, and +2.1% for those of ofram; and -4.0%, -6.3%, and +2.8% for those of koto. However, at 5% level of significance, these differences in MOE for samples of only sapele and mahogany were statistically significant, but those for edinam, ofram and koto were not (Table 4.3.7). On the other hand, the groups tested at 17±3%MC had differences (positive = increase and negative = decrease) in MOE for stem & stem FJ, stem & branch FJ, and branch & branch FJ relative to their respective stem controls in respective order of: +13.9%, +19.1%, +7.9% for those of sapele; -7.8%, -2.3%, and +8.7% for those of edinam; +13.2%, +16.7%, +5.0% for those of mahogany; -20.6%, -27.6%, and -21.0% for those of ofram; and -32.4%, -32.3%, 19.6% for those of koto.

Table 4.3.7. Descriptive Statistics and One-Way ANOVA of MOEof Stem Controls and Finger-Jointed Lumber combinations tested at Two Moisture Levels.

Species	MC level (%)	Specimen type	MOE (MPa) Mean (SD)	F-value	P-value
Entandrophragma cylindricum (sapele)	14-20.5	Solid stem control	5719.75 (145.80)	1.528	.211
		Stem & stem finger-joint	6512.10 (2227.07)		
		Stem & branch finger-joint	6812.53. (2140.61)		
		Branch & branch finger-joint	6172.07 (1381.47)		
	6-13.5	Solid stem control	10461.00 (3213.20) ^{abc}	10.787	.000***
		Stem & stem finger-joint	7844.76 (1568.53) ^{a}		
		Stem & branch finger-joint	7568.70 (1254.4) ^{b}		
		Branch & branch finger-joint	7841.03 (1695.87) ^{c}		
Entandrophragma angolense (edinam)	14-20.5	Solid stem control	7177.30 (983.54)	3.328	.022**
		Stem & stem finger-joint	6633.97 (1024.06) ^{a}		
		Stem & branch finger-joint	7011.53 (1295.15)		
		Branch & branch finger-joint	7799.63 (2101.46) ^{a}		
	6-13.5	Solid stem control	8119.75 (842.09)	4.424	.000***
		Stem & stem finger-joint	7378.70 (1638.29) ^{a}		
		Stem & branch finger-joint	8470.21 (1391.12)		
		Branch & branch finger-joint	8865.13 (2190.93) ^{a}		
Khaya ivorensis (mahogany)	14-20.5	Solid stem control	6576.75 (1021.81) ^{ab}	6.952	.000***
		Stem & stem finger-joint	7447.03 (957.42) ^{a}		
		Stem & branch finger-joint	7677.80 (891.07) ^{bc}		
		Branch & branch finger-joint	6903.17 (975.12) ^{c}		
	6-13.5	Solid stem control	10233.10 (721.39) ^{abc}	17.599	.000***
		Stem & stem finger-joint	8679.30 (756.49) ^{a}		
		Stem & branch finger-joint	8818.63 (982.77) ^{b}		
		Branch & branch finger-joint	8134.60 (1376.61) ^{c}		
Terminalia superba (ofram)	14-20.5	Solid stem control	7238.30 (1333.00) ^{abc}	12.985	.000***
		Stem & stem finger-joint	5746.63 (1115.76) ^{a}		
		Stem & branch finger-joint	5241.47 (1124.62) ^{b}		
		Branch & branch finger-joint	5722.10 (1027.63) ^{c}		
	6-13.5	Solid stem control	8100.55 (1124.54)	2.177	.095*
		Stem & stem finger-joint	8753.20 (1627.37)		
		Stem & branch finger-joint	8938.27 (1250.23)		
		Branch & branch finger-joint	8268.20 (1333.04)		
Pterygota macrocarpa (koto)	14-20.5	Solid stem control	9011.40 (946.56) ^{abc}	24.684	.000***
		Stem & stem finger-joint	6092.67 (1669.88) ^{ad}		
		Stem & branch finger-joint	6101.73 (1435.19) ^{be}		
		Branch & branch finger-joint	7248.43 (1022.30) ^{cde}		
	6-13.5	Solid stem control	10102.10 (1261.68)	2.522	.062*
		Stem & stem finger-joint	9695.27 (1687.41)		
		Stem & branch finger-joint	9461.60 (1465.00)		
		Branch & branch finger-joint	10383.00 (1066.33)		

Note: Mean values with the same letters indicate significant difference at 95% confidence level.
*significant at $p \leq 0.1$; **significant at $p \leq 0.05$ and ***$p \leq 0.01$.

However, from Table 4.3.7, at 95% confidence level, the differences in MOE were statistically significant for mahogany, ofram and koto, but not significant for sapele and edinam. All these results indicated that moisture levels and sample type appeared to have affected the MOE of both solid controls and the various finger-jointed lumber combinations.

A Two-way ANOVA (Table 4.3.8) was therefore carried out to ascertain the influence of MC and sample type on MOE. Results indicated that moisture levels had significant effect (F=429.636, p= 0.000), sample type (finger-joint combination) also had significant effect (F= 9.435, p= 0.000). Also, the interaction of moisture level and sample type had significant effect (F= 8.555, p= 0.000) all at 1% significance level on the MOE of the samples. Moreover, moisture level of sample type explained 42% of the variation in MOEs (Table 4.3.8).

Table 4.3.8. Two-way ANOVA of the Effect of MC and Sample Type on the MOE of Solid Stem Controls and Finger-Jointed Lumber combinations tested at Two Moisture Levels.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.423E9[a]	29	4.908E7	23.527	.000
Intercept	5.196E10	1	5.196E10	2.491E4	.000
Sample type	2.756E8	14	1.968E7	9.435	.000
Moisture Level	8.963E8	1	8.963E8	429.636	.000
Sample type * Moisture Level	2.499E8	14	1.785E7	8.555	.000
Error	1.811E9	868	2086245.756		
Total	5.519E10	898			
Corrected Total	3.234E9	897			

a. R Squared = .440 (Adjusted R Squared = .421)

4.3.2.2: Modulus of Rupture (MOR) of finger-jointed lumber combinations.

Figure 4.3.11 shows the relationship between the MOR of the 3 finger-jointed (FJ) lumber combinations and their species‟ solid stem controls, while Table 4.3.9 also presents summary descriptive statistics with one-way ANOVA of each species at the 2 moisture conditions.

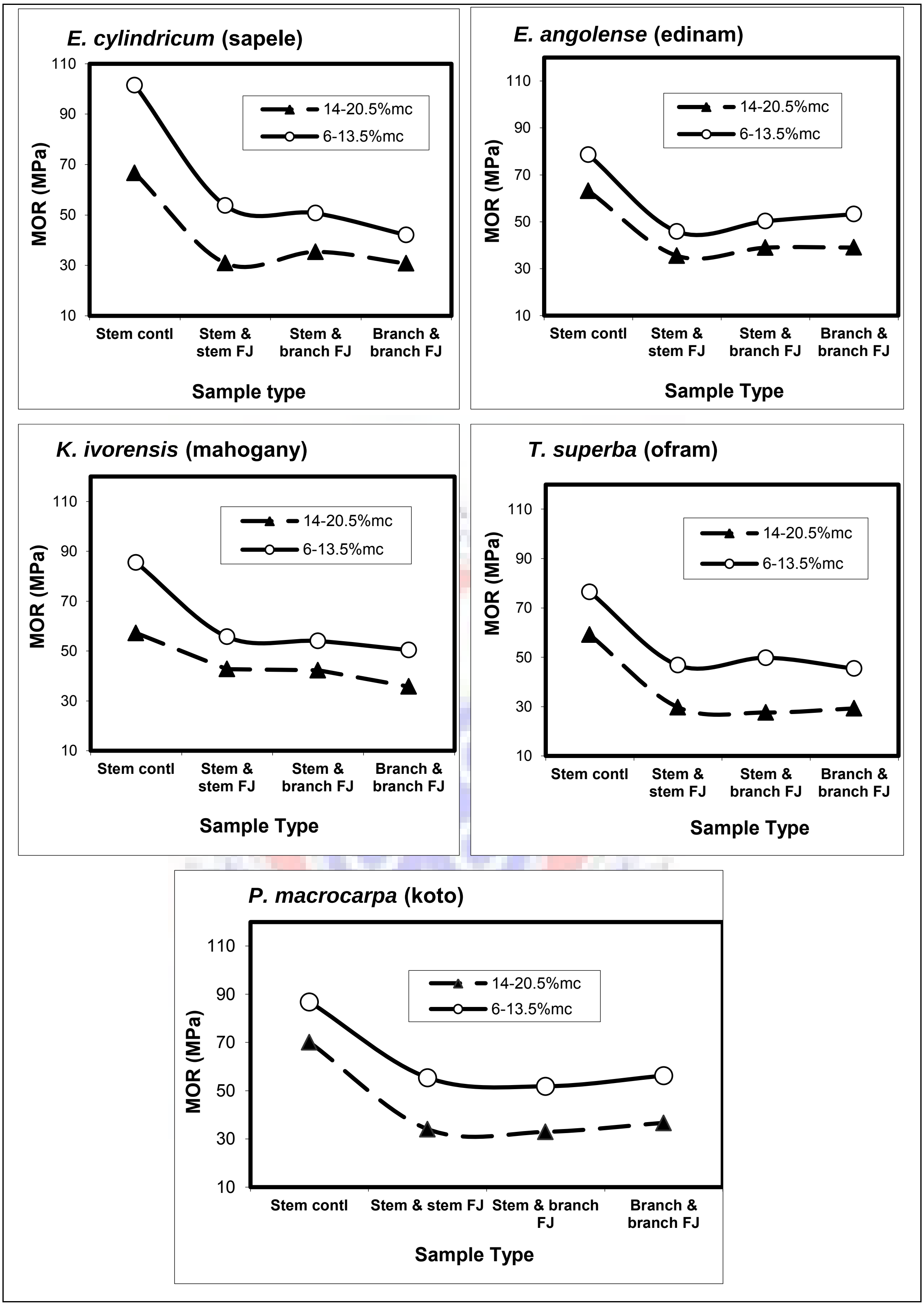


Figure 4.3.11: Mean modulus of rupture (MOR) of solid stem finger-jointed lumber combinations produced in green and dried states. N = 30.

From Figure 4.3.11, the MOR of the solid stemwood control and FJ lumber combinations tested at 10±4%MC exhibited higher MOR than those tested at

17±3%MC. This appear to suggest that, like MOE, lower moisture levels in wood produced finger-jointed lumber of higher MOR than wood with higher moisture levels. The MOR of the groups tested at 10±4%MC for solid stem control, stem & stem FJ, stem & branch FJ, and branch & branch FJ were respectively: 104.49MPa, 53.74MPa, 50.68MPa and 42.04MPa for those of sapele; 78.57MPa, 45.85MPa, 50.24MPa, and 53.24MPa for those of edinam; 85.48MPa, 55.70MPa, 54.01MPa and 50.36MPa for those of mahogany; 76.44MPa, 46.75MPa, 49.79MPa and 45.37MPa for those of ofram; and 86.87MPa, 55.43MPa, 51.82MPa and 56.23MPa for those of koto (Figure 4.3.11 and Table 4.3.9).

From Figure 4.3.10 and Table 4.3.9, results for the group tested at 17±3%MC showed a general reduction in MOR compared to those tested at 10±4%MC for the solid stem control, stem & stem FJ, stem & branch FJ, and branch & branch FJ, in respective order of: 34.38%, 42.50%, 30.25%, and 26.86% for those of sapele; 19.63%, 22.59%, 22.45%, and 26.73% for those of edinam; 33.10%, 23.23%, 21.72%, 29.01%, 22.70% for those of mahogany; 22.70%, 36.43%, 44.57%, and 35.51% for those of ofram, and 19.29%, 38.59%, 36.51%, 34.84% for those of koto.

However, from Figure 4.3.11 and Table 4.3.9, unlike MOE of which some finger-jointed lumber had higher values (increases) over those of their respective solid stem controls, for MOR generally, all the finger-jointed lumber combinations from all the species tested at each of the two moisture conditions had decreases over their respective solid stem controls (as could be clearly observed from Figure 4.3.11). Also, the MOR of the groups tested at 10±4%MC had reduction in MOR for stem & stem FJ, stem & branch FJ, and branch & branch FJ, compared to their respective stem controls in respective orders of: 47.05%, 50.06% and 58.58% for those of sapele; 41.64%, 36.06% and 32.24% for those of edinam; 53.46%, 36.82% and 41.09% for those of mahogany; 38.84%, 34.86% and 40.65% for those of ofram; and

36.19%, 40.34% and 35.27% for those of koto. All these differences were statistically significant for all species at 5% level of significance (Table 4.3.9).

Table 4.3.9: Descriptive Statistics and One-Way ANOVA of MOR of Stem Controls and Finger-Jointed Lumber combinations tested at Two Moisture Levels.

	Moisture		**MOR (MPa)**		
Species	**level (%)**	**Specimen type**	**Mean (SD)**	**F- value**	**P-value**
Entandrophragma cylindricum (sapele)	14-20.5	Solid stem control	66.60 (13.36) ^{abc}	44.780	.000***
		Stem & stem finger-joint	30.90 (12.59) ^{a}		
		Stem & branch finger-joint	35.35 (13.03) ^{b}		
		Branch & branch finger-joint	30.75 (9.42) ^{c}		
	6-13.5	Solid stem control	101.49 (35.37) ^{abc}	48.238	.000***
		Stem & stem finger-joint	53.74 (16.08) ^{a}		
		Stem & branch finger-joint	50.68 (8.63) ^{b}		
		Branch & branch finger-joint	42.04 (6.83) ^{c}		
Entandrophragma angolense (edinam)	14-20.5	Solid stem control	63.15 (5.64) ^{abc}	18.734	.000***
		Stem & stem finger-joint	35.49 (16.01) ^{a}		
		Stem & branch finger-joint	38.96 (13.71) ^{b}		
		Branch & branch finger-joint	39.01 (15.29) ^{c}		
	6-13.5	Solid stem control	78.57 (7.80) ^{abc}	70.802	.000***
		Stem & stem finger-joint	45.85 (17.1) ^{ad}		
		Stem & branch finger-joint	50.24 (7.98) ^{b}		
		Branch & branch finger-joint	53.24 (9.19) ^{cd}		
Khaya ivorensis (mahogany)	14-20.5	Solid stem control	57.19 (11.36) ^{abc}	36.020	.000***
		Stem & stem finger-joint	42.76 (6.33) ^{ad}		
		Stem & branch finger-joint	42.28 (4.01) ^{be}		
		Branch & branch finger-joint	35.75 (7.00) ^{cde}		
	6-13.5	Solid stem control	85.48 (10.76) ^{abc}	86.517	.000***
		Stem & stem finger-joint	55.70 (7.91) ^{a}		
		Stem & branch finger-joint	54.01(63.18) ^{b}		
		Branch & branch finger-joint	50.36 (9.18) ^{c}		
Terminalia superba (ofram)	14-20.5	Solid stem control	59.09 (15.64) ^{abc}	65.504	.000***
		Stem & stem finger-joint	29.72 (4.64) ^{a}		
		Stem & branch finger-joint	27.60 (8.12) ^{b}		
		Branch & branch finger-joint	29.26 (5.65) ^{c}		
	6-13.5	Solid stem control	76.44 (14.99) ^{abc}	30.618	.000***
		Stem & stem finger-joint	46.75 (14.67) ^{a}		
		Stem & branch finger-joint	49.79 (8.96) ^{b}		
		Branch & branch finger-joint	45.37 (11.06) ^{c}		
Pterygota macrocarpa (koto)	14-20.5	Solid stem control	70.11 (11.99) ^{abc}	89.155	.000***
		Stem & stem finger-joint	34.04 (8.24) ^{a}		
		Stem & branch finger-joint	32.90 (7.54) ^{b}		
		Branch & branch finger-joint	36.64 (8.19) ^{c}		
	6-13.5	Solid stem control	86.87 (14.76) ^{abc}	50.080	.000***
		Stem & stem finger-joint	55.43 (11.34) ^{a}		
		Stem & branch finger-joint	51.82 (7.57) ^{b}		
		Branch & branch finger-joint	56.33 (9.83) ^{c}		

Note: Mean values with the same letters indicate significant difference at 5% significance level.
*significant at $p \leq 0.1$; **significant at $p \leq 0.05$ and ***$p \leq 0.01$.

Moreover, the groups tested at 17±3%MC also had reductions in MOR for the stem & stem FJ, stem & branch FJ, and branch & branch FJ compared to their respective stem controls in respective order of: 53.60%, 46.92% and 53.83% for those of sapele; 43.80%, 38.31% and 38.23% for those of edinam; 25.23%, 26.07% and 37.49% for those of mahogany; 49.70%, 53.29% and 50.48% for those of ofram; and 51.4%, 53.07% and 47.74% for those of koto. These differences were also found to be statistically significant at 5% level of significance (Table 4.3.9). From the results, it appeared moisture content and sample type affected the MOR of the samples.

Hence, the effect of moisture level and speciment type on MOR were assessed with a Two-way ANOVA (Table 4.3.10) to provide further information.

Table 4.3.10: Two-way ANOVA of the effect of MC and Sample Type on the MOR of Solid Stem Controls and Finger-Jointed Lumber combinations tested at Two Moisture Levels.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	73947.124[a]	29	2549.901	25.823	.000
Intercept	1641407.787	1	1641407.787	1.662E4	.000
Finger-Joint combination	12899.034	14	921.360	9.331	.000
Moisture Level	57395.886	1	57395.886	581.256	.000
Finger-Joint combination * Moisture Level	3676.036	14	262.574	2.659	.001
Error	85710.335	868	98.745		
Total	1799603.956	898			
Corrected Total	159657.459	897			

a. R Squared = .463 (Adjusted R Squared = .445)

Results from Table 4.3.10 indicated that moisture level had significant effect (F=581.256, p = 0.000), sample type (finger-joint combination) also had significant effect (F= 9.331, p= 0.000), and the interaction of moisture level and sample type also had significant effect (F= 2.659, p= 0.001) all at 1% significance level on the MOR of finger-jointed lumber and their solid stemwood controls. Also, moisture level of wood and sample type explained about 45% of the variation in MOR of finger-jointed lumber combinations.

4.3.2.3: Joint efficiencies in MOE and MOR of Finger-jointed lumber combinations

Finger-joint MOE and MOR efficiencies (in terms of strength gained) as ratios of the MOE and MOR of solid/unjointed stemwood control of each species tested at 10±4%MC were determined and presented in Table 4.3.11. Generally, stem and branch wood combinations finger-jointed in the green state and tested at 17±3%MC obtained lower joint efficiencies in MOE that ranged from 59.0% (sapele branch & branch) to 96.0% (edinam branch & branch) compared to those wood jointed in dried state and tested at 10±4%MC, which obtained joint efficiencies in MOE in the range of 72.35% (sapele stem & branch) to 110.3% (ofram stem & branch). Ofram stem & branch FJ combinations (tested at 10±4%MC) obtained the highest efficiency in MOE of 110.34% while sapele branch & branch FJ combinations (tested at 17±3%MC) had the least of 59.0% compared with the MOE of their respective stemwood control samples. These findings also appear to confirm that the wood types/species jointed and the moisture condition/level during jointing have effect on the MOE of finger-jointed lumber produced from them and, for that matter, their joint efficiencies.

Also, from Table 4.3.11, the joint efficiencies in MOR were also higher for the various stem and branch wood dried before jointing and tested at 10±4%MC than those jointed in the green state and tested at 17±3%MC. The samples finger-jointed in dried state and tested at 10±4%MC had efficiencies in MOR that ranged from 41.4% (sapele branch & branch) to 67.8% (edinam branch & branch) whereas those jointed in the green state and tested at 17±3%MC had joint efficiencies in MOR that ranged from 30.3% (sapele branch & branch) and 50.0% (mahogany stem & stem). Hence, edinam branch & branch FJ combinations (tested at 10±4%MC) had the highest joint efficiency in MOR while sapele branch & branch FJ (tested at

17±3%MC) obtaining the least relative to the MOR of their respective stem control samples of their species. These further prove that the wood types/species jointed and the moisture condition during jointing have effect on the MOR of the finger-jointed lumber produced from them as well as their joint efficiencies.

Table 4.3.11. Joint Efficiencies in MOE and MOR of Finger-Jointed Lumber combinations.

Species & Finger-Joint Combinations	Modulus of Elasticity-MOE		Modulus of Rupture- MOR	
	Mean (MPa) ± SD	Efficiency (%)	Mean (MPa)±SD	Efficiency (%)
E. Cylindricum (sapele)				
Solid Stem- Control.(6-13.5%MC)	10460.80 ±3213.20		101.49 ±35.37	
Stem & Stem FJ (14-20.5%MC)	6512.10 ±2227.07	62.25	30.90 ±12.59	30.45
Stem & Stem FJ (6-13.5%MC)	7844.76 ±1568.53	75.00	53.74 ±16.08	52.95
Stem & Branch FJ (14-20.5%MC)	6812.53 ±2140.61	65.12	35.35 ±13.03	34.83
Stem & Branch FJ (6-13.5%MC)	7568.70 ±1254.47	72.35	50.68 ±8.63	49.94
Branch & Branch FJ (14-20.5%MC)	6172.07 ±1381.47	59.00	30.75 ±9.42	30.30
Branch & Branch FJ (6-13.5%MC)	7841.03 ±1695.87	74.96	42.04 ±6.83	41.42
E. Angolense (edinam)				
Solid Stem- Control.(6-13.5%MC)	8119.75 ±842.09		78.57 ±7.80	
Stem & Stem FJ (14-20.5%MC)	6633.97 ±1024.06	81.70	35.49 ± 16.01	45.17
Stem & Stem FJ (6-13.5%MC)	7378.70 ±1638.29	90.87	45.85 ±7.71	58.35
Stem & Branch FJ (14-20.5%MC)	7011.53 ±1295.15	86.35	38.96 ±13.71	49.59
Stem & Branch FJ (6-13.5%MC)	8470.21 ±1391.12	104.32	50.24 ±7.98	63.94
Branch & Branch FJ (14-20.5%MC)	7799.63 ±2101.46	96.06	39.01 ±15.29	49.65
Branch & Branch FJ (6-13.5%MC)	8865.13 ±2190.93	109.18	53.24 ±9.19	67.76
K. Ivorensis (mahogany)				
Solid Stem- Control.(6-13.5%MC)	10233.10 ±721.39		85.48 ±10.76	
Stem & Stem FJ (14-20.5%MC)	7447.03 ±957.42	72.77	42.76 ±6.33	50.02
Stem & Stem FJ (6-13.5%MC)	8679.30 ±756.49	84.82	55.70 ±7.91	65.16
Stem & Branch FJ (14-20.5%MC)	7677.80 ±891.07	75.03	42.28 ±4.01	49.46
Stem & Branch FJ (6-13.5%MC)	8818.63 ±982.77	86.18	54.01 ±4.61	63.18
Branch & Branch FJ (14-20.5%MC)	6903.17 ±975.12	67.46	35.75 ±7.00	41.82
Branch & Branch FJ (6-13.5%MC)	8134.60 ±1376.61	79.49	50.36 ±9.18	58.91
T. Superba (ofram)				
Solid Stem- Control.(6-13.5%MC)	8100.55 ± 1124.54		76.44 ±14.99	
Stem & Stem FJ (14-20.5%MC)	5746.63 ±1115.76	70.94	29.72 ±4.64	38.88
Stem & Stem FJ (6-13.5%MC)	8753.20 ±1627.37	108.06	46.75 ±14.67	61.16
Stem & Branch FJ (14-20.5%MC)	5241.47 ±1124.62	64.71	27.60 ±8.12	36.11
Stem & Branch FJ (6-13.5%MC)	8938.27 ±1250.23	110.34	49.79 ±8.96	65.14
Branch & Branch FJ (14-20.5%MC)	5722.10 ±1027.63	70.64	29.26 ±5.65	38.28
Branch & Branch FJ (6-13.5%MC)	8268.20 ±1333.04	102.02	45.37 ±11.06	59.35
P. Macrocarpa (koto)				
Solid Stem- Control.(6-13.5%MC)	10102.10 ±1261.68		86.87 ±14.76	
Stem & Stem FJ (14-20.5%MC)	6092.67 ±1669.88	60.31	34.04 ±8.24	39.19
Stem & Stem FJ (6-13.5%MC)	9695.27 ±1687.41	95.97	55.43 ±11.34	63.81
Stem & Branch FJ (14-20.5%MC)	6101.73 ±1435.19	60.40	32.90 ±7.54	37.87
Stem & Branch FJ (6-13.5%MC)	9461.60 ±1465.00	93.66	51.82 ±7.57	59.65
Branch & Branch FJ (14-20.5%MC)	7248.43 ±1022.30	71.75	36.64 ±8.19	42.18
Branch & Branch FJ (6-13.5%MC)	10383.00 ±1066.33	102.78	56.23 ±9.83	64.73

Note: Joint efficiencies are in relation to the respective species" control samples.

4.3.2.4: Relationship between density and joint efficiency in MOE and MOR.

Regression analysis was used to assess how mean density relates with mean finger-joint efficiency in both MOE and MOR for the individual species (Figure 4.3.12). These relationships were deemed necessary on account of being able to inform how density affects joint efficiencies and could also be possibly used as non-destructive method of determining joint efficiencies in MOE and MOR. Generally, except for *E. angolense* (Figure 4.3.12 b), density correlated negatively with finger - joint efficiencies. The negative correlations imply that FJ efficiencies decreases with increases in wood density of species/types that formed joints but the strength of the relationship is species dependent. In other words, high density wood species were found to produce lower joint efficiencies (i.e. low strength gained in relation to their solid stemwood).

Moreoever, except *P. macrocarpa*, the R^2 values generally suggested weak relationships between density and joint efficiencies in both MOE and MOR (Figure 4.3.12). But the weakest relationships were found with *T. superba* FJ combinations (R^2= 0.04 for MOE and 0.02 for MOR) whereas the strongest were found with *P. macrocarpa* (R^2= 0.96 for MOE and 0.89 for MOR). These results therefore indicated generally that density might be a weak predictor for joint efficiencies in both MOE and MOR for the four species, but it may be a good predictor of FJ efficiencies for koto. Also, from figure 4.3.12, 1kg/m^3 change in density could generally result in joint efficiencies from 0.05% to 2.04% in MOE and from 0.1% to 1.32% in MOR depending on the species. All these findings could be due to differences in chemical, anatomical, latewood and earlywood propoerions and other characteristic differences among the species and between the stem and branch woods of same species all of which contributed to the strength of the jointed lumber.

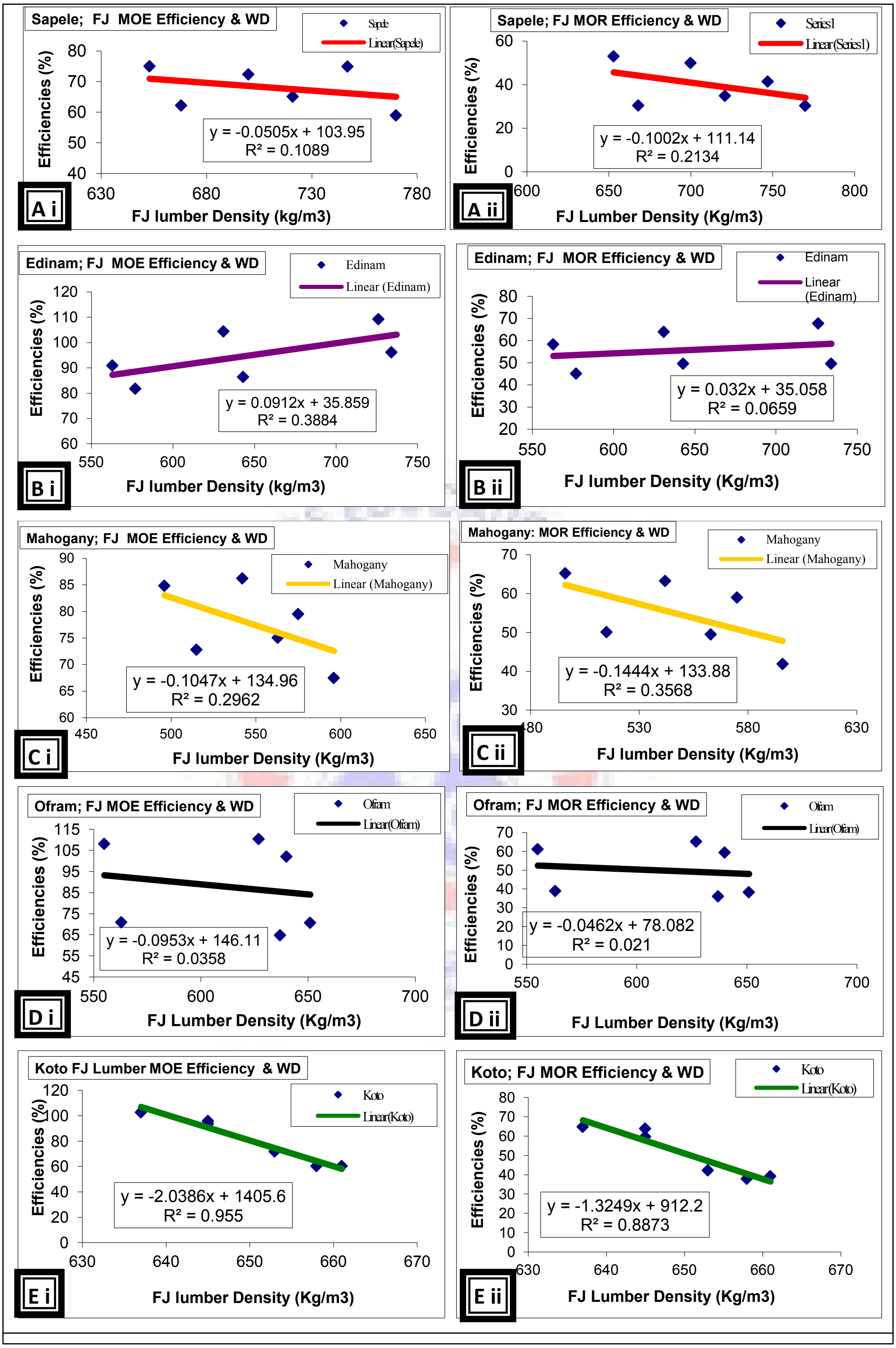


Figure 4.3.12. Relationships of Finger-Joint Lumber Efficiency in MOE and MOR with Wood Density (WD) for individual species. N= Means of 30.

Note on Figure 4.3.12: A=*E. cylindricum-sapele*; **B**=*E. angolense-edinam*; **C**=*K. ivorensis-mahogany;* **D**=*T.superba-ofram*; **E**=*P.macrocarpa-koto;* **i**= MOE efficiency, and **ii**= MOR efficiency.

4.3.2.5: Predicting bending strengths (MOE and MOR) of finger-jointed lumber from moisture content and wood density.

Regression analysis of the relationships between moisture content (MC) and wood density (WD) combined, and MOE and MOR of finger-jointed lumber at the two MC levels are as presented in Tables 4.3.12 and 4.3.13 respectively. The importance of this relationship is also to ascertain how best MC and WD can act together to accurately predict MOE and MOR of finger-jointed lumber. From Table 4.3.12, generally, MC correlated negatively whereas WD correlated positively with the MOE of all FJ combinations as indicated on the coefficients of MC (**α**) and the coefficients of WD (**β**).

Table 4.3.12. Relationship between Moisture Content and Density, and MOE of Finger- Jointed Lumber Combinations

				Coefficients					
Wood Species/Type & MC	**N**	**Equation**	**Symbol**	**Unstandardized B/Value**	**Std. Error**	**Standardized B/Value**	**t**	**P-Value**	**R^2 Adj.**
Sapele Stem & Stem FJ 17±3%MC	30	MOE= c-αMC+βWD	c	25355.728	7944.648		3.192	.004***	.739
			α	-1301.459	259.745	-.744	-5.011	.000***	
			β	6.080	5.790	.156	1.050	.303ns	
10±4%MC	29	MOE= c-αMC+βWD	c	5149.835	5555.379		.927	.362ns	.805
			α	-865.187	244.469	-.453	-3.539	.002***	
			β	19.193	4.807	.511	3.993	.000***	
Sapele Stem & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	4505.652	3463.997		1.301	.204ns	.738
			α	-457.921	108.913	-.473	-4.204	.000***	
			β	13.718	2.968	.520	4.622	.000***	
10±4%MC	30	MOE= c-αMC+βWD	c	10606.942	3661.900		2.897	.007***	.676
			α	-620.227	146.987	-.647	-4.220	.000***	
			β	5.191	3.353	.238	1.548	.133ns	
Sapele Branch & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	9574.000	6607.043		1.449	.159ns	.658
			α	-492.454	229.308	-.421	-2.148	.041**	
			β	7.570	3.353	.442	2.258	.032**	
10±4%MC	30	MOE= c-αMC+βWD	c	1556.788	1434.114		1.086	.287ns	.885
			α	-326.765	50.080	-.485	-6.525	.000***	
			β	12.244	1.535	.593	7.975	.000***	

Table 4.3.12. (Continuation)

Wood Species/Type & MC	N	Equation	Symbol	Coefficients			t	P-Value	R^2 Adj.
				Unstandardized B/Value	Std. Error	Standardized B/Value			
Edinam Stem & Stem FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	13998.976	1287.154		10.876	.000***	.811
			α	-159.766	108.352	-.204	-1.475	.152ns	
			β	-7.945	1.496	-.734	-5.309	.000***	
10±4%MC	30	$MOE= c-\alpha MC+\beta WD$	c	3979.917	7165.494		.555	.583ns	.432
			α	-329.281	236.371	-.335	-1.393	.175ns	
			β	13.170	8.202	.386	1.606	.120ns	
Edinam Stem & Branch FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	11279.887	3780.721		2.984	.006***	.683
			α	-438.508	132.400	-.571	-3.312	.003***	
			β	4.888	2.715	.310	1.800	.083*	
10±4%MC	29	$MOE= c-\alpha MC+\beta WD$	c	6833.713	3913.303		1.746	.093*	.819
			α	-473.493	112.388	-.583	-4.213	.000***	
			β	11.664	4.325	.373	2.697	.012**	
Edinam Branch & Branch FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	22096.945	4974.400		4.442	.000***	.592
			α	-868.712	193.721	-.773	-4.484	.000***	
			β	.330	2.846	.020	.116	.909ns	
10±4%MC	30	$MOE= c-\alpha MC+\beta WD$	c	17125.798	4752.753		3.603	.001***	.563
			α	-880.084	202.958	-.710	-4.336	.000***	
			β	2.126	4.043	.086	.526	.603ns	
Mahogany Stem & Stem FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	5432.144	2635.126		2.061	.049*	.607
			α	-134.459	86.951	-.291	-1.546	.134ns	
			β	8.015	2.762	.547	2.902	.007***	
10±4%MC	30	$MOE= c-\alpha MC+\beta WD$	c	-901.744	3045.328		-.296	.769ns	.794
			α	-106.669	93.327	-.180	-1.143	.263ns	
			β	21.371	4.541	.741	4.706	.000***	
Mahogany Stem & Branch FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	10537.609	2214.131		4.759	.000***	.544
			α	-273.564	84.323	-.596	-3.244	.003***	
			β	2.205	1.975	.205	1.116	.274ns	
10±4%MC	30	$MOE= c-\alpha MC+\beta WD$	c	5600.911	2734.024		2.049	.050*	.785
			α	-359.747	100.726	-.506	-3.572	.001***	
			β	11.495	3.712	.438	3.096	.005***	
Mahogany Branch & Branch FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	12826.581	2998.760		4.277	.000***	.639
			α	-401.630	110.631	-.750	-3.630	.001***	
			β	.837	2.268	.076	.369	.715ns	
10±4%MC	30	$MOE= c-\alpha MC+\beta WD$	c	9339.374	3390.011		2.755	.010**	.761
			α	-591.422	123.476	-.719	-4.790	.000***	
			β	5.821	4.494	.194	1.295	.206ns	
Ofram Stem & Stem FJ 17±3%MC	30	$MOE= c-\alpha MC+\beta WD$	c	30853.301	12209.986		-2.527	.018**	.720
			α	-185.420	94.812	-.314	-1.956	.061*	
			β	70.800	19.287	.590	3.671	.001***	

Table 4.3.12. (Continuation)

Wood Species/Type & MC	N	Equation	Symbol	Coefficients			t	P-Value	R^2 Adj.
				Unstandardized B/Value	Std. Error	Standardized B/Value			
Ofram Stem & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	31356.056	10912.155		-2.873	.008***	.652
			α	-192.704	98.749	-.285	-1.951	.061*	
			β	62.870	15.146	.606	4.151	.000***	
10±4%MC	30	MOE= c-αMC+βWD	c	-548.730	5013.050		-.109	.914ns	.653
			α	-265.679	118.873	-.354	-2.235	.034**	
			β	20.453	6.105	.530	3.350	.002***	
Ofram Branch & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	3343.772	5363.625		.623	.538ns	.812
			α	-434.122	116.113	-.550	-3.739	.001***	
			β	14.924	5.547	.396	2.690	.012***	
10±4%MC	30	MOE= c-αMC+βWD	c	20666.906	3877.703		-5.330	.000***	.918
			α	80.383	81.759	.113	.983	.334ns	
			β	43.743	4.740	1.060	9.228	.000***	
Koto Stem & Stem FJ 17±3%MC	30	MOE= c-αMC+βWD	c	48596.314	21258.178		2.286	.030**	.160
			α	-1346.163	540.392	-.791	-2.491	.019**	
			β	-28.288	19.000	-.473	-1.489	.148ns	
10±4%MC	30	MOE= c-αMC+βWD	c	-9330.535	6914.207		-1.349	.188ns	.847
			α	-478.542	176.608	-.348	-2.710	.012**	
			β	38.137	7.926	.618	4.811	.000***	
Koto Stem & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	-3118.011	5795.187		-.538	.595ns	.879
			α	-554.571	172.870	-.345	-3.208	.003***	
			β	28.509	4.757	.644	5.994	.000***	
10±4%MC	30	MOE= c-αMC+βWD	c	-14625.656	8073.920		-1.811	.081*	.773
			α	-346.647	147.260	-.335	-2.354	.026**	
			β	43.630	10.310	.601	4.232	.000***	
Koto Branch & Branch FJ 17±3%MC	30	MOE= c-αMC+βWD	c	2739.888	6347.364		.432	.669ns	.665
			α	-348.795	173.324	-.340	-2.012	.054*	
			β	16.955	5.323	.538	3.185	.004**	
10±4%MC	30	MOE= c-αMC+βWD	c	-8647.033	2652.817		-3.260	.003***	.922
			α	-198.743	39.171	-.372	-5.074	.000***	
			β	33.214	3.677	.663	9.033	.000***	

NOTE: The statistical analyses are significant at 95% confidence level. ***p < 0.01; **p < 0.05; *p <0.1; and non-significant, $^{ns}p > 0.1$; N; number of samples, WD: wood density (kg/m^3); MC: moisture content of wood (%).

From Table 4.3.12, the regression coefficients (R^2 values) suggested appreciably strong relationship between MC and WD and MOE, implying that MC and WD combined can predict MOE of finger-jointed lumber better (i.e to an accuracy of between 43% and 92%). The R^2 values ranged from 0.432 (edinam stem & stem FJ combinations tested at 10±4%MC) to 0.922 (koto branch & branch FJ combinations tested at 10±4%MC). Comparatively, these R^2 values are lower than those for solid stemwood (from 0.542 to 0.933) and branchwood (from 0.552 to 0.961) (Table 4.3.5) tested at similar MC levels. The coefficients of MC and WD (i.e. **α** and **β** respectively), were generally significant (at least $p<0.1$).

Table 4.3.13 shows the relationship between MC and WD combined and MOR. In general, the **α** and **β** values for finger-jointed samples tested at10±4%MC appeared to be higher than their counterparts tested at 17±3%MC and they were generally significant (at least $p< 0.1$). The **α** and **β** values suggested that the rate of increases in FJ lumber MOR per 1 unit change in MC and WD is higher at lower MC (10±4%) than at a relatively higher MC (17±3%). The regression coefficients (R^2 values) ranged from 0.029 (sapele stem & branch combinations tested at 10±4%MC) to 0.884 (koto stem & stem FJ combinations tested at 10±4%MC). This suggested that the strength of the relationship (or the predictive power) of MC and WD ranged from very weak to relatively higher accuracy and it appeared to be species dependent.

Table 4.3.13. Relationship between Moisture Content and Density, and MOR of Finger- Jointed Lumber Combinations

				Coefficients					
Species/Type of Wood	**N**	**Equation**	**Symbol**	**Unstandardized B/Value**	**Std. Error**	**Standardized B/Value**	**t**	**P-Value**	**R^2. Adj.**
Sapele Stem & Stem FJ 17±3%MC	30	MOR= c-αMC+βWD	c	113.852	52.465		2.170	.039**	.644
			α	-6.423	1.715	-.650	-3.745	.001***	
			β	.045	.038	.204	1.178	.249ns	
10±4%MC	29	MOR= c-αMC+βWD	c	28.154	102.699		.274	.786ns	.366
			α	-6.034	4.519	-.308	-1.335	.193ns	
			β	.144	.089	.375	1.623	.117ns	
Sapele Stem & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	-14.333	31.609		-.453	.654ns	.411
			α	-.978	.994	-.166	-.984	.334ns	
			β	.091	.027	.569	3.374	.002***	
10±4%MC	30	MOR= c-αMC+βWD	c	52.160	43.642		1.195	.242ns	.029
			α	-1.363	1.752	-.207	-.778	.443ns	
			β	.019	.040	.125	.471	.641ns	

Table 4.3.13: (Continuation)

				Coefficients					
Species/Type of Wood	N	Equation	Symbol	Unstandardized B/Value	Std. Error	Standardized B/Value	t	P-Value	R^2. Adj.
Sapele Branch & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	68.664	63.037		1.089	.286ns	.332
			α	-3.183	2.188	-.399	-1.455	.157ns	
			β	.028	.032	.242	.883	.385ns	
10±4%MC	30	MOR= c-αMC+βWD	c	19.685	6.651		2.960	.006**	.847
			α	-1.368	.232	-.505	-5.892	.000***	
			β	.046	.007	.553	6.456	.000***	
Edinam Stem & Stem FJ 17±3%MC	30	MOR= c-αMC+βWD	c	142.883	18.387		7.771	.000***	.842
			α	-1.606	1.548	-.131	-1.038	.309ns	
			β	-.138	.021	-.814	-6.438	.000***	
10±4%MC	30	MOR= c-αMC+βWD	c	19.921	34.011		.586	.563ns	.422
			α	-1.208	1.122	-.261	-1.077	.291ns	
			β	.072	.039	.450	1.856	.074*	
Edinam Stem & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	12.613	29.087		.434	.668ns	.833
			α	-2.556	1.019	-.314	-2.510	.018**	
			β	.108	.021	.649	5.176	.000***	
10±4%MC	29	MOR= c-αMC+βWD	c	-.206	28.916		-.007	.994ns	.699
			α	-1.366	.830	-.294	-1.645	.112ns	
			β	.106	.032	.593	3.323	.003***	
Edinam Branch & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	82.537	39.947		2.066	.049**	.502
			α	-4.094	1.556	-.501	-2.632	.014**	
			β	.034	.023	.284	1.491	.148ns	
10±4%MC		MOR= c-αMC+βWD	c	59.557	21.118		2.820	.009***	.510
			α	-2.605	.902	-.501	-2.889	.008***	
			β	.031	.018	.302	1.741	.093*	
Mahogany Stem & Stem FJ 17±3%MC	30	MOR= c-αMC+βWD	c	21.406	17.173		1.246	.223ns	.618
			α	-.637	.567	-.209	-1.124	.271ns	
			β	.061	.018	.628	3.385	.002***	
10±4%MC	30	MOR= c-αMC+βWD	c	-41.475	31.864		-1.302	.204ns	.793
			α	-1.214	.977	-.196	-1.243	.225ns	
			β	.219	.048	.727	4.615	.000***	
Mahogany Stem & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	55.524	8.385		6.622	.000***	.677
			α	-1.326	.319	-.642	-4.153	.000***	
			β	.012	.007	.243	1.576	.127ns	
10±4%MC	30	MOR= c-αMC+βWD	c	37.352	17.183		2.174	.039**	.614
			α	-1.399	.633	-.419	-2.210	.036**	
			β	.052	.023	.426	2.244	.033**	
Mahogany Branch & Branch FJ 17±3%MC	30	MOR= c-αMC+βWD	c	6.030	26.622		.227	.823ns	.447
			α	-.113	.982	-.030	-.115	.909ns	
			β	.053	.020	.671	2.627	.014**	
10±4%MC	30	MOR= c-αMC+βWD	c	23.351	25.728		.908	.372ns	.690
			α	-2.627	.937	-.479	-2.803	.009***	
			β	.082	.034	.411	2.409	.023**	

Table 4.3.13: (Continuation)

				Coefficients					
Species/Type of Wood	N	Equation	Symbol	Unstandardized B/Value	Std. Error	Standardized B/Value	t	P-Value	R^2. Adj.
Ofram Stem & Stem FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-81.108	57.325		-1.415	.169ns	.643
			α	-.999	.445	-.407	-2.244	.033**	
			β	.228	.091	.456	2.518	.018**	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	111.044	49.216		2.256	.032**	.526
			α	-5.498	1.110	-.744	-4.951	.000***	
			β	.004	.074	.007	.048	.962ns	
Ofram Stem & Branch FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-311.294	90.144		-3.453	.002***	.544
			α	-.274	.816	-.056	-.335	.740ns	
			β	.539	.125	.720	4.311	.000***	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-11.915	44.088		-.270	.789ns	.477
			α	-1.598	1.045	-.297	-1.528	.138ns	
			β	.130	.054	.472	2.429	.022**	
Ofram Branch & Branch FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	18.640	38.472		.484	.632ns	.680
			α	-2.231	.833	-.514	-2.679	.012**	
			β	.074	.040	.358	1.866	.073*	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-109.917	49.456		-2.223	.035**	.806
			α	-.965	1.043	-.163	-.925	.363ns	
			β	.259	.060	.757	4.289	.000***	
Koto Stem & Stem FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-38.208	50.206		-.761	.453ns	.808
			α	-2.716	1.276	-.324	-2.128	.043*	
			β	.182	.045	.616	4.052	.000***	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	9.860	40.474		.244	.809ns	.884
			α	-5.383	1.034	-.582	-5.207	.000***	
			β	.168	.046	.405	3.620	.001***	
Koto Stem & Branch FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	74.743	60.036		1.245	.224ns	.529
			α	-4.581	1.791	-.542	-2.558	.016**	
			β	.056	.049	.242	1.142	.263ns	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-104.417	42.139		-2.478	.020**	.768
			α	-1.175	.769	-.220	-1.529	.138ns	
			β	.264	.054	.703	4.897	.000***	
Koto Branch & Branch FJ 17±3%MC	30	$MOR= c-\alpha MC+\beta WD$	c	9.616	60.058		.160	.874ns	.533
			α	-2.685	1.640	-.327	-1.637	.113ns	
			β	.119	.050	.470	2.358	.026**	
10±4%MC	30	$MOR= c-\alpha MC+\beta WD$	c	-147.508	31.593		-4.669	.000***	.870
			α	-1.260	.466	-.256	-2.701	.012**	
			β	.341	.044	.739	7.789	.000***	

NOTE: The statistical analyses are significant at 95% confidence level. ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$; and non-significant, nsp > 0.1; N; number of samples, WD: wood density (kg/m^3); MC: moisture content of wood (%).

Comparatively, these R^2 values (Table 4.3.13) are lower than those for solid stemwood (from 0.582 to 0.928) and branchwood (from 0.77 to 0.911) (Table 4.3.6) tested at similar MC levels. Hence, MC and WD could also predict MOR of solid wood to relatively higher accuracy than for finger-jointed lumber. Moreover, from

Tables 4.3.12 and 4.3.13, a comparison of the R^2 values for MOE and MOR also suggested that, in general, MC and WD appeared to have a better predictive power for MOE (i.e. from 43% to 92% level of accuracy-Table 4.3.12) than for MOR (i.e. from 3% to 88% level of accuracy-Table 4.3.13).

4.3.2.6: Predicting MORs of finger-jointed lumber from their MOEs.

Figure 4.3.13 presents the regression analyses of the relationships between MOE and MOR of finger-jointed lumber of stemwood and branchwood sample groups tested at the two moisture levels (specifically stem & stem FJ and branch & branch FJ). As it occured for solid stem and branch woods, positive relationships were observed between MOE and MOR of both stem & stem FJ and branch & branch FJ at the two MC levels (i.e. 17±3%and 10±4%).

From figure 4.3.13, generally, it appeared that both second degree polynomial, exponential and power functions ($p< 0.001$, $R^2= 0.59-0.77$) and linear functions ($p< 0.001$, $R^2= 0.58-0.77$) provided the best fits in predicting MORs of both stemwood & stemwood FJ and branchwood & branchwood FJ of all the species as functions of their MOEs. For predicting the MORs of stem & stem FJ of the species at 17±3%MC, based on their MOEs, a power function proved to be the best fit and accounted for 65% of the variation whereas exponential function best predicted the MORs at 10±4%MC ($R^2 = 0.59$; Figure 4.3.13 c). Moreover, in predicting the MORs of branch & branch FJ from their MOEs, both polynomial and linear functions appeared to equally provide the best fits and accounted for 77% and 75% of the variations respectively at 17±3%MC and 10±4%MC. These meant that whereas in stem & stem FJ the MOE and MOR relationships at both 17%MC and 10%MC appeared to be different, in branch & branch FJ, the relationships at the two moisture levels generally appeared to be linear and not different. Thus, moisture level appeared to affect the MOE and MOR relationships in stem & stem FJ compared to the effect on branch & branch FJ of all the species together.

Comparatively, and considering the linear functions, the R^2 values for stem & stem FJ were lower than those of solid stemwood (i.e. 0.68 at 17%MC and 0.75 at 10%MC- figure 4.3.8 a and c) but those of branch & branch FJ appeared to be higher than those of solid branchwood (0.76 at 17%MC and 0.62 at 10%MC-figure 4.3.8 b and d). These imply that the relationships of MOE and MOR are relatively weaker when stemwoods are finger-jointed but they tend to be relatively stronger when branchwoods are finger-jointed.

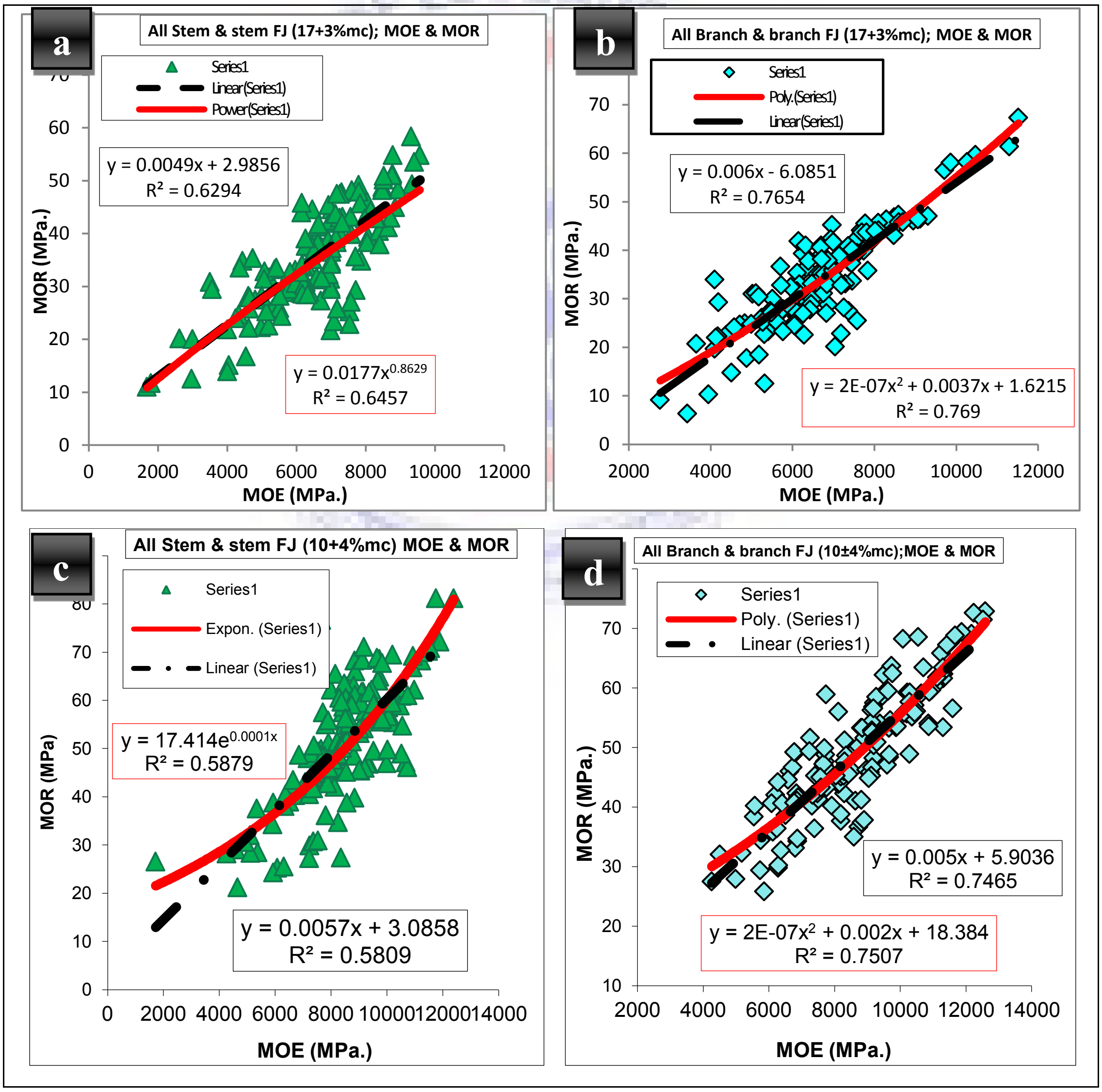


Figure 4.3.13: Relationship between MOE and MOR of Stem and Branch Wood tested at Two Moisture Levels; N= 100.

Additionally, from figure 4.3.13, the coefficient of MOE (**γ-** Equation 3.11) implied that 1MPa. change in MOE of stem & stem FJ lumber could result in 0.005MPa. and 0.0065MPa. change in MOR respectively at 17±3%MC and 10±4%MC levels. On the other hand, 1MPa. change in MOE of branch & branch FJ lumber could result in 0.006MPa. and 0.005MPa change in MOR respectively at 17±3%MC and 10±4%MC levels. These appear to suggest that whereas the effect of changes in MOE is high at lower MC level relative to a higher MC level for the stem & stem FJ (and solid stem and branch woods behaved similarly-figure 4.3.8), but the opposite is the case for the branch & branch FJ. These mean that the two finger-jointed lumber combinations could behave differently in terms the relationships of their MOEs and their MORs possibly due to anatomical, chemical and other structural as well as gluability differences.

4.4: Anatomical Study

Both qualitative and quantitative study of the anatomical properties of branch and stem woods of the studied species were undertaken to assess their similarities and differences in the wood types of same species. Qualitatively, photomicrographs were used to describe the appearances and arrangements of the various wood cells in stem and branch woods, using IAWA list of microscopic features for hardwood identification. Quantitatively, measurements were done to ascertain some dimensions and proportions of some cells using ImageJ software, and subsequently assessed their relationships with density, percentage weight loss (natural durability) and bending strength properties (MOE and MOR) of both solid or unjointed lumber in this study. These relationships were to provide further understanding of the behaviour of the wood types regarding the tests conducted in this study.

4.4.1: Qualitative anatomy of wood

Figures 4.4.1 to 4.4.6 present photomicrographs of stem and branch wood of sapele, edinam, mahogany, ofram, and onyina (only stemwood) respectively. From Figure 4.4.1, sapele vessels were observed to be partly solitary and partly in radial multiples of 2-4 with rounded outlines for both stem and branch woods with some occluded with tyloses (arrowed blue). Fibres are banded for both stem and branch woods but appear to be longer in stems than branchwood. Ray parenchyma (arrowed green) appears to be narrow in branchwood than those in stemwood. Axial parenchyma appear to be predominantly aliform confluent paratracheal in stemwood, but seemingly marginal bands in both stem and branch woods.

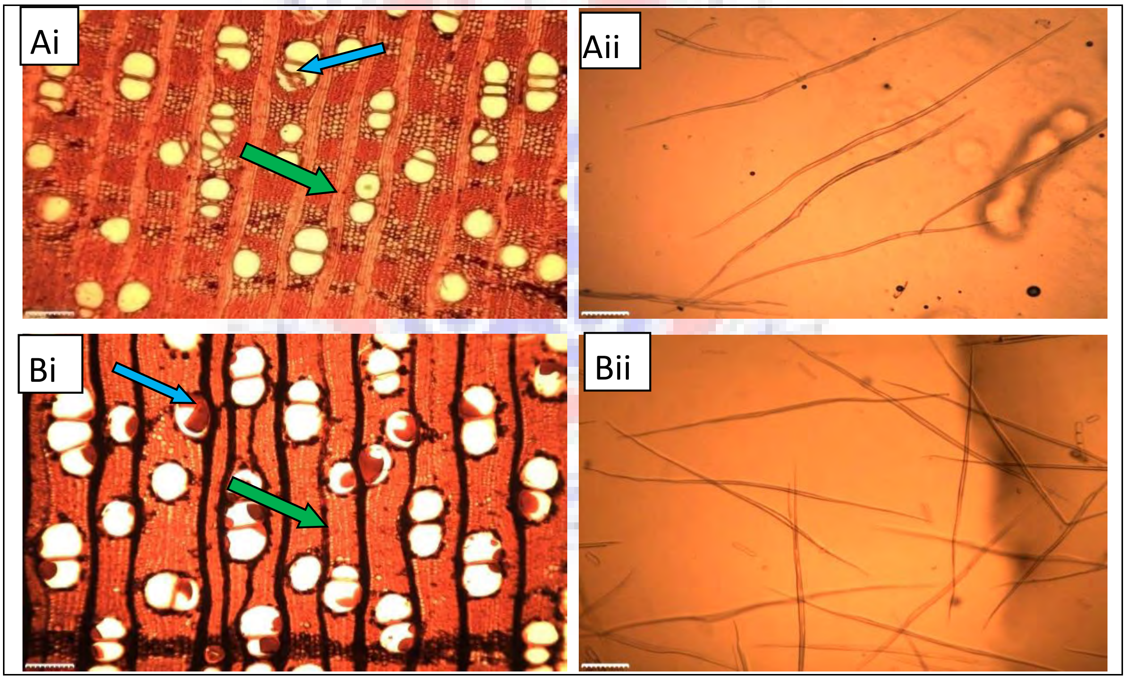


Figure 4.4.1. Transverse Sections and Fibres of *Entandrophragma cylindricum* (sapele), Scale bar = 200µm. (**A**= Stemwood, **B** = Branchwood, **i**= Transverse sections and **ii** = fibres).

E. angolense were observed to have vessels which are partly arranged in solitary and partly in radial multiples of 2-4 with rounded outlines in both stem and branch wood and some are occluded with some deposits/tylosis (arrowed blue) (Figure 4.4.2). Fibres appear to be longer in stem than branch wood. Ray parenchyma (arrowed green) appear to be narrow in branchwood than those in stemwood and both appear to contain some crystals or minerals. Axial parenchyma in stemwood appear to be predominantly vasicentric with narrow sheath.

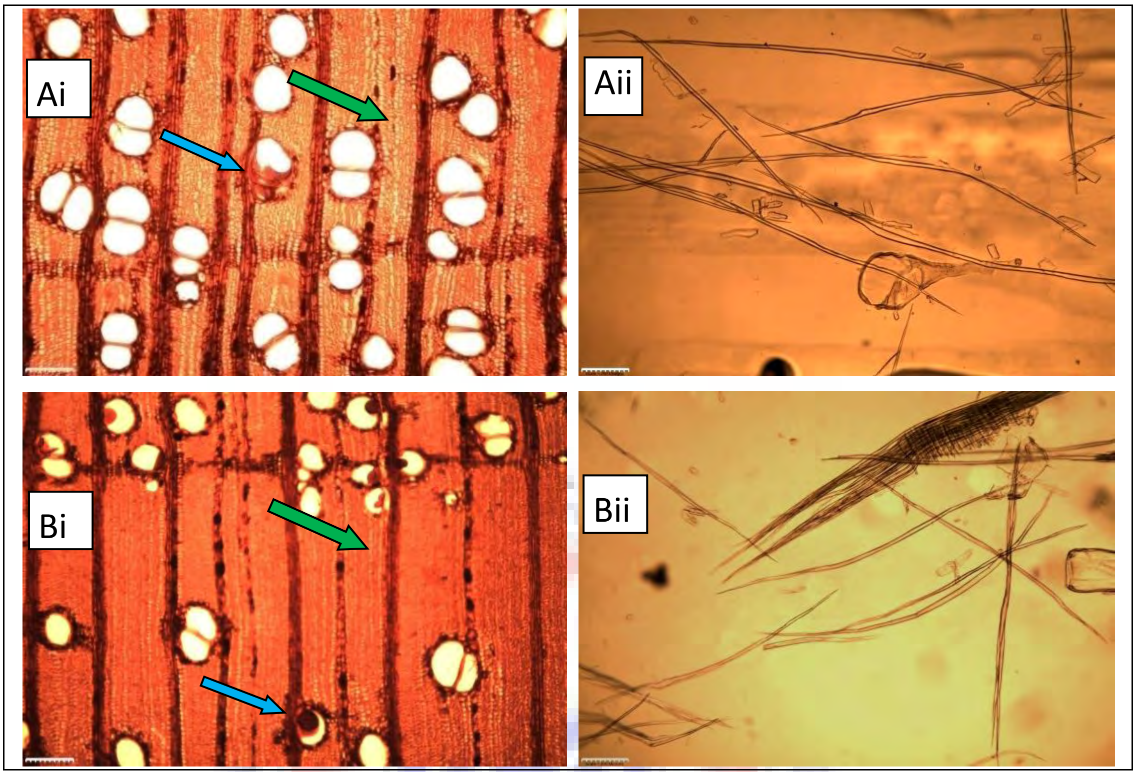


Figure 4.4.2 Transverse sections and fibres of *Entandrophragma angolense* (edinam), Scale bar = 200µm. (**A** = Stemwood, **B** = Branchwood, **i** = Transverse sections and **ii** = fibres).

Figure 4.4.3 shows the photomicrographs of stem and branch woods of *K. ivorensis* (mahogany). The vessels of *K. ivorensis* were found to be predominantly solitary in stemwood than in branchwood but all are partly in radial multiples of 2-4 with rounded outlines and with some deposits/tylosis (arrowed blue) (Figure 4.4.3). Fibres appear to be shorter in stemwood than branchwood. Ray parenchyma (arrowed green) appears to have some crystals or mineral inclusions and appear to be much distinct in branchwood than those in stemwood. Axial parenchyma appears to be rare in both stem and branch wood.

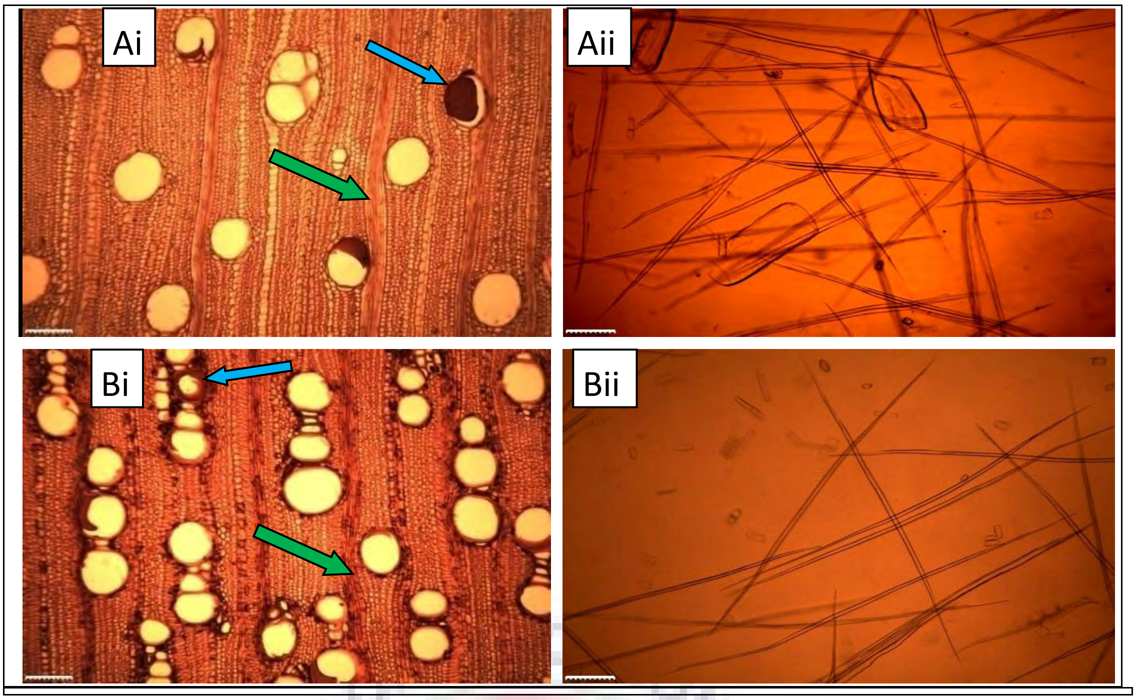


Figure 4.4.3. Transverse Sections and Fibres of *Khaya ivorensis* (mahogany); Scale bar = 200µm. (**A** = Stemwood, **B** = Branchwood, **i** = Transverse sections and **ii** = fibres).

Figuere 4.4.4 shows the photomicrographs of stem and branch woods of *Terminalia superba* (ofram).

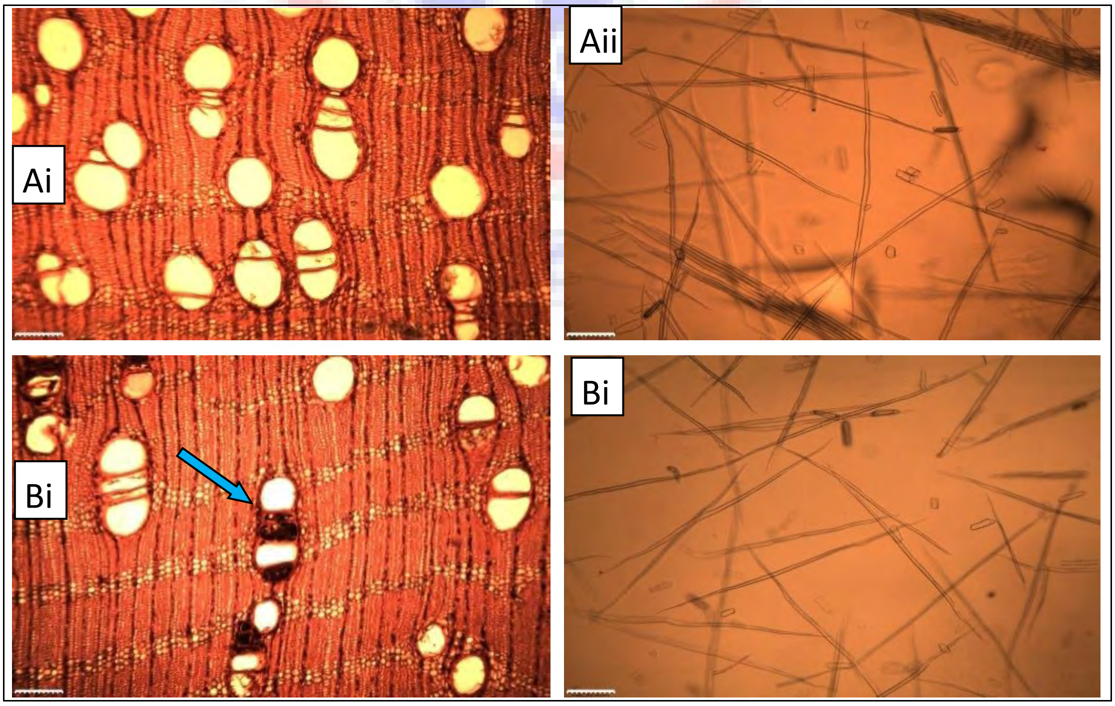


Figure 4.4.4. Transverse sections and fibres of *Terminalia superba* (ofram); Scale bar = 200µm. (**A** = Stemwood, **B** = Branchwood, **i** = Transverse sections and **ii** = fibres).

The vessels in both stem and branch woods if *T. superba* were observed to be partly solitary and partly in radial multiples of 2-4 with rounded outlines but some in branchwood are occluded with deposits/tyloses (arrowed blue). Fibres are banded in both stem and branch woods but they appears to be longer in stemwood than branchwood. Ray parenchyma in stemwood appears not to be visibly distinct from those in branchwood. Axial parenchyma appear to be predominantly aliform confluent paratracheal in stemwood but banded (narrow bands) in branchwood.

Figuere 4.4.5 also shows the photomicrographs of stem and branch wood of *Pterygota macrocarpa* (koto).

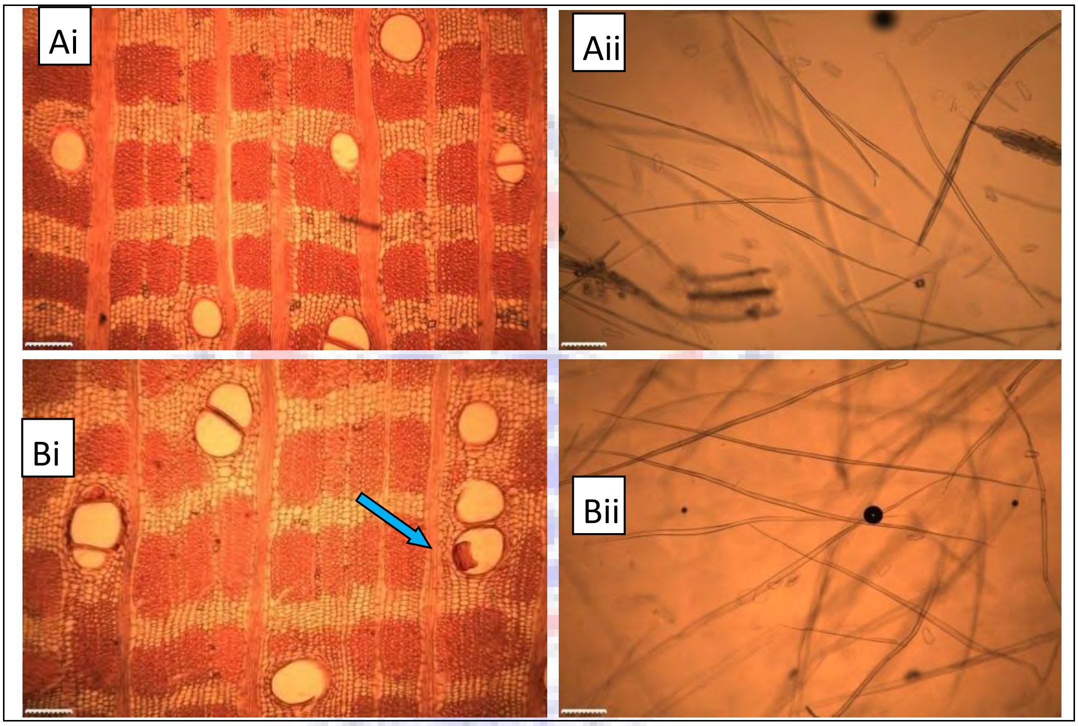


Figure 4.4.5. Transverse sections and fibres of *Pterygota macrocarpa* (koto), Scale bar = 200µm. (**A** = Stemwood, **B** = Branchwood, **i** = Transverse sections and **ii** = fibres).

From the photomicrographs of *P. macrocarpa* (Figure 4.4.5), vessels in both stem and branch wood are predominantly solitary and partly in radial multiples of 2-4 with rounded outlines but some in branchwood are occluded with deposits/tyloses (arrowed blue). Fibres are banded for both stem and branch wood but they appear to be longer in branchwood than in stemwood. Ray parenchyma in stemwood appear not to be visibly distinct in size from those in branchwood. Axial parenchyma in both stem and branch wood is predominantly in bands (more than three cells wide).

Figuere 4.4.6 shows the photomicrographs of stemwood of *Ceiba pentandra* (onyina- used as control for the natural durability test).

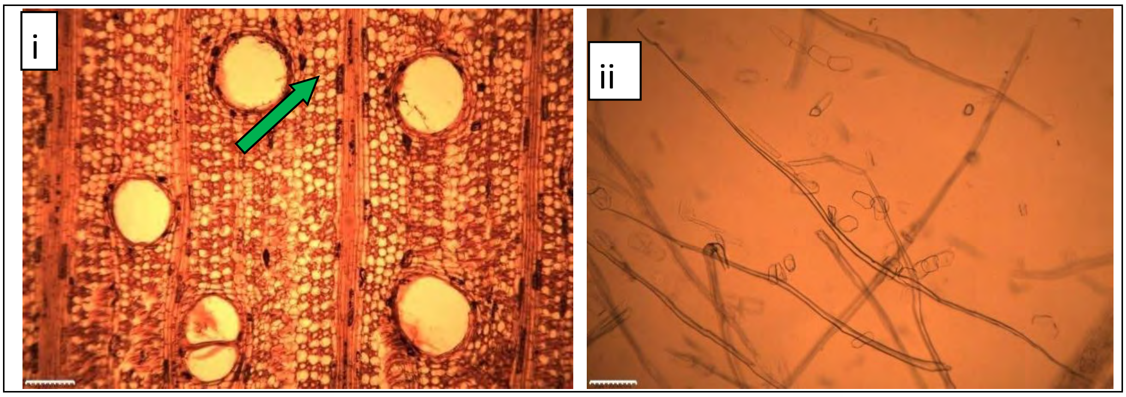


Figure 4.4.6 Transverse sections and fibres of *Ceiba pentandra* (onyina) stemwood; Scale bar = 200µm. (**i** = Transverse sections and **ii** = fibres).

From Figure 4.4.6, vessels of onyina were observed to be predominantly solitary and partly in radial multiples with rounded outlines. Fibres are very long. Crystals or mineral inclusions appear to be predominantly present in ray cells, Axial parenchyma is predominantly apotracheal and diffuse-in-aggregate.

4.4.2: Quantitative Anatomy of wood

Measurements made on some cells upon maceration and sectioning of stem and branch wood of the 5 studied species and stemwood of *Ceiba pentandra* (used as control for the natural durability test) produced the quantitative anatomical data presented in Table 4.4.1 and Figure 4.4.7. The results generally showed that fibres are either shorter or longer and vessel lumen diameters are either larger or smaller in some branchwood than stemwood of same species (Table 4.4.1). Also, the proportion of the 3 major cells/tissues in wood (fibres, vessels and parenchyma) per 1mm^2 cross-sectional area were either higher or lower in some branchwood than their stemwood of same species. However, some of these differences were statistically significant ($p<0.01$, $p<0.05$ and $p<0.1$) at 95% confidence level and others were not.

These suggest therefore that anatomical property differences between stem and branch woods of same species are species dependent.

Figure 4.4.7 also presents the graphical representation of percentages of the 3 major cells/tissues in wood (vessels, fibres and parenchyma) proportions/mm^2 cross-sectional area for stem and branch woods of the studied species. From Figure 4.4.7 and Table 4.4.1, it appeared that the species with higher proportion of fibres in their stem and branch wood generally tend to have lesser parenchyma proportion and vice versa. For instance, *Ceiba pentandra*- onyina stemwood (control), and stem and branch woods of both *Terminalia superba*-ofram and *Pterygota macrocarpa*-koto had the highest proportions of parenchyma but lower proportion of fibres. Again, the stem and branch wood of *Khaya ivorensis*-mahogany, *Entandrophragma angolense*-edinam and *Entandrophragma cylindricum*-sapele had relatively higher proportions of fibres but lower proportions of parenchyma cell tissues.

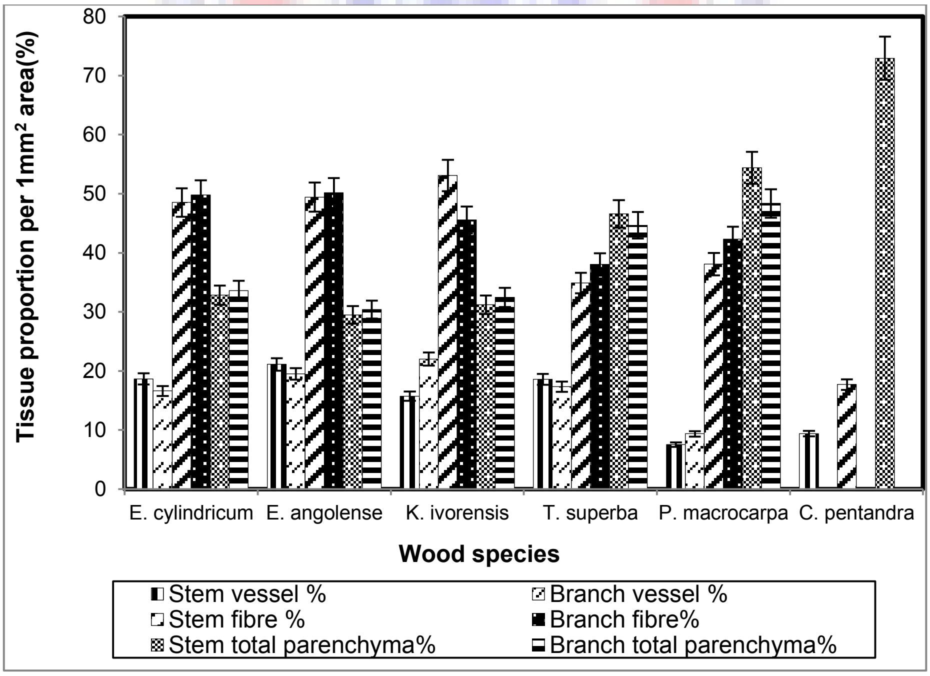


Figure 4.4.7. Mean Anatomical Tissue Proportions(%) in Stem and Branch Woods of the Five Studie Species; N= 50, Error bars = Percentages.

Table 4.4.1 represents the summary statistics of the five anatomical characteristics studied (i.e. fibre length, vessels diameter, fibre proportion, vessel proportion and parenchyma proportion). From this Table, except for vessel proportion per 1mm^2 cross-sectional area, all mean values of anatomical properties for stemwood of all the other species were significantly different ($p<0.05$) from those of *Ceiba pentandra*-onyina (control species for the natural durability test). However, among the branchwoods, all anatomical properties of all species except for fibre proportion were significantly different ($p<0.05$) from those of *Pterygota macrocarpa* (koto). Fibre lengths generally showed that, except for *Khaya ivorensis* and *Pterygota macrocarpa,* branchwood had relatively shorter fibres compared to stemwood of same species (Table 4.4.1). Fibre lengths of the stemwood were 1478.90µm, 1545.70µm, 1451.50µm, 1234.60µm, 1520.60µm and 1919.10µm respectively for sapele, edinam, mahogany, ofram, koto and onyina. The results showed decreases in fibre lengths for branchwood relative to those of stemwood as 11.97%, 14.24%, and 5.04% for sapele, edinam and ofram respectively, whereas those for branchwood of mahogany and koto registered increases of 1.52% and 24.23% respectively. These appear to confirm the qualitative assessements of the fibre lengths (Figures 4.4.1 to 4.4.6). However, independent sample T-Test indicated that these differences in fibre lengths were statistically significant at 1% level of significance for sapele (T=4.308), edinam (T=5.557) and koto (T= -5.946), but not significant ($p>0.1$) for those of mahogany and ofram (Table 4.4.1).

Table 4.4.1: Summary descriptive statistics of some anatomical properties of stem and branch wood.

Species/type of wood	**Sapele**	**Edinam**	**Mahogany**	**Ofram**	**Koto**	**Onyina**	**F-value**	**P-value**
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)		
				Fibre Length (µm)				
Stemwood	1478.90 (201.35) ^{af}	1545.70 (215.86) ^{bg}	1451.50 (281.70) ^{ch}	1234.60 (160.94) ^{dfghi}	1520.60 (254.69) ^{ei}	1919.10 (282.96) ^{abcde}	44.041	.000***
Branchwood	1301.90 (209.37) ^{mr}	1325.60 (178.56) ^{nst}	1473.50 (230.03) ^{prsu}	1172.40 (220.96) ^{qtu}	1889.00 (356.48) ^{mnpq}	-	62.841	.000***
T-value	4.308***	5.557***	-.428	1.610	-5.946***			
				Vessel Lumen Diameter (µm)				
Stemwood	134.52 (35.37) ^{afgh}	166.46 (36.02) ^{bfi}	144.31 (33.10) ^{cijk}	183.08 (32.33) $^{dg\ k}$	165.02 (40.80) ^{ehj}	227.21 (35.55)^{abcde}	42.533	.000***
Branchwood	124.38 (17.09) ^{mq}	138.08 (36.57) ^{nr}	133.52 (29.67) ^{ps}	161.42 (32.64) ^{qrs}	176.21 (39.99) ^{mnp}	-	22.195	.000***
T-value	1.826*	3.936***	1.715*	3.333***	-1.386			
				Fibre Proportion (%)				
Stemwood	48.52 (7.58) ^{afgh}	49.42 (8.13) ^{bij}	53.10 (8.33) ^{cfkl}	34.87 (6.64) ^{dgik}	38.07 (7.67) ^{ehjl}	17.69 (5.29) ^{abcde}	159.336	.000***
Branchwood	49.80 (10.72) ^{mp}	50.15 (7.31) ^{nq}	45.56 (17.05) ^{r}	38.03 (6.93) ^{pqr}	42.28 (9.99) ^{mn}	-	10.876	.000***
T-value	-.689	-.472	2.811***	-2.331**	-2.366**			
				Vessel Proportion (%)				
Stemwood	18.66 (5.55) ^{ae}	21.10 (6.49) ^{bfh}	15.71 (6.89) ^{cfi}	18.57 (5.01) ^{dj}	7.53 (3.83) ^{ehij}	9.38 (3.52) ^{abcd}	52.536	.000***
Branchwood	16.60 (3.17) ^{mr}	19.47 (8.10) ^{n}	22.01 (8.07) ^{prs}	17.31 (7.02) ^{qs}	9.35 (4.51) ^{mnpq}	-	26.729	.000***
T-value	2.273**	1.107	-4.197***	1.030	-2.174**			
				Total Parenchyma Proportion (%)				
Stemwood	32.82 (8.76) ^{afg}	29.48 (8.70) ^{bhi}	31.19 (7.39) ^{cjk}	46.57 (8.14) ^{dfhjl}	54.40 (7.78) $^{eg\ ikl}$	72.93 (6.93) ^{abcde}	227.705	.000***
Branchwood	33.60 (12.05) ^{mq}	30.38 (9.12) ^{nr}	32.43 (14.22) ^{ps}	44.66 (10.34)^{qrs}	48.36 (10.34) ^{mnp}	-	25.229	.000***
T-value	-.367	-.502	-.550	1.025	3.296***			

Note: The statistical analyses are significant at 95% confidence levell. ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$; Also mean values of the same letters indicate significant difference at 5% significance level.

Moreover, branchwood generally had marginally higher fibre proportion (though relatively shorter in length) than stemwood. Fibre proportions per mm^2 cross-sectional area (%) of stemwood were found to be 48.52%, 49.42%, 53.10%, 34.87%, 38.07%, and 17.70%, respectively for sapele, edinam, mahogany, ofram, koto and onyina (control) whereas those of the branchwood were 1.28%, 0.73%, 3.16%, 4.21% higher respectively for sapele, edinam, ofram and koto but lower by 7.54% for the branchwood of mahogany. These differences were however not statistically significant ($p>0.1$) for sapele and edinam but were significant for mahogany ($T=2.811$) at 1%, and ofram ($T=2.331$) and koto ($T= 2.366$) at 5% level of significance (Table 4.4.1).

Additionally, except for koto, vessel lumen diameter were relatively larger in stemwood than branchwood of same species. Vessel lumen diameter for the stemwood were 134.52µm, 166.46µm, 144.31µm, 183.08µm, 165.02µm and 227.21µm for sapele, edinam, mahogany, ofram, koto and onyina respectively. From the results, vessel lumen diameter in branchwood compared to their respective stemwood had decreases ranging from 7.47% (*mahogany*) to 17.17 % (*edinam*) whereas that of koto registered an increase of 6.78%. These differences in vessel lumen diameter were significantly different at 1% level of significance for edinam ($T=3.936$) and ofram ($T=3.333$), and at 10% level of significance for sapele ($T= 1.826$) and mahogany ($T=1.715$) – Table 4.4.1. Normally, it would have been expected that relatively larger vessel lumen diameter in stemwood should have translated into fewer number of vessels or lesser vessel proportion per mm^2 cross-sectional area. But findings were somehow on the contrary, possibly due to differences in the arrangements of vessels in the different wood species (Figures 4.4.1 to 4.4.6). Hence, except for mahogany and koto, generally, stemwood had higher vessel proportions (though larger in diameter) than in branchwood. The proportions in branchwood were lower than those of their stemwood by 2.05%, 1.62% and 1.26% respectively for sapele, edinam and ofram but higher by 6.30% and 1.82% respectively for mahogany and koto. These differences were statistically significant for sapele ($T= 2.273$, $p<0.05$), mahogany ($T= 4.197$, $p<0.01$) and koto ($T= 2.14$, $p<0.05$).

Total parenchyma proportion in the stemwood, besides those of ofram and koto, were found to be marginally lower in stemwood than branchwood (Figure 4.4.7 and Table 4.4.1). The total parenchyma proportion (ray plus axial) were found to be 32.82%, 29.48%, 31.19%, 46.57%, 54.40%, 72.93%, respectively for the stemwood of sapele, edinam, mahogany, ofram, koto and onyina (control). The branchwood were 0.77%, 0.89%, 1.25% higher in parenchyma in sapele, edinam and mahogany, but they tend to be lower by 1.91% and 6.03% in branchwood of ofram and koto respectively. However, only the differences occurring in koto ($T=3.296$) were statistically significant at 1% significance level.

Generally, from the quantitative anatomical properties assessements, stem and branch wood of at least 3 species had differences in fibre length, vessel lumen diameter, vessel proportion and fibre proportion that were statistically significant (at least $p<0.1$). However, the differences in parenchyma proportion were statistically significant between stem and branch wood in only 1 species among the 5 studied species. The expectation from all these findings is that, these anatomical property differences might have some level of significant influence on the density, percentage weight loss (natural durability) and bending strength properties of solid/unjointed stem and branch woods of the species. These were assessed through regression analyses subsequently.

4.4.3: Mean quantitative anatomical properties and mean wood density

Regression analyses indicated that all anatomical features, except fibre proportion, correlated negatively with mean density of both stem and branch wood (Figure 4.4.8).

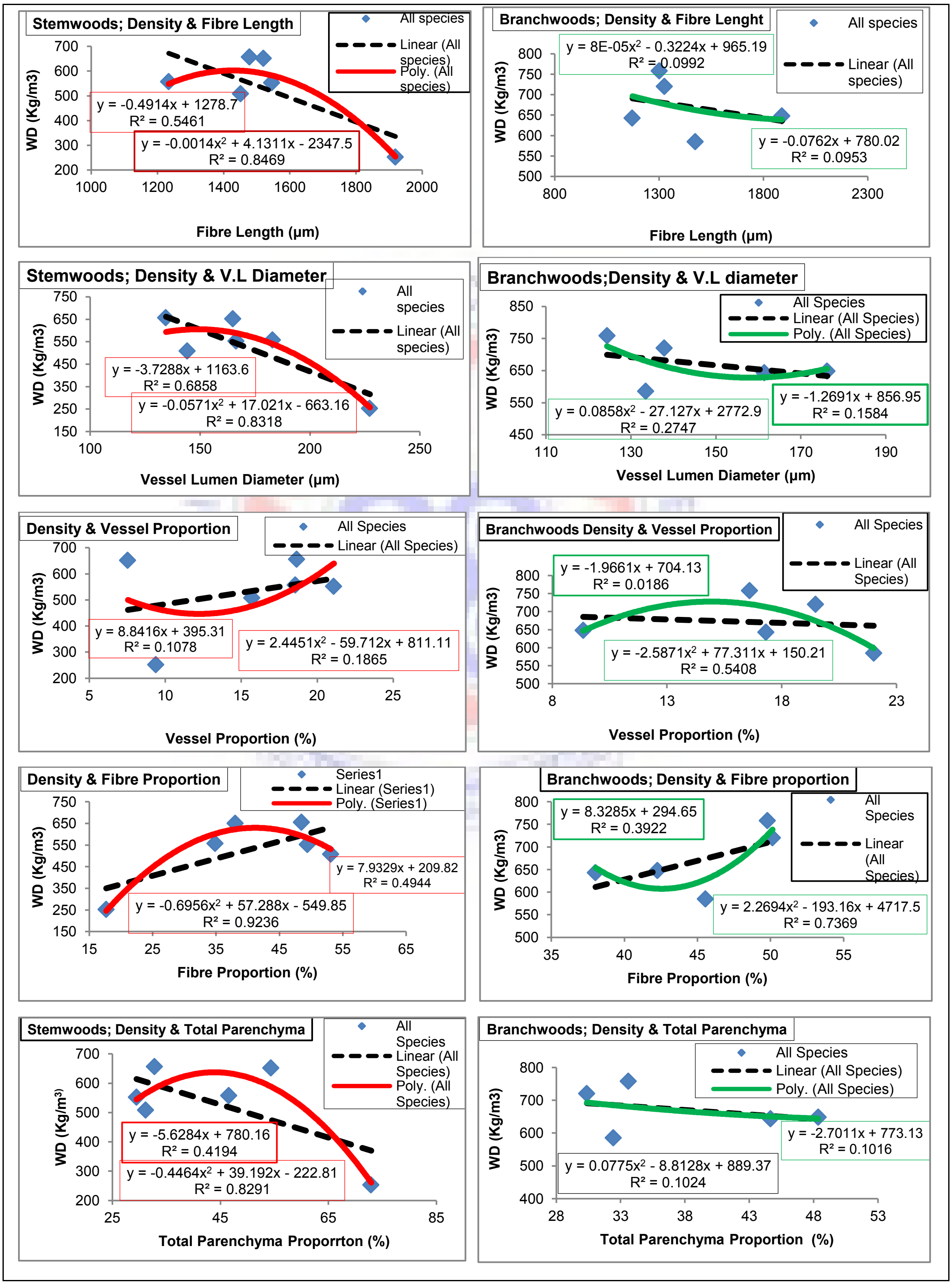


Figure 4.4.8: Relationship between mean Quantitative Anatomical Properties and mean Density of Branch and Stem Woods; N = Means of 50.

From Figure 4.4.8, vessel proportion corelated negatively and positively with density of branch and stem wood respectively. Though R^2 values for both linear and second degree polynomial functions were generally higher for stemwood than branchwood. These imply that the anatomical characteristics can predict stemwood density better than the densities of their branchwood counterparts. Also, comparatively, it appeared that second degree polynomial functions rather than linear functions provided the best fits in predicting densities of both stemwood ($p < 0.001$, $R^2 = 0.18\text{-}0.92$) and branchwood ($p < 0.001$, $R^2 = 0.095\text{-}0.740$) as a functions of their anatomical characteristics. Morever, whereas fibre proportion best predicted the densities of both stemwood ($R^2 = 0.92$) and branchwood ($R^2 = 0.74$), vessel proportion and fibre length were the poorest predictor anatomical characteritstics respectively for stemwood ($R^2 = 0.18$) and branchwood ($R^2 = 0.095$). These mean that, generally, the association between any of the five anatomical features and density of either stem or branch wood is not linear, and fibre content has similar strength of association with density of both stem and branch woods.

4.4.4: Quantitative anatomical properties and percentage weight loss (natural durability).

Regression analysis showed that each anatomical property correlated with percentage weight losses (%WL) or natural durability in the same manner (either positive or negative) for both stem and branch wood (Figure 4.4.9). From Figure 4.4.9, comparatively, second degree polynomial functions rather than linear functions provided the best fits in predicting the natural durability (i.e. in terms of percentage weitght loss) of both stemwood ($p < 0.001$, $R^2 = 0.36\text{-}0.88$) and branchwood ($p < 0.001$, $R^2 = 0.64\text{-}0.87$) as a functions of their anatomical characteristics. Also, vessel proportion and fibre proportion respectively best predicted the natural durability of stemwood (R^2 = 0.88) and branchwood (R^2 = 0.87). Meanwhile, all the five anatomical features strongly predicted the natural durability of branchwood (i.e. the least was vessel proportion with R^2 = 0.64) but fibre length was the poorest predictor of stemwood natural durability (R^2 = 0.36).

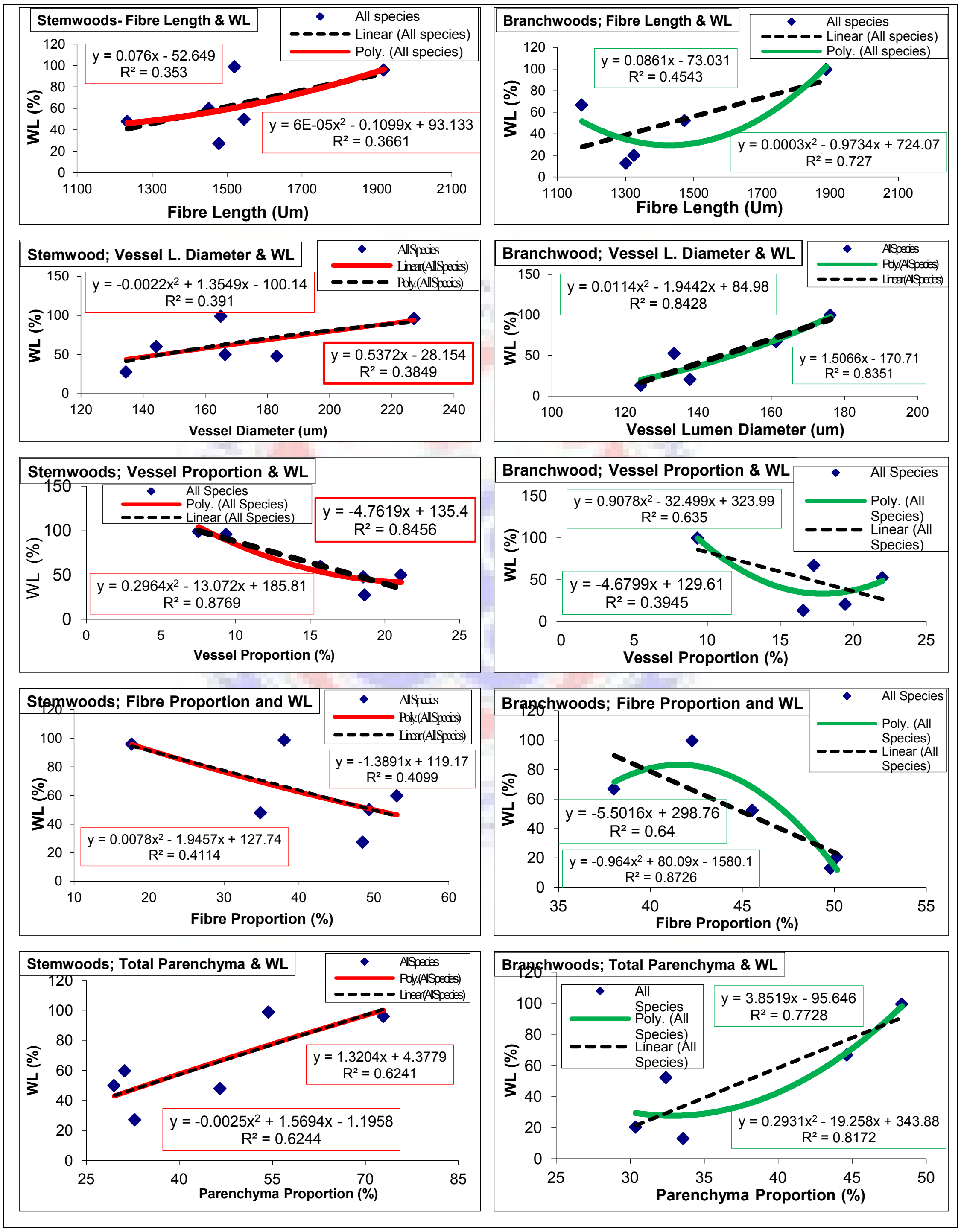


Figure 4.4.9. Relationship between mean quantitative anatomical properties and percentage weight loss (% WL) of stem and branch wood; N= Means of 50.

Again, from Figure 4.4.9, it was observed that unlike branchwood, the natural durability of stemwood of the studied species appeared to have almost linear relationships with their anatomical characteristics (at least for the ones measured). These findings mean that anatomical features have varied strength of association with natural durability of stemwood and branchwood of the species studied

4.4.5: Quantitative anatomical properties and bending strength of solid wood.

The relationships between mean quantitative anatomical property values and bending properties were to serve as another non-destructive method to predict the MOE and MOR of the studied wood species (Figures 4.4.10 and 4.4.11).

From Figure 4.4.10, generally, each anatomical property correlated in similar manner (either positive or negative) with the MOE of both stem and branch wood though the relationships were generally weak for branchwood. However, comparatively, second degree polynomial functions rather than linear functions provided the best fits in predicting the stiffness (MOE) both stemwood ($p < 0.001$, $R^2 = 0.06\text{-}0.69$) and branchwood ($p < 0.001$, $R^2 = 0.03\text{-}0.92$) as functions of their anatomical characteristics. But fibre length and parenchyma proportion respectively best predicted the MOE of stemwood ($R^2 = 0.69$) and branchwood ($R^2 = 0.92$). Again, it was observed that unlike stemwood, the MOE of branchwood of the studied species appeared to have very weak relationships with their anatomical characteristics (at least for the ones measured). These findings mean that except for parenchyma proportion, anatomical features may have weak associations with stiffness of branchwood, therefore could be poor predictors of branchwood MOE relative to those of stemwood.

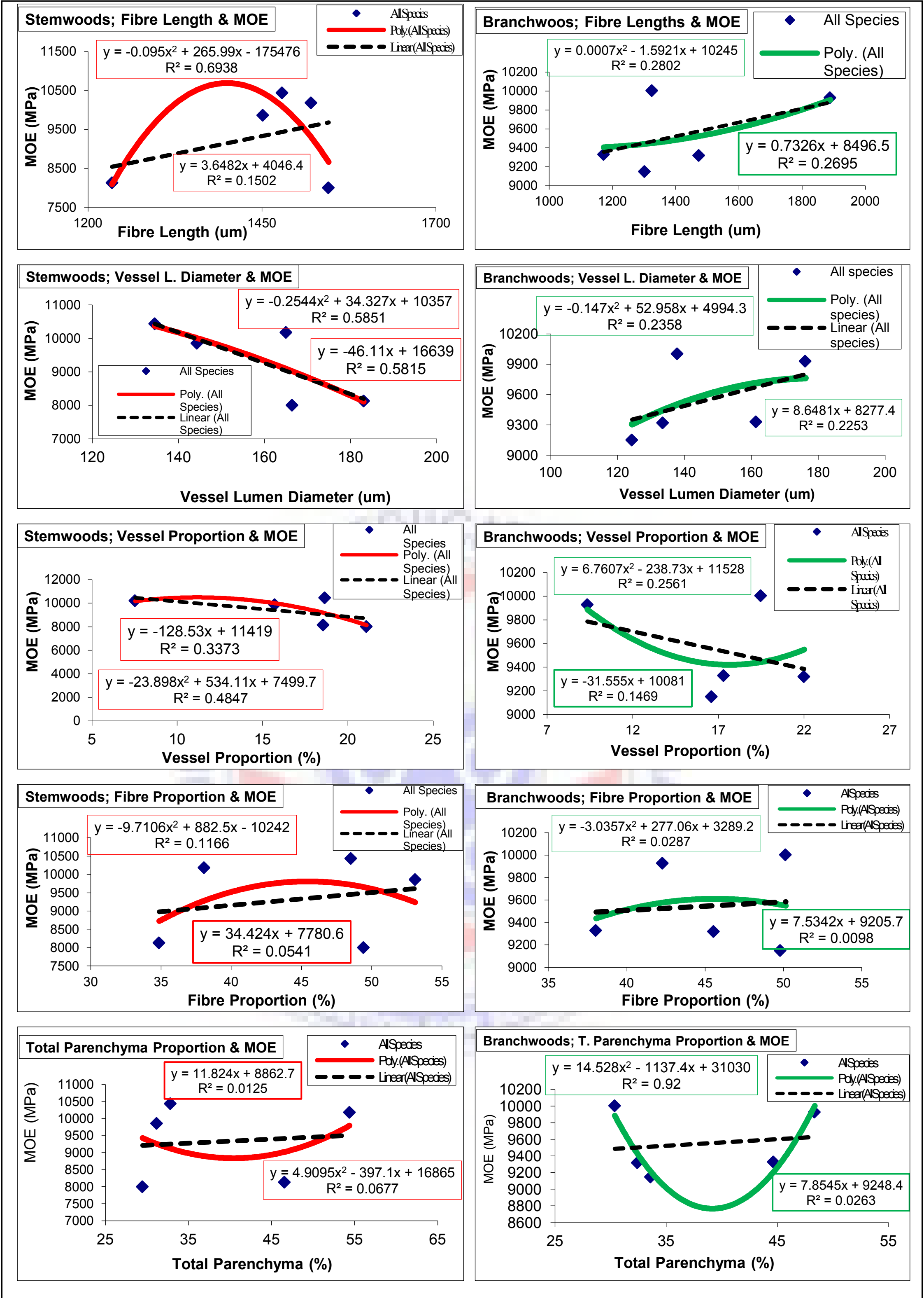


Figure 4.4.10. Relationship between mean anatomical properties of stem and branch wood and their mean MOE; N= Means of 50.

Also, from Figure 4.4.11, generally, anatomical properties of both stem and branch wood generally correlated in similar manner (either positively or negatively) with the MOR of the wood types. The exceptions in this trend were fibre length and vessel proportion. Fibre length and MOR correlated positively in stemwood but negatively in branchwood. Also, vessel proportion and MOR correlated negatively in stemwood but positively in branchwood.

Again, comparatively, the predictive powers of the anatomical characteristics in predicting MOR appeared to be higher for branchwood than stemwoods (Figure 4.4.11). Additionally, it was found that either second degree polynomial or exponential functions rather than linear functions provided the best fits in predicting the bending strength (MOR) of both stemwood ($p < 0.001$, $R^2 = 0.05\text{-}0.52$) and branchwood ($p < 0.001$, $R^2 = 0.22\text{-}0.95$) as functions of their anatomical characteristics. However, vessel diameter and paranchyma proportion respectively best predicted the MOR of stemwood ($R^2 = 0.52$) and branchwood ($R^2 = 0.95$). Vessel proportion was found to be the poorest predictor of the MOR of both stemwood ($R^2 = 0.05$) and branchwood ($R^2 = 0.22$). These findings mean that anatomical features have varied strength of association with MOR of stemwood and branchwood of the species studied.

Considering the R^2 values in Figures 4.4.10 and 4.4.11, they appeared to suggest generally that, the anatomical properties determined in this study were poor predictor variables for the bending properties of stemwood, but fibre length and vessel diameter appeared to be the best predictor of stemwood MOE ($R^2 = 0.69$) and MOR ($R^2 = 0.52$) respectively. Also, total parenchyma proportion appeared to be the best predictor for branchwood MOE ($R^2 = 0.92$) and MOR ($R^2 = 0.95$).

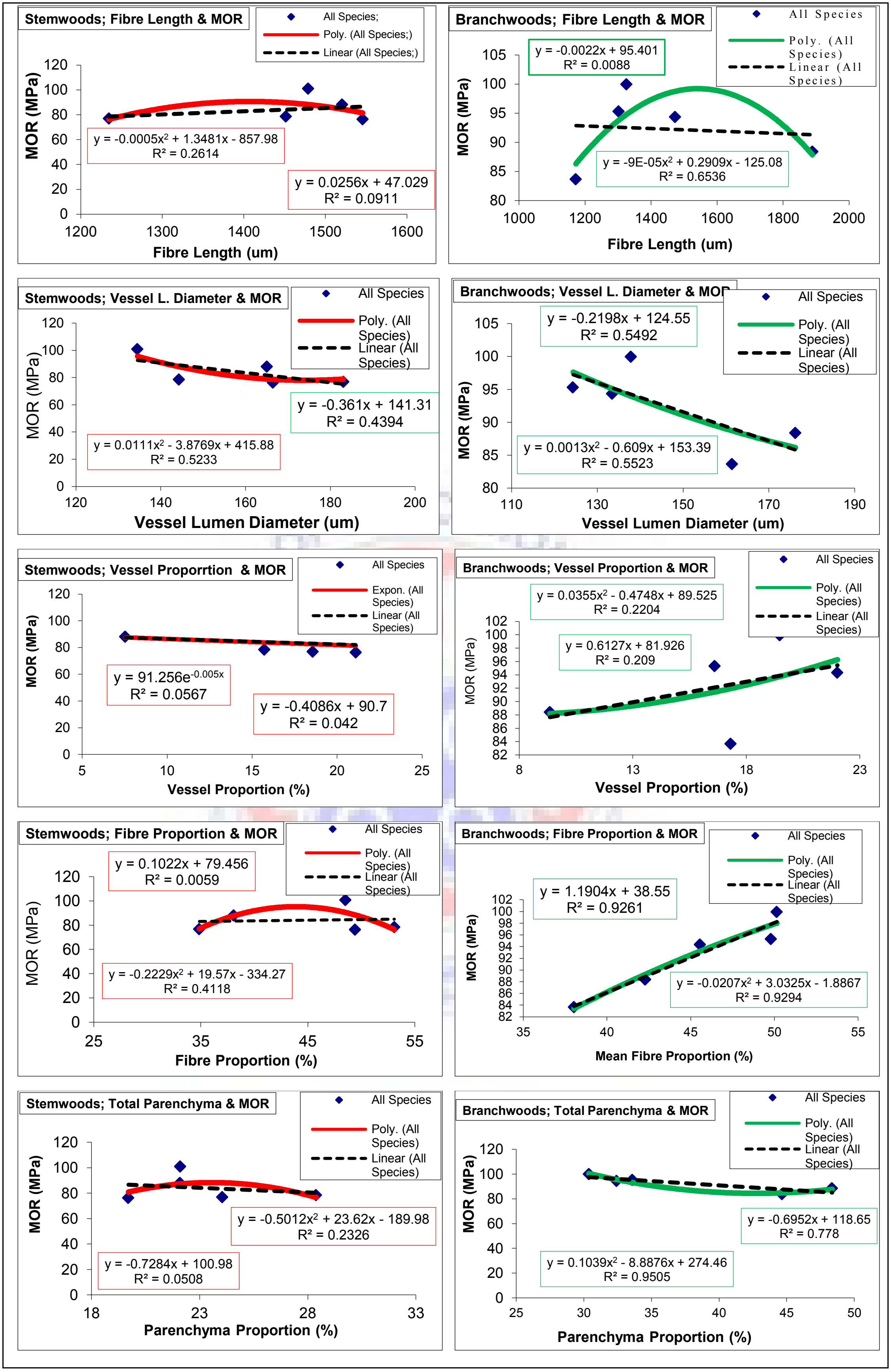


Figure 4.4.11. Relationships between mean anatomical properties and MOR of stem and branch wood; N= Means of 50.

CHAPTER FIVE

DISCUSSIONS

5.1: Above-Stump Merchantable Wood Quantity/Volume.

In the promotion of wood residue utilization to enhance efficient utilization of harvested wood, it is necessary that current quantity of merchantable residues is assessed on regular bases over relatively short periods of time, usually 2 to 10 years (Basuki, Van –Laake & Hussin, 2009). In this study, above-stump logging residues are quantified to know how much merchantable branchwood and off-cuts are available in the Ghanaian forests after logging, to warrant any investment in their extraction for use to supplement stemwood in wood products manufacturing. This information is expected to also provide knowledge on how much that quantity of branchwoods and off-cuts can contribute to reducing depletion and conserving the forests. Thus, this aspect of this study estimated merchantable residue volume (branchwoods and above-stump stem off-cuts) from three different forest ecological zones or sites and 20 different timber species, evaluated harvesting efficiencies among timber species, and assessed whether or not site or species has effect on branchwood volume, stem off-cuts volume, and logging efficiency. Finally, extracted log volumes (ELV) are used to predict total merchantable wood volume and total merchantable residue volumes for the various forest sites (site specific model), individual timber species (species specific model) and for mixed species and sites (mixed species and sites model).

In this present study, average logging efficiency of 74.95% was found (as a result of total extracted log volume-ELV of 2221.41m^3) from total merchantable wood volume (TMWV) of 2963.98m^3. Also, total merchantable residue volume (TMRV) of 25.05% was found to be made up of branchwood and stem off-cuts volumes of 556.01m^3 (18.76%) and 186.56m^3 (6.29%) respectively. These findings indicated that, generally, for each tree harvested, there were about 25.05% of TMRV in the form of branchwood and above-stump stem off-cuts which were discarded. The logging efficiency of about 75% disagrees with Eshun (2000) who found logging efficiency to be 68%. This could be attributed to the fact that Eshun (2000) used different companies which operated with different equipment and personnel of possible varied orientations on harvesting practices. Although this study did not cover stumps on the bases of the negative effects of their removal on the forest environment, the found logging efficiency and TMRV were consistent with the ranges reported in some previous studies (Amoah & Becker, 2009; Basuki et al., 2009; Noack, 1995; Ofori et al., 1993). For instance, Amoah and Becker (2009) obtained logging efficiency of about 75% and residue of 25% upon quantifying branchwood down to 31cm diameter and they also included stumps. The consistencies of this present study to some previous ones could be attributed to two reasons: first, an observed trend of efforts by forest managers in impressing upon loggers to reduce stump heights as much as possible based on which observations showed that loggers tried to fell trees closely down to the ground; and second, previous studies did not include branchwood of less than 30cm diameters but this study covered branchwood diameter up to a minimum of 13.5cm on the basis that normal branchwood are those of diameter ≥5cm (Gurau et al., 2008; Shmulsky & Jones, 2011). In a related literature which appeared to be in support of the normal branchwood diameter, Okai, (2003) successfully produced furniture from 10cm to 25cm diameter Ghanaian tropical hardwood branchwood. Therefore, the inclusion of branchwood of diameters down to 15cm (below 30cm), appeared to have increased branchwood volumes from other previous studies (Amoah & Becker, 2009; Eshun, 2000; Ofori et al, 1993) and that might have compensated for the stumps that were not covered in this study.

It is also worth mentioning that other previous studies have reported a lower logging efficiency of about 50% in Ghanaian forest (e.g. Acquah & White, 1998; Adam et al., 1993). However, the relatively higher efficiency found in this study could also be attributable to the awareness of the need to use the scarce and remaining wood resource efficiently and which has resulted in conscious efforts being made by forest managers to extract more merchantable stemwood as possible to meet their timber processing capacity or requirements.

On account of the measured diameters in this study being within the normal branchwood bracket, the quantity of merchantable residue obtained was considered to be of adequate quality to guarantee their utilization. Thus, from the data in Table 4.1.2, an equivalent volume of about 38 trees {(743/2964) x154} could have been saved if the firm had extracted the TMRV (which represented 25.05%) from the felled trees for processing and eventual utilization. According to Amoah and Becker (2009), about 5 trees per hectare are felled during felling cycles in tropical forests. Judging from this, the 38 trees that would have been saved should the TMRV be extracted, translates into about 7.6 hectares (i.e; 38/5). This implies that, had the firm extracted the merchantable residues for processing, about 7.6 hectares of forest land would have remained unlogged. This quantum of forest area would have then been available to provide the other service functions of forests (i.e. protection of soil and water bodies, shielding biodiversity, maintaining climate among others), at least till the next felling cycle. This could also be interpreted to mean that, timber volume equivalent to 38 trees or 7.6 hectares would have also been added to the volume obtained already, if the TMRV had been extracted from the felled trees. Better still, it also implies that, the extraction of the residues will make available to the firms additional quantity of wood equivalent to logging about 8ha. of forest land. Meanwhile, the running cost of machinery and equipment in logging additional 8ha. may possibly be higher than extracting the residues from the already logged trees, and therefore, residue extraction will likely be less costly.

5.1.1: Merchantable branchwood, stem (off-ctus) and logging efficiencies among species and ecological zones

Logging efficiency is a determinant of how much of harvested trees was extracted (ELV) and is also a function of how much TMRV (branchwoods and stem off-cuts) was discarded upon felling the trees. Therefore, the higher the logging efficiency, the likely it is to obtain a lower TMRV.

The significant differences of branchwood (p=.013-Table 4.1.4) and stem off-cuts (p=0.000 – Table 4.1.6) among the study sites were not very much expected. However the non-significant difference in logging efficiency (p=0.435- Table 4.1.7) among the study sites was expected. These differences in expectations were from the premise that, all the sites were being logged by the same firm, apparently with similar logistics and equipment for operations, except that worker groups were different among the sites. However, although worker groups from the same firm were expected to have similar skills, training and orientation on harvesting practices, there appeared to be the possibility of some workers at some sites disregarding any orientation on harvesting practices that aimed at avoiding waste etc, especially in the absence of their superiors at the sites. These possibilities, in addition to lack of experience on the part of some workers, might have contributed to the differences observed. It is also reported that, such differences in timber yield among different forest sites could basically be due to environmental factors like temperature, relative humidity, rainfall patterns, soil type and nutrients, as well as land topography and timber bole characteristics differentials (Basuki et al., 2009; Chave, Riera, & Dobois, 2001; Ketterings, Coe, Noordwijk, Ambagae & Palm, 2001). It is reported that soil nutrient content and fluctuations account for a third of biomass variability among different forest sites (Laurance et al., 1999). Additionally, water retention and drainage capacity also have greater influence on biomass variability among sites as they could lead to leaching of soil nutrients (Chave et al., 2001) and also destruction of various tree parts. Therefore all these might have contributed to the differences in TMWV, ELV (efficiency) and TMRV among the sites/ecological zones.

The significant differences in branchwood and stem off-cut quantities, and efficiencies among various species (Tables 4.1.3, 4.1.5 and 4.1.8) could also be partly due to tree architecture and genetics including; canopy areas, plant/tree form or geometry, bole height, branching type and size of branches, buttress height and sizes (Ketterings et al., 2001; Ford, 1985. This appears to have been manifested in this study. The species reported to have relatively large canopy areas and large branch diameters, and grow to about 50-65m high like *P. africanum, E. angolense; E. cylindricum*, *K. ivorensis* (Tchinda, 2008; Kémeuzé, 2008; Lemmens, 2008) were those found to have higher percentages of branchwoods (Table 4.1.2) but had relatively lower logging efficiencies as compared to *P. macrocarpa*, a species with relatively small crown area and grows up to about 35m high (Oyen, 2008). Moreover, tree canopy disturbances from past logging operations and tree positions within the forest canopy could have also been among the factors that contributed to the significant differences in TMRV (p=0.000 - Table 4.1.3) among species (Ford, 1985; Ketterings et. al, 2001).

5.1.2: Predicting total merchantable wood volume (TMWV) and total merchantable residue volume (TMRV) from extracted log volume (ELV)

ELV was used to predict TMWV and TMRV in three models, namely; site specific, species specific, and mixed species and sites specific models. These have some practical and theoretical implications. First, they will enable stakeholders (both industrialists and academics) in the wood industry to easily predict TMWV and TMRV from logs delivered at the mills" gate without necessarily having to spend energy, time and money to go to the forests to take inventory. Again, they will make negotiations on above-stump residue easier for both sellers and buyers, as the models could be used to easily estimate the volumes of such residues from specific sites, species and for all species in general for pricing and other purposes.

The site specific models resulted in positive correlations between TMWV and ELV with coefficient of determination (R^2) values that implied that, there is a strong association between TMWV and ELV than TMRV and ELV (Figure 4.1.1). These implies that, the ELV can best be used to predict TMWV and not the TMRVs based on sites or reserves from which the timber was extracted.

From the species specific models, the R^2 values (from 0.38 for *Entandrophragma angolense* to 0.99 for *Ceiba pentandra*) for TMWV and ELV found in this present study (Table 4.1.9) were within the range of findings from previous studies (Amoah & Becker, 2009; Eshun, 2000) and therefore it could be inferred that those of the TMRV and ELV depict the true situation. It follows then that, ELV is not a better predictor variable for TMRV based on species. Moreover, R^2 value of 0.87 found in this study for the final model (mixed species and sites model-Figure 4.1.2) that sought to predict TMWV indirectly from ELV for all species in general, corresponds with findings in previous studies (Amoah & Bercker, 2009). This also suggested that the R^2 value of 0.128 for the prediction of TMRV from ELV was also the true picture of the predictive power of ELV for TMRV. From the foregoing, ELV is generally a better predictor variable for TMWV and agrees with literature (Amoah & Becker, 2009), but not a good predictor for TMRV.

It is however necessary to indicate that, since the species covered in this study were mostly dominated by *Triplochiton Scleroxylon* (23.4%) and *Pitadiniastrum africanum* (15.6%), both the site and the mixed species models could be said to be basically applicable to these two species than the others. Again the use of all the models has some limitations. For instance, when logging efficiency (which comes from the ELV) changes substantially over some period of time, the models may not be accurate for that period within which such changes had occurred. In the light of this, the models could be validated periodically based on new data to assess current situation of the estimates. Moreover, an alternative variable to ELV could also be used either alone or in combination with ELV to estimate TMRV to a better level of accuracy. Meanwhile, until such a better alternative variable is found, it will be recommended that the site specific model is applied to find TMWV (which all sites had R^2 values ≥ 0.80) after which the ELV could be deducted to obtain the above-stump TMRV (i.e; TMWV-ELV=TMRV) without necessarily having to go to the forests for such inventories.

5.2: Natural durability of wood

Upon knowing that the sizes of wood residues warrants their extraction and subsequent utilization, one area of assessing wood materials‟ quality is natural durability. Interest in natural durability is growing, partly due to the need to promote new wood materials to supplement stemwood, the concerns about the chemicals used to make non-durable wood durable, and partly because species with higher natural durability generally attract higher prices (Brischke et al., 2011; Cookson, 2004). It was in this light that, in an effort to promote logging residues, especially branchwood utilization in this study, it became necessary to determine and compare the natural durability of stem (off-cuts) and branchwood which could be used either separately or together for the production of some furniture parts and finger-jointed wood products, some of which could be used outdoors and in-grounds. This aspect was expected to provide reliable database of the natural durability differences between stem and branch wood of same species.

The test for durability of stem and branch woods of the study species was carried out through a graveyard method for 12 months (1year) by adapting the European Standard EN 252 (1989) which also has the status of a British Standard BS 7282(1990). This standard has been recommended for use and has acceptably been used by some researchers including Brischke et al. (2011), Meyer et al. (2012), and Quartey (2009) for in-ground natural durability testing of wood. The test period in this study may appear short (EN252 is test standard for the efficacy of wood preservative for a period of 5 to 10 years but recommends and accepts modifications), but Brischke et al. (2011) asserted that, time span does not play any role in natural durability test of new type of wood once it provides avenue for similar degradation of samples or materials whose durability status through a long term test is known. Moreover, other studies have also used 6 weeks (Balasundaran et al., 1985) and 12 weeks (Ncube, 2010) to acceptably evaluate the natural durability of wood. Quartey et al. (2008) and Quartey (2009) have also used the standard EN 252 to evaluate the natural durability of sapwood and heartwood of some Ghanaian tropical lesser utilise wood spcies within 6 months. Hence, since the Ghanaian hardwood branches can be classified as new materials being promoted, the 1 year test period is not inadequate.

Branch and stem woods of each of the 5 study species were tested at 2 different moisture levels (i.e. air-dried MC of 14±2% specified by EN 252, and kiln-dried MC of 9±3% used for the production of most furniture parts and finger-jointed lumber in Ghana especially for exports). Stemwoods of *Ceiba pentandra* under the 2 moisture levels were used as reference materials.

5.2.1: Visual rating of extent of attack/destruction (qualitative assessment of natural durability)

Generally, the qualitative assessement and its subsequent visual ratings of extent of attack and durability classifications of the stemwood of all the species (i.e. moderately durable for sapele and edinam and non-durable for ofram and koto - Appendix 2 and Figure 4.2.1), except *Khaya ivorensis* (mahogany) appeared to corroborate records on the species (Duvall, 2011; Kémeuzé, 2008; Kimpouni, 2009; Lemmens, 2008; Pleydell, 1994; Tchinda, 2008;). The only exception was *K. ivorensis* which is found in literature as moderately durable (Lemmens, 2008; Pleydell, 1994) was found in this study as non-durable. The species is described as highly prone to termites attack (Ayensu & Bentum,1974; Richter & Dalwitz, 2000) and therefore the deviation of its durability status in this study could be attributable to the relatively aggressive nature of termite activities in the site used for the test in this study (Kumi-Woode,1996). The non-durability of mahogany could also be due to possible presence of juvenile wood on account of undue pressure on the species, arising from its demand for wood and furniture products manufacturing and which in turn leads to the harvesting of inmatured trees, compared to those harvested about 5 to 10 years ago.

The findings from a Two-Way ANOVA that there were significant effect of wood type/species (p=0.000) and moisture levels (p=0.000) on the visual ratings of attack (Table 4.2.1) also mean that, the rate of destruction on wood in service is highly dependent on the wood types of same species, and also the initial moisture contents of the wood. This in turn means that branch and stem wood of same species can have different service lives for the reason that it is a branch or a stem wood, and it has less or more amount of moisture. This appears to be consistent with findings that wood dried to moisture contents ≤ 12%MC has much leverage over those that have higher moisture content (i.e. beyond 12%MC) in terms of most wood properties, including resistance to biodegradation or natural durability (Eaton & Hale, 1993; National Association of Forest Industries-NAFI, 2003; Tsoumis, 1991)

5.2.2: Percentage weight losses of wood (quantitative assessment of natural durability)

Upon assessing what causes weight losses in wood exposed outdoors or inground, four main issues came out from literature as being responsible, namely; leaching (of water soluble toxic substances, etc by rainwater), loss of volatile chemicals, activities of microganisms (fungi is noted to be predominantly active colonizers of bare wood), and wood-feeding invertebrates (Ali, 2011; Ncube, 2010). It is however worthy of note that, during the test, no wood-boring beetles were observed to have attacked any sample and hence, all other destructions leading to loss of weight could be attributable to termites. However, it is necessary to also state that, in this study, no distinction was made between weight losses due to any of the contributors to percentage weight losses of the test samples.

The soil block/natural durability test results in terms of %WL presented in Figure 4.2.3 and Table 4.2.2 which suggested generally that both stem and branch wood samples kiln-dried to 9±3%MC level lost less weight (suggesting better resistance to biodegradation) relative to their counterparts air-dried to 14±2%

(suggesting poor resistance to biodegradation). Moreover, branchwood competed favourably with stemwood of same species but some branchwood even lost less weight (suggesting better resistance to biodeterioration) than stemwood of same species, especially when dried to 9±3% moisture range. This meant that, branchwood can be as good as its stemwood counterpart, in terms of natural durability, especially when dried to a relatively lower MC and possibly by kiln-drying method (since the 9±3%MC samples were kiln-dried). A Two-way ANOVA (Table 4.2.3) therefore affirmed the significant effect of moisture levels (p=0.000) and wood type/species (p=0.000) on the %WL obtained by both stem and branch woods at the 2 MC levels, and also indicated that moisture levels explained 57% of the variability in %WL.

The foregoing findings on moisture level effects appeared to be consistent with findings of Guangxi Universities Forestry College (2007a), that air-drying could sufficiently decrease the resistance of some wood species to the extent that it could compel reclassification of wood from a highly durable class to a durable class. Such disparities are also reported to be on the bases that during kiln-drying, the temperature and hot air in the kiln sterilize the wood to ensure that test specimens are clear of contaminations such as microorgainsims that might have already infested the wood and which could interfere with the test, by killing all such organisms (Dinwoodie, 2010; Ncube, 2010; Schmulsky & Jones, 2011). Hence, because kiln-drying was used to dry wood to 9±3%MC, the heat in the kiln might have sterilized the wood and killed all infestations and thereby provided the advantage of considerably delay of the period of infestation or reinfestation, growth and multiplication of biological agents. This might have subsequently led to the relatively reduced %WL (decay) in the sample group dried to 9±3%MC in kilns compared to those dried to 14±2% in air. Additionally, upon heat application to wood, the fatty acids in the lignin change, harden and cannot be altered from that more rigid state by any amount of moisture absorbed (Shepherd, 2009) and this also contribute to the durability of wood.

Moreover, some wood species could also contain some resins or inclusions (Forest Products Laboratory, 2010) that can get hardened once kiln-dried (Dinwoodie, 2010; Townsley, 2010). Such hardened occlusions/inclusions may block wood natural flow paths to reduce or disallow leaching of toxic substances from wood as well as impeding the admission of some level of moisture into wood and thereby reducing or delaying biodeterioration of the wood (Antwi-Boasiako & Atta-Obeng, 2009; Ncube, 2010). As a result, the rate of fungal and insect activities in some wood will be relatively limited on account of low moisture and blockages, which could all in turn slow down the activities of biodegrading agents and subsequently lead to relatively low %WL (high durability) in such woods relative to others. Thus kiln-drying could positively influence the durability of wood but it is, however, worthy of note that too high temperatures during kiln-drying could also either remove some volatile extractives or degrade some wood and subsequently alter the decay resistance of some wood species (Dinwoodie, 2010; Ncube, 2010).

Additionally, it is also found that although there is a possibility that during the field test the moisture content of all sample groups of stem and branch woods may reach equilibrium (EMC), drying itself affects EMC such that after the initial desorption of green wood to dried state (possibly below 12%MC), the hygroscopicity of some wood species is permanently reduced even at high relative humidity (Aker Woods company, n.d; Rowell, 2005). Hence, any of the aforementioned issues might have kept the EMC of some species or wood types at a level that was either favourable or not for biodeterioration, thereby leading to the differences in the percentage weight losses obtained by stem and branch woods at the 2 moisture levels.

In spite of the foregoing, it is also important to emphasize that, besides type of drying/moisture content, extractives and lignin content and its types and ratios, other factors like porosity, vessel-lumen diameter and wood structure (proportion of vessels, fibres and parenchyma) can contribute substantially to wood natural durability (% weight losses). For instance, it is reported that as the guaicyl (G) type lignin increases in proportion relative to the syringyl (S) type, wood durability reduces and vice versa (Ncube, 2010). Hence the ratios of the „S" to the „G" lignin types indicate the durability level of wood (Ncube, 2010). Hence, though esxtractives and lignin contents and their types in stem and branch woods were beyond the scope of this study, they are recognized to have generally played major roles in the results obtained. In the light of the scope of this study, the percentage weight losses differences between stem and branch woods of individual species are discussed on the bases of results of their density and anatomical properties found in this study.

5.2.2.1: *Entandrophragma cylindricum* (sapele)

The significant difference in the mean %WL between either stem or branch and the control sample, as well as between the stem and branch woods at both 2 moisture conditions at 5% significance level (Table 4.2.2), indicated that branchwood of the species at relatively low (9±3%MC) rather than high (14±2%MC) MC level could be used as supplement to its stemwood in outdoor or in-ground applications. However, the branchwood dried to 14±2% could possibly be used to supplement stemwood for indoor furniture, ceiling tongued and grooved panels, and other profile boards that are normally not exposed to severe hazard conditions as in outdoor applications.

However from Appendix 2, branch and stem wood dried to 9±3%MC were designated as moderately durable but obtained durability classes 1 and 2 respectively.

The designation of sapele stemwood dried to 9±3%MC as moderately durable agrees with findings in literature (Chudnoff, 1984; Forest Products Laboratory, 2010; Kémeuzé, 2008;Pleydell, 1994), and therefore that of its branchwood could also be a refletion of its true state. The durability classifications however implied that, whereas the branchwood can have a service life beyond 25years (as class 1 wood-Table 2.1), stemwood will have between 15 to 25years (as class 2 wood) under similar outdoor climatic conditions, and both could perform better in indoor applications (NAFI, 2003; New Zealand Forest Research Institute, 1997).

Again from Appendix 2, it could be said that the marginally higher density of *E. cylindricum* branchwood relative to its stemwood might have contributed to their durability differentials. This difference in density could also be attributable to the maginally higher proportion of fibres and significantly lower proportion of vessels ($T=2.273$, $p<0.05$) in the branchwood than in the stemwoods (Table 4.4.1 and Figure 4.4.1). This agrees with previous studies that the heartwood of the upper logs (or branches) of sapele has many fibres than vessels per mm^2 area (Antwi-Boasiako & Atta-Obeng, 2009).

5.2.2.2: *Entandrophragma angolense* (edinam)

The significant and non-significant difference in %WL between stem and branch wood dried to 9±2%MC and 14 ±2%MC respectively could partly be attributable to drying effect that improved the durability of the branchwood substantially (i.e from 35.26%WL to 20.25%WL) - Table 4.2.2. This improvement could also be partly attributable to the marginal differences in, percentage fibres, vessels, and total parenchyma proportions as well as the significantly different vessel lumen diameter ($T=3.936$, $p<0.01$) of 0.73%, 1.62% 0.89% and 14.24%, respectively (Table 4.4.1 and Figure 4.4.1) between stem and branch wood.

Except for stemwood dried to 14±2%MC, the general moderately durable description, and the durablility class 2 obtained by both stem and branch wood samples (Appendix 2) agreed with previous studies (Pleydell, 1994; Tchinda, 2008). Thus, both stem and branch wood could have similar average service lives of 15-25years (NAFI, 2003; New Zealand Forest Research Institute, 1997). It therefore implied that wherever stemwoods in either two MC levels are applicable, their branchwood counterpart at similar MC could also survive, in terms of durability and thus the branchwood could serve as supplements to their stemwoods.

5.2.2.3: *Khaya ivorensis* (mahogany).

The non-significant difference in the mean %WL by both stem and branch wood at the two MC levels imply that branchwood of mahogany can equally survive under similar hazard conditions as the stemwood, in terms of natural durability upon inground or outdoor applications, and both are better in natural durability than onyina stemwood. However, though both the stem and branch wood were described as non-durable according to %WL, they obtained durability classes 4 and 3 for their samples dried to 14±2%MC and 9±3%MC respectively. These classifications imply that, stem and branch wood of mahogany dried to 14±2%MC will have an average life of 0 to 5 years (durability class 4-Table 2.1) and will possibly need some preservation if they should be used in-ground. However, the stem and branch wood counterparts dried to 9±3%MC would have an average life of 5 to 15 years (NAFI, 2003; New Zealand Forest Research Institute, 1997).

The non-durable description of mahogany turns to disagree with some previous studies that have described the species as moderately durable (Forest Products Laboratory, 2010; Lemmens, 2008; Pleydell, 1994). However, unlike, sapele and edinam that are fairly resistant to termite attack, mahogany is highly prone to termite attacks (Lemmens, 2008). Hence the durability description in this study could be attributable to the site used for this study which is a higly termite prone site (Kumi-Woode, 1996). This could also explain why the differences in some anatomical properties between stem and branch wood (Table 4.4.1) could not influence any durability differences, though vessel lumen diameter, vessel and fibre proportions were significantly different ($p<0.05$; $p<0.01$; $p<0.01$ respectively).

5.2.2.4: *Terminalia superba* (ofram)

The findings that mean %WL of stem and branch wood dried to either 14±2%MC and 9±3%MC were not significantly different from each other, but they were all significantly different from the control species (*onyina*) - Table 4.2.2, indicated that, in terms of natural durability, branchwood of the species could supplement its stemwood once both are at same average moisture content. Again it also means that, if nothing at all, the branchwoods can be a better option than Ceiba in terms of natural durability.

Moreover, the non-durable description according to %WL and the durability classes 4 and 3 obtained by stem and branch wood dried to 14±2%MC and 9±3%MC respectively are consistent with literature (Forest Products Laboratory, 2010; Kimpouni, 2009; Pleydell, 1994). The durability classifications (class 4) for stem and branch wood dried to 14±2%MC imply that they could have average service lives of 0 to 5 years (Table 2.1), and therefore for in-ground applications, they will need preservative treatment to extend their service lives. However, the sample dried to 9±3%MC and belonging to class 3 could have an average life of 5 to 15 years (NAFI, 2003; New Zealand Forest Research Institute, 1997).

5.2.2.5: *Pterygota macrocarpa* (koto)

The findings that %WL of stem and branch wood dried to either 14±2%MC and 9±3%MC were not significantly different ($p>0.1$) from each other and the control species (onyina) - Table 4..2.2, pointed out that, in terms of natural durability, branchwood of the species could supplement or substitute its stemwood once both are at same average moisture content. Again it also meant that, in terms of natural durability, both stem and branch wood of koto were no better than *Ceiba pentandra* stemwood in terms of natural durability status.

Also, the non-durable description and durability class 4 obtained by both stem and branch wood samples dried to 14±2%MC and 9±3%MC meant that all of them could have average service life of 0 to 5 years upon in-ground or outdoor application (Appendix 2). However, they could be made to last longer if they are treated with preservatives (NAFI, 2003; New Zealand Forest Research Institute, 1997). Meanwhile, the non-durable descriptions obtained in this study for stemwood of onyina and both stem and branch wood of koto corroborate previous findings, and both species are described as being susceptible to fungi and termites (Chudnoff, 1984; Forest Products Laboratory, 2010; Oyen, 2008; Pleydell, 1994). However, it must be noted that, the *Ceiba* (onyina) stemwood samples were replaced once during the test (as required by the EN 252 standard used), and at the time of this replacements, a number of the koto samples were in place till the end of the test. Therefore, it could be inferred that, koto can perform better than onyina, and as a result, koto (both stem and branch) is a little durable than onyina.

5.2.3: Predicting percentage weight losses (natural durability) from moisture content and wood density

Regression analyses (Figures 4.2.4 and 4.2.5 and Table 4.2.4) respectively depicted the relationships existing between moisture content (MC), wood density (WD) as single variables, and MC and WD as combined variable and percentage weight loss (%WL). These relationships are necessary in the sense that, they could serve as non-destructive methods of determining natural durability of wood.

The findings that MC correlated positively with %WL imply that, the more moisture in wood the more it loses weight on account of been easier for fungi to colonise it and also create favourable conditions for other biodeteriorating agents to further destroy the wood. Therefore, wood with high MC are less resistant to biodeterioration and less durable than relatively dried ones. Moreover, the negative correlation between WD and %WL also means that, the higher the density of wood, the lesser the wood is liable to be biodeteriorated upon application. These relationships with MC and WD agree with what is reported in literature (Antwi-Boasiako & Pitman, 2009; Antwi-Boasiako & Atta-Obeng, 2009; Dinwoodie, 2010). It is reported that, the negative correlation between WD and %WL could be due to a number of factors including fibre cell wall thickness, lumen diameter-a determinant of porosity of the wood, lignin content and type, extractive availability and proportion of wood cells, all of which give wood its density. These components of density either prevent or delay biodeterioration and therefore making denser woods relatively durable (Dinwoodie, 2010; Shmulsky & Jones, 2011).

From the R^2 values, MC as a single variable predicted the %WL to predictive accuracies ranging from 18% to 68% for stemwood and from 4% to 72% for branchwood, whereas WD as a single variable also predicted the %WL to predictive accuracies ranging from 5% to 93% for stemwood and from 12% to 91% for branchwood. However, with MC and WD as combined predictor variables, the prediction accuracies ranged from 15% to 92% for stemwood and 19% to 95% for branchwood. These indicated that the use of MC and WD as combined predicted variable of %WL had marginally better predictive power than when MC and WD were used as single predictor variables. This might have occurred because MC has influence on wood density and therefore the two variables acting together in the wood triggered the relatively higher influence on wood durability. Thus such combination can offer a better accuracy in predicting the natural durability of stem and branch wood of the studied species.

Again, from the coefficients for MC and WD (i.e., **α** and **β** respectively), results in Table 4.2.4 showed that both coefficients were higher for both stem and branch wood samples with high MC (14±2%MC) than those with relatively low MC (9±3%MC). This meant that, wood with high moisture content lost much weight (implying less resistant to biodeterioration) than those with relatively low moisture (implying high resistance to biodeterioration) for every 1 unit change in MC and WD. Also the finding that many of the **β** coeffieciets of WD were significant (at least $p<0.1$) compared to the **α** coefficients of MC for both branch and stem wood, except for koto meant that density affected the natural durability significantly relative to MC, but it did not apply to all wood species, like koto. This was not surprising because, althought koto had high density than some of the species studied, it was the most perishable (as could be observed in Figure 4.2.2). This also appears to corroborate earlier findings that some high density wood can be less durable though some low density wood can also be durable (Antwi-Boasiako & Pitman, 2009; Ncube, 2010).

Moreover, according to Wiedenhoeft and Miller (2005), density is principally governed by wood structure and therefore, WD increases as the proportion of cells with thick cell walls (basically fibres) increases. Meanwhile, hardwood density generally, does not depend on only fibre wall thickness, but also on the amount of void spaces occupied by vessels and parenchyma. The relationship of WD and the anatomical properties determined in this study (Figure 4.4.8) appears to support this literature information as it showed clearly that density increases with fibre proportion in wood for both stem and branch wood.

Additionally, Figure 4.4.9 also indicated that in both stemwood and branchwood, vessel lumen diameter and proportion of parenchyma had relatively moderate to strong positive correlations with %WL (i.e. R^2 values in stemwood = 0.385-for vessel lumen diameter, 0.624 – for parenchyma proportion; in branchwood = 0.835-for vessel lumen diameter; 0.773-for parenchyma proportion) whereas fibre proportion also had relatively modereate but negative correlations with %WL (R^2 value in stemwood = 0.41 and branchwood = 0.64). These findings generally tend to agree with the assertion that large vessels, abundance of parenchyma with relatively few fibres results in high %WL (low natural durability). However, if fibres (which are relatively thick walled cells) are abundant in relation to vessels and parenchyma, there is relatively high wood density (Forest Products Laboratory, 2010; Skadsen, 2007; Wiedenhoeft & Miller, 2005) and such woods normally experience low %WL (high natural durability). This, according to Eaton and Hale (1993), is due to the fact that the biological agents enter wood through the vessels and the parenchyma cells, and also they attack the parenchyma cells first (because of stored photosyntates there) before other cells close to them and the vessels. In affirmation of this, Antwi-Boasiako, (2004) reported that wood with more vessels and rays make it light for easy grazing by termites and other bio-degraders and also form the easiest courts for fungal hyphae to attack more wood cells.

5.3: Static bending strength of solid and finger-jointed lumber

Among the reasons usually given for the non-extraction of timber from the crown area of trees is the lack of knowledge on the wood quality, including mechanical properties (Ayarkwa, 1998). This section of this study investigated the densities, modulus of elasticity (MOE) and modulus of rupture (MOR) of both unjointed and finger-jointed stem (off-cuts) and branch woods of the 5 studied species.

Finger-jointing (FJ) technique is used for jointing short pieces of wood end to end together with adhesive for the production of a variety of engineered wood products for structural and non-structural applications. The technique removes strength reducing defects like knots and also reduces waste (since it can be used on short, small, and crooked thinned-out logs that are often discarded) to ensure better materials utilization for yield improvement.

In this section of this study on both solid and FJ lumber however, moisture content (MC), wood type/species, and wood density (WD) effect on joint strength are assessed. However, because moisture content (MC) affects most properties of wood and therefore any MC at which any property of wood is determined should be stated (ASTM D 143-94 2000; Dinwoodie, 2010; Shmulsky & Jones, 2011). Hence, both solid and FJ stem (off-cuts) and branch woods are tested at two moisture levels (i.e., MC1=17±3%MC; and MC2= 10±4%MC).

5.3.1: Static bending strength of solid wood

Static bending strength propertied (i.e. stiffness-MOE and breaking strength-MOR) of solid stem and branch wood were determined under the two MC levels.

5.3.1.1: Modulus of elasticity (MOE) of solid wood

The results indicated that the modulus of elasticity (MOE) of both stemwood and branchwood of the same species tested at 17±3%MC were generally lesser than their counterparts tested at 10±4%MC. This is generally so because as wood dries, the hydrogen bonds that link the microfibrils shorten and strengthen (Shmulsky & Jones, 2011) and this provides the relatively higher strength properties for wood dried to relatively lower moisture content. Also, the difference in MOE of stem and branch wood of the same species appeared to be species dependent as branchwood of some species exhibited either higher or lower MOE than their stemwood counterparts (Figure 4.3.1, Table 4.3.1). This points to differences in the properties of individual tree species. However, all these findings appear consistent with previous studies reported in literature that, as wood dries from a higher moisture content range to a lower one, the MOE increases and such increases are species dependent (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). Again, both moisture level and wood type had significant influence on MOE at 1% significant level (Table 4.3.2). Moisture content and wood type, however, explained 49% of the variations in MOE. Moreover, at 5% level of significance, the MOE of branchwood were significantly higher than their stemwood counterparts for *E. angolense* and *T. superba,* at both two MC levels and *K. ivorensis* tested at 17±3%MC level (Table 4.3.1). These findings imply that, the branchwood of the studied species can safely be used to supplement their stemwood and some could even perform better in MOE in wood products manufacturing, especially in situations where MOE is of concern. The findings on MOE appear to corroborate previous studies (Amoah et al., 2012; Gurau et al., 2008; Okai, 2002; Okai, 2003) who also found the MOE of branchwood of some species either comparable or higher than the MOE of their stemwood counterparts.

5.3.1.2: Modulus of rupture (MOR) of solid stem and branch wood

MOR of stemwood and branchwood of all the studied species tested at 10±4%MC showed higher MOR than their counterparts tested at 17±3%MC. This therefore implies that moisture level has significant effect on MOR as confirmed in Table 4.3.4 (i.e. F=247.42, p=0.000). This means that either branch or stem wood with higher moisture will have relatively lower breaking strength in bending (MOR) than when it has relatively lower moisture. This stems from the finding that, as wood dries to a lower moisture content, the MOR increases as a result of the shortening and subsequent strengthening of the hydrogen bonds that link the microfibrils of the wood (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). However, these findings in this present study appeared consistent with previous studies (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011) who also found that wood improve in many strength properties, including MOR, as they dry to relatively lower moisture levels.

Also generally, the results suggested that branchwood exhibited higher MOR than their counterpart stemwood of same species tested at the same MC level. However, these differences in MOR between stem and branch wood of the same species were not generally signifcant at 5% significance level except for those of edinam and mahogany at both two moisture levels (Table 4.3.4). These findings meant that branchwood of almost all the species studied could conveniently serve as supplements to their stemwood and those of edinam and mahogany could even perform significantly better in wood products manufacturing, especially in applications where MOR would be of importance. Meanwhile, the MOR values of stemwood of the species fall within the range of values reported in literature about the species (Kémeuzé, 2008; Lemmens, 2008; Tchinda, 2008). However, the significant differences in MOR between branch and stemwood of edinam could also be attributable to the substantial density difference of 30.6% between branch and stem woods (Figure 4.3.3 and Appendix 3) which also might have arisen from significantly wider vessel diameter (P=0.000, T=3.936) and longer fibre length (P=0.000, T=5.557) in stemwood (Table 4.4.1) that possibly contribute to low density in wood. This finding on MOR agrees with some previous studies (Amoah et al., 2012; Gurau et al., 2008; Ayarkwa, 1998) but tend to disagree with findings of Okai (2002) and Okai, (2003). The finding also implied that wood type/species had effect on the MOR, and Table 4.3.4 affirmed this (F=9.576, p=0.000). However, moisture content and wood type/species explained 48% of the variability in MOR.

Generally from the findings on both MOE and MOR it could be said that; moisture content and wood type/species significantly affected the MOE and MOR of both stem and branch wood, and that the differences in both MOE and MOR between stem and branch wood depended on the species. However, such differences for all the species, except edinam and mahogany were not statistically significant at 5% level of significance. As a result, it could be concluded that, generally, branchwood of sapele, ofram and koto can all be good substitutes and supplements for their stemwood, and branchwood of edinam and mahogany could even be better than their stemwood in wood products manufacturing, especially in applications where bending strengths (MOE and MOR) are of a necessity.

5.3.1.3: Predicting bending strength of solid wood from moisture content and wood density

Wood density (WD) and moisture content (MC) are among the factors that influence mechnanical strength of wood. These relationships were deemed necessary because, they could be non-destructive methods of determining the MOE and MOR of the stem and branch wood without having to spend energy, money and time to go through machine testing. These relationships were found for stem and branch wood tested at two moisture levels (i.e. 17±3%-air-dried MC, and 17±3%-kiln-dried MC).

Generally, except for *Pterygota macrocarpa*-koto, branchwood of the studied species at each of the two MC levels exhibited higher density than their stemwood counterpart of same species at the same MC level. This deviation of koto from the found general trend about stem and branch wood density appeared to corroborate with findings of Ayarkwa (1998), that the wood from the crown area of koto had lesser density than the wood from the bottom and middle portions. This appeared to have resulted from the significantly longer fibre length (P=0.000, T= 5.946) and vessel quantity (P=0.000, T=2.174) in koto branchwood compared to its stemwood counterparts (Table 4.4.1) which were also deviations from what were found on the other four species. However, all these findings appear to corroborate findings from earlier studies that density generally varies with moisture content, and branchwood generally show higher density than their counterpart stemwood at same moisture level (Amoah et al., 2012; Dinwoodie, 2010; Forest Products Laboratory, 2010; Gurau et al., 2008; Okai, 2003; Okai, 2002; Shmulsky & Jones, 2011). Such inconsitencies in density of branch and stem woods of different species also appear to agree with and support assertions made by some researchers (Gurau et al., 2008; Shmulsky & Jones, 2011) that stem and branch wood density vary among species rather unpredictably. Again, the findings also affirm that unlike branchwoods of softwoods which are 5-20% lower in density/specific gravity relative to their stemwoods, hardwood branchwood tend to have specific gravity or density that range from higher in some species to lower or the same in orders (Shmulsky & Jones, 2011).

In predicting MOE, regression analysis indicated that, whereas WD correlated positively with MOE, MC correlated negatively with MOE. Findings were that generally, the model that sought to predict MOE from WD and MC as combined predictor variables (Table 4.3.5) predicted MOE a little more better (i.e highest R^2=0.933 for stemwood and 0.961 for branchwood) than the models that used WD and MC as single predictor variables. The model that used WD alone as predictor variable (Figure 4.3.4) had the predictive accuracy up to the highest of 92% for both stem and branch wood, whereas the model that used MC alone (Figure 4.3.6) had up to the highest of 76% and 90% predictive accuracies for stem and branch wood respectively. These mean that, WD and MC combined can predict MOE of both stem and branch wood better than using either WD or MC alone. These could have resulted from the possibility that two factors could have much influence on a variable than a single factor and also because, moisture content itself influences wood density.

Moreover, the **β** coefficient for WD and the **α** coefficients of MC indicated that changes in WD affected the MOE of branchwood more than stemwood, but changes in MC affected stemwood more than branchwood. Since density itself is influenced by MC, this finding could be attributed to differences in the influences that MC has on some chemical, anatomical and other characteristic properties of stem and branch woods. However, the findings appeared to agree with literature that, the extent of influence of MC and WD on wood strength properties depends on the species and possibly the position of wood within a tree (Dinwoodie, 2010; Forest Products Laboratory, 2010). These trends could also be attributable to the higher density of the branchwood than stemwood which possibly caused the higher influence on the MOE of branchwood. Also, generally, **α** coefficient of MC were higher for both stem and branch wood samples tested at 10±4%MC than those tested at 17±3%MC. This means that as either stem or branch wood dries to 10±4%MC, the rate of increases in MOE per 1% change in MC will be higher than those wood dried to 17±3%MC as a result of a further shortening and strengthening of the hydrogen bonds in the wood microfibrils (Shmulsky & Jones, 2011). The shortening of the hydrogen bonds in the cells could lead to compacting of the wood cells and subsequently make them relatively stronger stiffness. However, this trend found in this study also tend to corroborate some publications (Forest Products Laboratory, 2010; Gurau et al., 2008; Shmulsky & Jones, 2011;) that, as wood dries MOE increases, but the degree of the increase per 1% decrease in MC is higher when the MC moves from a higher range to a relatively lower range. However, the quantum of the increase depends on wood species.

In predicting MOR, the regression analysis showed again that, whereas WD correlated positively with MOR, MC correlated negatively with MOR. A comparison of the R^2 vlues of the model that combined WD and MC to predict MOR (Table 4.3.6) with those of either WD (Figure 4.3.5) or MC (Figure 4.3.7) alone suggested that the 2 variables combined had better predictive power for MOR too, as in the case of MOE, than when the variables acted as single predictors. R^2 values for WD and MC combined were up to the highest of 0.928 for stemwood and 0.911 for branchwood, but WD alone exhibited R^2 values up to the highest of 0.77 for stemwood and 0.88 for branchwood, whereas MC alone produced R^2 values up to 0.90 for both stem and branch wood. These mean that, WD and MC combined can also predict MOR of both stem and branch wood better than using either WD or MC alone. Likewise in the case of MOE, these findings on MOR, WD and MC could have resulted from the possibility that two factors could have much influence on a variable than a single factor and also because, moisture content itself influences wood density.

The **α** coefficient of MC and **β** coefficient of WD indicated that, the combined effect of MC and WD appeared to be greater on branchwood than stemwood at a lower MC (10±4%MC), but tend to be greater on stemwood than branchwood at a relatively higher MC (17±3%MC) - Table 4.3.6. These could mean that MC affected the MOR of stem and branch wood differently. These findings could have resulted from differences in inherent characteristics of stem and branch wood of the species. However, the findings appeared to agree with earlier research that, the degree of influence of MC and WD on wood strength properties depended on the species and possibly the wood type (Dinwoodie, 2010; Forest Products Laboratory, 2010). These trends could also be attributable to the higher density of the branchwood than stemwood. Moreover, generally, the **α** coefficients of MC were found to be higher for both stem and branch wood samples tested at 10±4%MC than those tested at 17±3%MC. This trend is also consistent with literature (Forest Products Laboratory, 2010; Gurau et al., 2008; Shmulsky & Jones, 2011) that, as wood dries the MOR increases, but the degree of the increase per 1% decrease in MC is higher when the MC moves from a higher range to a relatively lower range. However, the degree of the increases depend on wood species.

In all, the results of these relationships (MC and WD with MOEs and MORs) in this study tend to affirm, appreciate and agree that a full explanation of the effect of moisture on strength in terms of the basic structure of wood is still either unavailable or uncertain (Desh & Dinwoodie, 1996). However, the overall increase in strength resulting from reduction in moisture could be due to the shortening and consequent strengthening of the microfibrils in the wood secondary cell wall (Desh & Dinwoodie, 1996; Forest Products Laboratory, 2010; Shmulsky & Jones, 2011). Such shortening of the hydrogen bonds in the cells could also lead to compacting of the wood cells and subsequently making them relatively stronger or capable of withstanding higher loads. Also, since wood from branches has some varied anatomical characteristics from the wood of the main bole (as observed in Figure 4.4.1 and Table 4.4.1), it is a possibility that the microfibrils in stemwood may be different from those in the branchwood. Hence, the sensitivity or response to moisture and density changes of same strength property of stemwood and branchwood of same species may also differ, as observed from results on MOE and MOR in this study. However, based on the R^2 values, MC and WD combined could be a better non-destructive predictor variable of MOE and MOR of solid/unjointed stem and branch wood.

5.3.1.4: Predicting MOR of solid wood from their MOE

The relationship between MOE and MOR provides another non-destructive alternative for predicting MOR of wood using a known MOE and which is obtainable without damaging the wood (through longitudinal vibration methods etc.). Hence, this relationship is of both practical and theoritical importance.

Generally, MOE was found to correlate positively with MOR at both 2 MC levels for either stemwood and branchwood of all species together (Figure 4.3.8) and individual species (Figure 4.3.9). Generally, MOE and MOR relationship in stemwood appeared not to be different at both 2 MC levels (i.e. R^2 = 0.76 at both 17±3%MC and 10±4%MC) but the relationship differed in branchwood at different moisture levels (i.e. R^2= 0.78 at 17±3%MC and 0.65 at 10±4%MC). This suggested that moisture levels appeared to affect the MOE and MOR relationships in branchwood, but not in stemwood. This could be attributable to the some structural and chemical characteristic differences between stemwood and branchwood, some of which could affect the MOE and MOR of stem and branch woods differently, leading to such disparities in the relationships of MOE and MOR. Moreover, comparatively, the R^2 values from the linear functions of either all stemwood or branchwood together and those of individual species suggested that some individual species had either stronger or weaker predictive powers than all the species together. However, for stemwood mahogany had the weakest predictive power (i.e. accuracy levels of 62% at 17±3%MC and 47% at 10±4%MC) whereas sapele had the strongest predictive power (i.e. accuracy levels of 89% at 17±3%MC and 95% at 10±4%MC)for their MORs from their MOEs. Also for branchwood, again, mahogany had the weakest predictive power (i.e. accuracy of 22% at 10±4%MC) while koto exhibited the highest predictive powers (i.e. accuracies of 86% at 17±3%MC and 90% at 10±4%MC) for their MORs from their MOEs. These mean that it is will not be the best to use the MOE of both stem and branch woods of mahogany to predict its MOR but such predictions will be favourable to sapele stemwood and koto branchwood. However, the positive correlations of MOE and MOR found in this study and the R^2 values appear consitent with previous studies (Dinwoodie, 2010; Shmulsky & Jones, 2011).

The γ coefficient of MOE which indicate the degree of change in MOR upon 1MPa change in MOE appeared higher for all branchwood together (0.0063) than stemwood (0.00049) at 17±3%MC, but it turns to be higher in stemwood (0.0087) than branchwood (0.0078) at 10±4%MC (Figure 4.3.8), and similar trends were found for stemwood and branchwood of the individual species (Figure 4.3.9). This also mean that the effects of 1MPa. change in MOE on MOR of stemwood and branchwood are moisture content and species/wood type dependent.

5.3.2: Static bending strength of finger-jointed lumber

For each of the 5 wood species studied, three different combinations of FJ lumber were produced using thermosetting type (crosslink) polyvinyl acetate adhesive and tested at each of the two MC levels (17±3% - air-dried MC and 10±4% -kiln-dried MC). These combinations were stem & stem FJ (which is the status quo in finger-jointing in Ghana currently), stem & branch FJ, and branch & branch FJ. Those tested at 17±3%MC level were jointed in green state whereas those tested at 10±4%MC range were kiln-dried to MC range of 6% to 11% before jointing.

Assessement of failure types/modes and other causes of finger-joint failure were beyond this study. Hence, in discussing the bending strength results of the FJ lumber, all failures and for that matter bending strengths (MOE and MOR) were considered to have resulted from moisture content, species/wood type (branch or stem), density and anatomical property differentials. The discussions on individual species also focused on comparing the three combinations of FJ lumber with each other and with solid/unjointed controls of each species (also tested at the 2MC levels and drawn from Table 4.3.1).

5.3.2.1: Modulus of elasticity (MOE) of finger-jointed lumber combinations

Generally, as expected, the finger-jointed combinations of stem and branch woods jointed in the dried state and tested at 10±4%MC exhibited higher MOE than their counterparts jointed in the green state and tested at 17±3%MC (Figure 4.3.10 and Table 4.3.7). This appeared to indicate that, wood with low MC (both branch and stem) before jointing produced finger-jointed lumber of high MOE than same wood types with relatively high MC. This trend could be attributable to moisture in green wood partially filling the lumens of wood cells which tend to limit and inhibit glue absorption and adsorption capacity during pressing (Research and Development Summary, 2008; St. Pierre et al., 2005). The relatively high moisture in green wood could have also either diluted the glue, and led to starved joint or aided the squeezing out of some glue upon application of end-pressure which resulted in a thin glue line that produces relatively weaker joint (Research and Development Summary, 2008). Again, glueline thickness profile is less uniform for FJ lumber produced in the green state compared to those produced in the dried state and this situation generates some types of glueline spots that tend to produce stress concentrations larger enough to weaken the joints (Research and Development Summary, 2008; St. Pierre, et al., 2005).

However, the results in this study appeared consistent with results reported in previous studies elsewhere that same wood type/species‟ FJ lumber made at different moisture contents could produce different MOE values on account of the moisture content effect (Forintek Canada Corp., 2003; Hoffmeyer & Thógersen, 1993; IDRC,1997; Research and Development Summary, 2008; St. Pierre et al., 2005). Also, a test of the influence of MC on MOE indicated that MC level had significant effect (F=429.636, p=0.000 Table 4.3.8).

Comparing the MOE of FJ lumber to those of solid/unjointed control lumber specimens, the MOE of FJ lumber were found to be either higher or lower than the MOE of their solid lumber of same species. The higher MOE of some FJ lumber than their solid wood could be attributable to those samples failing with low load and leading to very minimal deflection (which is a major determinant of MOE of samples with same species with same dimensions) compared to the deflection of the solid wood, therefore resulting in the high MOEs (Vrazel & Sellers, 2004). However, the significance of these differences appeared to be moisture content dependent. At both 2 moisture levels, only *K. ivorensis* had significant differences ($p<0.05$) in the MOEs of its FJ lumber combinations and their solid controls. *T. superba*, *P. macrocarpa* also had significant differences ($p<0.05$) in the MOEs of their FJ lumber combinations and their solid controls at only 17±3%MC whereas *E. cylindricum* also significant differences ($p<0.05$) in the MOEs of its FJ lumber combinations and their solid controls at only 10±4%MC (Table 4.3.7 and Figure 4.3.10). These trends therefore appear partly consistent with what have been reported previously that finger-joint do not have much influence on MOE as it has on MOR (Ayarkw et al., 2000a; Barboutis & Vasileiou, 2013; Hwang & Hisung, 2001; Mantanis et al., 2010; St.-Pierre et al., 2005). However, part of the findings in this study also appear inconsistent with the previous studies. This inconsistencies could possibly have resulted from the incorporation of branchwood in finger-jointing which appear to have caused some deviations in the established general trend by making some FJ lumber obtaining either significantly higher or lower MOE than solid stemwood lumber of same species at same MC.

Additionally, in general, it appeared the branch & branch FJ samples performed better in stiffness (MOE) relative to stem & stem or stem & branch combinations at both two MC levels. This also suggested that specimen/combination type had effect on the MOE, and a Two-Way ANOVA test indicated significant effect (F=9.435, p=0.000-Table 4.3.8) of specimen type on MOE. The performance of the branch & branch FJ combination of the species could be attributed to the generally high density of the branchwood which probably arose from a generally high fibre proportion in branchwood (Figure 4.4.1 and Table 4.4.1). This relatively high fibre proportions might have provided relatively good bonding at the joints which led to a general high FJ strength, since finger-joint strength increases with increasing density (Ayarkwa et al., 2000a; St.Pierre et al., 2005). This was also manifested in the relationship between density and MOE (Table 4.3.12) where wood density (WD) generally correlated positively with MOE of FJ lumber.

5.3.2.2: Modulus of rupture (MOR) of finger-jointed lumber combinations.

Regarding the breaking strength (MOR) also, generally, stem and branch wood finger-jointed combinations jointed in dried state and tested at 10±4%MC exhibited higher MOR than their counterparts jointed in the green state and tested at 17±3%MC (Figure 4.3.11 and Table 4.3.9). This appeared to indicate that, wood with low MC (both branch and stem) before jointing produced finger-jointed lumber of high MOR than same wood types with relatively high MC. This agrees with findings reported from similar studies elsewhere that FJ lumber from the same wood type/species made at different moisture contents produced different MOR values on account of the moisture content effect (Forintek Canada Corp., 2003; Hoffmeyer & Thógersen, 1993; IDRC,1997; Research and Development Summary, 2008; St. Pierre et al., 2005). A test of the influence of MC on MOR showed that MC level had significant effect (F=581.256, p=0.000 Table 4.3.10).

However, this trend could be attributable to the findings that relatively green wood have parts of their cells voids partially filled with moisture that tend to limit and prevent glue absorption and adsorption capacity during pressing (Research and Development Summary, 2008; St. Pierre et al., 2005). Also, moisture either dilutes the glue and leads to starved joint or aids the squeezing out of the glue upon application of end-pressure. This results in a thin glue line that exhibits less strength (Research and Development Summary, 2008). Again, it is found that the glueline thickness profile happens to be less uniform for FJ lumber produced in the green state compared to those produced in the dried state and such situation generates some types of glueline spots that produce stress concentrations larger enough to weaken the joints (Research and Development Summary, 2008; St. Pierre et al., 2005).

Moreover, comparing the MOR of the solid control specimens and those of the FJ lumber combinations, unlike in the case of MOE, the MOR of all the FJ exhibited lower values than their solid lumber of same species. Again, unlike in the case of MOE, the differences in MOR of all FJ combinations of all the species and those of their control samples tested at both two MC levels were statistically significant at 95% confidence level (Table 4.3.9). It was found that specimen type/FJ combination also had significant effect (F=9.331, p= 0.000). Meanwhile, it appeared that the MOR of the FJ combinations involving branchwood, especially the stem & branch combinations had relatively higher MOR than the stem & stem FJ combination (the status quo in finger-jointing in Ghana). However, the differences in MOR of the stem & stem FJ combination and those of the cobinations involving branchwood were generally not statistically significant at 95% confidence level. This means that incorporating branchwood in finger-jointing will even produce lumber with relatively higher MOR than the status quo, though the differences were not significant.

Hence, considering the MOE of FJ lumber involving branchwood relative to even solid stemwood and also the MOR of the FJ lumber involving branchwood and those involving only stemwood (the status quo), it can be concluded that branchwood could be good supplements to stem wood for finger-jointed products manufacturing.

In general terms, it could be concluded that the trend/behaviour of finger-jointed lumber found in this study, in terms of MOE and MOR, affirms reports that finger-jointing does not have much influence on MOE as it does on MOR and this corroborates earlier research (Ayarkw et al*.*, 2000a; Barboutis & Vasileiou, 2013; Hwang & Hisung, 2001; Mantanis et al., 2010; St.-Pierre et al., 2005). However, it is worth mentioning that although generally, bending strength of finger-jointed lumber increases with increases in wood density, it is reported that high bending strength could be obtained from some low density wood like Obeche, whereas low bending strength could also be obtained by jointing wood species of density beyond 700kg/m^3

and 800kg/m^3 (Ayarkwa, 2000). Therefore, gluing hardwoods of density in excess of 700kg/m^3 is found to sometimes produce inconsistent results while finger-joints in hardwoods of densitiy below 700kg/m^3 appear to perform better (Forest Products Laboratory, 2010; Ayarkwa, 2000; Ayarkwa et al., 2000a; 2000b). Therefore, though this study has proven that incorporating branchwood in producing finger-jointing lumber could produce relatively high MOR values, caution should be exercised since some branchwood of some species could have higher density that may be beyond 700kg/m^3.

5.3.2.3: Joint efficiencies in MOE and MOR of finger-jointed lumber combinations

Generally, finger-joint efficiency measures how much strength was lost or gained upon finger-jointing wood, in relation to the strength of solid/unjointed stemwood of the same species. Hence, it is a ratio of the MOE or MOR of FJ lumber combinations to the MOE or MOR of solid stem controls of the same species and expressed as a percentage.

In terms of strength gained, joint efficiency in MOE and MOR were higher for samples tested at 10±4%MC than their counterparts tested at 17±3%MC, but those of MOR were generally lower than those of MOE. Samples tested at 10±4%MC had joint efficiencies in MOE ranging from 72.4% to 110.3% whereas those tested at 17±3%MC had joint efficiencies in MOE that ranged from 59.0% to 96.0% (Table 4.3.11). From the results on joint efficiencies in both MOE and MOR, it could be said that whereas some MOE efficiencies of FJ lumber were more than 100%, those of MOR were all less than 100% in relation to their solid stem wood. Similar results have been reported by Kumar, Sharma and Gupta (2015) upon using PVA adhesive to produce finger-jointed lumber from mango wood. These findings suggested that, MOE of wood were not much affected by finger-jointing technology, but MOR were much affected. Similar results on joint efficiencies in MOR have been reported. For instance, using resorcinol formaldehyde (PRF) resin, Mantanis et al. (2010) found MOE of FJ green wood of *Pinus nigra* ranging from 90% to 100% and MOR efficiencies ranging from 68% to 87%. Also, Ayarkwa et al. (2000a) found joint efficiency in MOR to be between 43.8% to 98% upon finger-jointing of obeche, moabi and makore wood species. Again, the findings in this present studies appear to be consistent with findings of some additional previous studies that finger-jointing can reduce MOR of wood to about 45% of the strength of solid stemwood or less (Barboutis & Vasileiou, 2013; Biechele et al., 2010; Bustos et al., 2003a; 2003b; Castro & Paganini, 1997; He et. al., 2012; Hoffmeyer & Thógersen, 1993; Meng et. al., 2009; St.Pierre, et.al., 2005; Vrazel & Sellers, 2004;).

5.3.2.4: Relationship between density and joint efficiency in MOE and MOR

This relationship is to ascertain how density of wood relates with the joint efficiencies in MOE and MOR of finger-jointed lumber produced from them. Again, it is also to assess the possibility of predicting the joint efficiency in either MOE or MOR with density. Upon using regression analyses, findings indicated that wood density correlated negatively with finger-joint efficiency in both MOE and MOR (Figure 4.3.12). This suggested that the higher the density of wood, the lower is the joint efficiency in both MOE and MOR of finger-jointed lumber produced from it. This is because, density differentials of different wood species at the same moisture content could be due to presence of extractives or some inclusions in wood. These materials, however, tend to impede adhesive penetration into wood and result in the production of finger-jointed lumber of very low strength compared to the strength of solid wood of the same species at same MC. However, this finding on the relationships of FJ efficiencies and wood density appear consistent with the reports on some Ghanaian hardwood species (Ayarkwa et al., 2000a).

5.3.2.5: Predicting bending strengths (MOE and MOR) of finger-jointed lumber from moisture content and density

This relationship has important practical significance as it could provide a non-destructive method of estimating the MOE and MOR of FJ lumber without necessarily testing the FJ lumber to destruction. Regression analyses generally, indicated negative correlation between MC and MOE, and also between MC and MOR of all the finger-joint combinations tested at both two MC levels, but both MOE and MOR correlated positively with WD for all FJ combinations tested at the two MC levels (Tables 4.3.12 and 4.3.13). These meant generally that both MOE and MOR of FJ combinations decreased with increases in MC levels but the MOE and MOR of FJ combinations increased with increases in WD.

The coefficient of determination (R^2) values for the relationship between MC and WD together and MOE (ranging from 0.432 to 0.922). This indicated that MC and WD conbined could predict MOE of finger-jointed lumber to accuracies of between 43% and 92%. Moreover, unlike solid/unjointed lumber, the coefficients of MC and WD (i.e., $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ respectively), generally appeared not conforming to any particular consistent trend upon comparing FJ lumber samples tested at 10±4%MC and those tested at 17±3%MC. This situation could be attributed to the fact that the lumber is jointed and other factors like differences in density and anatomical as well as chemical properties between the stem and branch wood that formed the joints.

Regarding the relationship of MC and WD with MOR, R^2 values also suggested that MC and WD combined can predict MOR to accuracies between 3%

and 88%. These imply that, comparatively, WD and MC can predict the MOE of FJ lumber better than the MOR. However, unlike solid/unjointed lumber, the **α** and **β** coefficients of MC and WD respectively generally appeared not conforming to any particular consistent trend upon comparing FJ lumber samples tested at 10±4%MC with those tested at 17±3%MC. This inconsistency could also be attributed to the fact that the lumber is jointed and other factors like differences in density, and anatomical as well as chemical property differences between the stem and branch wood that formed the joints.

Meanwhile, the findings on the relationship between MOE or MOR , with MC and WD of FJ lumber jointed in green and dried state appear to be generally consistent with some findings in previous studies in literature (Ayarkwa, 2000; Castro & Paganini, 1997; Forintek Canada Corp., 2003; Hoffmeyer & Thógersen, 1993; Research and Development Summary, 2008; Meng et al., 2009; St.-Pierre, et. al., 2005).

5.3.2.6: Predicting MORs of finger-jointed lumber from their MOEs

As observed with the relationship between MOE and MOR of solid stemwood and branchwood of the five species studied (Figure 4.3.8), positive relationship also existed between the MOE and MOR of FJ lumber produce from stem and branch woods at both 2 moisture levels (specifically the stem & stem FJ and the branch & branch FJ combinations) (Figure 4.3.13).

Comparing the relationship of MOE and MOR of solid stem and branch wood with those of FJ lumber, linear functions produced relatively higher R^2 values (0.68 and 0.75) for solid stemwood than finger-jointed stemwood (i.e stem & stem FJ –R^2= 0.63 and 0.58). However, R^2 values of solid branchwood (0.76 and 0.62), unlike solid stemwood, were lower than those of FJ lumber produced from branchwood only (i.e.

branch & branch FJ- R^2= 0.77 and 0.75). These mean that the relationships of MOE and MOR of branchwood appeared to be enhanced when they are finger-jointed but those of stemwood appeared to decrease upon finger-jointing. These R^2 values are, however within the ranges found by Tsoumis (1991) who used linear functions to investigate the MOE and MOR relationships for some European woods, North American woods and tropical hardwoods together and found the R^2 value to be 0.745. Again, Dinwoodie (2010) also found the mean R^2 value of a second degree power function for similar relationship to be 0.702 for some hardwoods.

Incidentally, however, the coefficient of MOE (γ- Equation 3.11) of the linear functions for solid stemwood (0.0049) and its stem & stem FJ lumber (0.0049) as well as branchwood (0.0063) and its branch & branch FJ lumber (0.006) for the samples tested at 17±3% appeared equal but the ones for the samples tested at 10±4% were different from one another (i.e. ranging from 0.005 for branch & branch FJ to 0.0084 for solid stemwood). These mean that the rate of change in MOR as a result of 1MPa. change in solid stemwood lumber of the five studied species altogether could be similar to that of all stem & stem FJ lumber produced from the species.

The differences in the relationships of stemwood and branchwood and their respective FJ lumber could be due to some chemical or anatomical characteristic differences that may affect MOE and MOR of finger-jointing lumber produced from them as well as affecting the relationship between them (i..e. MOE of solid and FJ lumber of same wood at same MC). For instance, for solid wood in this study, whereas vessel diameter correlated negatively with MOR of both stem and branch woods, it correlated negatively with stemwood MOE but positively with branchwood MOE. Also, fibre length and vessel proportion correlated in the same direction with MOE of both stem and branch woods, but they tend to correlate in different directions with MOR of stemwood and branchwood Figures 4.4.10 and 4.4.11).

5.4: Anatomical study of wood

The patterns/arrangements of the various cells in wood determine its structure and density which also give wood majority of its properties (Shmulsky & Jones, 2011; Wiedenhoeft, 2010). However, the structure of typical hardwood is much more complicated than that of softwood. In this wise, understanding the interrelationships between form and function of these cells in wood aids better insight into the realm of wood as an engineering material, its strength and limitations (Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005). As a result, some anatomical properties of stem and branch woods of the studied species were qualitatively and quantitatively assessed after which their relationships with percentage weight losses (natural durability), density and bending strength properties were ascertained.

5.4.1: Qualitative anatomy of wood

Qualitatively, photomicrographs of sections and macerates of stem and branch woods were used to describe the arrangement of the cells in them by following the terminologies in IAWA committee‟s recommendations of 1989. The descriptions obtained for the anatomical properties/features of stemwood and their arrangements as they appeared in the photomicrographs obtained for stemwood comparable and consistent with what exist in literature about stemwood of the various wood species (Duvall, 2011; Forest Products Laboratory, 2010; Kémeuzé, 2008; Kimpouni, 2009; Lemmens, 2008; Oyen, 2008; Tchinda, 2008). Therefore, the description obtained for the branchwood of the species also represent the true features of branchwood anatomy of the species studied since same procedures and guidelines as used for the stemwood were also used for the branchwood.

5.4.2: Quantitative Anatomy of wood

Branchwood and stemwood of same trees can be different from each other because some kinds of cells are abundant or less in wood from branches than wood from the main bole (Shmulsky & Jones, 2011). These differences, if significant could in some instances pose utilization challenges in an effort to use wood from the branches either alone or in combination with wood from the main stem. It was in this light that this aspect of this study was done to ascertain any significant differences in the cells in wood from the main stem compared to that from branches, quantitatively.

Currently, Ghanaian tropical hardwood branchwood anatomy has not been sighted in literature, especially regarding the species sampled for this study. Such data is either limited or absent. However, anatomical data on the stemwood of the species are available. In the light of this, in discussing the results obtained, a comparison with published quantitative data on stemwood anatomy was made and which aided the substantiation of data on branchwood anatomy for subsequent comparison. This aspect of this study compared five anatomical features of stem branch woods of individual species {i.e. fibre length- obtained from maceration, vessel-lumen diameter, fibre proportion, vessel proportion and total parenchyma proportion (rail plus axial)- obtained from transverse or cross sections}. The relationships between mean quantitative anatomical features of stem and branch wood and, wood density, percentage weight losses (natural durability), bending strength (MOE and MOR) were also ascertained.

5.4.2.1: Comparison of quantitative anatomical properties in stem and branch wood

Comparison of the anatomical properties of stem and branch woods are discussed separately for the individual studied species in order that any variability could be clearer and appreciated.

5.4.2.1.1: *Entandrophragma cylindricum* (sapele)

Findings were that, averagely, stemwood fibre length was 1479µm and vessel lumen diameter was averagely 135µm. These appeared consistent with published data on the species that; fibre length range from 690µm to 2005µm (Richter & Dallwitz, 2000), and vessel diameter is in the range of 90µm to 200µm (Kémeuzé, 2008; Richter & Dallwitz, 2000). The fibre lengths of the stemwood were however significantly longer ($p<0.01$) than those of branchwood (1302µm) and the vessel lumen diameter was also significantly ($p<0.01$) larger than that of branchwood (124µm) - Table 4.4.1. Moreover, branchwood had higher fibre and total parenchyma proportions but lesser vessel proportion than stemwood. However, only the difference in the vessel proportion was significantly different ($p<0.05$). These could mean that the stemwood might be only significantly porous than the branchwood due to their vessel lumen diameter differences (Shmulsky & Jones, 2011) therefore, besides applications where porosity is a requirement, branchwood of sapele will not possibly pose any significant utilization difficulties when used to supplement its stemwood, especially in the production of furniture and FJ lumber.

5.4.2.1.2: *Entandrophragma angolense* (edinam)

The findings on edinam that averagely the stemwood fibre length was 1546µm and vessel lumen diameter was 167µm appeared to have corroborated published data on the species that; fibre length range from 960µm to 2225µm (Richter & Dallwitz, 2000) and vessel diameter is in the range of 45µm to 220µm (Richter & Dallwitz, 2000; Tchinda, 2008). The stemwood fibre length was significantly longer ($p<0.01$) and the vessel lumen diameter was also singnificantly larger ($p<0.01$) than those of branchwood (Table 4.4.1). Moreover, branchwood had higher fibre and total parenchyma proportion but lesser vessel proportion than stemwood (Figure 4.4.1). However, the differences in all these property proportions were not significant ($p>0.1$). These mean that the stemwood will be significantly porous but strong in tearing/tension than the branchwood on account of larger vessel lumen diameter and longer fiber length respectively (Shmulsky & Jones, 2011). Therefore, with the exception of applications where porosity and tensile strength are the needed requirements, branchwood of edinam will not possibly pose any significant utilization difficulties when used to supplement its stemwood in wood products manufacturing.

5.4.2.1.3: *Khaya ivorensis* (mahogany)

This study found stemwood fibres to be averagly 1452µm and vessel lumen diameter to be 144µm. These appeared to be within the range of published data about the species that; fibre length range from 1250µm to 1650µm (Richter & Dallwitz, 2000), vessel diameter is in the range of 80µm to 245µm (Lemmens, 2008; Richter & Dallwitz, 2000). The stemwood fibre length was not significantly shorter ($p>0.1$) but the vessel lumen diameter was singnificantly larger ($p<0.1$) than those of branchwood (Table 4.4.1). Additionally, in this study, branchwood had significantly lesser fibre and vessel proportions ($p<0.01$) but non-significantly higher total parenchyma ($p>0.1$), than stemwood. These mean that the stemwood and branchwood porosity levels could balance on account of stemwood having significantly larger diameter but lesser quantity of the vessels, whereas branchwood had significantly much quantities of vessels whose diameters are relatively smaller. Therefore, what may create any significant utilization differences will be the fibre proportion differences, but this is even advantageous in terms of mechanical strength (Shmulsky & Jones, 2011; Tsoumis, 1991). This appeared manifested in the relatively high MOE and MOR values of the branchwood than its stemwood (Tables 3.3.1 and 3.3.3). As a result, with the exception of applications where too many fibre proportion may not be helpful branchwood of mahogany will not necessarily pose significant utilization differences or difficulties when used to supplement its stemwood in wood products manufacturing.

5.4.2.1.4: ***Terminalia superba*** **(ofram)**

The findings on ofram that averagely the stemwood fibre length was 1235µm and vessel lumen diameter was 183µm appeared to be in the range of findings in published data on the species; fibre length range from 550µm to 1998µm (Richter & Dallwitz, 2000), vessel lumen diameter is in the range of 70µm to 300µm (Kimpouni, 2009; Richter & Dallwitz, 2000). The stemwood fibre length was not significantly longer ($p>0.1$) but the vessel lumen diameter was singnificantly larger ($p<0.01$) than those of branchwood (Table 4.4.1). Moreover, branchwood had higher fibre (significantly - $p<0.05$) but lesser total parenchyma and vessel proportions (but non-significantly, $p>0.1$) compared to stemwood (Figure 4.4.1 and Table 4.4.1). These could imply that the stemwood will be significantly porous than the branchwood on account of the relatively large vessel lumen diameter, but branchwood may also have significantly higher mechanical strength due to the many fibres which is good in many wood products manufacturing (Shmulsky & Jones, 2011; Tsoumis, 1991). This appeared manifested in the MOE and MOR values exhibited by the branchwood (Tables 4.3.1 and 4.3.3). Therefore, except for situations where porosity is of much concern, branchwood of ofram will not significantly pose utilization differences or difficulties when used to supplement its stemwood in wood products manufacturing, especially for furniture and wood products manufacturing.

5.4.2.1.5: *Pterygota macrocarpa* (koto)

In this study, findings on koto were that, averagely, stemwood fibre length was 1521µm and vessel lumen diameter was averagely 165µm. These appeared consistent with literature on koto that; fibre length range from 1265µm to 2780µm (Richter & Dallwitz, 2000), vessel lumen diameter is also in the range of 95µm to 240µm (Oyen, 2008; Richter & Dallwitz, 2000). Meanwhile, the fibre length of the stemwood were shorter (singnificantly-$p<0.01$) but the vessel lumen diameter was not significantly($p<0.1$) smaller than those of their branchwood (Table 4.4.1). Moreover, branchwood had higher proportions of fibre (significantly, $p<0.05$) and vessel (significantly, $p<0.05$) but lesser total parenchyma proportion (significantly, $p<0.01$) than the stemeood. These could mean that the stemwood might be significantly less porous than the branchwood on account of significantly lesser vessel proportion, and the branchwood can also have higher mechanical strength due to significantly higher fibre proportions, but both may be highly susceptible to microbial attack on account of about 50% of their cross-sectional areas per mm^2 being occupied by parenchyma (Eaton & Hale, 1993; Shmulsky & Jones, 2011). These appeared manifested in the insignificant differences exhibited by the stem and branch woods in respect of bending strength (Table 4.3.1) and natural durability

(Figures 4.2.1 and 4.2.2; Table 4.2.2) found in this study. Therefore, it appears that branchwood of koto as supplement to its stemwood may not pose any significant utilization differences or difficulties.

5.4.2.1.6: *Ceiba pentandra* (onyina) -Natural durability test's control species

This study found fibre length of onyina stemwood to average 1919µm and vessel lumen diameter of 227µm (Table 4.4.1). These findings appeared to agree with literature on *Ceiba* that fibre length range from 1400µm to 2850µm (Richter & Dallwitz, 2000), and vessel diameter is in the range of 145µm to 360µm (Duvall 2011; Richter & Dallwitz, 2000). Generally, the anatomical properties of *Ceiba* stemwood were significantly different (p=0.000) from those of all the 5 main studied species. This might have resulted in its show of much difference from the other species in the natural durability test results (Figures 4.2.1 and 4.2.2; Table 4.2.2).

On the whole, the findings obtained in this study on anatomical property differences between stem and branch wood of the species, except for those of koto, in general terms, appeared to agree with literature that branchwood have relatively shorter fibres and lesser lumen diameter in most hardwood than in their stemwood. Also, some kinds of cells are either more or less abundant in wood from branches than wood from the main bole (Samariha, Kiaei, Talaeipour, & Nemati, 2011; Shmulsky & Jones, 2011; Stokke & Manwiller, 1994).

5.4.3: Quantitative anatomical properties and wood density

This relationship was to find out how the various anatomical properties relate with wood density. These relationships are of importance as they could be used to predict the density of stem or branch wood. In this study, the general finding was that except fibre proportion that correlated positively and vessel proportion that correlated in opposite directions, almost all the other anatomical properties determined correlated negatively with both stem and branch wood density (Figure 4.4.8). This suggested that density increases with increases in fibre proportion per mm^2 cross sectional area of wood while it decreases with increases in the proportion of the other cells or properties. This is however consistent with literature that density/specific gravity increases with increases in proportion of cells with thick cell walls, particularly fibres, but tends to decrease with increases in the proportions of void/pores and other cells with thin cell walls (such as vessels and parenchyma) (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005). Upon considering the R^2 values in this relationships, it appeared that vessel diameter (R^2=0.685) and fibre proportion (R^2=0.392) are the relatively stronger anatomical features for predicting stemwood and branchwood density respectively.

5.4.4: Quantitative anatomical properties and percentage weight loss (natural durability)

This association was aimed at investigating how the various anatomical features relate with mean weight losses of stem and branch wood of the studied species. This is necessary because it could also be used as a non-destructive method to predict the percentage weight loss (%WL) or natural durability of those wood species without necessarily performing the grave-yard/soil block test. Generally, all the anatomical features correlated in same direction with stemwood as with branchwood (Figure 4.4.9). The positive correlations of fibre length, parenchyma proportion and vessel lumen diameter, and the negative correlations of vessel proportion and fibre proportion with percentage weight loss found in this study, appear to agree with findings in literature (Ali, 2011; Nzokou et al., 2005; Forest Products Laboratory, 2010; Ncube, 2010).

It is reported that, increases in the natural flow paths (particularly vessels) and the food storage cells (parenchyma cells i.e. ray and axial) lead to low natural durability of wood (i.e. increases in %WL), because these cells serve as entry and colonizing areas for fungi (Ali, 2011; Eaton & Hale,1993; Ncube, 2010; Shmulsky & Jones, 2011). Again, besides providing shelter, oxygen and ready food for fungi to grow and multiply for speedy destruction of wood. These cells (the natural flow paths) also influence permeability of moisture and leachability of toxic extractives that could have offered some toxicity/resistance to biodeterogens (Ncube, 2010; Shmulsky & Jones, 2011; Skadsen, 2007; Panshin & de Zeeuw, 1980) and lead to much percentage weight losses. The reverse is the case where percentage of cells with thick cell walls (particularly fibres) is high. In such instances, since fungi typically erode wood outward from the lumens (Shmulsky & Jones, 2011), it will take a little longer time to eat up wood with more thick walled cells and therefore, the higher the proportion of fibres, the higher the natural durability of wood or the lower the percentage weight losses (especially those with thicker firbre cell walls).

The R^2 values of these relationships suggest that vessel proportion (R^2 = 0.395) and fibre length (R^2 = 0.353) are the poorest predictor variable for %WL (natural durability) of branch and stem woods respectively, whereas vessel lumen diameter (R^2=0.835) and vessel proportion (R^2 = 0.846) appeared to be the strongest predictor variables for natural durability branch and stem woods respectively, and these appear to agree with Anoop et al. (2014).

5.4.5: Quantitative anatomical properties and bending strength propeties of solid stem and branch woods

In this study, the general findings that both stem and branch woods MOE and MOR had similar correlations with each of the anatomical features (Figures 4.4.10

and 4.4.11). The patterns of correlation generally appeared to corroborate with literature. For instance, it is reported that increases in fibre proportion increases both MOE and MOR (positive correlations), whereas increases in vessels (i.e. their lumen diameter or and proportion) and parenchyma proportion decreases MOE and MOR – negative correlations (Forest Products Laboratory, 2010; Shmulsky & Jones, 2011; Wiedenhoeft & Miller, 2005).

Considering the R^2 values of the relationships, the determined anatomical features can best predict MOR of branchwood than stemwood but they can predict the MOE of stemwood better than branchwood. However, it appeared that total parenchyma was the poorest predictor anatomical feature variable for MOE of both stemwood ($R^2 = 0.0125$) and branchwood ($R^2= 0.0098$), and vessel lumen diameter ($R^2= 0.439$) and fibre proportion ($R^2=0.926$) were the relatively best anatomical predictor variables for stemwood and branchwood respectively.

CHAPTER SIX

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Findings and Conclusions

It is established that there is a general concern about the need to reduce the depletion of Ghana‟s tropical forests on account of its importance in contributing substantially to the national GDP, offering employment, protecting the forest ecosystem, and sequestering carbon to reduce GHGEs. The challenge in this quest is the already existing industrial round logs deficit of about 1.5million M^3 between the processing capacity of the wood products industries (WPIs) and the Annual Allowable Cut (AAC) that need to be made up. If the WPIs are to be sustained and further expanded to create more jobs while at the same time achieving reduction in depletion rate of the forests, utilization of logging residues (stem off-cuts and branchwood) as alternatives and supplements to extracted stemwood appears to be one of the promising and readily available solution. Upon the findings in this study on wood residues, the following conclusions were drawn:

6.1.1: Above-Stump Merchantable Wood Quantity/Volume

This study has shown that the average proportion of felled trees that are actually extracted and delivered to the mills resulted in logging efficiency of 74.95%, and above-stump total merchantable residue volume (TMRV) of 25.05% per each tree harvested. These were within the range of findings of previously published studies.

By calculations, the use of the 25% of stem off-cuts and branchwood (TMRV) from the 154 trees whose residues were quantified can lead to the conservation of about 8ha. of forest land, per 154 trees harvested, at least till the next felling cycle. In other words, the extraction of these residues can make available to the firms additional volume of wood equivalent to logging 8ha. of forest land to take care of their timber requirements.

It is also established in this study that both branchwood and stem off-cut quantities were statistically significant among species and sites/ecological zones. Logging efficiency was, however, significantly different among species but not among sites. Reasons assigned to these were varied and included workers orientation, genetics, topography of the sites, natural defects and commercial value of the species.

This aspect of the study further showed that extracted log volume (ELV) is a better predictor of total merchantable wood volume (TMWV) but a poor predictor of total merchantable residue volume (TMRV). For all the three models; viz. site specific, species specific, and mixed site and species specific, there were higher prediction accuracies for TMWV (i.e. from the least of 86.6% - site specific to highest of 99% - species specific) than for TMRV (i.e. from the least of 12.8% - mixed species and site specific to highest of 52.7% - site specific).

Also, for the purposes of pricing TMRVs, it will be better to use the species or site specific models to predict TMWV after which the ELV could be deducted to obtain the TMRV, since ELV was a poor predictor of TMRV.

Across the four reserves within the 3 ecological zones covered in this studies, *P. africanum* and *T. scleroxylon* were the dominant wood species. Thus, the use of mixed sites and species specific models for prediction coould be more geared towards these two species to the disadvantage of the others.

6.1.2: Natural Durability of Wood

Generally, moisture content and wood type (stem or branch) influenced the natural durability of both branchwood and stem off-cuts and can therefore affect the service lives of the wood types from all the species studied upon application.

For specific species, generally, at the same moisture level, branchwood was either significantly better than or comparable to stemwood in natural durability based on percentage weight loss. In fact, branchwood of *Entandrophragma cylindricum* (sapele), *Entandrophragma angolense* (edinam) kiln-dried and tested at 6 ±3%MC were significantly durable than their stemwood counterparts. Hence, in terms of natural durability, branchwood of the species studied could either be better or as good as their stemwood at similar MC, except sapele branchwood air-dried and tested at 14±2%MC. The durability status found in this study for the stemwood of all the species were consistent with their status in literature, except for *K. ivorensis* whose status deviated from moderately durable in literature to non-durable in this study.

This study has established that the association existing between natural durability (i.e. %WL) and either MC or WD are similar (positive for MC and negative for WD) for both stemwood and branchwood, except that the associations were stronger at relatively lower than higher MC levels. For both stem and branch woods, %WL increased (i.e. natural durability reduced) with high moisture levels and vice versa, but %WL decreased (i.e. natural durability is enhanced) as WD increases and vice versa .

Again, MC and WD combined had better predictive power (up to 92% for stemwood and 95% for branchwood) for percentage weight loss (%WL) or natural durability of both stem and branch woods compared to the predictive powers of MC (i.e. up to highest of 68% for stemwood and 72% for branchwoods) and WD (i.e. up to highest of 93% for stemwood and 91% for branchwood) acting as single predictor variables. However, generally, at high MC range, the combined effect of a unit change in MC and WD on %WL (i.e **α** and **β** coefficients of MC and WD respectively) were higher at a relatively higher than at a lower MC ranges, indicating that the rate of biodeterioration of wood is higher at relatively higher MC level than at a relatively lower MC level and this was consistent with literature.

6.1.3: Static bending strength of solid/unjointed and finger-jointed lumber

6.1.3.1: Static bending strength of solid lumber.

This study did establish that moisture content as well as wood type (stem or branch wood) had significant effect at 1% significant level on MOE and MOR of stemwood and branchwood and the higher the MC, the lower the MOE and MOR and vice versa.

It has also been estabilished in this study that branchwood was not inferior to stemwood of the same species in terms of bending properties. The MOEs of branchwood were either significantly higher than or comparable to those of stemwood of same species at same MC. In fact branchwood of sapele at both 2 moisture levels (i.e, 17±3%MC and 10±4%MC) in addition to branchwoods of mahogany and ofram at 17%MC and 10%MC respectively were significantly higher in MOE than their stemwood counterparts at same moisture levels. Moreover, in terms of MOR, branchwood values were either significantly higher or comparable to those of stemwood of same species at same moisture level. The MOR of edinam and mahogany branchwood were significantly higher than their stemwood counterparts at both 17% and 10%MC. Thus, branchwood of all the species studied appeared to be able to perform either better or equivalently in bending upon application. On this basis, branchwood of the species can serve as good alternatives or supplements to their stemwood in producing furniture parts and for other light structural applications where bending strength (MOR) are requirements. However, branchwood of *edinam,* and *K. ivorensis* may even perform better at same MC range than their stemwood counterparts.

Findings in this study have generally shown that branchwood of the studied species, except koto, had higher density than their stemwood at same MC level and MC has influence on density (the higher the MC the higher the WD and vice versa) and this was also consistent with earlier reports in literature. The study also indicated that, MC associated negatively with both MOE and MOR while WD associated positively with both MOE and MOR of both stemwood and branchwood. However, there was relatively high prediction accuracies for both MOE and MOR (93% for both MOE and MOR of stemwood, and 96% and 91% for MOE and MOR respectively of branchwood) for the prediction model that used MC and WD as combined predictor variable, compared to using each as a single predictor variable. Hence, on the basis of the R^2 values, MC and WD combined in a model could be a better option of non-destructive prediction of MOE and MOR of both branchwood and stem off-cuts.

Moreover, the study has also shown that, for both stemwood and branchwood generally, the quantum of increase in MOE and MOR of solid lumber, due to a unit change in MC and WD, could be higher for wood at lower MC range relative to the same wood at higher MC range. These relationships were also found to be consistent with what have already been reported in literature on stemwood (e.g. Shmulsky & Jones, 2011).

It has also been established in this study that, as another non-destructive method, MOE can be used to predict MOR of both branchwood and stemwood of all species together to accuracies of 75% for the stemwoods at both 2 moisture levels, and 76% and 62% for branchwood at 17%MC and 10%MC respectively. But the prediction accuracies for individual species vary from 47% (mahogany) to 89% (sapele) for stemwood, and 22% (mahogany) to 90% (koto) for branchwood. Thus, predicting MOR of mahogany (both branch and stem wood) with their MOE could be the least accurate.

6.1.3.2: Static bending strength of Finger-jointed lumber

Regarding finger-jointed (FJ) stemwood and branchwood lumber, this study has shown that finger-jointing stem off-cuts and branchwood in the green and dried state with PVA adhesive (i.e. crosslink or thermosetting type) is possible, at least for the species studied.

Generally, the various FJ combinations (stem & stem FJ, stem & branch FJ, and branch and branch FJ) dried before jointing and tested at 10±4%MC level had relatively higher MOE and MOR than their counterparts jointed in the green state and tested at 17±3%MC level. Both MC and specimen type (various combinations of FJ lumber of stem and branch wood) significantly affected both MOE and MOR produced by the jointed lumber.

For the individual species, though MOE of FJ lumber were either lower or higher than the MOE of their solid/unjointed stemwood (controls), but not all of such differences were significant at both 2 moisture levels. However, except for the combinations of *Pterygota macrocarpa*-koto jointed in the green state and tested at 10±4%MC, generally, differences in MOEs among the status quo (i.e. stem & stem FJ combinations) and the ones involving branchwoods (i.e. stem & branch and branch & branch FJ combinations) were not significant at both 2 MC levels. To this end, pairing stem off-cuts and branchwood in finger-jointing is comparable to the status quo (i.e. stem & stem pairings/combinations) in terms of MOE.

Also, the MOR of all finger-jointed lumber combinations of all the species at both 2 MC levels were significantly different from those of their solid/unjointed control stemwood. However, at 95% confidence level, besides the FJ combinations of edinam and mahogany, the MOR of stem and branch wood FJ combinations of all other species were not significantly different from the MOR of the current status quo (stem & stem FJ combination). On account of this, the use of branchwood to supplement stemwood in finger-jointing technology to produce usable lumber will offer a good and helpful alternative or supplement to the status quo. This will ensure efficient utilization of branchwood and timber in general and such lumber produced could be used for some furniture parts and other light structural applications where bending strengths are requirements.

This study has also established that for the species studied, the various FJ combinations jointed in the green state had MOE and MOR efficiencies (strength gained) lower than those dried before jointing. Results in this study have shown that FJ lumber MOE efficiencies can be higher than 100% but those of MOR is lesser than 100%. Moreover, it has been established in this study that FJ efficiency generally correlated negatively with wood density, and therefore high density wood generally produced joints of low efficiency and vice versa. All these findings however, corroborated with earlier findings in literature.

This study has also indicated that, negative correlations exist between MC and FJ MOE or MOR, whereas positive correlations exist between WD and MOE or MOR of FJ lumber. The R^2 values obtained in this study however pointed out that, MC and WD combined can predict both MOE and MOR better (i.e. prediction accuracies of up to 92% and 88% respectively) than when MC and WD are used as single predictor variables for predicting either MOE or MOR of the FJ lumber combinations. However, prediction accuracies for FJ MOEs were generally lower for the stem & stem FJ combinations and higher for the branch & stem FJ combinations, but those of MOR appeared not to show any consistent general trend.

Also, this study has established that both linear and scond degree polynomial and power functions best described the relationships between MOE and MOR for stem & stem FJ and branch & branch FJ lumber of all species together. However, considering the linear functions, comparatively, R^2 values suggested that MOE and MOR relationships appeared weakened when stemwood are finger-jointed (i.e. R^2 = 0.68-0.75 for solid stemwood and 0.58-0.63 for stem & stem FJ) but the relationship tends to be stronger when branchwood are finger-jointed (i.e. 0.62-0.76 for solid branchwood and 0.75-0.77). Interestingly, from the coefficient of MOE (**y**), the effect of 1MPa. change in MOE on MOR appeared to be similar for both solid stemwood and their stem & stem FJ lumber (i.e. 0.0049- Figures 4.3.8 a and 4.3.13 a) at relatively higher MC of 17±3%, and also for both solid branchwood and their branch & branch FJ lumber (0.006 - Figures 4.3.8 b and 4.3.13 b).

6.1.4: Anatomical Study of Wood

The anatomical properties helped to explain the results obtained on stem and branch wood regarding their density, percentage weight loss (natural durability), and bending strengths of solid/unjointed lumber.

Based on careful examinations of photomicrograps, this study has found that, qualitatively, there are some marginal differences in the arrangements and appearances of some cells in stem and branch woods of same species.

The study has also established that generally, the sizes and quantities of some anatomical features in stem and branch woods of the same species are not the same. The sizes and proportions of some wood cells were either more or less significantly different ($p<0.01$) in stem than in branch woods. Except for branchwood of koto, fibres were shorter and vessel lumen diameters were smaller in branchwood than in stemwood of same species. The trend for *P. macrocarpa* appeared to be responsible for its deviation from the general trend found in this study that branchwood had relatively higher density and also exhibited higher MOE and MOR than their stemwood counterpart. These trends, however, generally agreed with published literature on the stemwood of the species.

Moreover, it has also been established in this study that among the species and their wood types, as parenchyma proportion/mm^2 cross-sectional area (%) in stem or branch wood increases, fibre proportion/mm^2 cross-sectional area (%) decreases.

Again, based on the predictive powers (R^2 values) for wood density exhibited by the anatomical features, it appeared that density depended much on fibre proportion and vessel diameter than the other anatomical features measured in this study. Therefore wood with higher proportion of fibres and smaller vessel diameter should be expected to be generally denser than those with higher proportions of the other cells.

Additionally, on account of the predictive powers for percentage weight loss (natural durability) exhibited by the anatomical properties determined in this study, for both stemwood and branchwood, it was evident that natural durability was strongly linked to vessel proportion, vessel diameter and parenchyma proportion relative to the other anatomical properties, and it corroborated other published findings in literature.

Also, considering the predictive powers of the relationships among the anatomical features and MOE or MOR it appeared that MOE and MOR depended much on fibre proportion, vessel lumen diameter and parenchyma proportion, and this agreed with some literature. However, it was evident that anatomical properties can predict MOR of branchwood a little bit accurately than stemwood, but they can however predict MOE of stemwood better than that of branchwood.

6.1.5: Contributions to Knowledge

From the findings and conclusions drawn, this study has contributed to knowledge as follows:

1. Additional information has been provided to the effect that if branchwood are quantified down to 15cm diameters while leaving stumps to keep the soil and its nutrients intact, the logging residues will still be in the range of the 25% to 30% of total merchantable wood as reported in literature.
2. Information on the natural durability of branchwood compared to stemwood of five Ghanaian tropical hardwoods at two different moiture levels have been provided.
3. Bending strength properties (MOE and MOR) of stemwood and branchwood of five additional Ghanaian tropical hardwoods at two moisture levels have been added to existing literature.
4. Data on bending strength properties (MOE and MOR) of finger-jointed lumber of five Ghanaian tropical hardwoods at two different moisture contents have been provided as new information in literature.
5. Variations in some anatomical characteristic of stemwood and branchwood of five Ghanaian tropical hardwoods have been added to literature as new information.

6. Relationships among selected anatomical properties and density, natural durability, bending strength properties of branchwood compared to stemwood have been added to literature.

6.2: Recommendations

Based on the findings in this studies and the conclusions drawn, the following recommendations were made:

1. The wood products industries in Ghana should be made to develop logging residue utilization frameworks that could be enforced as part of requirement for the acquisition or approval of timber utilization contracts (TUCs). These frameworks should also be monitored with all seriousness by officials of the forestry commission, to ensure their compliance towards extraction of branchwood and stem off-cuts for processing. In this regard, the government of Ghana can also collaborate with the wood products industries to acquire equipment and machinery for the processing of logging residues. Per this collaboration, cottage industries could even be established in the forest areas to process the residues into furniture parts and finger-jointed lumber, a step which could create direct and indirect employment for many people in the forest areas in particular, and the country in general.

2. For the species studied and in terms of natural durability, branchwood were recommended to be used as substitutes or supplements to their respective stemwoods.

3. Moisture content and wood density should be used as combined predictor variables for non-destructive determination of natural durability of stem and branch wood instead of using each of them as a single variables, should the need be.

4. In finger-jointing, pairing stem off-cuts with branchwood should be used as substitutes and supplements to the stem & stem FJ combinations (status quo) in applications where bending strengths are required especially for light structural works.

5. Though FJ wood in the green state appear to compromise strength, by virtue of their economic and environmental benefits, they could be produced and used for non-structural applications where strength is not of prime importance.

6.2.1: Suggestions for further studies

To strengthen the recommendations made and contribute to further utilization of branchwood, some further studies including the following are required in addition to the coverage of this study to augment the data on branchwood compared to stemwood:

1. Furher natural durability test should be conducted to establish which biodeteriorating agent (fungi or termite and their types) destroys stem or branch wood of same species the greatest.

2. A study should also be conducted to analyse the chemical content differentials between stem and branch woods of same species and to evaluate their roles in the durability of stem or branch woods.

3. A comparative study of the equilibrium moisture contents and sorption characteristics of stem and branch woods of the species should be conducted to ascertain and understand the behaviour of stem and branch woods better in those regards.

4. The same method of drying should be used to dry wood to different moisture contents for natural durability test to ascertain whether or not drying method in itself actually influences natural durability of stem and branch woods of the same species differently.
5. Bending test other than one involving small clear solid samples should also be conducted to ascertain the bending strength of branchwood in comparison with their stem wood when applied as structural sizes for beams.
6. Since some furniture parts are also subjected to compression and shear stresses, a comparative study in these regards should be conducted on branch and stem woods of the species studied in this research to add to the mechanical strength data on the branchwood.
7. Drying characteristics of stem off-cuts and branch wood should also be studied to understand the behaviour of the branchwood in relation to their stemwood counterparts during drying.
8. Some finger-jointed lumber are used to produce laminated boards for Doors, table tops, and laminated beams. Hence, the shear strength of laminated stem and branch woods of same species should be investigated.
9. Other quantitative anatomical data should be conducted to establish other differences between stem and branch wood of same species. This will provide additional anatomical data on branchwood of the species and will also help to understand the variability in bending strengths, natural durability, absorption and bonding characteristics of branchwood in relation to their respective stemwood of same species.

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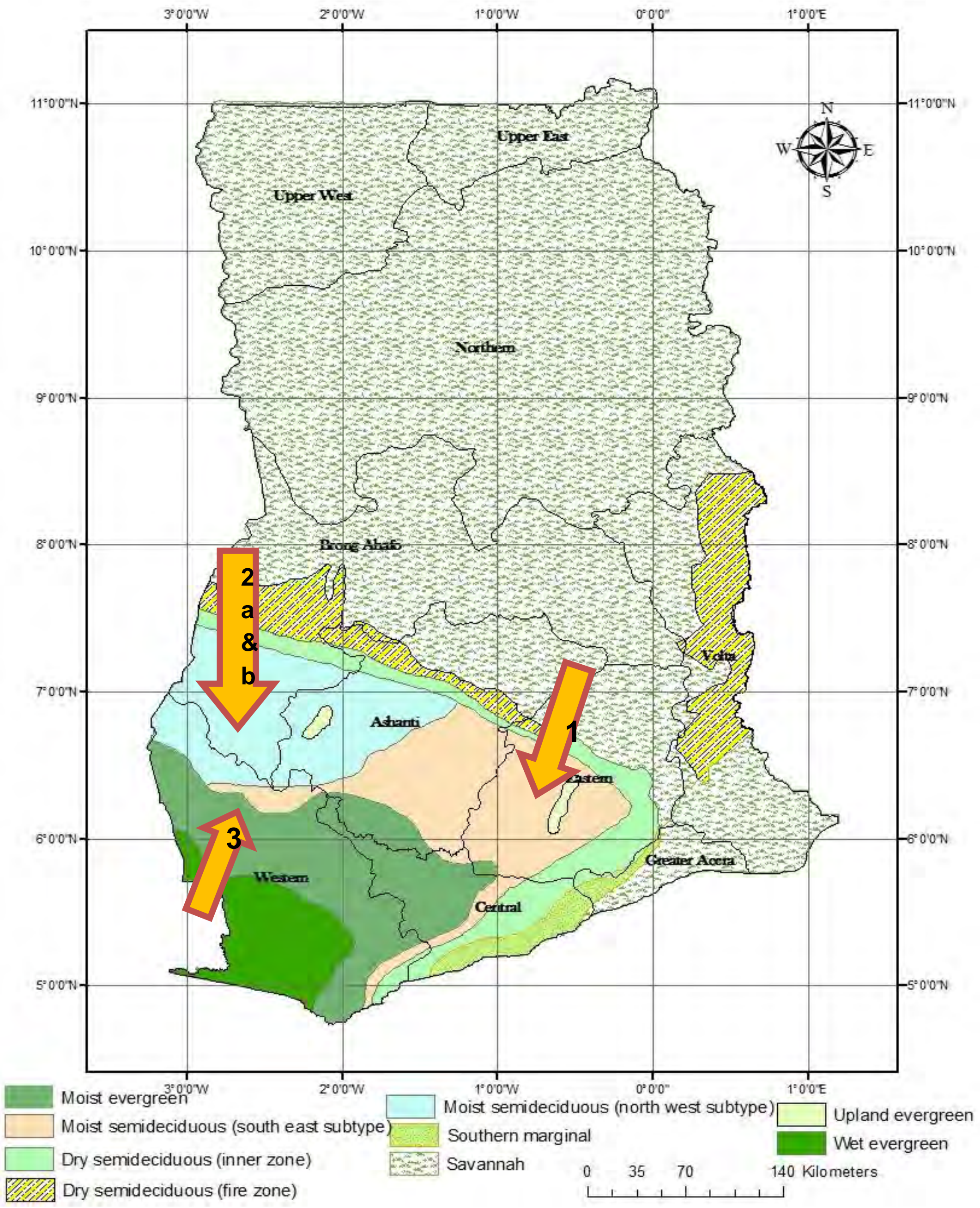
APPENDICES

Appendix 1:

Ecological map of Ghana indicating longitudes and latitudes (arrows are estimating the position of the forest reserves 1, 2 a & b, and 3, as indicated on Figure 3.1, in the text, where study samples were obtained)



Source: Ministry of Lands and Natural Resources- MLNR, (2012)

Appendix 2: Descriptive Statistics on Natural Durability test Results for the Stem and Branch Woods

Species & wood types		**Moisture content (%)**	**N**	**Density (Kg/m^3).**		**Weight loss (%).**		**Visual Rating of attack or destruction**		**Durability class.**	**Durability description**
				Mean	**±SD**	**Mean**	**±SD**	**Mean**	**±SD**		**(by % weight loss).**
E. cylindricum	**Stem**	MC1 (14±2)	16	658.936	25.64	31.255	33.03	2.312	1.35	2	Moderately durable
(sapele)	**Stem**	MC2 (9±3)	16	640.356	7.57	27.242	12.37	1.750	0.68	2	Moderately durable
	Branch	MC1 (14±2)	16	665.384	15.03	64.980	41.16	3.250	0.93	3	Non-durable
	Branch	MC2 (9±3)	16	649.624	12.29	12.850	6.03	1.313	0.48	1	Moderately durable
E. angolense	**Stem**	MC1 (14±2)	16	555.776	9.51	47.970	37.60	3.000	1.10	3	Non-durable
(edinam)	**Stem**	MC2 (9±3)	16	540.720	9.76	40.23	43.53	2.93	1.32	3	Moderately durable
	Branch	MC1 (14±2)	16	571.744	19.20	35.26	34.17	2.438	1.32	2	Moderately durable
	Branch	MC2 (9±3)	16	550.272	12.42	20.251	16.44	2.188	0.98	2	Moderately durable
K. ivorensis	**Stem**	MC1 (14±2)	16	548.968	12.65	73.188	27.60	3.563	0.73	4	Non-durable
(mahogany)	**Stem**	MC2 (9±3)	16	491.920	41.55	59.733	24.45	3.313	0.60	3	Non-durable
	Branch	MC1 (14±2)	16	568.304	6.12	71.878	24.79	3.625	0.62	4	Non-durable
	Branch	MC2 (9±3)	16	547.672	6.49	52.188	25.18	3.188	0.66	3	Non-durable
T. superba	**Stem**	MC1 (14±2)	16	610.536	49.64	65.603	32.75	3.438	0.73	4	Non-durable
(ofram)	**Stem**	MC2 (9±3)	16	542.336	5.46	47.813	27.05	3.189	0.83	3	Non-durable
	Branch	MC1 (14±2)	16	688.616	25.51	66.692	17.89	3.625	0.0.5	4	Non-durable
	Branch	MC2 (9±3)	16	652.128	35.61	49.318	24.38	3.250	0.86	3	Non-durable
P. macrocarpa	**Stem**	MC1 (14±2)	16	657.020	11.00	99.049	3.81	4.000	0.00	4	Non-durable
(koto)	**Stem**	MC2 (9±3)	16	605.885	60.29	98.770	4.92	4.000	0.00	4	Non-durable
	Branch	MC1 (14±2)	16	656.704	12.29	99.700	1.20	4.000	0.00	4	Non-durable
	Branch	MC2 (9±3)	16	597.000	23.69	99.464	2.14	4.000	0.00	4	Non-durable
C. pentandra	**Stem**	MC1 (14±2)	16	324.880	33.81	100.00	0.00	4.000	0.00	4	Non-durable
(onyina)	**Stem**	MC2 (9±3)	16	251.568	4.58	95.843	9.39	4.000	0.00	4	Non-durable
TOTAL			**352**								

Key to Table4.2.1; Durability description by weight loss, according EN 252 (1989) and Eaton and Hale, (1993) : 0-5% = very durable,; 6-10%= durable; 11-40%= moderately durable; and 41-100%= non-durable.

Appendix 3: Experimental Results on Density and Static Bending Strength of Solid/ Unjointed Lumber

		MC range (%)		Density (kg/m3)	MOE (Mpa)	MOR (Mpa)
Species & type of wood	**N**	**Min**	**Max**	**Mean ±SD**	**Mean ±SD**	**Mean±SD**
E. Cylindricum (Sapele)						
Stem (MC1)	20	14	20.3	666 ±71.38	5719.75 ±1451.80	66.60 ±13.36
Stem (MC2)	20	9.4	13.4	655 ±44.03	10461.00 ±3213.20	101.49 ±35.37
Branch (MC1)	20	14.2	20.5	772 ±49.88	6385.10 ±1052.90	67.17±8.88
Branch (MC2)	19	10.4	13.5	759 ±72.38	9094.50±1638.80	94.13 ±13.12
E. Angolense (Edinam)						
Stem (MC1)	20	14.6	20.4	565 ±38.26	7177.30 ±983.54	63.15 ±5.64
Stem (MC2)	20	6.5	13.4	550 ±55.26	8119.75 ±842.09	78.57 ±7.80
Branch (MC1)	20	14.3	20.5	738 ±20.55	7853.90 ±1224.39	77.37 ±8.12
Branch (MC2)	20	6.6	13.5	721 ±24.55	10025.50 ±1565.00	100.52 ±16.42
K. Ivorensis (Mahogany)						
Stem (MC1)	20	14.8	20.6	522 ±22.88	6576.75 ±1021.81	57.19 ±11.36
Stem (MC2)	20	6.8	13	502± 30.58	10233.10 ±721.39	85.48 ±10.76
Branch (MC1)	20	14.4	20.3	598 ±57.01	7448.70 ± 613.65	70.16 ±7.19
Branch (MC2)	20	6.0	12.4	581 ±35.73	9642.80 ±1768.87	101.24 ±14.23
T. Superba (Ofram)						
Stem (MC1)	20	14.4	20.5	560 ±36.73	7238.30 ±1333.00	59.09 ±15.64
Stem (MC2)	20	6.8	13.4	557 ±41.53	8100.55±1124.54	76.44 ±14.99
Branch (MC1)	20	15.2	19.9	650 ±31.75	6135.55 ±1320.13	58.54 ±16.80
Branch (MC2)	19	10	13.5	643 ±26.26	9221.68 ±1474.66	81.88 ±17.17
P. Macrocarpa (Koto)						
Stem (MC1)	20	15.7	20.4	668 ±25.63	9011.40 ±946.56	70.11 ±11.99
Stem (MC2)	20	8.7	13.5	656 ±28.84	10102..10 ±1261.68	86.87 ±14.76
Branch (MC1)	20	15.3	19.8	660 ±49.86	8490..90 ±1847.87	69.94 ±16.80
Branch (MC2)	20	8.5	13.2	647 ±22.30	9952.15 ±1669.99	88.92 ±13.79
TOTAL	**398**					

Appendix 4: Summary of Experimental Data on Finger-Jointed (FJ) Lumber with Solid /Unjointed Stem as Controls.

Species & Finger-Joint Combinations	N	Moisture Content (%)		Density (Kg/m3)	Modulus of Elasticity - MOE (MPa)	Modulus of Rupture- MOR (MPa)
		Min	Max	Mean ±SD	Mean ±SD	Mean ±SD
E. Cylindricum (sapele)						
Solid Stem Contrl (MC1)	20	14	20.3	666 ±71.38	5719.75 ±1451.80	66.60 ±13.36
Solid Stem- Contl.(MC2)	20	9.4	13.5	655±44.03	10461.00±3213.20	101.49±35.37
Stem & Stem FJ (MC1)	30	15.8	20.4	668± 57.13	6512.10 ±2227.07	30.90±12.59
Stem & Stem FJ (MC2)	29	9.8	13	653±41.8	7844.76 ± 1568.53	53.74 ± 16.08
Stem & Branch FJ (MC1)	30	13.9	19.8	721±81.09	6812.53 ±2140.61	35.35 ± 13.03
Stem & Branch FJ (MC2)	30	7.1	12.8	700±57.40	7568.70 ±1254.47	50.68 ± 8.63
Branch & Branch FJ (MC1)	30	16	20.5	770± 80.69	6172.07 ±1381.47	30.75 ± 9.42
Branch & Branch FJ (MC2)	30	5.7	12.5	747± 82.12	7841.03 ± 1695.87	42.04 ± 6.83
E. Angolense (edinam)						
Solid Stem Contl (MC1)	20	14.6	20.4	565 ±38.26	7177.30 ±983.54	63.15 ±5.64
Solid Stem- Contl.(MC2)	20	6.5	13.4	550±55.26	8119.75±842.09	78.57±7.80
Stem & Stem FJ (MC1)	30	15.8	20.4	577± 94.66	6633.97± 1024.06	35.49±16.01
Stem & Stem FJ (MC2)	30	6.9	13.5	563 ±47.99	7378.70 ± 11638.29	45.85 ± 7.71
Stem & Branch FJ (MC1)	30	14.8	20.4	643 ± 82.27	7011.53 ±1295.15	38.96 ±13.71
Stem & Branch FJ (MC2)	29	6.7	13.5	631 ± 44.48	8470.21 ± 1391.12	50.24 ±7.98
Branch & Branch FJ (MC1)	30	14.7	20.5	734 ± 127.24	7799.63 ± 2101.46	39.01 ± 15.29
Branch & Branch FJ (MC2)	30	6.4	12.7	726 ±88.78	8865.13 ± 2190.93	53.24 ± 9.19
K. Ivorensis (mahogany)						
Solid Stem Contrl (MC1)	20	14.8	20.6	522 ±22.88	6576.75 ±1021.81	57.19 ±11.36
Solid Stem- Contl.(MC2)	20	6.8	13	502±30.58	10233.10±721.39	85.48±10.76
Stem & Stem FJ (MC1	30	13.7	20.4	515 ± 65.30	7447.03 ± 957.42	42.76 ± 6.33
Stem & Stem FJ (MC2)	30	7.6	11.9	496±26.25	8679.30 ± 756.49	55.70 ± 7.91
Stem & Branch FJ (MC1)	30	13	20.6	563±82.82	7677.80 ± 891.07	42.28 ± 4.01
Stem & Branch FJ (MC2)	30	6.3	11.5	542 ± 37.48	8818.63 ± 982.77	54.01 ± 4.61
Branch & Branch FJ (MC1)	30	14.2	20.1	596 ±88.76	6903.17 ± 975.12	35.75 ± 7.00
Branch & Branch FJ (MC2)	30	6.1	12.7	575 ±45.98	8134.60 ± 1376.61	50.36 ± 9.18
T. Superba (ofram)						
Solid Stem Contrl (MC1)	20	14.4	20.5	560 ±36.73	7238.30 ±1333.00	59.09 ±15.64
Solid Stem- Contl.(MC2)	20	6.8	13.4	557±41.53	8100.55±1124.54	76.44±14.99
Stem & Stem FJ (MC1	30	14.4	20.7	563 ± 9.30	5746.63±1115.76	29.72 ± 4.64
Stem & Stem FJ (MC2)	30	6.3	13.5	555±29.96	8753.20 ± 1627.37	46.75 ± 14.67
Stem & Branch FJ (MC1)	30	14.5	20.3	637 ±10.84	5241.47 ±1124.62	27.60 ± 8.12
Stem & Branch FJ (MC2)	30	7.8	13.6	627 ± 32.40	8938.27 ± 1250.23	49.79 ± 8.96
Branch & Branch FJ (MC1)	30	14.8	19.7	651± 27.27	5722.10 ± 1027.63	29.26 ± 5.65
Branch & Branch FJ (MC2)	30	6.2	13.2	640 ±32.29	8268.20 ± 1333.04	45.37 ± 11.06
P. Macrocarpa (koto)						
Solid Stem Contrl. (MC1)	20	15.7	20.4	668 ±25.63	9011.40 ±946.56	70.11 ±11.99
Solid Stem- Contl.(MC2)	20	8.7	13.5	653±36.56	10102.10 ± 1261.68	86.87±14.76
Stem & Stem FJ (MC1	30	14.9	20.3	661± 27.92	6092.67 ± 1669.88	34.04 ± 8.24
Stem & Stem FJ (MC2)	30	9	13.5	645±27.34	9695.27 ± 1687.41	55.43 ± 11.34
Stem & Branch FJ (MC1)	30	15.2	19.4	658 ±32.4	6101.73 ± 1435.19	32.90 ± 7.54
Stem & Branch FJ (MC2)	30	8.2	13.3	645 ±20.19	9461.60 ± 1465.00	51.82 ± 7.57
Branch & Branch FJ (MC1)	30	14.8	20.4	653± 32.45	7248.43 ± 1022.30	36.64 ± 8.19
Branch & Branch FJ (MC2)	30	8.1	13.4	637 ±21.28	10383.00 ± 1066.33	56.23 ± 9.83