UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION, KUMASI

ASSESSMENT OF PROPERTIES OF JUVENILE AND MATURED BAMBUSA VULGARIS AND ITS POTENTIAL UTILIZATION AS ENGINEERING COMPOSITE MATERIAL

MICHAEL AWOTWE – MENSAH

MAY, 2021

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A THESIS/DISSERTATION IN THE DEPARTMENT OF WOOD AND CONSTRUCTION, SCHOOL OF WOOD TECHNOLOGY, SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE

DOCTOR OF PHILOSOPHY

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DECLARATION

STUDENT'S DECLARATION

I, **MICHAEL AWOTWE – MENSAH**, 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.

SIGNATURE:…………………………………………………..

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SUPERVISOR'S DECLARATION

I 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.

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DEDICATION

To my wife Mrs. Linda Awotwe-Mensah and children Theodora Awotwe-Mensah, Godwin Awotwe-Mensah and Michael Awotwe-Mensah, Jnr.

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TABLE OF CONTENT

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

LIST OF TABLES

CONTENT **PAGE**

LIST OF FIGURES

CONTENT **PAGE**

ABSTRACT

This study compared the chemical, anatomical, and physical properties of juvenile and matured *Bambusa vulgaris* culms and its potential utilization for engineering composite product. It also assessed the physical, mechanical and durability properties of laminated *Bambusa vulgaris* culm of two-year (Juvenile *Bambusa vulgaris*) and four-year (Mature *Bambusa vulgaris*) old. Culms were harvested and prepared to the length of twenty-one internodes. The first seven internodes were taken as bottom and the second seven internodes were also taken as middle whiles the third seven internodes were taken as the top. The study focused on the bottom and top portions. EN 13183-1, ISO 13061-2, BS 373 and TAPPI standard methods were used in determining the physical, chemical and anatomical properties of the mature and juvenile bamboo as well as the bamboo laminates. The study showed that, mature *Bambusa vulgaris* basic density ranged from 660.50kg/m^3 – 691.80kg/m^3 and that of juvenile *Bambusa vulgaris* density ranged from 383.53kg/m^3 – 562.26kg/m^3. The main chemical composition of juvenile *Bambusa vulgaris* was as follows: Cellulose = 48.62%; hemicellulose = 51.39% and lignin = 22.98%. That of the mature *Bambusa vulgaris* was Cellulose = 55.93%; hemicellulose = 44.08% and lignin = 29.11%. The vascular bundle arrangement for juvenile and mature *Bambusa vulgaris* was in both Type III and Type IV respectively. The mechanical properties of juvenile laminated bamboo were MOE = 587.7MPa; MOR = 43.42MPa and compressive strength = 37.58MPa whilst mature laminated bamboo was MOE = 13379MPa; MOR = 82.48MPa and compressive strength = 62.78MPa. Additionally, both treated juvenile and mature laminated bamboo were classified as resistant to fungi attack. It is recommended that mature *Bambusa vulgaris* is suitable to be used as engineered composite material.

CHAPTER ONE

INTRODUCTION

1.1 Background

Bamboo is a perennial plant belonging to the family *Gramineae* (*Poaceae*), sub-family of *Bambusoideae*, order of *Graminales* and the tribe *Bambuseae* (Chapman & Peat, 1992; Ohrnberger, 1999; Wong, 2004). There are approximately 1,500 species of bamboo under 87 genera worldwide (Ohrnberger, 1999; Khalil et al., 2012) but this number has grown to about 1,662 species and 121 genera (Kaur, 2018). It is estimated that approximately 40 million hectares of forestland are covered with bamboo, representing 1% of global forest area (FAO, 2005). Studies have shown that China is known as one of the centres of bamboo growth in the world, possessing about 400 species of 50 genera, covering an area of bamboo growth exceeding 4.21 million hectares (Qisheng et al., 2001).

Bamboo in its natural form is cylindrical, hollow and tapered in size from the bottom to the top. It grows very tall and divides in the nodes to form internodes. Bamboo is an extremely fast-growing plant that takes up to 5-6 months to attain its maximum height, and further attains maturity within a period of 3 to 5 years (Abd. Razak, 1992; Razak et al., 2010; Singnar et al., 2017). Ramanuja, Gnanaharan and Sastry (1988) reported that under the right conditions, some bamboo species display faster rates of growth which can produce culms which are 40m high and of 30cm in diameter, in just four months. Bamboo tolerates poor soils, and even without the application of fertilizer, it grows fast with rich green foliage that makes it useful for planting on degraded land (Hunter, 2003; Muller & Rebelo, 2014).

Bamboo as a woody plant has a long history as an exceptionally versatile and widely used resource in the world (Ramanuja et al., 1988; Shanmughavel, 1997). It is estimated that about 2.5 billion people use bamboo, in one form or the other, worldwide for their basic needs (Salleh, 1995). Technology advancement has further enhanced bamboo utilization potentials and it has been established that nearly 4,000 commercial products manufactured from bamboo are in daily use across the world (Singh, 2008). Bamboos have been used in many ways, ranging from household products through to industrial applications, because of advancement in technology of processing, as well as increased market demand. These many uses of bamboo include containers, chopsticks, woven mats, fishing rods, flutes, fishing traps, handicrafts, walking sticks, packing cases for teas and fruits, cages for poultry, pipes for water supply and irrigation, cradles, cart yokes, bullock carts, ladders, winnows, and sieves for cleaning grains (Das, 2002). According to Abd.Latif, Tarmeze, and Fauzidah (1990), bamboo is also one of the oldest building materials used by humankind. This has been widely used in building applications such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters and purlins. It is further being used as structural material for bridges, water transportation facilities, and skyscraper scaffoldings. The use of bamboo in some countries like Indonesia, Malaysia, India, China and Japan has contributed to the growth of their economy (FAO, 2007). According to Maoyi and Xiaosheng (2004), world bamboo trade had reached the value of 4 billion U.S dollars, and China is dominating and monopolizing this global market.

Bamboo has been with the people, especially those in the Asian countries, and serves as a source of food, energy, shelter, medicines, tools and fibre. It has some form of description in predominated countries where bamboo is the primary and secondary sources of raw material. Bamboo is called "the poor man's timber" in China, "the friend of the people" in India and "the brother" in Vietnam. In the other Asian countries, the common nicknames are “the cradle to- coffin timber” and “green gold” (Farrelley, 1984; Salleh, 1995).

Bamboo is cheap, and is known for providing numerous ecosystem and environmental services such as biodiversity preservation, soil conservation, environmental amelioration, water filtration, carbon sequestration (Krishna et al., 2015; Van der Lugt et al., 2018). It is also recognised as one of the natural renewable, biodegradable and recyclable material with superior physical and mechanical properties compared to most wood species. It has been proven to have greater potentials in changing the various environmental and economic situations, especially in countries with limited timber resources (Yiping et al., 2010).

There are several varieties of bamboo species known under different genera, and *Bambusa vulgaris* species is one of such varieties. This type of bamboo is common and grows well in Africa, Asia and Latin America (Lobovikov et al., 2007). It has been reported that the culm of this bamboo can grow as high as 20m (Widjaja, 2001). *Bambusa vulgaris* has several potential advantages as a constructional material because of its high strength and straightness, its lightness in weight, how easy it is to propagate, its growth rapidity, flexibility, range in size, renewability, and sustainability. More so, it has mechanical properties similar to timber, and is suitable for almost endless variety of purposes (Espiloy et.al., 1999; Jayanetti, 2001). This has given rise to the growing interest in the development of *Bambusa vulgaris* into products that are sustainable, cost-effective, environmentally friendly, and recyclable in nature. *Bambusa vulgaris* indeed serves as a responsible alternative constructional material capable of meeting furniture and building industries demand, especially in rapid developing areas where timber resources are often limited (Yiping et al., 2010).

In Asia for instance, both juvenile and mature *Bambusa vulgaris* species have been used for the manufacturing of several products ranging from furniture production, papermaking, fibre for making cloth, to packaging materials, medicines and other health care products (Xiang, 2010). *Bambusa vulgaris* further serves as a source of food with its shoots consumed as edible delicacy: both fresh and processed forms. It has been reported that about 200 species of bamboo including *Bambusa vulgaris* provide shoots for human consumption (Mertens et al., 2007).

In Ghana, *Bambusa vulgaris* is known as “Green Bamboo”. It is commonly found along the river banks, botanical gardens and also distributed in the southern and middle zones of the country. *Bambusa vulgaris* is the commonest indigenous, forming about 95% of the total bamboo resources in Ghana (Ebanyenle & Oteng-Amoako, 2007). It is normally used, especially in the rural communities, for fencing houses, roofing buildings; for constructing maize and rice storage structures, for weaving cocoa mats (locally known as "apa") in cocoa growing areas, for handicrafts, props to support plantain and banana stems, as climbing poles for yam stems. It is therefore necessary to consider the study of *Bambusa vulgaris* that could offer a potential substitute for wood worldwide.

1.2 Problem Statement

Forest, today, is depleting at a faster rate and this has been a global challenge that needs to be addressed with all the seriousness it deserves in order to help control the climate change challenges. In 2016, the University of Maryland estimated that the global deforestation rate was at 29.7 million hectares, representing 51% rise over the previous years. This shows that deforestation is on the increase, with highest percentage occurring in tropical Africa (Gorte & Sheikh, 2010; Weisse & Goldman, 2017). Additionally, ITTO (2002) classifies about 60% of the world‟s tropical forest as degraded forest.

Ghana is one of the tropical countries that has suffered massive forest degradation due to over dependence on timber which has led to excessive logging, firewood harvesting, wood charcoal production and infrastructural development (Ministry of Land and Natural Resources, MLNR, 2016). The rich forest reserve in Ghana is gradually reducing into farmlands and deforestation zones. In 2008, United Nations Environmental Programme (UNEP, 2008) also reported that, Ghana lost 26% of its forest cover between 1990 and 2005, representing 1,931,000 hectares. The Food and Agriculture Organization (FAO) of United Nations (2010) also carried out a global forest resources assessment in 2010 and reported that, Ghana‟s forest resources reduced from 7.45 million ha to 4.94 million ha from 1990 to 2010 representing 34% loss of forest cover. The 2015 forest assessment of the high forest zone estimated the total forestland of Ghana at 9.337 million ha and this included 1.556 million ha and 7.781 million hectares of closed forest and open forest respectively (MLNR, 2016). The forest degradation rate of Ghana is estimated at 45,931.03 ha per annum since 1990. The size of the closed forest has reduced from 2.704 million ha in 1990 to 1.556 million ha indicating a depreciating rate of 38,529.65 ha per annum (Ministry of Land and Natural Resources, MLNR, 2016). As a result, the exported volumes of timber and timber products has reduced from 442,078.22m^3 to 144,300.079 m^3 representing 67.4% drop from 1997 to 2018 (TIDD, 2018). In 2020, it was reported that the total demand for logs in Ghana was estimated to be approximately 2.5 million m^3 of which 1.2 million m^3 (AAC) was available leaving the log demand deficit of 1.3 million m^3 (www.fao.org).

This demand has been justified because Ghana‟s population has increased considerably and the corresponding quantity and quality of wood from natural forest has not been met due to the diminished timber resources. This trend should be controlled in order to save the country‟s natural forest from complete depletion. It is this phenomenon which has attracted the attention of government, academia and research institutions to look for alternative raw materials suitable to replace timber in order to reduce the over dependence of timber and thereby help to preserve Ghana‟s forest cover. One of such alternative materials that is currently gaining attention worldwide is bamboo. It has been widely considered as an alternative material to replace wood due to the excellent strength properties associated with it. Similarly, this suitable alternative raw material is commonly available, cheaper in acquisition, environmentally friendly, fast growing, meeting existing processing technologies and possessing comparable physical and mechanical properties as well. Bamboo is a naturally occurring composite material, as it consists of cellulose fibres imbedded within a lignin matrix (Li, 2004). It therefore provides a solution as a fast-growing plant which takes up to 5-6 months to attain its maximum height and matures in 3 to 5 years compared to that of the 10 – 50 years for most timber species (Abd. Razak, 1992; Razak et al. 2010; Mishra et al., 2014; Singnar et al., 2017). The effective use of *Bambasu vulgaris* in furniture and building industries will mean a reduction in the use of structural timber. This will go a long way to solve Ghana"s burden on deforestation.

Ghana has approximately 300,000 ha of bamboo resources and *Bambusa vulgaris* is the major bamboo specie occurring in the natural stands (Ebanyenle & Oteng-Amoako, 2007). *Bambusa vulgaris* culm has been used as structural material in the construction industry due to the strength properties coupled with its availability, and the fact that it is cheap and easy to transport. Today, the need has increased rapidly due to scarcity of timber products. This, together with the high cost of building materials, has occasioned the demand for *Bambusa vulgaris,* resulting in the use of both juvenile and mature culms in the construction industry. The commercial traders normally purchase them from farmers based on the sizes, height and straightness of the culms without necessarily considering the age (matured and juvenile) variations of the culms. Once they can identify it as "green bamboo" and the size is big, and straight, it eventually ends up in the timber markets for sale without any classification into matured and juvenile respectively. The danger of this phenomenon has created a lot of anxiety among the industry players due to lack of adequate information about the differences between matured culm and juvenile culm properties of *Bambusa vulgaris,* as well as establishing the effect of using both juvenile and matured culm of *Bambusa vulgaris* for structural and non-structural applications in Ghana.

The utilization of full *Bambusa vulgaris* culm is problematic, especially where flat surfaces are required for building and furniture applications. The hollow and cylindrical nature also makes it difficult to be used to construct suitable joints for structural applications. This has further limited the acceptability of full bamboo culm as raw material for construction. However, these limitations in the light of technology advancement have transformed the use of full culm bamboo into engineered bamboo composites to meet the demand for sustainable building and furniture products. There are several engineered bamboo products such as bamboo ply, strand woven bamboo, bamboo scrimber and glued laminated bamboo which have been researched and proven to be comparable with other structural materials such as timber and reinforced concrete (Xing et al., 2018). The two most preferred engineered bamboo composites are scrimber and laminated bamboo (Sharma et al., 2014). According to Sharma et al., (2014), engineered bamboo composites are of particular interest due to the standardisation of shape and the relatively low variability in material properties. Laminated bamboo is made of bamboo strips pressed and glued together to make a beam or panel. Studies on the anatomy of bamboo internode cross-section have revealed that the strength properties change (increase) from inner to outer layer of the culm (Kariuki et al., 2014). This implies that the orientation of the strips in laminated bamboo panel and direction of loading affects the strength of the panels. Laminated bamboo is the modern methods of making bamboo durable for structural applications. Xiao and Li (2015) reported that, glued laminated bamboo and bamboo-based panel are two types that can be used in modern bamboo structures. The strength properties promote the bamboo to be the material considered for building and furniture construction.

Comparatively, bamboo has not received global attention as a common building material. The global use of conventional building materials such as steel is 56%, concrete is 28%, and other forest products is 16%, while bamboo use makes up less than 0.1% of the total global building materials used (Trujillo, 2018). This has generally attributed to lack of information, understanding of the material properties, and research findings to advance the use of bamboo for construction.

Studies have shown that there are large gaps in knowledge regarding bamboo properties (Valero et al., 2005; Fabiani, 2015). Liese (1992) reported that a thorough understanding of the relations between structures, properties, behaviour in processing and product qualities is necessary for promoting the utilization of bamboo. Wang et al. (2014) reported that to promote the widespread application of bamboo in construction and other engineering fields, far more knowledge and understanding of its properties is required. It is against this backdrop that this study sought to determine the differences between the properties of juvenile and mature raw culms of *Bambusa vulgaris* and consequently evaluate their utilization potentials.

1.3 Purpose of the Study

The purpose of the study is to determine the differences between physical, anatomical and chemical properties of juvenile and mature *Bambusa vulgaris* raw culms and evaluate their utilization potential in the production of laminated bamboo composite using available adhesive on the local market.

1.4 Objectives of the Study

The specific objectives of this study are to determine:

1. The morphological and physical properties of juvenile and mature *Bambusa vulgaris* culms.
2. The anatomical properties of juvenile and mature *Bambusa vulgaris* culms.
3. The chemical properties of juvenile and mature *Bambusa vulgaris* culms.
4. The physical and mechanical properties of laminated bamboo composite (LBC) made from juvenile and mature *Bambusa vulgaris* culm using Rapid Lion (RL) 5 minutes" express wood adhesive as binder.
5. The natural durability of laminated bamboo composite with and without chemical treatement for juvenile and mature *Bambusa vulgaris* using accelerated laboratory method.

1.5 Research question of the Study

1. What are the morphological and physical properties of juvenile and mature *Bambusa vulgaris* culms?

2. What are the anatomical properties of juvenile and mature *Bambusa vulgaris* culms?
3. What are the chemical properties of juvenile and mature *Bambusa vulgaris* culms?
4. What are the physical and mechanical properties of laminated bamboo composite (LBC) made from juvenile and mature *Bambusa vulgaris* culm using Rapid Lion (RL) 5 minutes" express wood adhesive as binder?
5. What is the natural durability of laminated bamboo composite with and without chemical treatement for juvenile and mature *Bambusa vulgaris* using accelerated laboratory method?

1.6 Significance of the Study

The study will contribute to existing knowledge of the properties of bamboo species in general and more especially for the *Bambusa vulgaris* species from Ghana. The study will further contribute to existing knowledge in the utilization potentials of bamboo for engineered bamboo composite products. This will serve as a means of supporting existing literature, and also provide a medium of academic reference point for discussions and citations.

This work will encourage researchers to research into the area of renewable natural fibres like non - wood or plant fibres that are considered as environmental friendly raw materials for composite production, especially in developing countries in Africa and the world at large, where timber resources are limited. This will further ensure the promotion of sustainability of Ghana‟s forest resources as the demand is shifting to the utilization of bamboo as renewable material for the production of quality structural engineering products to replace solid wood. It will further help to reduce the over dependence on timber and timber products in Ghana and beyond. This will ensure the protection of Ghana‟s forest reserves against excessive logging and thereby promote forest conservation and environmental sustainability.

This research study will create enabling environment for construction industry due to the availability of comprehensive information on *Bambusa vulgaris* properties and its utilization. This will help promote *Bambusa vulgaris* in the construction industry since industry players now have primary understanding of these properties of this emerging natural raw material that will influence the choice and utilization potential respectively. The study will further enhance the material ability to be used for structural and non-structural applications, and this will ensure the selection of right culms, especially in the production of engineered composites as well as supporting of formworks.

Furthermore, it will help to reduce deforestation and cost of building affordable houses. The interest in bamboo as a building material will improve especially by people who live in places where bamboo grows naturally and abundantly and are used to build houses. Additionally, this will always serve as an income generating venture that tends to improve the livelihood of the rural communities especially the bamboo dominated areas.

The study will further present a number of test results that will meet the set standards. This will show some level of data, proving to be feasible to produce laminated bamboo composite in Ghana. These test results will also contribute to the statistical valid data that could add to the on-going research about improving bamboo composites manufacturing in Ghana and the world at large. Through presentation and discussion of results, this research work would serve as the basis for further studies for students, researchers and scientists, as well as serving as a relevant source for their work.

1.7 Limitations of the Study

Several difficulties were faced in carrying out this research work. Some of these could be attributed to financial constraints as a result of transporting the material samples. The problem of insufficient SEM, planner, sanding and press machines also affected the research especially during the production and testing stages. Another difficulty was the milling of bamboo strips. This really affected the scheduled period for the chemical compositions test.

CHAPTER TWO

LITERATURE REVIEW

2.1. Bamboo Material

Bamboo is a plant identified as lignocellulosic material in nature. It is also known globally as an excellent raw material that can grow faster in almost every continent except Europe. This versatile raw material is considered as one of the most abundant natural resources that is renewable, fast growing, recyclable, environmental friendly and a sustainable plant in the world. It has been used to serve the interest of humanity in diverse ways like food, medicine, household articles and structural applications (Mertens et al., 2007).

Bamboo is one of the oldest building materials used by mankind (Abd.Latif et al., 1990). It has been utilized very extensively across the globe in the production of various products, ranging from domestic through to industrial applications due to technology advancement in processing. These include houses, rafts, bridges, scaffolds, containers for liquids, fishing rods, water pipes, musical instruments, chopsticks, skewers, toothpicks, furniture, baskets, mats, hats, fish traps, cradles, cart yokes, bullock carts, ladders, winnows and sieves for cleaning grains (Das, 2002). This has contributed significantly in meeting the increased market demands, especially in some tropical countries like China, India, Japan and Indonesia.

Today, utilizing this natural resource material has necessitated a complete assessment of bamboo and its structural applications in order to diversify continuously, and then become one of engineering-structural materials capable of meeting the growing needs of the world. Bamboo is an anisotropic and heterogeneous material (Ghavami, 2005; Ray et al., 2005) having physical and mechanical properties suitable for structural applications.

2.1.1. Global Bamboo Resources

Bamboo is the most abundant natural material in the grass family which is renewable, eco-friendly, strong, recyclable, versatile and a highly sustainable plant. It is one of the plants, which can grow very well in moist, deciduous, semi-evergreen, tropical, subtropical and temperate areas of a forest. Bamboo plants are divided into the subfamily of *Bambusoideae,* family of *Gramineae,* order of *Graminales,* class of Monocotyledons, subphylum of Angiosperms and phylum of *Spermayophyta*. Bamboo is a monocotyledon belonging to Angiosperm in plant kingdom. The embryo of monocotyledon has only one cotyledon; vascular bundles in stems are arranged radially, with primary tissue, without cambium and secondary tissue. The leaf veins are parallel or curve. The main root is not developed; the root system is fibrous in general (Qisheng et al., 2001).

Both *Bambusoideae* and *Gramisoideae* are under the family of *Gramineae*. The differences are that, plants of *Bambusoideae* are woody and perennial, the stem and haulm lignify intensively, the petioles of leaves are short, and there are joints between the leaves and sheaths; consequently, the leaves fall easily. Members of *Graminsoideae* are herbs, the leaves are connected to sheaths directly without petioles, and they hardly fall from sheaths (Qisheng et al., 2001).

Bamboo distribution is associated with the annual precipitation and temperature of the growing zone. Another area that influences bamboo growth is environmental factors like latitude, altitude and soils. According to Uchimura (1987), the high temperatures promote bamboo growth and low temperatures inhibit the growth rate. Bamboo plantations of various sizes can help in shaping the world deforestation challenges, and also benefit from the numerous growing properties of bamboo for major applications from the harvest. It is therefore important to treat and season bamboo well enough before subjecting it to any structural applications.

2.1.2. Distribution of Bamboo Plants

According to Sharma (1980), bamboos have 1,250 species under 75 genera spread all over the world. This account was reviewed by Ohrnberger and Georrings (1985) who reported approximately 110 genera and 1,010 to 1,400 species. Ohrnberger (1999) also reported that, there are approximately 1,500 species under 87 genera of bamboo worldwide. Bamboo species are not evenly distributed in various parts of humid tropical, sub-tropical and temperate regions of the earth (Scurlock et al., 2000).

Globally, bamboo grows in many countries throughout the world, especially in Asia, Africa and Latin America. The study on the world"s bamboo resources was conducted jointly by the FAO, (2005) and INBAR, (2005) in the framework of the „Global forest resources assessment 2005" (Lobovikov et al., 2007). It was reported that bamboo forest covered about 36 million ha. Asia has a total bamboo forest area of about 23.4 million ha representing 65% of the world"s total, followed by Latin America with approximately 10 million ha, representing 28% of the total world"s forest bamboo, and Africa has approximately 2.7 million ha representing 7% of the world"s total cover.

In Asia, the countries with the largest bamboo resources are India (11.4 million ha) and China (5.4 million ha), followed by Indonesia (2 million ha) and Laos (1.6 million ha). Brazil (9 million ha) has the largest bamboo resources in Latin America, followed by Chile (900,000 ha); Colombia, Equador and Mexico have abundant bamboo resources as well. Most of the bamboo resources in Africa are found in Nigeria (1.5 million ha) and Ethiopia (800,000 ha).

It is reported that about 500–534 species of bamboo are found in China with a total of approximately 4.84–5.71 million ha bamboo forestland (FAO, 2010; Song et al., 2011). In India, the bamboo forest area is 13.96 million ha with 123 species of 23 genera (FSI, 2011). In China, the most widely spread types of bamboo are *Phyllostachys heterocycla var. Pubescens,* also called Moso bamboo, covering two thirds of the total bamboo forest area (Xuhe, 2003). The market for bamboo is best developed in China, which has large scale plantations, and processing facilities, mostly for domestic use. Almost 50% of the world"s bamboo biodiversity is from South and Central America, with Brazil as the country with the largest national complement of species, with 134, followed by Venezuela with 68, Colombia 56 and Peru 48 (Takahashi, 2006). There are few indigenous bamboo species in North America; no naturally distributed bamboo plants in Europe. In recent years however, bamboo plants have been introduced into the continent (Europe) (Qisheng et al., 2001).

2.1.3. Bamboo Resources in Ghana

Ghana could be accounted for reserves of bamboo resources, which were found in almost all 16 regions of the country. It is estimated that, bamboo covers about 200,000 ha of land in Ghana (UNIDO, 2001). Today, Ghana has resorted to bamboo plantation as a means of growing the bamboo reserves across the country. It is reported that the Ghana Forest Plantation Strategy is to establish 50,000 ha of bamboo plantation by the year 2040 with annual plantation rate of 2,000 ha per annum (INBAR, 2018). In addition to this, the Ghana Forestry Commission signed a public-private partnership agreement with an innovative forestry company (Ecoplanet Bamboo) to develop integrated bamboo plantations as an alternative raw material resource to timber, to reduce deforestation and provide a long-term sustainable source of bamboo fibre for the production of pulp and paper, packaging materials and textiles (INBAR, 2018).

Bamboo grows well in Ghana, predominately in areas where rainfall pattern is heavy such as Moist Evergreen Forest areas. These growing areas include Brong Region, Central Region, Western Region, Ashanti Region, Volta Region, and Greater Accra Region. Studies have shown that Ghana is endowed with seven known bamboo species. These include *Bambusa arundinacea, Bambusa multiplex, Bambusa pervariabilis, Bambusa vulgaris, Bambusa bambos, Bambusa vulgaris var. vitata and Dendrocalamus strictus* (Baah, 2001; UNIDO, 2001). Among these varieties of bamboo species in Ghana, only *Bambusa vulgaris* is indigenous. According to Ebanyenle and Oteng-Amoako (2007), *Bambusa vulgaris* forms about 90 – 95 % of bamboo resources in Ghana while the *Bambusa multiplex* forms 4 % of bamboo resources as well. These species are normally found at river banks, botanical gardens and forest zones in Ghana. Research has shown that the bamboo species known as *Oxythenanthera abyssinica* is mostly found in the savannah areas of Ghana (Abbiw, 1990).

Tekpetey (2011) reported that some of the bamboo species that produce edible shoots are available in Ghana. They are *Bambusa oldhanmii, Dendrocalamus latiflorus, Dendrocalamus brandisii, Thrysostachis siamensis, Gigantochloa albociliata, Bambusa textilis, Guadua chacoensis, Dendrocalamus strictus, Bambusa membranaceus, Bambusa burmanica, Bambusa nutans* and *Guadua angustifolia*. He further reported that, the distribution of bamboo resources in Ghana is based on the favourable climatic condition prevailing in a particular ecological zone. The bamboo species identified and their ecological zones of distribution are presented in Table 2.1.

Table 2.1: Ecological distribution of bamboo resources in Ghana.

Species	Zone	Forest Eco-Zone
Bambusa vulgaris (the green type) *Bambusa vulgaris var. vitata* (the yellow type) *Bambusa arundinacea* / *Bambusa bambos* *Bambusa multiplex* *Bambusa pervariabilis* *Dendrocalamus strictus*	Southern and Middle	• The wet evergreen forest • The moist evergreen forest • Dry and moist semi-deciduous forest • Coastal savannah • Forest savannah • Transitional zones (Southern & Northern)
Oxythenanthera abyssinica	Northern	Sudan or Guinea savannah grasslands

Source: (Tekpetey, 2011)

2.2 Physical Characteristics of Bamboo

2.2.1 Morphology and Growth of Bamboo Plant

In general, the growth habit of bamboo plant is normally classified into two parts, which allow for proper assessment. The parts consist of underground portion and above ground portion as shown in Figure 2.1. The rhizome is the underground portion of bamboo culm and it is made of roots, and buds. The culm is the above ground portion of bamboo, made up of internodes, nodes, branches, and leaves.

The underground part of bamboo planet rhizome that develops into buds, shoot under proper humidity spread horizontally under the soil. The buds on the rhizomes always grow into shoots that form from the ground. The new shoots grow vertically into short culms (Seethalakshmi et al., 1998) and then continue to develop to become full culms (Mohanan, 1997). The distance between culms is determined by the type of rhizome the bamboo species has, and this has been grounded by taxonomist due to the growth habits of bamboo species.

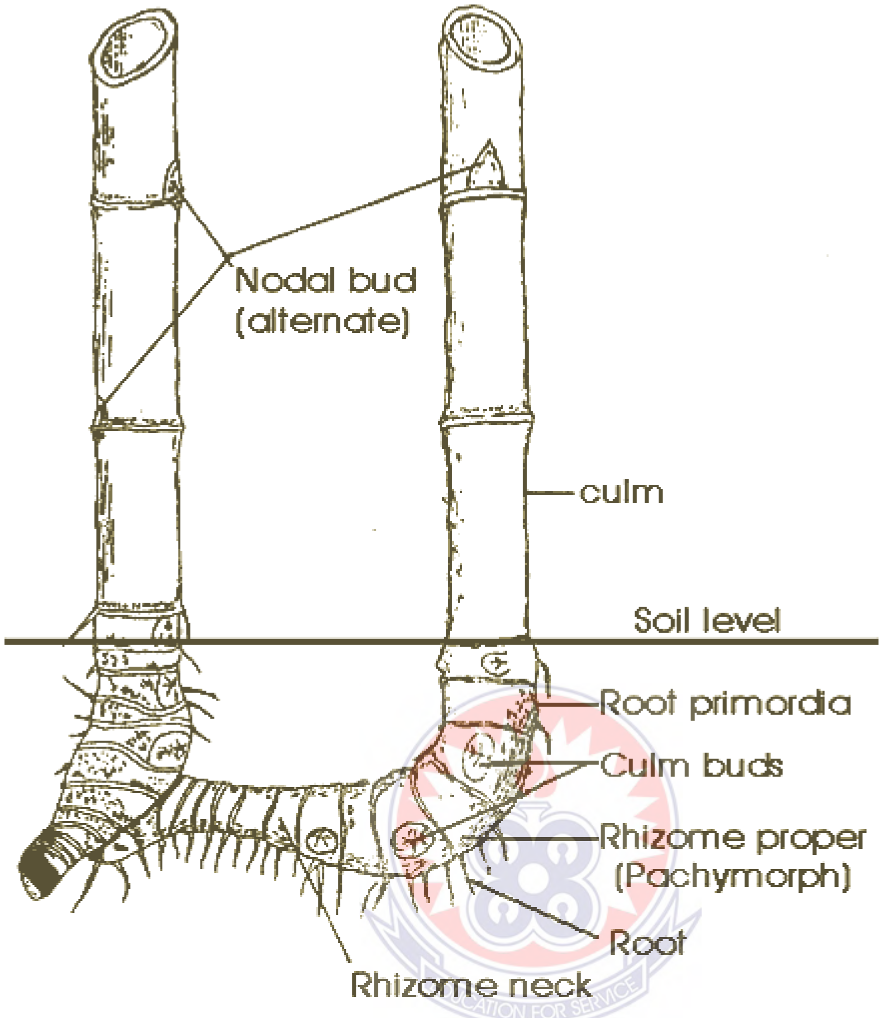

Figure 2.1: Morphology of bamboo plants (www.pinterest.co.uk)

2.2.1.1. Types of Bamboo Rhizome

There have been two main schools of thought regarding the types of bamboo rhizome groupings. While one school of thought groups bamboo rhizome into two distinct types, another school of thought groups bamboo rhizome into three or more distinct types. These groupings of bamboo types are based on some studies in the past and the present. Some researchers have shown that, bamboo rhizome can be grouped into two distinct varieties, namely sympodial and monopodial, which are easily identified by the growth patterns of their roots, or rhizomes, and geographical origins (Liese, 1985). Both types look the same above ground level, but their differences lie in their root structure. The rhizome is the major factor for taxonomic identification of *Bambusoideae* species. The rhizome type of every bamboo species cannot be changed and it has direct influence on the distribution of bamboo culms above the ground.

2.2.1.1.1. Sympodial Bamboo Rhizome

This type of bamboo is also called pachymorph or clumping due to its growth pattern behaviour. Clumping bamboo species tend to spread slowly, as the growth pattern of the rhizomes is to simply expand the root mass gradually (Wikipedia, 2019). The bamboo culms grow in close range to each other in order to form clump. The pachymorph or clumping bamboo grows in dense groups. They cannot resist frost and therefore are only found in tropical zones. *Bambusa vulgaris var. vitata* and *Oxythenanthera abyssinica* are some of the examples of sympodial bamboo species.

2.2.1.1.2. Monopodial Bamboo Rhizome

This type of bamboo is also called leptomorph, or running due to its growth pattern orientation. Monopodial bamboo requires proper controlling system during plantation due to its nature of growth structure. The bamboo spread directly through their rhizomes which spread widely underground because of an extensive root system which allows new culms to spring up in the surface. Running bamboo species are highly variable in their tendency to spread; this is related to both the species and the soil and climate conditions. Some can send out runners of several metres a year, while others can stay in the same general area for long periods. If neglected, over time, they can cause problems by moving into adjacent areas (Wikipedia, 2019).

The leptomorph, or running bamboo, sends out long runners, spreading the bamboo plant far wider than sympodial. This growth trait makes this type of bamboo useful in soil retention and is used commonly to prevent the collapse of riverbanks (Witte, 2018). Leptomorph bamboo is frost resistant and therefore can be found in temperate climates or at high altitudes in the tropics. *Phyllostachys edulis* and *Phyllostachys pubescence* are some of the examples of monopodial bamboo species.

2.2.1.1.3. Amphipodial Bamboo Rhizome

This type of bamboo is where the second school of thought believe that bamboo can be grouped into three distinct varieties. This type of bamboo is also known as mixpodial because of the formation of the growth structural development. Amphipodial bamboo is a combination of monopodial and sympodial bamboo patterns of growth where the two root bases are developed together. Amphipodial bamboo spreads as the rhizome runs along the ground with shoots emerging from the tip of the rhizome and growing upwards. According to Qisheng et al. (2001), the auxiliary buds on stem base of mother bamboo develop into root rhizome, which spreads in the soil horizontally. The composition of the amphipodial bamboo stem or culm includes longitudinal fibres, which are aligned in vertical direction of the bamboo within the lignin matrix. At the positions of the nodes along the culm, the fibres are aligned in the transverse direction. A typical example is the *Guadua angustifolia* that forms clusters or clumps (Gross, 2009).

Qisheng et al. (2001) also grouped bamboo into four distinct types, namely monopodial, sympodial tufted, sympodial scattered and mixpodial, based on the nature of the rhizome. The monopodial type has auxiliary buds on the stem base that develop into thin rhizomes running horizontally for a long distance underground. Some of the buds grow into rhizomes in the soil while some turn into shoots (Kigomo, 2007). The bamboo culms of such species grow in scattered state, forming scattered bamboo bushes. *Phyllostachys* and *Pleioblastus* are common genera that thrive well in the temperate zones.

Kigomo (2007) also reported that, bamboo can be grouped into five types of rhizome systems as distinguished by taxonomists, namely: (1) Simple pachymorph; (2) Long necked pachymorph; (3) Simple leptomorph; (4) Tillering leptomorph, and (5) Amphimorph. Short-necked pachymorph rhizomes and long necked pachymorph both exhibit sympodial branching. Simple leptomorph rhizomes, on the other hand, always exhibit monopodial branching. Tillering leptomorph rhizomes have not been observed in tropical woody bamboos. A species with this rhizome formation is *Shibataea kumasaka*, an herbaceous temperate bamboo that is used as an ornamental plant. Amphimorph rhizomes are extremely rare in bamboos, and have been observed in Latin America in only three species, namely *Aulonemia fulgor*, *Chusquea fendleri*, and *Chusquea scandens*.

The extensive network of bamboo rhizomes effectively binds up the soil to a depth of approximately 300mm (Chapman & Peat, 1992). This makes removal of bamboo difficult although planters are investigating ways to use the rhizome material for products. The rhizome system also has potential for providing soil stabilization. Janssen (2000) wrote that there have been cases of bamboo preventing riverbank erosions and therefore protecting villages. However, while the rhizomes are effective in binding up the soil, the shallowness and density of the underground system also introduces a potential weak plane between the bound shallow soil and the soil beneath the rhizomes. In the northeast hill region of India, for example, stands of clumping bamboo are believed to be the cause of slope failures during the rainy season as the heavy clumps and attendant soil slips along the weak shallow plane beneath the rhizomes.

2.2.1.2. The Bamboo Culm

The above ground portion of bamboo plant has different names depending on the stage of growth. When it forms on the rhizome node, it is called a bud. When it grows from the ground to the time it develops side branches, it is called a shoot. It is then called a culm when the side branches are formed. The culm is called a pole when it is cut or harvested. The growth of a culm is completed in a year (www.bamboobotanical.ca). However, in some of the bamboo species, new culms can grow beyond 787.4 inches height within 3 months. The culms have diameters ranging from 0.25 inch to 12 inches, and height ranging from 12 inches to 1440 inches (Lee et al., 1994). Qisheng et al. (2001) also reported that bamboo grows most rapidly in plant kingdom and it reaches the height of maturity for 1574.8 inches within 120 days. The height growth of bamboo shoots and culm is realized by the growth of internodes by intercalary meristems distributed in them. The sum of growth in length of all internodes is the total height growth of bamboo culm (Qisheng et al. 2001).

The culm is divided by the nodes to form internodes. The internodes portions of the culm are always hollow inside and cylindrical. The inside cavity is called a lacuna, which is present in almost all bamboos, although there are some which have solid internodes (Liese, 1998). The internodes are separated from each other by a diaphragm at the lower and upper end of the culm. This diaphragm has an out-growth, which can be seen as a ring around the culm, called a node. There are two rings found in the region of a node, which consist of upper and lower. The lower one is called sheath ring, which normally occurs as a scar formed after the sheath has fallen. The upper one is called culm ring, which usually occurs as a scar formed after the growth-cease of inter-node tissue. The portion between the upper and lower rings is the node.

The outside of the culm wall is formed by a thin cortex which has a high silica content which served as an important barrier against water and degrading organisms like fungal, mould and borers, and is covered by a thin layer of wax. According to Tewari (1992), bamboo culms have no bark but have hard smooth outer skin due to the presence of silica. The inner side of the culm wall is mostly protected by heavily thickened and lignified parenchyma cells, called the pith ring. In some species, the pith ring is covered by a paper-thin membrane called the pith cavity membrane, and this can be found in *Phyllostachys pubesces*.

Branches of bamboo culm are only developed at the node areas. The culm further develops leaves and side branches at the portions of nodes. The thickness of culm wall varies largely depending on the type of species. The cells are axially oriented at the internodes and with their transverse interconnections at the nodes. The bark which is the outermost part of the bamboo culm is formed by a layer of epidermal cells whereas the innermost part is covered by a layer of sclerenchyma cells. The inner layer is thicker and highly lignified.

Comparatively, timber takes more than 10 years (softwood) or 30 years (hardwood) to mature, but bamboo culms mature in only 3 to 5 years depending on the type of species (Mishra et al., 2014; Singnar et al., 2017). Aminuddin and Abd.Latif (1991) stated that bamboo might have 40 to 50 stems in one clump, which adds 10 to 20 culms yearly. Large bamboo can reach their full height of 590.55 inches – 1181.1 inches 15-30m (49-98 ft) in a period of approximately 2 to 4 months (Liese, 1987). *Dendrocalamus giganteus* is the world‟s largest grass with a height of 1181.1 inches – 1377.95 inches (Chapman, 1996). There are variations concerning how long lignification continues in the growth of bamboo after it has reached its full height. Some reports indicated that lignification is completed after the first year of growth while others reported that the lignin content could continue to increase in fibre and parenchyma cells for one to three and even up to seven years. The lignin content of bamboo (20-26%) is similar in value to both North American softwoods (24−37%) and hardwoods (17−30%) (Li et al., 2007).

2.3 Anatomy of Bamboo Culm Wall

The anatomy of bamboo is normally based on the culm structure which is the most needed portion for utilization. The anatomical classification of bamboo culm wall is mainly based on consideration from outer to inner portions. The studies of anatomical properties of bamboo culm wall have been reported in several literatures by many researchers such as Grosser and Liese, (1971), Liese, (1985), (1998), Abd. Latif et al. (1990).

The structure of bamboo material is the morphological study that could be achieved by using different media. The anatomical structural characteristics viewed with either magnifying glasses or naked eyes referred to macrostructure of bamboo while those that are viewed with the help of optical microscope are referred to as microstructure of bamboo; super microstructures are viewed with the help of x-ray and electron microscope. Macrostructure is morphology of tissues whiles microstructure is morphology of cells composing the material (Qisheng et al. 2001).

The anatomical classification of bamboo culm is mainly based on consideration from outer to inner portions. Habibi and Lu (2014) reported that bamboo consists of three fundamental tissues namely parenchyma, vascular bundles and epidermis. The macrostructure of cross section of bamboo culm wall ranged from the skin to the pith as presented in Figure 2.2. Bamboo culm wall is made up of three parts and these include the skin, timber and pith of bamboo. Bamboo skin refers to the outermost part of cross section of culm wall where vascular bundles cannot be found while Pith refers to the part of culm wall next to bamboo cavity and it does not contain vascular bundles as well. The bamboo timber refers to the portion between skin and pith (Qisheng et al. 2001).

2.3.1 Vascular Bundles

Vascular bundles are a combination of vessels and sieve tubes, with companion cells and fibers. The vascular bundle in culm of bamboos consists of xylem with one or two smaller protoxylem elements and two large metaxylem vessels accumulating wall material, which are connected with each other by membranes in the early stages of development. During extension growth of the cell, they are disrupted. The walls of metaxylem vessels of bamboo are characterized by a middle lamella and a primary wall with a well-developed zonation of the secondary wall into S1 and S2. Both the metaxylem vessels and the phloem tissue are surrounded by sclerenchyma sheaths. They differ considerably in size, shape and location according to their position in the culm and the bamboo species (Grosser & Liese, 1971, 1973; Wu & Wang, 1976; Jiang & Li, 1982).

Liese (1985) reported that there are five major types of vascular bundles. These include Type I: Consisting of one central vascular strand, supporting tissue only as sclerenchyma sheaths; Type II: Consisting of one central vascular strand, supporting tissue only as sclerenchyma sheaths, sheath at the intercellular space (protoxylem) strikingly larger than the other three; Type III: Consisting of two parts, the central vascular strand with sclerenchyma sheaths and one isolated fibre bundles; Type IV: Consisting of three parts, the central vascular strand with small sclerenchyma sheaths and two isolated fibre bundles outside and inside the central strand; Type V: A semi-open type representing a further link in the evolution tendency (Lessard & Chouinard, 1980; Rao et al. 1985; Qisheng et al. 2001).

The vascular bundle types and their distribution within the culm correlate with the taxonomic classification system of Holttum (1956) based on the ovary structure. Therefore, having only vascular bundle Type I, the bamboo genera like *Arundinaria, Phyllostachys, Fargeria, Sinarundinaria* are classified here. The vascular bundle Type II alone, have the bamboo genera like *Cephalostachyum, and Pleioblastus* classified under it while having Type III alone, the bamboo genera like *Schizostachyum* are classified under this type. The vascular bundle Type II and III, have the bamboo genera like *Oxytenanthera, Melocanna* classified under them, with vascular bundle Type III and IV alone, having the bamboo genera like *Bambusa, Dendrocalamus, Gigantochloa, Sinoclamus* classified under the group. Leptomorph genera have only the vascular bundle Type I, whereas Pachymorph genera possess Types II, III and IV. Size and shape of the vascular bundles vary across an internode but also with the height of a culm (Liese, 1985).

According to Qisheng et al. (2001), the vascular bundle consists of four features as explained in Figure 2.3, and is distributed among the fundamental tissues of culm wall. Vascular bundles are a combination of vessels and sieve tubes, with companion cells and fibres (Abd. Razak et al. 1995). Zhan et al. (2020) reported that the distribution, size and shape of the bundles change continuously from the periphery towards the center of the culm. Additionally, the anatomical characteristics of bundles vary from the culm base, middle and top. Vascular bundles were longer and smaller at the outer portion but shorter and larger towards the inner portion (Wang et al. 2011). The smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer portions had higher

structure, post-xylem are the two large vessels also known as metaxylem vessels with one or two proto-xylem elements. The vessels are larger at the inner part of the culm wall and become small toward the outer part. In the vascular bundle structure, the role of vessel is to transport water and nutrients in the longitudinal direction. The vessels are surrounded by sclerenchyma sheaths. They differ considerably in size, shape, and location, according to their position in the culm and the bamboo species.

2.3.1.1.2 Phloem

Phloem is one of the features of vascular bundle system found in the culm wall. Phloem can be divided into proto-and post-phloem. Proto-phloem matures when all the parts of stem are growing in length, its cells are strained, stop functioning and fade away at last. Therefore, in bamboo documents, phloem is not mentioned as proto- or post-. Actually, it is post-phloem, which functions in the whole period of the culm growth (Qisheng et al., 2001). The phloem is surrounded by sclerenchyma sheaths: they differ considerably in size, shape, and location, according to their position in the culm wall. The phloem with thin-wall, and unlignified sieve tubes connect with companion cells. This conducting tissue functions throughout the lifetime of a culm without addition of any new conducting tissue in contrast to hardwoods and softwoods with their cambial activity. In older culms, vessels and sieve tubes can become impermeable due to depositions of gum-like substances. Also, blocking of sieve tubes by tylosoid-like outgrowths occurs. (Lessard & Chouinard, 1980; Rao et al., 1985; Qisheng et al., 2001).

2.3.1.1.3 Fibre

In the vascular bundle structure, there are two main types of fibre. These include the fibre sheath and the fibre bundle. Fibres are specific cells of bamboo culm structure. They are elongated, with both ends pointed. Their walls thicken with aging, with a few small round pits. The average length is 1.5 - 4.5 mm; the ratio of length to width is high (Qisheng, et al. 2001). In the vascular bundle structure, fibres are supposed to play a key role in providing bamboo material with strength and toughness (Lo et al., 2004; Zou et al., 2009). Wai et al. (1985) reported that bamboo fibre was suitable for pulping, the fibre wall layers could be separated in beating process, and the fibre walls expanded outwardly. All these properties are different from those of wood fibre.

Gritsch et al. (2004) studied developmental changes in cell wall structure of phloem fibres of the bamboo *Dendrocalamus asper*. Their study reported that within the fibre caps, the typical pattern of wall thickening was observed, with fibres close to xylem and phloem elements maturing first. The walls of fibres immediately adjacent to the phloem completed their thickening at the same time as large-diameter fibres at the periphery of the phloem cap. The study further indicated that the metaxylem fibres undergo a similar pattern of development. The main period of secondary wall deposition and thickening in phloem fibres occurred during the first year of growth, between 6 months and 1 year. The fibre cell wall thickness increased significantly from 6 months to 1 year old and from 1 year to 3 years of age. In total, an average increase of over 3 mm in cell wall thickness occurred between 6 months and 3 years. Although the average thickness of the fibre cell wall in the mature culm was 4.5 µm, the maximum wall thickness measured was up to 12 µm or more in some individual cells. They stated further that during culm elongation, the majority of the fibres had a low number of layers, with an average of two. However, a distinct multi-layered wall structure with up to 5–6 layers was discernible in individual fibres close to the phloem elements. After 1 year, 55 % of fibres had an average of 5–6 layers and the percentage of fibres with 7–8 layers had increased from 1 % to 26 %. The main change in the 3-year-old culm was seen in the further increase in the number of fibres with seven and more layers. Their study concluded that within the phloem fibre caps of *D. asper*, six different fibre types could be distinguished and were all already present in the young, elongated culm. In the mature stage, the layering structure was independent of the cell wall thickness, i.e. thinner-walled fibres could also have a large number of wall layers. Nevertheless, the number of wall layers rose in fibres at the periphery of the fibre bundles and in those close to the phloem. In both areas, the same high degree of layering in individual fibres was observed. These findings demonstrate not only a great heterogeneity in the fibre wall structure but also a degree of „order" in the distribution of multi-layered fibres within the caps.

2.3.2 Parenchyma Cell

Fundamental tissue is parenchyma, mainly distributed within vascular system as stuffing material. These are the fundamental part of bamboo material and are called fundamental tissue. The ground tissue consists of parenchyma cells embedding the vascular system. The parenchyma tissue has two types of vertically positioned cells: the long and short parenchyma cells. The long parenchyma cells, with thickened polylamellated and lignified wall, usually have starch granules in them. The starch content of oblong parenchyma cells in bamboo stem of 1 - 2 years of age is abundant. But in those of bamboo stem younger than one year, there is hardly any starch. Short cells also contain no starch, even if their wall thickens. The short parenchyma cells are scattered among the long parenchyma cells and characterized by dense cytoplasm, thin walls and no lignification. The wall of oblong cell is multi-layered, lignified at the beginning of shoot growth. The lignin content of wall is high, with tumour layer attached. A short cell does not lignify, even if the whole culm is mature.

The total culm consists of about 50% parenchyma, 40% fibres, and 10% conducting cells (vessels and sieve tubes). The percentage distribution shows a definite pattern within the culm, both horizontally and vertically. All the primary xylem and primary phloem are surrounded by lignified parenchyma cells, except the outer side, covered by fibre. Parenchyma cells of vascular bundles are smaller in comparison with those of fundamental tissues, and there are more pits on parenchyma cell wall. Parenchyma and conducting cells are more frequent in the inner portion of the wall, whereas in the outer portion, the percentage of fibres is higher. The type of vascular bundle present influences the distribution of cell types within the culm (Lessard & Chouinard, 1980; Rao et al.1985; Qisheng et al. 2001).

2.3.3 Variation in Anatomical Properties of Bamboo Culm Wall

There are variations within the fibre properties across the bamboo culm wall that has been reported in literature by several researchers across the globe. The classification of the International Association of Wood Anatomists splits fibres into three groups:

medium-length (0.91-1.60 mm), moderately long (1.61-2.20 mm) and very long (2.21-3.00 mm) (IAWA 1989).

Pande (2009) described the fibre morphology of ten economically important bamboo species. Variations among the species were significant for the fibre dimensions. It showed that material from one bamboo species of the same site carry similar fibre properties while they are different for different bamboo species.

Chew et al. (1992) studied the fibre of *Bambusa vulgaris*. Their report indicated that the fibre is long and slender, with a narrow lumen. The average fibre length and width was found to be 2.8 mm and 0.013mm, whilst the lumen width and cell wall thickness was 0.003mm and 0.005mm respectively.

Rusch et al. (2019) studied morphology, density and dimensions of bamboo fibres. Their study indicated that among the studied species, the mean fibre length ranged from 1.65 mm for *G. spinosa* to 3.63 mm for *D. asper*, with an overall mean of 2.29 mm. Thus, in a general context, the analysed species can be classified as owning very long fibres. *B. vulgaris, D. asper, D. giganteus* and *B. vulgaris var. vittata* presented the highest values, all of them with more than 3 mm in length. In turn, *G. spinosa* and *G. amplexifolia* have fibres shorter than 1.7 mm in length. They further reported that the mean fibre width ranged from 14.22 µm for *G. superba* to 19.97 µm for *B. nutans*, with an overall mean of 16.4 µm. *B. nutans* and *D. giganteus* are those with values above 19.09 µm, whereas *G. superba, B. molingensis, G. spinosa, G. amplexifolia* and *B. ventricosa* had a width of less than 14.8 µm. *B. tulda, B. tuldoides* and *B. nutans* are the ones with the highest average wall thickness, with values higher than 7.09 µm, which are much higher than the diameter of their respective lumens. In turn, *B. ventricosa* and *B. vulgaris* present the lowest average thickness. The largest lumens were found for *D. asper* and *D. giganteus*, which were greater than 5 mm, i.e., similar to their wall thickness. On the other hand, values lower than 3 mm were found for *B. stinostachya, B. nutans, B. tulda, G. superba* and *G. angustifolia*. However, all values obtained represent diameters classified as narrow, which increase the strength of the product to tearing. They further stated that bamboo fibres have a length well beyond their width (wall thickness + lumen diameter). This fact is relevant, because there is a correlation between these fibre dimensions and the physical-mechanical properties of the resulting product. Their study concluded that the fibres of the surveyed bamboo species have an intermediate length, in relation to the main commercially cultivated tree species (*Gymnospermas* and *Angiospermas*). However, their dimensions vary according to the region of the stem wall, reducing from the peripheral zone towards the central zone. In general, the fibres tend to be 20 % to 40 % shorter in the inner zone of the stem wall. In the longitudinal direction, its maximum length occurs in the median range of the internode and decreases in the extremities. Bamboo fibres are thin, with a narrow lumen, relatively thick cell walls and smaller length than the *Gymnospermas* fibres. Due to these characteristics, they present higher values for the wall-fraction index and lower for the coefficient of flexibility, thus conferring high values for strength, stiffness and resistance to collapse on processing, if compared to arboreal species.

Mustafa et al. (2011) studied anatomical properties and microstructures features of four cultivated bamboo *Gigantochloa* species. Their study reported that the result for the vascular bundles distribution on the four (4) selected *Gigantochloa* species have shown the mean number of vascular bundle for G. scortechinii was 6.38 bundle/4 mm^2 followed by *G.wrayi* at 6.84 bundle/4 mm^2 and *G. brang* at 6.38 bundle/4 mm^2 under one group and the lowest was *G. levis* at 4.33 bundle/4 mm^2. The results on the measurement of the vascular bundles length is shown that the higher mean of vascular bundle length at internodes were *G. levis* (1171.14 µm) followed by *G. brang* (788.82 µm), *G. scortechinii* (787.19 µm), and *G. wrayi* (754.06 µm) while the results on the measurement of the vascular bundles width is showed that the higher mean of vascular bundle width was *G. levis* (798.26 µm), *G.wrayi* (532.88 µm), *G. brang* (509.47 µm) and *G. scortechinii* (501.38 µm) respectively. They further reported that the results for the fibre lengths study of the various *Gigantochloa* species showed that the longest fibre length were obtained from the *G. levis* (2039.98 µm) followed by *G. brang* (1909.68 µm), G. wrayi (1798.79 µm) and G. scortechinii (1745.27 µm). The results on the fibre diameter study in the *Gigantochloa* genera showed that the larger mean average of fibre diameter were *G. brang* (22.75 µm), followed by *G. levis* (22.67 µm), *G. wrayi* (17.86 µm) and *G. scortechinii* (17.26 µm). The lumen diameter for *G. scortechinii, G. brang, G. levis* and *G. wrayi* were 8.60 µm, 4.75 µm, 4.75 µm and 4.75 µm, while the results on the measurement of the wall thickness of various *Gigantochloa* species showed that *G. levis* (9.34 µm) possess thicker wall compared to the *G. brang* (9.02 µm), *G. wrayi* (7.02 µm) and *G. scortechinii* (4.30 µm). Their study concluded that the anatomical structure varies significantly with the species. The distribution and the size of vascular bundle are different between species, and even in the same genera. The vascular bundle of four species were almost similar and were classified under Type III, consisting a single vascular sheath fibre and one fibre strand. However, the vascular bundle size was significantly different between position (node and internode) and position (outer, middle and inner layers). They further stated that the fibre morphology for each species has a different measure of size in terms of length, diameter, lumen and wall thickness. The study identified that there was differences in fibre dimensions on the position (node and internode) and position (outer, middle and inner layer) in the same species. Fibre length was longer at the internode node while the middle layer has the longest fibre length compared to the outer and inner layer.

Abd.Latif and Tarmizi (1993) studied the anatomical properties of three Malaysian bamboo species, 1 to 3-year-old *Bambusa vulgaris*, *Bambusa bluemeana* and *Gigantochloa scortechinii.* This study showed that the highest mean concentration of vascular bundles was observed in the top location of the 2-year-old *B. bluemeana* (365 bundles/cm^2), *B. vulgaris* (307 bundles/cm^2) and *G. scortechini* (223 bundles/cm^2). The lowest mean concentration of vascular bundles was in the middle location of the 1-year old *G. scortechini* (132 bundles/cm^2), 2-year-old *B. vulgaris* (215 bundles/cm^2) and 1-year old *B. bluemeana* (200 bundles/cm^2). They further reported in this study that, age does not significantly affect the radial/tangential ratio, and the trend is a decrease with height except for *G. scortechini*. Their study concluded that vascular bundle size is larger at the bottom and gradually decreases at the top. The fibre lengths between the three species were significantly different. However, the age does not significantly affect fibre length. The fibre wall thickness was significantly different among the bamboo species. *G. scortechinii* was in the range of 0.006mm to 0.01mm, *B. vulgaris* in the range of 0.006mm to 0.008mm and 0.004 to 0.006mm for *B. bluemeana*. Their study concluded that there is variation of the anatomical characteristics of bamboo, and there are certain patterns between and within culms respectively.

2.3.4 Bamboo Anatomy in Relation to Physical and Mechanical Properties

The fibre proportion occupied by vascular bundles would determine the physical and mechanical properties of a bamboo species (Janssen, 1991; Liese, 1998). As engineering structural material, the strength of bamboo depends mainly on the mass of its cell wall, indicated by basic density. The higher proportions of fibres as reported by Tomalang et al. (1980) have a higher density and better mechanical properties. Density is a variable that influences the mechanical properties (Rusch et al., 2019).

Rusch, et al. (2019) studied Morphology, density and dimensions of bamboo fibres. Their study indicates that genus had below-average density values, especially *D. asper* (0.599 g cm-3) and *D. giganteus* (0.552 g cm-3). Similarly, *Guadua* presented below-average values for *G. angustifolia* (0.451 g cm-3), *G. spinosa* (0.489 g cm-3) and *G. superba* (0.559 g cm-3). In contrast, the genus with the highest average density was *Bambusa* (0.685 g cm-3), ranging from 0.608 g cm-3 to 0.780 g cm-3, being *B. dissimulator* the highest density species. On the other hand, the values for basic density ranged from 0.451 g cm-3 to 0.654 g cm-3 for *Guadua* and from 0.552 g cm-3 to 0.683 g cm-3 for *Dendrocalamus*. The total bulk density ranged from 0.451 g cm-3 for *G. angustifolia* to

0.780 g cm-3 for *B. dissimulator*. The basic density is directly influenced by the cell wall thickness of the fibres, which interferes in the final resistance of the generated product. Species with a lower basic density have fibres with thinner walls that flatten during the production process of different products (paper, panel, etc.), resulting in a greater adhesion among the fibres. Their study concluded that the basic density in the test stem-specimens of the surveyed bamboo genera differs and increases in order (*Bambusa spp.*, *Dendrocalamus spp., Guadua spp*.). The bamboo fibres in the surveyed species can be considered light, rigid and strong. Such characteristics give them a high firmness, thus positively influencing the physical and mechanical resistance of materials produced with bamboo.

The anatomical characteristics in relation to the mechanical properties of Malaysian bamboo have been studied by Abd.Latif et al. (1990). The three species, 1 to 3-year-old *Bambusa vulgaris, Bambusa bluemeana* and *Gigantochloa scortechinii* were used. They concluded that vascular bundle size (radial/tangential ratio) and fibre length correlated positively with Modulus of Elasticity (MOE) and stress at proportional limit. The authors implied that the increase in the size (mature stage), and fibre length could be accompanied by an increase in strength properties. They mentioned that bamboo posses longer fibres and might be stiffer, if it had a greater vascular bundle size. The correlation between fibre length and shear strength was negative. The fibre wall thickness correlates positively with compression strength and MOE, but negatively with modulus of rupture (MOR). There was also a correlation between lumen diameter and all of the mechanical properties, except compression strength.

The effects of anatomical characteristics on the physical and mechanical properties of *Bambusa bluemeana* were determined (Abd.Latif et al., 1993). The studies were carried out by using nine culms of 1, 2 and 3-year-old bamboo from Malaysia. This study found that the frequency of vascular bundles does not significantly vary with age and height of the culm. They observed that the highest mean concentration of vascular bundles was at the top location of the 2-year-old culm, and the lowest mean concentration was in the middle location of the 1-year-old culm. The high density of vascular bundles at the top was due to the decrease in culm wall thickness (Grosser & Liese, 1971). The size of vascular bundles was not significantly different with height and age. There was no correlation of vascular height of the culm. The fibre length of the species of bamboo studied did not significantly differ with age and culm height. They explained that the reason for the higher ratio of vascular bundle size near the basal location was due to the presence of mature tissues. The radial diameter decreases faster than the longitudinal diameter of the vascular bundles within the height of the culm. The fibre length of the species of bamboo studied did not significantly differ with age and culm height. Fibre wall thickness is not significant by age or height of the culm. They observed that there is a decrease of lumen diameter with the increase of age and height of the culm.

2.4 Chemical Composition of Bamboo

Chemical composition is one of the important properties of bamboo, which can influence the durability of its products. The comprehensive knowledge of the chemical properties in different bamboo species will enhance the utilization of this versatile natural material in the construction and building industrial sectors as well as the bio-chemical and other related industries. The amount of each component, especially holocellulose, lignin and extractive, varies considerably between the materials. Variation in the chemical constituents occurred in different species, location of cell within the tree (Thomas, 1977; Browing, 1975). The chemical composition of bamboo is known to be similar to that of wood and over 90% of which consists of cellulose, hemicelluloses and lignin (Sandu et al., 2003; Chaowana, 2013).

2.4.1 Extractive Content of Bamboo

The extractive content of bamboo are diverse substances such as resin acid, fatty acid, turpenoid compounds and alcohols and most of these substances are soluble in water or neutral organic solvent (Ma et al., 2014). The extractive substances are normally referred to as minor constituents. The minor components are pigments, tannins, protein, fat, pectin and ash. Others include resins, waxes and inorganic salts. These constituents play an important role in physiological activity of bamboo, and they are found in cell cavity or special organelles (Khalil et al., 2012). Extractive content contributes significantly in the natural durability of bamboo material. The extractive content varies from one species to the other depending on the type of genera. Bamboo culm walls consist of between 90 to 98% hemicellulose, cellulose and lignin, while the other 2 to 10% are mainly made up of extractives, resins, tannins, waxes and inorganic salts (Tomalong et al., 1980; Razak et al., 2009). Peng and She (2014) also reported that the major constituents of bamboo are extractive (0-5%), cellulose (45–55%), hemicelluloses (25–35%), and lignin (20–30%). Comparatively, bamboo has higher alkaline extractives, ash and silica contents (Chen et al., 1985) than wood species. Extractive content of any fibrous materials are very important element that could positively or negatively influence the material utilization potential for pulping and papermaking operations. Higher extractive content lowers the pulp yield while lower extractive content improves the pulp yield. Studies have shown that higher extractive content may lead to a lower pulp yield (Jahan et al., 2008; Brahma & Brahma, 2017).

Sulaiman et al. (2016) in their study determined the percentage extractive of *Bambusa vulgaris* at different ages and portion. They reported that, the top portion to *Bambusa vulgaris* with 4.96% and 6.51% for young and mature respectively has shown a slightly higher extractive content compared to the middle and bottom portion with 4.27% and 2.92% for young and mature to the middle portion then 3.67% and 2.57% for young and mature to the bottom portion, respectively. In different ages, *Bambusa vulgaris* showed the extractive content on young and mature ages with 3.67%, 4.27% and 4.96% for young and 2.57%, 2.96% and 6.51% slightly increased from bottom to the top, respectively. Their study concluded that *Bambusa vulgaris* of the mature age had the higher extractive content compared to the other age and portions. They further added that, the higher extractive was relative to higher density with influence on high cell wall volume such as thick and width cell wall structure.

Razak et al. (2013) in their study determined the extractive content for various bamboo species at different internodes and nodes. They reported that the extractive content in four species of *Gigantochloa* bamboo ranged between 8.30 to 9.23%. The extractive content of *G. brang, G. levis, G. scortechinii* and *G. wrayi* were 8.30%, 9:23%, 8:00% and 8.62%

respectively. The extractive content was higher in *G. levis* (9.23%), followed by *G. wrayi* (8.62%), *G. brang* (8.30%) and the lowest value in *G. scortechinii* (8%). The extractive content at internode was 8.46%, while at the node was 8.63% for all species. Inner position for the internode, the extractives contains were 12.32% to 14.17% and for the node were 11.90 to 16.41%. The middle positions for internode were from 5.15 to 9.74% and nodes were 5.71 to 7.57 %. The extractive content was at 13.42 % (inner layer), 7.21% (middle layer) and 4.99% (outer layer).

2.4.2 Holocellulose Content of Bamboo

Holocellulose consist of cellulose and hemicellulose in the chemical structure of bamboo culm. Depending on the type of bamboo species available, difference usually occur in the main chemical composition when bamboo culms mature. Study has shown that the hemicellulose and cellulose are actually made of the carbohydrate polymers which consists of simple sugars monomer and lignin from phenylpropane (Browning, 1975). Peng and She, (2014) reported that the holocellulose content in bamboo accounted for 70 – 90% of the chemical composition.

Sulaiman et al. (2016) in their study determined the holocellulose content of *Bambusa vulgaris* in different ages and portion. They reported that *Bambusa vulgaris* of young age with 94.96%, 94.24% and 95.07% for bottom, middle and top, respectively was showing a slightly higher value of holocellulose content compared to mature age from *Bambusa vulgaris* with 86.36%, 85.50% and 82.52% for bottom, middle and top, respectively. Their study concluded that *Bambusa vulgaris* of young age from top portion had the higher percentage of holocellulose yield within over than 90% content. This is because, holocellulose was relatively equipped with lignin content; the part which removed less lignin as shown by the higher content of holocellulose.

Razak et al. (2013) in their study determined the holocellulose content for various bamboo species at different locations (internodes and nodes) and different positions. They reported that the highest was *G. levis* (85.08%) followed by *G. wrayi* (84.53%), *G. brang* (79.94%) and *G. scortechinii* (74.62%) respectively. The holocellulose content for the cultivated bamboo genus *Gigantochloa* were from 74% to 85%. The content of holocellulose at internode was from 73.48% to 86.74% and for the node, 76.76% to 85.65%. Their study concluded that the holocellulose content is highest at internode (81.65%) compared to node (80.02%).

2.4.3 Cellulose Content of Bamboo

Cellulose is carbohydrate polymers constituents of simple sugars monomers (Browing 1975). According to Razak et al. (2013), cellulose is long-chain polymer of glucose that differs from starch in configuration. The fibrous nature of the wood cells is the result of linear, oriented, crystalline arrangement of cellulose component. The cellulose structure is the same in different species. The cellulose content contributes significant difference in determining the durability and service life of bamboo. The biodegradable agents such as mould, fungal and borers attack bamboo material because of high cellulose content. Peng and She, (2014) reported that cellulose content accounted for 45 – 55% of the major constituents of bamboo. Li et al. (2010) in their studies reported that cellulose content accounted for 73.83%. They further reported that cellulose content decreases with increase in age of bamboo.

Sulaiman et al. (2016) in their study determined the alpha cellulose content of *Bambusa vulgaris* in different ages and portion. They reported that mature *Bambusa vulgaris* with 53.85%, 58.50% and 52.02% for bottom, middle and top, respectively has shown slightly higher alpha cellulose content compared to the young *Bambusa vulgaris* with 46.43%, 51.25% and 52.93% for bottom, middle and top, respectively. In different portions culm of bamboo such as bottom, middle and top portion, indicated that the middle portion of mature *Bambusa vulgaris* with 58.50% has shown the higher value compared to the other portions. Their study concluded that middle portion of mature *Bambusa vulgaris* has indicated the higher percentage of alpha cellulose. This is because the middle portion had the larger and longer fibre size compared to the bottom and top portion. Consequently, there were influences to high content of alpha cellulose on the part.

Razak et al. (2013) in their study determined the cellulose content for various bamboo species at different internodes and nodes positions. They reported that the highest was *G. brang* (51.58%) followed by *G. scortechinii* (46.87%), *G. wrayi* (37.66%) and *G. levis* (33.80%). Based on the result, the average of α-cellulose content for the cultivated bamboo genus *Gigantochloa* were 33.79 to 51.76%. The α-cellulose content at difference location internode and node in bamboo culm for this genus, showing not much differences between internodes and nodes. The content of α-cellulose at internodes was 31.76% to 50.82% and for the nodes 33.79% to 51.76%. Their study concluded that the average value of α- cellulose content at internodes was 42.22% and for the nodes was 42.74%.

Other different researchers have investigated different bamboo species and parts to establish chemical composition of cellulose content. They include bamboo (Kumamoto, Japan) with cellulose content of 47% (Scurlock, et al. 2000); bamboo with cellulose content of 43% (Sathitsuksanoh et al., 2010); bamboo (*Dendrocalamus sp.*) with cellulose content of 47% (Kuttiraja et al., 2013); bamboo with cellulose content of 44% (Yasuda et al., 2013); Moso bamboo (*Phyllostachys pubescens Mazel*), with cellulose content of 46% (Yamashita et al., 2010); bamboo (*Dendrocalamus asper*) with cellulose content of 41% (Leenakul & Tippayawong, 2013); Moso bamboo (*Phyllostachys heterocycla*), with cellulose content between 42–47% (Li et al., 2014); bamboo with cellulose content of 38.4% (Littlewood et al., 2013); Moso bamboo (*Phyllostachys heterocycla*), with cellulose content of 37% (Li et al., 2013); bamboo shoots shell fibre (BSSF), with cellulose content of 23% and bamboo stem and leaf (BSL), with cellulose content of 21% (He et al., 2013).

2.4.4 Hemicellulose Content of Bamboo

Hemicelluloses are carbohydrate polymers constituents of simple sugars monomers (Browing, 1975). Razak et al. (2013) reported that hemicelluloses are shorter, or "branched polymers of five-carbon sugars (pentoses), such as xylose, or six-carbon sugars (hexoses) other than glucose. They are amorphous in nature and serve with the lignin to form the matrix, in which the cellulose fibrils are embedded. The hemicelluloses structure varies considerably among species. The hemicellulose content contributes significant difference in determining the durability and service life of bamboo. The biodegradable agents such as mould, fungal and borers attack bamboo material because of high hemicellulose content. Peng and She, (2014) reported that hemicellulose content accounted for 25 – 35% of the major constituents of bamboo. Peng and She‟s, (2014) study of the content of hemicelluloses in bamboo was influenced by the conditions of species, age, climate, harvest etc. Hemicelluloses were also perceived as different from cellulose as they are composed of a series of sugar monomers such as xylose, mannose, glucose, galactose and others (Peterson et al., 2008).

Sulaiman et al. (2016) in their study determined the hemicellulose content of *Bambusa vulgaris* in different ages (young and mature) and portion. They reported that young *Bambusa vulgaris* with 48.53%, 41.71% and 40.48% for bottom, middle and top, respectively showed slightly higher hemicellulose content, compared to mature *Bambusa vulgaris* with 32.18%, 29.32% and 33.17% for bottom, middle and top, respectively. At different portions such as bottom, middle and top they indicated that the *Bambusa vulgaris* with bottom young age showed the highest value of 48.53% when compared with the others. Their study concluded that bottom portion in young *Bambusa vulgaris* had the higher hemicellulose content that were consistent, and had the highest content of polysaccharides in the primary and secondary wall.

Several researchers have investigated different bamboo species and parts. They include bamboo (Kumamoto, Japan) with hemicelluloses of 23% (Scurlock et al., 2000); bamboo with hemicelluloses of 15% (Sathitsuksanoh et al., 2010); bamboo (*Dendrocalamus sp.*) with hemicelluloses of 16% (Kuttiraja et al., 2013); bamboo with hemicelluloses of 30% (Yasuda et al., 2013); Moso bamboo (*Phyllostachys pubescens Mazel*), with hemicelluloses of 23% (Yamashita et al., 2010); bamboo (*Dendrocalamus asper*) with hemicelluloses of 27% (Leenakul & Tippayawong, 2013); Moso bamboo (*Phyllostachys heterocycla*), with hemicelluloses between 22–23% (Li et al., 2014); bamboo with hemicelluloses of 20.5% (Littlewood et al., 2013); Moso bamboo (*Phyllostachys heterocycla*), with hemicelluloses of 22% (Li et al., 2013); bamboo shoots shell fibre (BSSF), with hemicelluloses of 14% and bamboo stem and leaf (BSL), with hemicelluloses of 12% (He et al., 2013).

2.4.5 Lignin Content of Bamboo

Lignin is the third cell wall component in bamboo. It is a three-dimensional polymer formed from phenylpropane units, which have randomly grown into a complicated large molecule with many different kinds of linkages between the building blocks. Lignin acts as cement between the bamboo fibres and as a stiffening agent within the fibres. In the production of chemical wood or bamboo pulps, it is dissolved by various chemical processes, leaving the cellulose and hemicelluloses behind in fibrous form. Lignin plays critical role as a bonding agent that holds the cells in bamboo together. During this process, lignification of the parenchyma tissue and cell walls continue as more lignin accumulates. Lignin is a phenolic heteropolymer that constitutes the second most abundant organic constituent on earth, after cellulose (Rastogi & Dwivedi, 2008). According to Shi et al. (2012), the high lignin content makes bamboo fibre brittle in comparison to other natural plants. Peng and She, (2014) reported that lignin content accounted for 20 – 30% of the major constituents of bamboo. The lignin content of bamboo accounted for 20-26%, similar in value to both North American softwoods (24−37%) and hardwoods (17−30%) (Li et al., 2007).

Sulaiman et al. (2016) in their study determined the lignin content of *Bambusa vulgaris* in different ages and portion. They reported that young age Bambusa *vulgaris* with 21.86%, 18.27% and 16.27% showed decreasing order percentage in the value of lignin content from bottom to the top, while mature age with 19.58%, 22.29% and 25.97% showed increasing order percentage of lignin content from bottom to the top. Their study concluded that mature age on top portion in *Bambusa vulgaris* had higher content of lignin. This is because the lignin content was slightly increasing within the age (mature), and as a binder provided of its most hard and strong fibre on the part. Therefore, due to the results, the part had a good potential for mechanical strength by-product and excellent properties including biodegradability, biocompatibility, bioactivity, and so on.

Razak et al. (2013) in their study determined the extractive content for various bamboo species at different internodes and nodes. They reported that the lignin content in the four species of *Gigantochloa* bamboo ranged between 24.84 to 32.65%. The highest were obtained in *G. scortechinii* (32.55%), *G. wrayi* (30.04%), *G. levis* (26.50%) and lowest in *G. brang* (24.83%). The lignin content at the internodes were 15.72% to 43.68%, while the content at the nodes were 18.28% to 33.33% for all species.

Several researchers have investigated different bamboo species and parts. They include bamboo (Kumamoto, Japan) with lignin of 28% (Scurlock et al., 2000); bamboo with lignin of 26% (Sathitsuksanoh et al., 2010); bamboo (*Dendrocalamus sp*.) with lignin of 18% (Kuttiraja et al., 2013); bamboo with lignin of 26% (Yasuda et al., 2013); Moso bamboo (*Phyllostachys pubescens Mazel*), with lignin of 26% (Yamashita et al., 2010); bamboo (*Dendrocalamus asper*) with lignin of 27% (Leenakul & Tippayawong, 2013); Moso bamboo (*Phyllostachys heterocycla*), with lignin between 23–31% (Li et al., 2014); bamboo with lignin of 20.8% (Littlewood, et al. 2013); Moso bamboo (*Phyllostachys heterocycla*), with lignin of 24% (Li et al., 2013); bamboo shoots shell fibre (BSSF), with lignin of 11% and bamboo stem and leaf (BSL), with lignin of 12% (He et al., 2013).

2.5. Physical and Mechanical Properties of Bamboo

Physical and mechanical properties of bamboo depend on the species, site/soil and climatic condition, silvicultural treatment, harvesting technique, age, density, moisture content, position in the culm, nodes or internodes and bio-degradation (Lee et al., 1994). Several studies have been conducted in order to establish the various fundamental properties associated with bamboo material that can equally influence the utilization potentials.

2.5.1. Moisture Content

Moisture content is the amount of water in the bamboo culm that needs to be determined before its utilization. It is believed to be influenced by position on the culm as well as the age of which the test sample could be cut for the necessary investigation. The moisture content of bamboo varies vertically from the bottom to the top portions and horizontally from the outer layer to the inner layers. Bamboo possesses very high moisture content. Green bamboo may have 100% moisture (oven-dry weight basis) and can be as high as 155% for the innermost layers to 70% for the peripheral layers. The vertical variation from the top (82%) to the bottom (110%) is comparatively less. The fibre saturation point of bamboo is around 20-22 % (Kishen et al., 1956). The MC range of *Bambusa bluemeana* is 57-97% (Abd.Latif, 1993). Lee et al. (1994) revealed that *Phyllostachys bambusoides* has an average MC of 138%.

Hamdan et al. (2009) reported that the average moisture content of *G. scortechinii* at the cutting age is approximately 90%. The moisture content for *Bambusa vulgaris* in green condition is reported by Talukdar and Sattar (1980) to be between 48.7-52.8% and 85.7-94.5% for mature and juvenile culms respectively. This implies that moisture content decreases as bamboo matures. This further explains the rationale involved in the growth of bamboo, that the woody material replaces moisture as bamboo matures.

Razak et al. (2010) also conducted a study on anatomical and physical properties of cultivated two- and four-year-old *Bambusa vulgaris*. They found moisture contents in green conditions of the cultivated *Bambusa vulgaris* decrease from 97.3 to 94.4% at bottom portion, 92.1 to 90.3% at middle portion and 86.4 to 82.5% at the top portion, in 2- and 4-year-old culms, respectively. Their study shows that in green condition *Bambusa vulgaris* possesses the highest moisture content that is influenced by age, height and position in the culms wall thickness. The moisture content decreases with age, from bottom portion to top portion, and from inner to outer layer in the culms wall. The conclusion was that, the age, height and position in the culms wall thickness influence the present of moisture content in *Bambusa vulgaris*.

Gebremariam and Assefa (2018) investigated the effects of ages and culm height on the moisture content of bamboo species. They reported that moisture content value ranged from 94.3 to 152.7%, 72.2 to 136.7% and 65.9 to 115.1% for two, three and four-year-old bamboo respectively. Their conclusion was that, the moisture content decreased as the stand age increased whilst on the culm height, the moisture content decreased significantly, as it moved from the bottom to top.

Qisheng et al. (2001) also found the moisture content of a growing bamboo to be very high depending on different seasons and species. They stated that the average moisture content of *P. pubescens* at the cutting age to be approximately 80% with equilibrium moisture content of bamboo material after air seasoning changes in connection with atmosphere temperature and humidity as 15.7% of *P. pubescens* in the Beijing area.

The variation of moisture content within the culm wall was very much attributed to the distribution of vascular bundles (Qisheng et al., 2001). They further found that the vascular bundles at the peripheral zone were much more distributed than in the inner zone, and most of the cells were parenchyma, which has a better water holding capacity than the vascular bundles. Hence the higher the content of parenchyma cells in the inner zone, the higher the water holding capacity and thereby affecting shrinkage.

Razak et al. (2012) investigated relationship between physical, anatomical and strength properties of 3-year-old cultivated tropical bamboo *Gigantochloa scortechinii*. They found that the moisture content of the bamboo culms in green condition at the outer layer was 49.87%, middle layer 83.82% and for the inner layer was 125.90%. They further reported that, the moisture content at the internodes was 94.45% and for the node was 78.61%. Their conclusion was that the anatomical factor might contribute to the differences of the moisture content between two locations. At the internodes, the metaxylem vessels structure was more uniform and larger, while at the nodes the metaxylem vessels are not uniform and smaller. They further stated that the moisture content is lower at the outer position and increases toward the inner positions. This is because the area contains high fibre strand and thus has low capacity for water storage.

2.5.2. Density

Density is one of the elements of determining the strength properties of a material especially wood. Most fibrous materials such as bamboo have relationship of density and strength as directly proportional, in that density increased along the strength properties with the variations among the species. The density of bamboo material is calculated by the green weight per the green volume, whiles the basic density is the oven dry weight per the green volume of bamboo. The basic density ranges from 0.40 - 0.9 g/cm³ and this depends on some factors like the type of species, age, location, anatomic structure and so on. The density of bamboo culm always increases from inner to outer portion and from lower to upper portion seems to be like a rule.

Wahab et al. (2010) also conducted a study on anatomical and physical properties of cultivated two- and four-year-old *Bambusa vulgaris*. They reported that the basic density of the cultivated *Bambusa vulgaris* were found to vary from 472.6 to 565.3 kg/m^3 for the 2-year-old bamboo culms and 504.3 to 591.8 kg/m^3 for the 4-year-old culms. The study reported that, the basic density of the 4-year culms is consistently higher than the 2-year-old culms and increases from the lower to the upper internodes. There was an increase in basic densities between the two-age groups based on the 2-year-old culms, which ranged between 3.7 to 7.5%. It was then concluded that, the increases showed that there was a maturation process going on between the two age-groups relative to the two of tissue types.

Santhoshkumar and Bhat (2014) investigated the variation in density and its relation to anatomical properties in bamboo culms. It was found that, the higher basic density of the outer portion of the culm wall may be attributed to the presence of higher number of vascular bundles and higher proportion of fibrous tissue at this portion. The investigation concluded that a definite uniform trend was noticed in distribution of tissues and its influence on physical properties.

Santhoshkumar and Bhat (2015) investigated variation in density and its relation to the distribution, frequency and percentage of tissues in bamboo culms. The results of density ranged from the outer value of 760.77 kg/m^3, 664.74 kg/m^3 for the middle and 624.17 kg/m^3 for the inner portion. They reported that the basic density of the culm increased with increasing height levels of the culms of the species. The reason for higher basic density of the top height level of bamboo culm was attributed to the presence of higher proportion of fibrous tissue and higher frequency of vascular bundles at top height level. They concluded that the density varied with positions of the culm wall and different height levels of the culm in the species. And this variation may affect the density of the culm of the species.

Gebremariam and Assefa (2018) investigated the effect of age and height on some selected physical properties of Ethiopian highland bamboo, *Yushania Alpina*. They found that the basic density of *Yushania alpina* were found to vary from 485.5 to 689.77 kg/m^3 for the two years-old bamboo culms, 563.06 to 704.03 kg/m^3 for the three years-old bamboo culms and 588.13 to 719.92 kg/m^3 for the four years-old culms. They further reported that the four-years-old culms had higher density than the two and three years-old culms. In relation to height positions, the highest basic density of 682.75 kg/m^3 was observed in top bamboo culms while the lowest basic density of 613.75 kg/m^3 was found in bottom bamboo culms. They concluded that, the basic density of the culm increased with increasing height levels of the culms.

2.5.3. Shrinkage

Bamboo Shrinkage refers to the process whereby the fibres in the culm begin to dry out after harvesting. This happens mostly in the thickness of the fibres. Shrinkage normally occurs in a relatively dry humidity. The type of bamboo, the location from which it was removed, can also influence shrinkage. There are direct correlation between the amount of shrinkage and the moisture lost below the fibre saturation point of bamboo culm. This is because the amount of shrinkage in bamboo culm is directly proportional to the moisture lost. Shrinkage usually occurs in three directional planes. These include longitudinal, radial and tangential shrinkage. Mostly, shrinkage that occurs longitudinally is lesser than radial and tangential shrinkages. Tangential shrinkage is however similar to radial shrinkage. Unlike wood, bamboo usually shrinks from the very beginning of drying. This immediate shrinkage behaviour of bamboo has attracted several attributions by researchers based on their observations.

Gebremariam and Assefa (2018) investigated the effect of age and height on some selected physical properties of Ethiopian highland bamboo, *Yushania Alpina*. They reported that, the proportion of shrinkage in wall thickness was higher in two-age bamboo culm, lower in three, four-age bamboo culms, while the proportion of shrinkage in culm diameter was higher in two- age bamboo culm and lower in three, and four- age bamboo culms.

Mansur (2000) related this to the presence of free water (water in the lumen) and bound water (water in the cell wall) in bamboo. The considerably small amount of water in the former could possibly explain shrinkage of bamboo as soon as it begins to lose moisture immediately after felling.

According to Anwar et al. (2005), the shrinkage of *G. scortechinii* from green to oven dry condition indicated that bamboo, in the form of a strip (without epidermis and inner layer), shrank more than the split (with epidermis and inner layer) and outer split in the radial and tangential directions. The term strips are defined as squared splits obtained by removing the epidermis and the inner layer of bamboo splits.

The radial and tangential shrinkage for bamboo strips were reported to be 23.7% and 19.8% respectively (Anwar et al., 2005). Bamboo splits on the other hand, experienced less radial and tangential shrinkages with the respective values of 20.9% and 12.4%. Hamdan et al. (2007) observed that the geometry of the samples also has some effects on the sorption properties as observed in strips being more hygroscopic than splits.

2.5.4. Mechanical Properties of Bamboo

The determination of mechanical properties of bamboo is very essential in the utilization of any structural application. These properties discussed the strength and durability of bamboo material. The strength of bamboo depends on the type of species, moisture content, density, age and culm height (Rangqui & Kuihong, 1987; Razak & Latif, 1995).

The strength of bamboo increases as it becomes older due to the hardening of the culm walls. Abd. Latif (1987) concluded that with age increment, mature tissues start to develop and continue to influence density, strength properties, growth of branches, and established root system in one to three-year old Malaysian bamboos. He reiterated that as bamboo matures, the culm wall thickness becomes hard resulting in maximum strength. Bamboo matures in about three years; it reaches its maximum strength (Young & Haun, 1961; Zhou, 1981; Liese, 1985). Bamboo splits and strips behave more like solid wood as the mechanical properties increase, with decrease in MC (Gnanaharan, et al., 1994; Hamdan, 2004).

2.5.4.1. Modulus of Rupture

The strength of bamboo strip in bending is an important mechanical property since most of the structures constructed from bamboo are likely to be subjected to loads that may cause it to bend. This is usually expressed by Modulus of Rupture (MOR) or bending strength of the flexural test that shows the highest stresses in the outmost fibres of bamboo. Sulaiman et al. (2018) in their study determined the mechanical properties of *Bambusa vulgaris* and *Schizostachyum brachycladum* in different ages. They reported that the *Schizostachyum brachycladum* showed slightly higher value of MOR compared to *Bambusa vulgaris* bamboo species. The mature age from *Schizostachyum brachycladum* with 245.28 N/mm^2 had the higher value modulus of rupture compared to the young age on this species with 102.68 N/mm^2. While, the *Bambusa vulgaris* species also showed the mature age with 185.52 N/mm^2 had the higher MOR compared to young age with 63.17 N/mm^2. Their study concluded that mature *Schizostachyum brachycladum* had the higher strength properties and the most stability in their structure. This is because the part was supported by unique physical properties such as density, basic density and dimension stability that have the larger and longer fibre length that can be supported by anatomical structure with high content of lignin as a binder.

Appiah-Kubi et al. (2014) in their study determined the mechanical properties of some bamboo species for efficient utilization in Ghana. They reported that *Dendrocalamus* *brandisii* had the highest mean MOR of 99.73 N/mm^2 with the application of the polyurethane glue and *Bambusa vulgaris* had the least mean MOR with the application of the same glue. *Bambusa vulgaris* recorded a good mean MOR of 94.3 N/mm^2 with the application of the polyvinyl acetate white glue and 91.54 N/mm^2 with the use of the formaldehyde adhesive. *Guadua chacoensis* seemed to have consistent results with all the three different adhesives. Their study concluded that *Bambusa vulgaris* and *Dendrocalamus brandisii* recorded good strength properties with the application of the PVA and FWC adhesives. *Bambusa vulgaris* laminates attain the highest MOR when PVA adhesive is used in the lamination. They further stated that *Bambusa vulgaris* and *Dendrocalamus brandisii* could be laminated into boards and beams using the readily available adhesives, FWC and PVA, for constructional purposes. With the dwindling wood resources, the use of laminated bamboo boards and beams should be promoted.

2.5.4.2 Modulus of Elasticity

The strength of bamboo strip in bending is an important mechanical property since most of the structures constructed from bamboo are likely to be subjected to loads that may cause it to bend. This is usually expressed by Modulus of Elasticity (MOE) or young modulus test. Sulaiman et al. (2018) in their study determined the mechanical properties of *Bambusa vulgaris* and *Schizostachyum brachycladum* in different ages. They reported that the *Schizostachyum brachycladum* showed slightly higher value of MOE compared to *Bambusa vulgaris* bamboo species. The mature age from *Schizostachyum brachycladum* with 50671.92 N/mm^2 had the higher value modulus of elasticity compared to the young age on this species with 37236.70 N/mm^2. While, the *Bambusa* *vulgaris* species also showed the mature age with 25218.25 N/mm^2 had the higher MOE compared than young age with 13006.08 N/mm^2. Their study concluded that mature *Schizostachyum brachycladum* had the higher strength properties and most stability in their structure. This is because the part was supported by unique physical properties such as density, basic density and dimension stability that have the larger and longer fibre length that can be supported by anatomical structure with high content of lignin.

Appiah-Kubi et al. (2014) in their study determined the mechanical properties of some bamboo species for efficient utilization in Ghana. They reported that *Dendrocalamus brandisii* had the highest mean MOE of 11797 N/mm^2 with the application of the formaldehyde adhesive whilst *Guadua chacoensis* had the least MOE of 7861 N/mm^2 with the application of the PVA. The mean MOE results of *Bambusa vulgaris* were consistent with all the three different adhesives 9794 – 9923 N/mm^2. Their study concluded that *Bambusa vulgaris* and *Dendrocalamus brandisii* recorded good strength properties with the application of the PVA and FWC adhesives. *Dendrocalamus brandisii* also had the highest MOE with the application of the FWC adhesive. *Bambusa vulgaris* and *Dendrocalamus brandisii* can be laminated into boards and beams using the readily available adhesives, FWC and PVA, for constructional purposes. With the dwindling wood resources, the use of laminated bamboo boards and beams should be promoted.

Mansur (2000) also found the mechanical properties to be greater at the top portion when nodes and internodes were tested at dry condition. They also found modulus of elasticity (MOE) is usually determined from the static than the dynamic bending tests of bamboo under dry conditions to be increased in height though with no significant difference. The static bending is preferable due to its accuracy in result values (Tsoumis, 1991).

2.5.4.3 Compression Strength

Compression strength is one of the important mechanical properties that help in determining the behaviour of bamboo under a given load. Compression parallel to grain is the application of a load to the ends of column along the grains of the bamboo. The use of compression test is to predict the behaviour of a bamboo column in a structure.

Appiah-Kubi et al. (2014) determined the mechanical properties of some bamboo species for efficient utilization in Ghana. They reported that *Bambusa vulgaris* had the highest compressive strength with the application of the FWC (52.41 N/mm^2) and PVA (50.71 N/mm^2). However, *Dendrocalamus brandisii* had the highest compressive strength with the application of the 5PU glue out of the three species. For compressive strength, FWC gave better results for all the three bamboo species. Their study concluded that *Dendrocalamus brandisii* recorded the best results with the application of the 5PU for compressive strength. *Bambusa vulgaris* laminates attain the highest compressive strength when FWC is used in the lamination. *Bambusa vulgaris* and *Dendrocalamus brandisii* can be laminated into boards and beams using the readily available adhesives, FWC and PVA, for constructional purposes. With the dwindling wood resources, the use of laminated bamboo boards and beams should be promoted.

Leoncio (2017) conducted investigation on comparative mechanical properties of selected bamboo species. The study aimed to evaluate some basic mechanical properties of selected bamboo species that are applicable to structural applications. Seven bamboo species planted inside the Central Mindanao University Campus were tested, namely: *Dendrocalamus merrillanus; Gigantochcloa atter; Bambusa vulgaris Var. Schrad; Dendrocalamaus asper; Dendrocalamus latiflorus; Bambusa vulgaris Schrad;* and *Bambusa blumeana* were subjected to compression parallel to grain test. Data were taken from bottom, middle and top portion of the bamboos. The study concluded that *Dendrocalamaus asper* has the stronger compressive strength, compared to other species. The study further reported that, the top portion of most bamboo species gives the higher mechanical properties than the middle portion and the basal portion is the weakest. It stated further that all seven bamboo species produced high values of compression strength parallel to grain.

Sharma et al. (2015) conducted a study on engineered bamboo for structural applications and determined the compression strength parallel to grain. They reported that the laminated bamboo recorded compression strength of 77 MPa. The representative curves show that laminated bamboo material exhibit bilinear behaviour. The failure mode for laminated bamboo material was fracture of the matrix and bamboo fibres. In comparison to other material, the laminated bamboo showed no influence of the direction of the glue line. Their study concluded that the products (bamboo scrimber and laminated bamboo) have properties that compare with or surpass that of timber.

Li (2004) conducted compressive strength of some bamboo species including *Phyllostchys pubescens* perpendicular to the longitudinal direction. The study reported that an increase in compressive stress corresponded with an increase in a bamboo"s age. A one-year-old bamboo was found to exhibit the lowest compressive stress with an average of 16.1 MPa while a five-year- old bamboo had the highest compressive stress with an average of 34.3 MPa. For the effect of height on compressive stress, the top portion of bamboo had the highest compressive stress while no significant difference was revealed between bottom and middle portion of some samples. The study further reported that, compression properties parallel to the longitudinal direction were significantly higher than that of the perpendicular to the longitudinal direction. This clearly shows that bamboo is a material that has directional properties. The variability of compression perpendicular to the longitudinal direction was significantly greater due to the weaker bond between fibres and more frequent random break of bond in tangential directions (Li, 2004).

2.6. Engineered Composite Products

Today, most material researchers and developers have shifted from monolithic to composite materials thereby adjusting to the global need for reduced weight, low cost, quality, and high performance in structural materials (Ejiofor & Reddy, 1997). Composite is a material formed by combining two or more distinct materials to improve the properties that are entirely different from the original components. According to Ates et al. (2008), composites are combination of two or more different materials to form an individual product of excellent properties and performance. Degarmo et al. (1980) also stated that composites are heterogeneous solids consisting of two or more different materials that may be mechanically, metallurgically or chemically bonded together.

Composites are materials made up of more than one constituent that are different on physical level possessing different properties which is significantly not the same as any of the constituents. Such products may be considered as unique and advanced engineering materials due to their versatility in applications.

Research has shown that, composites have moved through high technology and have emerged as engineering materials and advanced structural composite (Premomony, 1990) with an additional advantage of offering flexibility in design (Gasser, 2000). These have been used for several structural and non-structural applications as panels for both interior and exterior purposes as well as supporting other buildings structures (Laks, 2002). Bamboo has been utilized regularly in its natural form just like timber. However, due to technology advancement, bamboo has been transformed into engineered bamboo products by many researchers across the globe. Ganapathy et al. (1999) reports that there has been not less than twenty-eight (28) types of bamboo composite products developed by researchers in China and in other bamboo growing countries such as India, Indonesia, Japan, Laos, Malaysia, the Philippines, Taiwan, Thailand, Vietnam and Costa Rica. The laminated bamboo composite is one of the many engineered composite products that could be considered as structural material for both building and furniture industries. To obtain any engineered composite products the conversion of bamboo begins primarily in the processing of bamboo into basic raw materials such as slivers, bamboo mat or strips (Ganapathy et al. 1999) to be used for further processing into useful products. Bamboo can also be split open, crushed and glued to panel products.

2.6.1 Manufacturing of Engineered Bamboo Composites

The manufacturing of engineered bamboo products uses the whole culm, with different sections used for various manufacturing processes. The process of manufacturing bamboo boards began in the 1970s in China and has increased in production through industrialisation of the manufacturing process (Ganapathy et al. 1999). China leads the production and export of bamboo-based products. Export is mainly to Western countries and Japan (Lobovikov et al., 2007). Mahdavi et al. (2011) reviewed different methods used to manufacture different types of engineered bamboo products - scrimber, laminated and rolled bamboo. The manufacturing processes of engineered bamboo composites, particularly laminated bamboo have been analysed in three methods.

2.6.1.1 Method 1

Nugroho and Ando (2001) investigated a technique to process glue laminated bamboo beams by progressively crushing Moso bamboo culms to produce strips using roller press crushers and create zephyr strand mats. The mats were then hot-pressed between 150°C and 180°C in order to achieve dimensional stability of the strips and create a smoother surface reducing the irregularity and fewer voids, since spaces between strands are likely to weaken the material. Dipping specimens in boiling water for one minute was found to aid in the flattening of fibres at lower press temperatures ranging between 100°C and 130°C but had less effectiveness at higher press temperatures ranging between 150°C and 180°C. After hot pressing, the mats were then passed through a planer to remove their inner and outer layers that contains wax and silica known for weakening adhesive bonding. The mats were then coated with resorcinol-based adhesive and placed on top of each other. Inner surfaces of the strips were bonded to inner or outer surfaces. Three glue-spreading rates were tested for optimal internal bond (IB) strength. Internal bond strength was optimal when using a glue spreading rate of approximately 300 g/m^2 and joining outer to inner surfaces of the mats. After applying the adhesive, the stacks of zephyr mats were cold pressed until the adhesive was fully bonded with the strips. The final product was then conditioned at 25°C and 65% relative humidity for a period of at least two weeks.

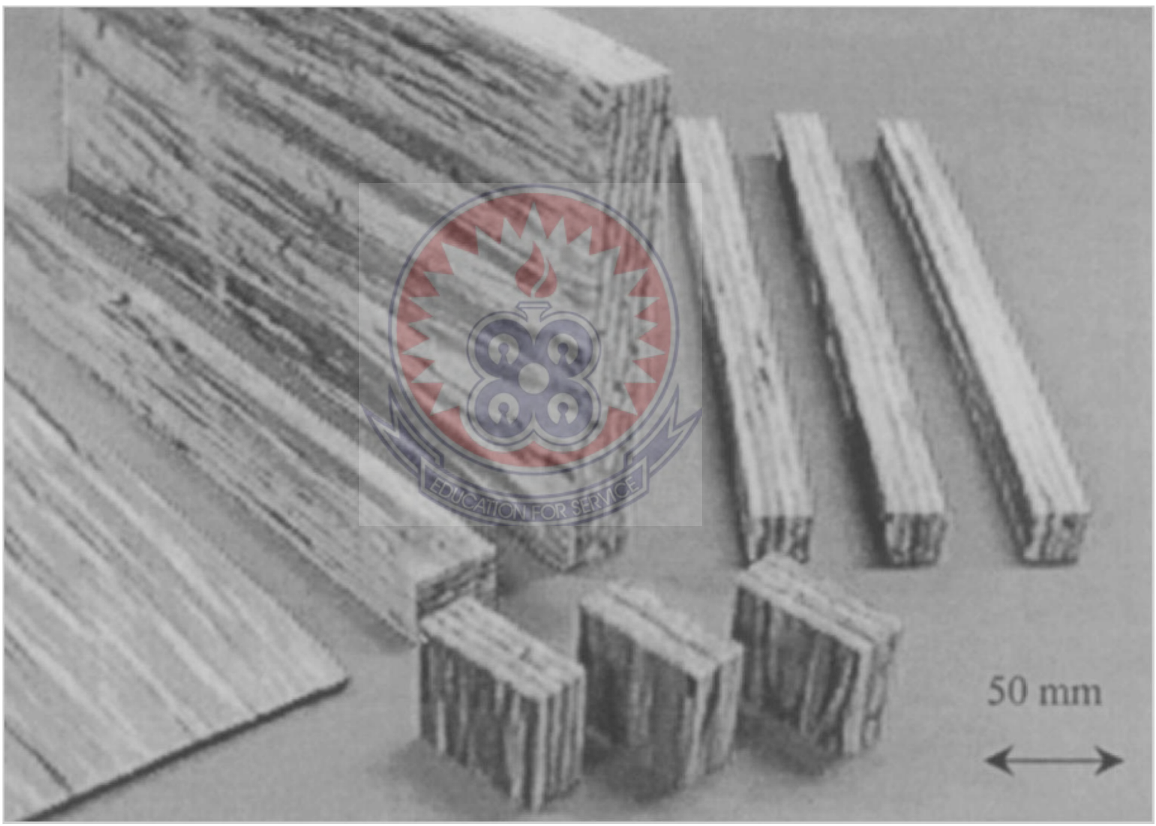

Figure 2.4 Samples of laminated bamboo lumber (LBL) (Nugroho & Ando 2001)

The effect of varying ply arrangement for Moso bamboo on strength properties was considered in this method, based on inner surface versus outer surface contact at interfaces where mats meet while joining in the presence of adhesive. Specimens made for testing were 4-ply, so, for each specimen, there were three interfaces to be glued, one at the centre of the mats and two on either side of the centre. Three variations were tested in this case:

1. Types I - Inner surfaces of culm were glued to outer surfaces of the mats at all interfaces.

2. Type II - Outer surfaces of culm were glued together at the centre interface of the mats, and at the outer interfaces inner surfaces were glued together.

3. Type III - Inner surfaces of culm were glued together at the centre interface of the mats, and at the outer interfaces, inner surfaces were glued together.

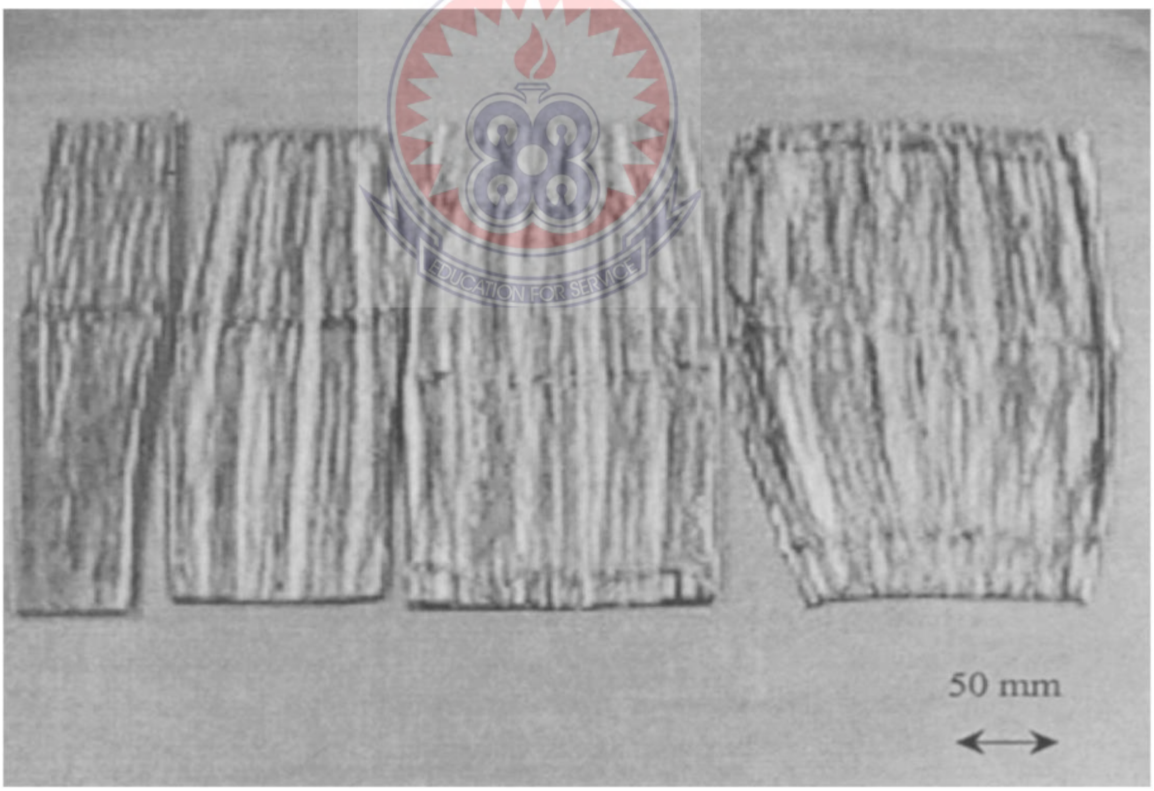

Figure 2.5 Bamboo zephyr strand mat made from Moso bamboo after a prehot- pressed treatment (Nugroho & Ando, 2001).

2.6.1.2 Method 2

Another technique of processing glue laminated bamboo beams was investigated by Sulastiningsih and Nurwati (2009), Rittironk and Elnieiri (2007). In this case, bamboo strips were produced by feeding bamboo culms through a splitter machine that cut the bamboo culm into slender strips. Both surfaces of the strips were scraped and planned to remove the wax and silica and create rectangular cross sections for ease of use. Adhesive was then applied to the strips that were then neatly arranged on top of one another to create the final product. Based on the approach by Sulastiningsih and Nurwati (2009), the strips were left to air-dry at room temperature for a period of one week after cutting them. The air-dried strips were then immersed in a boron solution and left to dry in the sunlight to reduce their moisture content to 12%. By placing bamboo strips, side-by-side and edge gluing them using tannin resorcinol formaldehyde (TRF) extracted from black wattle, bamboo sheets were produced. The sheets were then stacked on top of one another, while keeping the grains parallel and using the same adhesive clamping them with no heat for four hours.

This method considered two different bamboo species namely: -

1. Bamboo tali [*Gigantochloa apus* (Schult. & Schult. f.) Kurz] and
2. Awi mayan (*Gigantochloa robusta Kurz*).

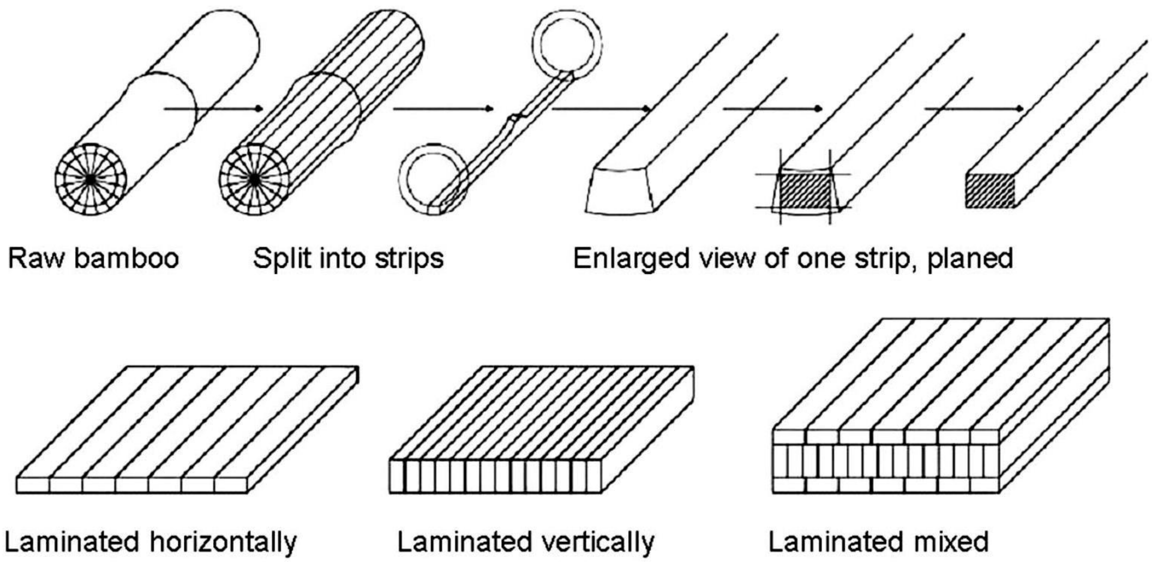

Figure 2.6: The Manufacturing process of LB using bamboo strips (Rittironk & Elnieiri 2007)

2.6.1.3 Method 3

A third technique was investigated by Lee et al. (1998). First Moso bamboo culms were split in half longitudinally. The splits were then flattened at a pressure of 690 kPa for one to four minutes. The curvature and thickness of the bamboo splits achieved determined whether or not to increase or decrease the amount of time during pressure application. The inner and outer layers of the flattened bamboo were passed through a planer in order to remove the wax and silica usually contained in these layers. Resorcinol based adhesive was then applied to the flattened and planed surfaces of the bamboo splits. The splits were then carefully stacked on top of one another and the stack placed under a pressure of 1,380 kPa for twelve hours. The resulting product was then conditioned at 25°C and 65% relative humidity for a period of at least two weeks. This method considered a 2 × 3 factorial design where two moisture contents and three glue-spread rates with Moso bamboo were varied.

2.6.2 Adhesives Composition

During the 20th century, wood adhesives shifted from natural to synthetic organic polymers. A polymer is a large molecule constructed of many small repeated units. Natural polysaccharide and protein polymers in blood, hide, casein, soybean, starch, dextrin, and other biomass have been used as adhesives for centuries (Frihart & Hunt, 2010). These polymers are still in use today, although they have been largely replaced by petrochemical and natural-gas-based systems. The first wood adhesives based on synthetic polymers were produced commercially during the 1930s (Frihart & Hunt, 2010). Synthetic polymers can be made stronger, more rigid, and more durable than wood and they generally have much greater water resistance than do traditional adhesives from natural polymers. However, recent advances in biomass-based adhesives have made them more competitive with fossil-fuel-based adhesives than are traditional ones (Frihart & Hunt, 2010).

Whether a synthetic adhesive is thermoplastic or thermosetting has a major influence on its performance in service. Thermoplastics are long-chain polymers that soften and flow on heating and then harden again upon cooling. They generally have less resistance to heat, moisture, and long-term static loading than do thermosetting polymers. Common thermoplastic adhesives for wood include poly (vinyl acetate) emulsions, elastomerics, contacts, and hot-melts. Thermosetting polymers make excellent structural adhesives because they undergo irreversible chemical change when cured, and on reheating, they do not soften and flow again. They form cross-linked polymers that can have high strength, have resistance to moisture and other chemicals, and are rigid enough to support high, long-term static loads without deforming. Phenol-formaldehyde, resorcinol-formaldehyde, melamine-formaldehyde, urea-formaldehyde, isocyanate, and epoxy adhesives are examples of thermosetting polymers (Frihart & Hunt, 2010).

In composite production, adhesive is the key element to facilitate the realization of the product. It must provide adequate penetration and enhance interface bonding among the materials. The manufacturing of bamboo composite products for structural or non-structural applications are largely influenced by the kind of adhesive selected since it has greater influence on the products‟ durability. Studies have shown that formaldehyde-based resins are the most preferred adhesive by industry players in the production of some bamboo products due to their cost-effectiveness (Xiao et al., 2013; Bansal & Prasad, 2004).

2.6.3. Uses of Laminated Bamboo Composite

Bamboo is considered as a substitute material to wood in the furniture industry, due to its numerous qualities seen over the years. According to Ladapo et al. (2017), bamboo is difficult to differentiate it from wood when laminated and used for furniture. It provides an excellent alternative to wood in the production of various furniture products in some tropical countries like China, India, Thailand, Vietnam and so on. These products include mat board, composite board, particleboard, ply bamboo, laminated bamboo, mat ply bamboo, curtains ply bamboo, laminated bamboo strips, mat curtain plywood, bamboo chipboard, floor tiles and composites, beds, cupboard, table, upholstery chairs (Sattar et al., 1990; Naxium, 2001; Ladapo et al., 2017).

Laminated Bamboo Lumber is used in the US for such non-structural components as flooring, countertops, and railings but has been shown to have structural properties and quality similar or better to wood lumber (Rittironk & Elnieiri 2007). Bamboo plywood is also formed from the lamination of bamboo strips into sheets (van der Lugt, 2009). China is the leading producer of bamboo board and flooring material, as well as woven bamboo mats. Other engineered products include bamboo mat board, bamboo mat veneer composite, bamboo mat corrugated sheets (roofing material), bamboo sliver laminated lumber, strand woven bamboo, and bamboo particleboard similar to wood oriented strand board (OSB) which all attempt to optimize strength and utilize more of the raw bamboo culms in production (Vengala et al., 2008; Van der Lugt, 2009).

Bamboo provides an excellent viable alternative to timber for construction because of its low-cost and fast growth rate (Ogunwusi & Onwualu, 2013). Bamboo can be used as posts, roofs, walls, floors, beams, trusses and fences (Lobovikov et al., 2007) in the construction of various housing units. Bamboo can also be used for irrigation and drainage pipes, bridges, flooring and floor covering, lamination of strip (plywood), decking, bamboo scaffolding and cladding, engineered bamboo flooring products, high-density beams and panels, composite board, particleboard, bamboo prefabricated house

(Lipangile, 1991; Lobovikov et al., 2007; Akinbile et al., 2011; Ogunwusi & Onwualu, 2013; Ladapo et al., 2017).

Bamboo has been used as a substitute for materials like steel for fabrication of concrete structures. According to Ladapo et al. (2017), bamboo is suitable for reinforcing concrete. This was possible as results of studies done on the properties of bamboo. Some bamboo products for building construction purpose include ply bamboo, bamboo panels/composite boards of different types, particle boards, mat boards, bamboo parquet and bamboo fibre-reinforced plastic (Sattar et al., 1990; Naxium, 2001; Ogunwusi, 2011). Xiao et al. (2008, 2010) developed Glubam using 2,440 mm by 1,220 mm bamboo veneer sheets (bamboo „plywood") that are finger jointed and cold pressed. Through this process, girders were produced, tested, and used in the construction of a Glubam girder bridge able to carry an eight-ton two-axle truck. Xiao et al. (2008) have also constructed a pedestrian bridge, a single-story house, and a two-story house using Glubam components. Laminated Bamboo Lumber was used as substitute for Traditional Wood Carving in Ghana (Asmah et al., (2016).

2.7 Natural Durability of Bamboo

The natural durability of bamboo material can be described as the ability of bamboo species to resist biodegradable organisms such as termites, fungi and beetle. Bamboo is more susceptible to decay than timber due to a lack of natural toxins (Janssen, 2000), generally higher levels of starch and its typically thin walls, which means that a small amount of decay can have a significant percentage change in capacity.

Wei et al. (2013) studied durability test of five bamboo species against fungi. They reported that, considerable variability exists in the durability of the bamboo species. *Guadua angustifolia* was rather resistant to *Trametes versicolor* and *Dendrocalamus asper* against *Chaetomium globosum*. Among the brown-rot fungi, the four strains of *Coniophora puteana* and two strains of *Gloeophyllum trabeum* produced low mass loss (maximum 2.9 %). Of the white-rot fungi, *T. versicolor* yielded the highest decay (max. 15.3 %), whereas *Schizophyllum commune* was rather inactive (max. 3.2 %). Of the soft-rot fungi, *Ch. globosum* showed medium degradation (max. 9.6 %) and *Paecilomyces variotii* low decay (max. 3.1 %). Their study concluded that, bamboo species differ in their susceptibility to fungal decay. With regard to the different groups of rot fungi, bamboo seems to be rather resistant against brown-rot fungi, whereas some soft-rot and white-rot fungi produce considerable deterioration.

Kim et al. (2011) studied fungi associated with bamboo and their decay capabilities. They concluded that, 18 fungal species belonging to 16 genera were isolated from bamboo used outdoors. Among them, 76.2% of isolates were *Ascomycetes* and 23.8% *Basidiomycetes*. They further stated that in decay tests, the greatest weight losses were observed for bamboo samples associated with *T. versicolor*, whereas in the soft-rot test, the greatest weight loss occurred with *A. arundinis*, regardless of the bamboo species tested. Although *T. versicolor* and *A. arundinis* were the second most dominant species of *basidiomycetes* and *ascomycetes* isolated, respectively, they might be the major agents of decay.

Thwe and Liao (2003) studied durability of bamboo-glass fibre reinforced polymer matrix hybrid composites. Their study concluded that bamboo fibre degrades by decomposition into thin fibrils and detached layers while the PP matrix degrades by dissolution. They further mentioned that the hybrid approach of blending more durable glass fibre with bamboo fibre is an effective way to improve the durability of natural fibre composite under environmental aging.

Falemara et al. (2018) studied durability assessment of cashew nut shell liquid on *Bambusa vulgaris* schrad in timber graveyard test. Their study concluded that treatment of bamboo samples with undiluted cashew nut shell liquid (CNSL) extract can be used to prolong its serviceable lifespan to a considerable extent since it performed better next to the solignum preservative.

Bui et al. (2017) studied bamboo treatment procedure and its effects on the durability and mechanical performance. Their study concluded that, the treatment duration influenced properties of treated bamboos. Additionally, the treatment methods increase both the durability and the mechanical properties of treated compared to untreated bamboo.

Ridzqo et al. (2020) studied sustainable material: Development experiment of bamboo composite through biologically binding mechanism. Their study concluded that, composite boards are highly potential to be developed for building non-structural function. In addition, the engineered composite boards made of bamboo powder are assessed very well from the aspect of density, internal bonding, and swelling thickness. They finally concluded that, this novel biocomposite board is expected to replace the need of non-structural composite boards which are not environmentally friendly and have been widely used in buildings.

2.7.1 Overview of Boron Compounds

Boron compounds may have been known for about 6000 years, starting with the Babylonians. The Egyptians, Chinese, Tibetans and Arabians are reported to have used such materials. The Arabic word for borax baurach, which also represents a number of other minerals, is found in old manuscripts from Persia and Arabia. Specimens of Chinese pottery utilizing colourful borax glazes made in third century exist today. „Tincal", the mineral name for borax decahydrate (Na2B4O7 .10H2O), was derived from tincana, the Sanskrit word for borax. The element boron was not discovered until 1808 when Humphry Davy (1778-1819), Joseph-Louis Gay-Lussac (1778-1850) and Louis-Jacques Thénard (1777-1857) prepared it independently by reducing boron trioxide with potassium and by electrolysis of moistened boric acid. The purity of their products was about 50%. Highly pure boron (~100 %) was not prepared until 1909. Boric acid deposits were discovered by 1772 in Italy, and about 1836 borates were discovered in Chile and Argentina. These deposits quickly became the major source of borates until the twentieth century when the huge fields discovered in the Nevada and California superseded them (Wisniak, 2005).

2.7.1.1 Borax and Boric Acid

History has shown that the Babylonians brought borax from the Far East more than four thousand years ago to be used by the goldsmiths. Archaeological evidence shows that tinkar (tincal) was first used in the eight century around Mecca and Medina, having been brought there (and to China) by Arab traders. The use of borax flux by European goldsmiths dates to about the twelfth century. Since then, borax has been used for several activitiesup till date (Wisniak, 2005).

Literature has shown that the first proof of the composition of boracic acid and isolation of boron the element, was given independently by Davy, Gay-Lussac and Thenard in 1808, when they decomposed it by reduction with potassium. Since then, several studies have been done to support this composition of boric acid and also promoting the modification of the composition as well. Today, world production of borax minerals has risen from about 10,000 tonnes a year in the nineteenth century to over 4.5 million tonnes today. The U.S. is responsible for the bulk of the world"s production of borate, coming from the Kramer deposits and the brines at Searles Lake (Wisniak, 2005).

Boron in its combined form of borax has been used since early times. Early uses were as a mild antiseptic and cleaner because of its detergent and water softening properties. Later it was used as a soldering flux and ceramic flux because of its ability to dissolve metal oxides. Glass and related uses consume about one-half of the borates as boric anhydride, B_2O_3, in the US. Fiberglass accounts for the largest share, comprising about

69% of the total (50% for insulation fiberglass, 19% for textile grade). Small amounts are used in sealing and optical glasses, Vycor, and vitrifying nuclear waste (Wisniak, 2005).

Boric oxide can be added to the glass formulation as borax pentahydrate, boric acid, or colemanite, with price and cation compatibility determining which is used. Boron minerals and compounds (B_2O_3), are used in Borosilicate glasses, Enamels, frits, glazes, Fire retardants, Insulation grade glass fibres, Metallurgy, Soaps and detergents, Textile-grade fibres and many others. Boron gives a blue-green flame, and the brown amorphous form is often used in pyrotechnical devices for this purpose. The colour can be distinguished from the emerald green of copper. Boron will not form BH_3. Instead, it forms larger borohydrides called boranes. Tetraborane has a foul smell; diborane, B_2H_6 has no boron-boron bonds, but two bridging hydrogens out of plane in the planar molecule (Wisniak, 2005).

2.8. General Utilization Potential of Bamboo Resources

Bamboo is one of the important natural resources that play a major role in shaping consumer preference on products. Globally, bamboo has been accepted as versatile and vital raw material (Salam, 2008) that has numerous potentials for economic development of nations (Ladapo et al. 2017). Gielis (2002) grouped the various uses of bamboo into two. These include the use of bamboo as plant and the use of bamboo as material. Gielis further grouped the use of bamboo as plant into three which include Ornamental horticulture, Ecology and Agro-forestry while the use of bamboo as material was also subdivided into four, and these include Local industries, Wood and paper industries, Nutritional industries, and Chemical industries.

Bamboo industrial acceptability is based on its technological characteristics (Okumura, et al., 2011). This has therefore helped in promotion of bamboo products because the production of these products contributed significantly in meeting the demands of the growing population of the world. Today, the demands for globally acceptable materials for development have been based on one that is biodegradable, sustainable and recyclable (Khalil, et al., 2012) in order to save the environment. Today, there are almost 3000 companies around the world that produced various bamboo related products (Xuhe, 2003).

Bamboo has been utilized in different sectors of industries including civil construction, wood, paper and pulp, textile, electrical and electronics, agriculture and agro-allied, food, chemical and pharmaceutical, reinforcement, automobile and medicine. Some bamboo-based products include house construction materials, household items, biofuel, chemical and pharmaceutical products, pulp and paper, irrigation and drainage pipes and textiles materials, panels, flooring materials, charcoal, edible shoots and other daily-use articles (Xuhe, 2003; Ladapo et al., 2017). Bamboo has industrial utilization potentials in areas of applications such as structural and non-structural purposes.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Introduction

This chapter describes the research methodology employed in the study. It discusses the materials and material preparation. Laboratory experiments were conducted for the chemical, anatomical and physical properties of *Bambusa vulgaris* in order to ascertain their effect on the laminated bamboo composite. Additionally, tests were conducted on the physical, mechanical and durability properties of the laminated bamboo composite to determine their suitability in the construction industry. The laboratory investigations on the laminated bamboo composite were undertaken at the Forestry Research Institute of Ghana (FORIG) in Kumasi and at the Wood and Construction Department laboratory in the University of Education, Winneba - Kumasi Campus. The statistical tools used for the data analysis are also discussed.

3.2. Materials and Material Preparation

The materials used in this experimental study were matured bamboo culm, juvenile bamboo culm, rapid lion (RL) 5 minutes express wood adhesive and others. The under listed sections give full description of the materials used in the study.

3.2.1. *Bambusa vulgaris* Culm

Bambusa vulgaris culms used for this study were obtained from clumps in Bibiani, in the Western North Region of Ghana located between latitude 6° N, 3° N and longitude 2° W, 3° W. Bibiani falls within the Equatorial Rain Forest Zone and the natural vegetation is moist-deciduous forest. Humidity is relatively high, averaging between 75 percent in the afternoon and 95 percent at night and early morning.

Mature (4-years) and juvenile (2-years) culms were used for the study and the culms in each sampled group were classified according to their portions of bottom and top respectively. The determination of the culm‟s age was based on the features of culm sheath, the development of branches and leaves, and the external colour of the culm (Singnar et al., 2017). The culm ages were determined as follows: 1-year-old bamboo had sheath still on the culm and the culm has pale surface colour covered with a white powder. The 2-year-old bamboo had few sheaths at the base of the culm with some beginning to rot; have well-developed branches on 5th and 6th internodes, the white powder on the culm surface also begging to disappear while the culm is turning dark green in colour. For the 3-year-old bamboo, the culm had sheaths already dropped and the culm‟s bottom had turned dark green symbolizing near maturity, and characterized by the appearance of few lichens and mosses on culm surfaces. The 4-year-old bamboo had the sheath disappeared from the surface of the culm, which was mouldy and had become light yellowish green in colour with increased quantities of lichens and mosses. For bamboos that were 5 years old or greater, the culm surface was covered with abundance of moulds or mosses and had turned brownish green in colour (Singnar et al., 2017). *Bambusa vulgaris* culm of 2 years old and 4 years old were used for the experimental study as shown in Figure 3.1.

Figure.3.1: *Bambusa vulgaris* clumps showing A= mature culm and B= juvenile culm

The mature and juvenile culms were selected based on their straightness and culm diameter before harvesting for the study. Ten culms were selected from each of the five clumps. In total, (50) *Bambusa vulgaris* culms were harvested, of which (25) were juvenile culms and the other (25) mature culms. The culms were cut approximately 30 cm above ground level and were coated with wax immediately to reduce sap evaporation and prevent fungal and insect attack. *Bambusa vulgaris* culms were then transported to Allahji Wood Workshop at Bibiani-Mota for further processing into various sample sizes for testing. Both mature and juvenile culms were labelled to ensure easy identification and collection for various tests samples.

3.2.2. Rapid Lion Express Pu Wood Adhesive

Rapid lion express wood adhesive is a one-component, fast curing liquid polyurethane adhesive. It possesses high water resistance and bonding strength. This adhesive is normally used for both exterior and interior purposes. It is a waterproof – liquid and gap filling material. It also has acid and chemical resistant properties. The rapid lion (RL) 5 minutes express wood adhesive was sourced from Bibiani Central Market in the Western North Region of Ghana. In all, a bottle was purchased for the experimental studies as shown in Figure 3.2.

Figure 3.2: Rapid lion 5 minutes express pu wood adhesive used.

3.3.1 Processing of *Bambusa vulgaris* Culms

The total length of *Bambusa vulgaris* culms used for the study was determined using the number of internodes. In all, 21 internodes were used to represent the total length of the culms for both mature and juvenile in the study. The whole culm was divided into three equal part with 7 internodes per culm section (bottom, middle and top). The juvenile and mature culms were crosscut and grouped accordingly to ensure easy identification and collection for various tests samples. Out of this division, the study only focused on the bottom and top parts for the tests conducted for the study.

3.3.2. Sample Preparation of *Bambusa vulgaris* Culms for Chemical Test.

Four *Bambusa vulgaris* culms were selected of which two each from juvenile and mature groups as samples for preparation for chemical test and these culms were separately prepared. They were split with cutlass into strips before cutting them into smaller sizes samples. These samples were air dried at room temperature for three weeks. The samples were then sent to milling machine for grinding into fine particle sizes as shown in Figure 3.3. The samples of these materials milled were sent to the chemical laboratory of Forestry Research Institute of Ghana (CSIR-FORIG) for further milling in order to meet the sieving requirement of British standard 0.600mm aperture before performing the chemical composition test. The chemical test conducted included acetone soluble extractive content, ethanol soluble extractive content, holocellulose soluble content, cellulose soluble content, lignin soluble content, hemicelluloses soluble content, cold water-soluble extractive content and hot water-soluble extractive content.

Figure 3.3: Grinding of bamboo culms samples at Alahaji milling shop, Bibiani old town.

All tests were conducted under the standards of TAPPI, except for alcohol-benzene solubility. There was a minor modification for the extractive content test. Instead of alcohol-benzene, ethanol was used. The exact standard that was followed for each chemical property performed is presented in the Table 3.1.

Table 3.1: TAPPI Standard used for Chemical Analysis

Soluble Content	Standard Methods
Acetone*	TAPPI standard method T 204 cm-97
Alcohol	TAPPI standard method T 204 cm-97
Hot-water	TAPPI standard method T 207 cm-97
Cold water	TAPPI standard method T 207 cm-97
Holocellulose	TAPPI standard method T 203 cm-74
Cellulose	TAPPI standard method T 203 cm-74
Lignin	TAPPI standard method T 222 cm-06

The total extractives were determined in three successive steps, an extraction with acetone soluble, an extraction with alcohol soluble and a hot water-soluble extraction, according to TAPPI standard listed in the Table 3.1. The dried samples were ground into powder with Wiley mill in order to pass 40-mesh (425 µm) sieve and retained on 60-mesh (250 µm) sieve. The extraction was performed using soxhlet extractor. After the extractions, the bamboo samples were air-dried prior to the determination of its chemical components.

3.3.2.1 Alcohol Solubility Content of *Bambusa vulgaris*

The extraction apparatus consisted of a soxhlet extraction tube connected on the top end of a reflux condenser and joined at the bottom to a boiling flask. A two-gram (2g) oven-dried sample was placed into a cellulose extraction thimble. The thimble was plugged with a small amount of cotton and placed in a soxhlet extraction tube. The boiling flasks contained a 2:1 solution of 95 percent ethyl alcohol and distilled toluene, and placed on a heating mantle. The extraction was conducted for eight hours (8hrs) at the rate of approximately six siphoning per hour. When the extraction was completed, all of the remaining solution was transferred to the boiling flask that was heated on a heating mantle, until the solution was evaporated. The flasks were oven-dried at 103±2°C, cooled in a desiccator, and weighed until a constant weight was obtained. The following formula was used to obtain the alcohol-toluene solubility content of bamboo:

Alcohol soluble content (%) = $(W_2 / W_1) \times 100$

Where,

W_1= initial weight of oven-dry test specimen (grams).

W_2= weight of oven-dry extraction residue (grams).

3.3.2.2 Hot-Water Solubility Content of *Bambusa vulgaris*

Two-gram (2g) sample was oven-dried and placed in a 250 ml Erlenmeyer flask with 100 ml of distilled water. A reflux condenser was attached to the flask and the apparatus was placed in a gently boiling water bath for three hours. Special attention was given to ensure that the level of the solution in the flask remained below that of the boiling water. Samples were then removed from the water bath and filtered by vacuum suction into a fritted glass crucible of known weight. The residue was washed with hot tap water before the crucibles were oven-dried at 103±2°C. The Crucibles were then cooled in a desiccator and weighed until a constant weight was obtained. The following formula was used to obtain the hot-water solubility content of bamboo:

Hot-water solubility, (%) = $[(W_1 - W_2) / W_1] \times 100$

Where,

W_1= initial weight of oven-dry test specimen (grams).

W_2=weight of oven-dry specimen after extraction (grams).

3.3.2.3 Cold Water Solubility Content *Bambusa vulgaris*

Two-gram (2g) samples was oven-dried and placed in 400ml beaker and 300ml of distilled water was slowly added, making sure the bamboo is well wetted initially to avoid the tendency to float. The extraction was carried out at 23 ± 2°C with constant stirring for 48 hours. Then, the material was transferred to a tared filtering crucible which has been previously dried to a constant weight at 105 ± 3°C. It is then washed with 200ml of cold distilled water, and dried to constant weight at 105 ± 3°C. After that, the heated crucible is placed in a tared, loosely-stoppered weighing bottle and cooled in a desiccator before weighing. The following formula was used to obtain the cold-water solubility of bamboo:

Cold water solubility content, (%) = $[(W_1 - W_2) / W_1] \times 100$

Where,

W_1= initial weight of oven-dry test specimen (grams).

W_2= weight of oven-dry specimen after extraction (grams).

3.3.2.4 Holocellulose Solubility Content in *Bambusa vulgaris*

Holocellulose content was determined by weighing 2g of extractive free sample in a 250ml conical flask with a small watch glass cover. The sample was then treated with

180ml of distilled water, 8.6g of Sodium acetate, 6.0ml of acetic acid and 6.6g of Sodium chlorite. The sample was covered and place on hot-water bath for 3hrs. The sample was removed and placed in an ice water bath until cold to room temperature. The sample was filtered into a coarse porosity fitted-glass of known weight and washed free from ClO_2, with distilled water. The crucible was oven-dried at 103°C, cooled in desiccator, and weighed until a constant weight was reached. The percentage of holocellulose was calculated. The following formula was used to determine the holocellulose content in bamboo:

Holocellulose solubility content in bamboo (%) = $[(W_4 - W_3)/(100 \times W_2)] \times (100 - W_1)$

Where;

W_1=alcohol-toluene extractive content (%).

W_2=weight of oven-dried extractive-free sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

3.3.2.5 Alpha-cellulose Solubility Content in *Bambusa vulgaris*

Cellulose was determined by weighing 1.5g of the holocellulose into 250ml Erlenmeyer flask with a small watch glass cover. The flask was placed into water bath at 25°C and 100ml of 17.5% NaOH solution added while thoroughly stirring. After 30 minutes of stirring, another 100ml of water was added as stirring continued for another 30mins. The Erlenmeyer flask was removed and filtered with a fritted-glass crucible of known weight. The residue was washed with 25ml of 9.45% NaOH solution, and then with 40ml of 10% acetic acid and finally washed to free from acid with plenty of water. The residue was oven-dried in an oven at 103°C, cooled in a desslcator, and weighed until a constant weight was reached. The percentage of alpha-cellulose was then calculated. The following formula was used to obtain the alpha-cellulose content in bamboo:

Alpha-cellulose solubility content (%) = $[(W_4 - W_3)/ (100 \times W_2)] \times W1$

Where,

W_1= Holocellulose content (%).

W_2= weight of oven-dried holocellulose sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

3.3.2.6. Lignin Solubility Content in *Bambusa vulgaris*

Lignin was determined by weighing 1g of extractive-free sample into a conical flask.15 ml of cold sulfuric acid (72%) was slowly added while stirring, in order to obtain an even mixture. The reaction proceeded for two hours with frequent stirring in a water bath maintained at 18-20°C. When the two hours had expired, the specimen was transferred by washing it with 560 ml of distilled water into a 1,000 ml flask, diluting the concentration of the sulfuric acid to three percent. A condenser was attached to the flask and placed in a boiling water bath for four hours. The flasks were then removed from the water bath and the insoluble material was allowed to settle. The contents of the flasks were filtered by vacuum suction into a fritted-glass crucible of known weight. The residue was freed of acid by washing with 500 ml of hot tap water, and then oven-dried at 103°C. Crucibles were then cooled in a desiccator and weighed until a constant weight was obtained. The following formula was used to obtain the lignin content of bamboo:

Klason lignin solubility content in bamboo (%) = $[(W_4 - W_3)/ (100 \times W_2)] \times (100 - W_1)$

Where,

W_1=alcohol-toluene extractive content (%).

W_2=weight of oven-dried extractive-free sample (grams).

W_3=weight of oven-dried crucible (grams).

W_4=weight of oven-dried residue and crucible (grams).

3.3.3. Sample Preparation of *Bambusa vulgaris* Culms for Anatomical Test.

Four *Bambusa vulgaris* culms were randomly selected of which two each from juvenile and mature groups as samples for preparation for anatomical test and these culms were separately prepared. The first internode for the bottom and the last internode for the top were selected as test samples for the study. These samples were sent to the anatomical laboratory of the Forestry Research Institute of Ghana (CSIR-FORIG) for further preparations in order to meet the required standard before performing the anatomical test. The anatomical test conducted included fibre properties (length, diameter, and lumen width, wall thickness), tissue proportions per mm^2, vascular bundle properties (vascular bundle type, vascular bundle radial length, vascular bundle tangential diameter), vessel diameter, Transverse and Longitudinal sections of raw bamboo.

3.3.3.1 Vascular Bundle

For vascular bundle determination, 2cm square of both juvenile and mature bamboo samples were prepared. The samples were put in a labelled plastic vial containing water for at least 21 days. After 21 days, the water was replaced with equal parts 1:1 solution of ethanol and glycerol for at least one week. Thin sections were made from the two-dimensional faces (cross-section and longitudinal) using a microtome. The microtome sections were placed into a petri dish containing distilled water. This removed the ethanol and glycerol from the sections. A stain solution with safranin was prepared and the best-selected sections carefully dropped into it. The stained sections were removed and washed with distilled water. The sections were then transferred through increasing concentration of ethanol (30%, 50%, 70% 95% and 100%) after keeping each concentration for 15 minutes, to slowly take out moisture in the thin section and to avoid crumbling. The dehydrated microtome sections were then put in xylene for another 15 minutes to remove little traces of water. Finally, the single sections for the 2-dimensional face were mounted on a slide and Canada balsam added. Sections were carefully covered with slips, making sure bubbles were not trapped. Prepared slides were placed in an oven at 60°C to enhance drying.

Microscopic observation of the slide was done in a light compound microscope at 40X magnification. The focused area was divided into three; outer, middle and inner sections and photograph of sections were taken before the vascular bundle properties with the help of Image – j 152 java8 software were measured.

3.3.3.2 Determination of Fiber Properties

The strength and durability of bamboo culm as well as their physical and mechanical properties are highly influenced by the fibre component. The determination of fibre properties of the bamboo culms was carried out in accordance with the procedure of

Franklin (1927). Anatomical analysis of the fibre properties includes the investigation of the fibre‟s length, diameter, lumen width and wall thickness.

Four bamboo samples of which two each of juvenile and mature culms were prepared to a match-stick size wood and placed in a labelled vial tube. Hydrogen peroxide and acetic acid of equal proportion were added. The tube is kept in an oven at 60°C to facilitate the chemical reaction on the bamboo. A check is done every 24 hours until the bamboo is completely macerated. The macerated is then transferred into a clean vial and washed with distilled water to remove chemicals.

Figure 3.4: Samples of macerated fibres in distilled water and alcohol for preservation.

Water and alcohol are then added to preserve the macerate as shown in Figure 3.4 above. A macerate is then taken into a petri dish and glycerol drops are added. The macerates were carefully teased out to separate the individual bamboo components. Drop of macerate was fetched onto a slide and then covered using cover slips. The slip was then mounted on a microscope for the measurement.

The fibres were randomly selected from the focused area and the fibre length on the image was measured as shown in Figure 3.5 by using camera fitted microscope and Motic Image Plus 2.0 software. On the whole, hundred (100) fibres were selected and measured.

Figure 3.5: *Bambusa vulgaris* fibre measurement.

3.3.3.4. Bambusa vulgaris Culms for Scanning Electron Microscopy Analysis

Bambusa vulgaris species of different ages (juvenile and mature) were visualized under scanning electron microscopy (SEM) to study some detailed features of bamboo culm structure. The SEM micrographs were taken from the cross-section and longitudinal section of the sample specimens prepared to the size of 15mm x 15mm x 15mm. The specimens were in dry condition before they were coated with gold by an auto fine coater (JFC-1600 Instruments, Japan) as shown in Figure 3.6. The specimens were then visualized by Scanning Electron Microscope Phenom-World BV, Dillenburgstraat 9T, 5652 AM Eindhoven, Netherlands as shown in Figure 3.7. These included cross-section and longitudinal section of internodes and nodes, as well as detailing the parenchyma cell

density, basic density, moisture content, shrinkage (longitudinal, tangential and radial) and volumetric shrinkage.

3.3.5.1 Determination of Morphological properties

Internode distance, culm diameter and culm thickness were determined based on the measurement of (4) samples each selected from juvenile and mature bamboo culms. Each section of the culm sample was assigned a unique number for easy identification. The first five internode distance were measured internode by internode for all culms of the sections using steel tape measure whilst the culm diameter and culm thickness were measured using digital calliper respectively.

3.3.5.2. Determination of Moisture Content of *Bambusa vulgaris*

The moisture contents (MCs) of mature and juvenile *Bambusa vulgaris* culms were determined in accordance with EN 13183-1 (2002). The samples for the bottom and top culms were randomly selected for the study. In all, 30 replicates were cut from the prepared strips of each culm type sections for the determination of MC with the samples sized 20mm x 20mm x culm wall thickness (mm). Each sample was assigned a unique number. The MC for each culm type was obtained by first measuring its initial weight before drying, using an electronic weighing balance. The test samples were then oven dried for 24 hours at 103 ± 2ºC. The specimens were dried until the final oven dry weights were constant, after two successive weighings. The initial and oven dry masses of each specimen type were recorded. The MC was then calculated using this equation:

$MC\ (\%) = [(W_1 - W_2) / W_2] \times 100$

Where W_1 is the initial weight before drying (g) and W_2 is the oven-dried weight (g). The mean MC was then obtained by finding the mean value of MC for all the specimens of each bamboo type sections.

3.3.5.3 Determination of Shrinkage of *Bambusa vulgaris*

Determination of shrinkage for mature and juvenile *Bambusa vulgaris* culms was carried out in accordance with the procedure adopted by Dinwoodie (1989). In all, 30 replicates were cut from the prepared strips of each portion of the culms for the determination of shrinkage (S). Radial, Tangential, and Longitudinal shrinkages were measured with the samples sized 20mm x 20mm x culm wall thickness (mm). The samples were labelled „R", „T" and „L" respectively and identified. The initial dimensions (D_1) of the samples were taken using digital caliper before drying. The samples were then oven-dried at 103 ± 2°C until attainment of constant weight for 24 hours, after which the final dimensions (D_2) were recorded on the radial, tangential and longitudinal directions. The percentage of shrinkage (S_h) for each dimension was calculated using this equation:

Shrinkage (%) = $[(D_1 - D_2) / D_1] \times 100$ …………….. (1)

Where D_1 is the initial dimension before drying (mm) and D_2 is the final dimension after oven drying (mm).

Volumetric shrinkage (Vs) was estimated in accordance with the procedure adopted by Dinwoodie (1989) as given in Equation 2 and 3:

VS = SR + ST + SL …………….. (2)

Where VS= volumetric shrinkage; SR = radial shrinkage, ST = tangential shrinkage and SL= longitudinal shrinkage

3.3.5.4 Determination of Basic Density

Determination of basic densities for mature and juvenile *Bambusa vulgaris* culms were carried out in accordance with ISO 13061-2 (2014). In all, 30 replicates were cut from the prepared strips of each culm type sections for the determination of basic density (BD) with the samples sized 20mm x 20mm x culm wall thickness (mm). Each sample was identified. The basic density for each culm type was obtained by first measuring its initial weight, and then its dimensions, before drying. The test samples were then oven dried for 24 hours at 103 ± 2ºC until a constant weight was attained. The test sample specimens were then weighed to give the oven dry weight. The volume of specimens was obtained using the water displacement method. The weight displaced is converted to volume of the sample as a green volume. The oven dried mass (m) by green volume (v) of each test samples is given by the formula:

Density (ρ) = m / v

Where,

ρ = the density by green volume in kg/m^3,

m = the mass in grams (g) of the test samples oven dried

v = the green volume of the test samples in mm^3

3.3.6 Production of Laminated Bamboo Composite

Fifteen *Bambusa vulgaris* culms each were randomly selected from the bottom section of juvenile and mature as samples for preparation for laminated bamboo composites and these culms were separately prepared. The juvenile and mature culms were split into strips. The strips were edged and trimmed to 93cm x 3cm x culm thickness (length x width x thickness), before the inner and outer surfaces (wax and cortex) of the strips were removed through sanding. A Hitachi SP 18 VA portable sanding machine with Velcro paper grit: P80 was used as shown in Figure 3.8 to remove the inner and outer surfaces of the test samples for smooth lamination.

(a). Sander machine (b). Velcro paper grit: P80 (c). Fixing of Velcro paper

(d). Fixed Velcro paper. (e). Sanding of test samples.

Figure 3.8: Sanded test samples.

The sanded strips were glued together using rapid lion express wood adhesive resin with the trade name "5 Minutes". Two strips were glued and clamped together as shown in Figure 3.9 at a time before gluing them together to achieve the laminated dimension.

Figure 3.9: Picture of glued *Bambusa vulgaris* strips in clamps

The laminated bamboo composites produced measured 90cm x 7.5cm x 7.5cm (length x width x thickness) as shown in Figure 3.10 and six (6) replicates were produced in all. Each of the laminated bamboo composites produced was clamped together in cold-pressed method to ensure proper penetration of the adhesive and a strong bonding formation as well.

Figure 3.10: Sample of laminated bamboo: sample „A" for mature and sample „B" for juvenile.

3.3.7. Testing of Physical Properties of Laminated Bamboo Composites

The laminated *Bambusa vulgaris* composites produced from juvenile and mature groups as samples for preparation for physical test were sent to the wood and furniture testing centre of FORIG for further preparations in order to meet the requirement prescribed in the standard before performing the physical test. The physical test conducted included moisture content, shrinkage (longitudinal, tangential and radial), volumetric shrinkage and basic density.

3.3.7.1. Determination of Moisture Content

The MC of mature and juvenile laminated composites produced with 5RL adhesives were determined in accordance with EN 13183-1 (2002). In all, 10 replicates were cut from the prepared laminated composite types for the determination of MC with the samples sized 20mm x 20mm x 20mm. Each sample was identified. The initial weight (W_1) for each sample was measured using an electronic weighing balance, before drying. The samples were then oven dried for 24 hours at 103 ± 2ºC. The specimens were dried until their final weights were constant after two successive weighings. The oven-dried weight (W_2) of each specimen was recorded and the MC was calculated using this equation:

$$MC\ (\%) = [(W_1 - W_2) / W_2] \times 100$$

Where W_1 is the initial weight before drying (g) and W_2 is the oven-dried weight (g). The mean moisture content was then obtained by finding the mean value of MC for all the specimens of each laminated bamboo type.

3.3.7.2 Shrinkage Determination of Laminated Composites

Determination of shrinkage for mature and juvenile laminated composites produced with 5RL adhesive was carried out in accordance with the procedure adopted by Dinwoodie (1989). In all, 10 samples were cut from the prepared laminated bamboo type for the determination of shrinkage (S_h) with the samples sized 20mm x 20mm x 20mm. The specimens were labelled „R", „T" and „L" respectively and identified. The percentage of shrinkage (S_h) for each dimension was calculated using this equation:

Shrinkage (%) = $[(D_1 - D_2) / D_1] \times 100$ …………….. (1)

Where D_1 is the initial dimension before oven dry (mm) and D_2 is the final dimension after oven dry (mm).

Volumetric shrinkage (Vs) was estimated in accordance with the procedure adopted by Dinwoodie (1989) as given in Equation 2:

VS = SR + ST + SL …………….. (2)

Where VS= volumetric shrinkage; SR = radial shrinkage, ST = tangential shrinkage and SL= longitudinal shrinkage

3.3.7.3 Basic Density Determination of Laminated Composites

The determination of basic density for mature and juvenile laminated composites produced with 5RL adhesive was in accordance with BS 373 (1957). In all, 10 samples were cut from the prepared laminated composite types for the determination of basic density with the samples sized 20mm x 20mm x 20mm. Each sample was identified. The initial weight for each sample specimens were taken using electronic weighing balance, as well as its dimensions, using digital caliper before oven dry. The test samples were then oven-dried for 24 hours at 103 ± 2ºC until a constant weight was attained. The test sample specimens were then weighed to give the oven dry weight. The volumes of the samples were obtained using the water displacement method. The weight displaced was converted to the volume of the sample as a green volume. The oven-dried mass (m) by green volume (v) of each test sample is given by the formula:

Density (ρ) = m / v

Where,

ρ = the density by green volume in kg/m^3,

m = the mass in grams (g) of the test samples oven-dried

v = the green volume of the test samples in mm^3

3.3.8. Testing of Mechanical Properties of Laminated Bamboo

Prior to testing, all the samples were stored in controlled conditions at 65% RH and 20°C for 24 hours. The following properties of the produced laminated composites were determined according to BS 373 (1957) methods of testing small clear specimens of timber; Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) and compressive strength parallel to grain (CS//). The data obtained were statistically analysed.

3.3.8.1. Modulus of Rupture and Modulus of Elasticity

From each laminated composite, 10 bending test samples measuring 20 mm x 20 mm x 300 mm were selected and each labelled. The static bending test was done for the samples using INSTRON – 4482 testing machine as shown in Figure 3.11.

Figure 3.11: INSTRON 4482

3.3.8.2. Compressive Strength Parallel to Grain Test

From each laminated composite, 10 testing samples measuring 20 mm x 20 mm x 60 mm were selected for the compressive strength test and labelled. The compressive strength parallel to grain test was done for the samples using INSTRON – 4482 testing machine as shown in Figure 3.11.

3.3.9. Samples Preparations for Durability Test of Laminated Composites

The durability test was very essential in the utilization potential of laminated composites. The durability experiment for laminated bamboo composite was conducted using simple accelerated laboratory (soil block) method in accordance with the standard ASTM D 2017-05. These included the determination of the absorption of chemical formulation in the treated laminated bamboo composite; the determination of the fungicidal efficacy of preservative in the protection of laminated bamboo composite against *Coriolopsis polyzoma* fungi attack.

3.3.9.1 Soil and Wood Strip

Moist black top soil was collected from FORIG plantation yard and screened for the experiment. The soil had pH of 6.2 and moisture holding capacity of 39%. It was then half-filled into 500 ml glass jars. Wood strips measuring 50 mm x 15 mm x 3 mm of *Triplochiton scleroxylon* with the trade name "wawa" were prepared from a board to be used for receiving actively growing mycelium of the test fungus. In all, 60 strips were prepared for the experimental study.

3.3.9.2. Laminated Bamboo Composite Specimens

The bamboo sample specimens of 40, measuring 14 mm x 14 mm x 14 mm were prepared from mature laminated bamboo and juvenile laminated bamboo for the experimental study. These include 20 specimens as control samples of which 10 each were for the mature and juvenile laminates whereas 10 specimens each of mature and juvenile laminates for the preservative.

3.3.9.3. The Fungus used

The white rot fungi *Coriolopsis polyzona* was used to feed on the laminated bamboo blocks for the experimental study.

3.3.9.4. Growth Medium Preparation

A 50g of malt extract agar was added to 14g of bacteriological agar in 2L conical flask. Deionized / distilled water was added to bring the volume to 1L. It is then mixed thoroughly and heated gently to bring to boiling. The mixture was then distributed in

500ml conical flasks and corked with cotton wool. It was then autoclaved at 15 psi pressure for 15 minutes at 121^{o}C, before adding about 5 mg of chloramphenicol (antibiotic) to each conical flask. It was then dispensed into 20 – 25ml portions, into sterilised 15 x 100mm petri dishes, and allowed to set.

3.3.9.5. Treatment of Laminated Bamboo Test Blocks

A combination of boric acid and sodium tetraborate (borax) was used in the ratio of 1-part boric acid and 1.5 parts of sodium tetraborate decahydrate (1:1.5) by mass for the formation of disodium octaborate tetrahydrate (DOT) ($Na_2B_8O_{13}.4H_2O$) (Richardson, 1993). The solution of the preservative was prepared using 3g borax + 2g boric acid, per 45 grams of cold water. The conditioned laminated bamboo composite samples were completely submerged in a cold bath of the formulated fungicides for 24 hours. After treatment, each test block was removed from the formulated preservative, drained and re-weighed to determine the preservative absorption, using the method employed by Olajuyigbe et al. (2010) as described below:

Absorption (Kg/m^3) = WPA / V

Where: WPA = Weight of preservative absorbed (Kg),

V = Volume of laminated bamboo sample (m^3).

3.3.9.6. Procedure for Testing

Glass jars were used as decay chambers. The jars were half-filled with screened top soil. Wood strips measuring 50 mm x 15 mm x 3 mm of *Triplochiton scleroxylon* were

of 70% for 6 weeks for the mycelia of the fungus to completely colonize the wood strip as the process shows in Figure 3.15.

Figure 3.15: Processes on how grown mycelium of the test fungus was introduced.

After 6 weeks incubation period, the laminated bamboo blocks measuring 14 mm x 14 mm x 14 mm were oven dried at 103 ± 2°C to consistent dry weight, sterilized at 121°C at 1 atm for 20 minutes and placed transversely on the mycelial mats in the rumina flow chambers. The glass jars were then incubated again for 12 weeks for the *Coriolopsis polyzona* to feed on the laminated bamboo blocks.

3.3.9.7. Weight Loss Determination

Evaluation of weight loss of laminated bamboo samples decayed by the fungi was done after 12 weeks of incubation. At harvest, the mycelium was removed from the sample surface and the sample blocks were then oven dried at 103 ± 2°C for 24 hours and finally re-weighed to determine the weight loss. The weight loss caused by the fungal decay was then determined according to the equation:

$$\text{Weight loss (\%)} = [W_1 - W_2 / W_1] \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: W_1: Oven-dry weight before incubation; W_2: dry weight after incubation

3.3.9.8. Evaluation of Decay Rating of Laminated Bamboo

The decay rating of laminated bamboo samples were based on the weight loss classification adopted from US Standard ASTM Designation (D2017-05) Table 3.2.

Table 3.2: Weight loss classification

Average weight loss (%)	Decay resistance class
0-10	Highly resistant (Class I)
11-24	Resistant (Class II)
25-44	Moderately resistant (Class III)
45 and above	Susceptible (Class IV)

3.4. Statistical Analysis of Test Results

Statistical analysis was performed using SPSS software 16.0 version. The experimental test was conducted to ascertain the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), maximum compressive strength parallel to grain (MCS//) and maximum compressive strength perpendicular to grain (MCS), shrinkage, volumetric, moisture content (MC), and basic density (BD) of the laminated bamboo produced from *Bambusa vulgaris* bonded with rapid lion (RL) 5 minutes express wood adhesive. The strength effects of the bamboo and adhesive, as well as their interaction on the MOE, MOR, compression, shrinkage, volumetric, moisture content, basic density of the laminated bamboo and one-way factorial analysis (bamboo age), with the descriptive statistics. ANOVA was further used to determine significant differences among different specimens at $p>0.05$. Microsoft excel was also used to analysis the data.

The other properties such as acetone soluble extractive content, ethanol soluble extractive content, holocellulose soluble content, cellulose soluble content, hemicellulose soluble content, lignin soluble content, vascular bundle type, vascular bundle length, vascular bundle width, vascular bundle size, metaxylem diameter, fibre length, fibre diameter, lumen width, double wall thickness, parenchyma cell proportion, vessel proportion, fibre proportion, internode distance, culm diameter, culm thickness, shrinkage, volumetric, moisture content (MC), and basic density (BD) of the raw *Bambusa vulgaris* culm were examined using two-way factorial analysis (bamboo age and culm section), one-way factorial analysis (bamboo age) and the descriptive statistics mainly used to summaries the results from the properties of the bamboo. ANOVA was further used to determine significant differences among different specimens at $p<0.05$. Microsoft excel was also used to analysis the data.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.0. Introduction

This chapter presents the results and discussions of the experiment conducted on the physical, anatomical and chemical properties of *Bambusa vulgaris*. It also discusses the physical and mechanical properties of laminated *Bambusa vulgaris*.

4.1 Morphological and Physical Properties

4.1.1. Morphological Properties

Some basic morphological properties of *Bambusa vulgaris* culm have been studied and the results were presented in Figures 4.1, 4.2 and 4.3.

4.1.1.1 Internode Distance of *Bambusa vulgaris* Culm

Figure 4.1 shows the internode distance for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The internode distance of the bottom part of the mature bamboo culm was 365.60 mm whilst that of the top part was 442.20 mm. Similarly, the internode distance of the bottom part of the juvenile bamboo culm was 300.60 mm whilst that of the top part was 355.96 mm. For both the matured and juvenile *Bambusa vulgaris* the internode distance for the top part was longer than that of the bottom portion. Additionally, the study indicates that both the bottom and top internode distance of the mature bamboo were longer than that of the juvenile ones. Comparatively, the internode distance of the bottom part of the mature bamboo culm was 65 mm longer than that of the juvenile one whilst for the top portion the matured one was 86.24 mm longer than that of its corresponding juvenile bamboo.

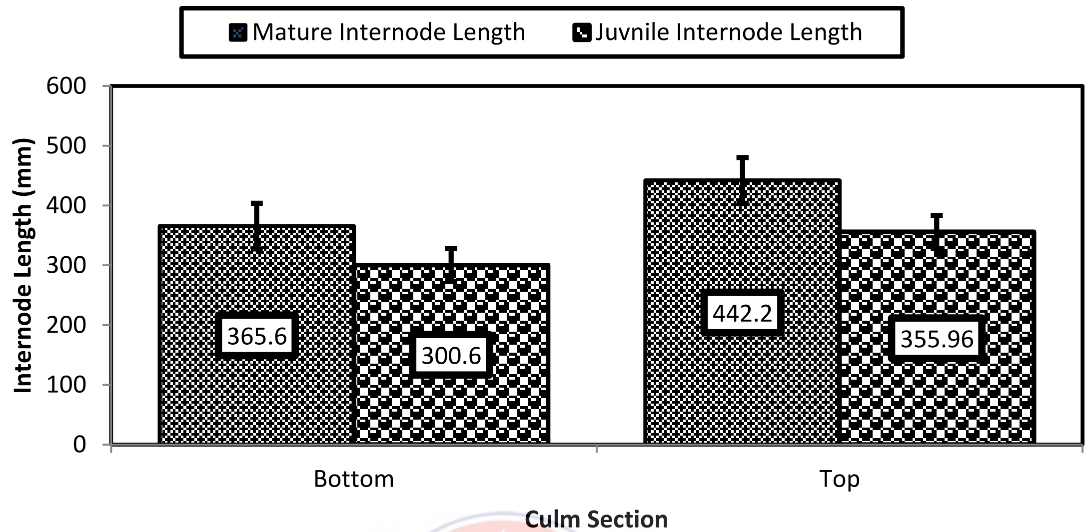

Figure 4.1: Internode length of *Bambusa vulgaris*; N= 10

The result of this study compares to a similar study conducted by Razak et al. (2010). Their study reported that the internode distance for juvenile bottom culm was 245.3 mm and its corresponding top culm was 358.1 mm while that of mature bottom culm was 222.7 mm and its corresponding top culm was 339.3 mm. Ebanyenle and Oteng-Amoako (2007) and Tekpetey (2011) reported similar trend of result. Generally, internode distance gradually increases from bottom portion through to the top portion in both juvenile and mature bamboo culms (Razak et al. 2010; Atmawi &Apri, 2018).

The differences in internode distance for both the bottom and top portions of the matured and juvenile bamboos studied could be as a result of the general structure of the culm that tapered from the bottom portion towards the top (Huang et al., 2015).

Differences in bamboo properties by species, age, location, and portion can influence processing procedures and affect the performance of end products (Hisham et al., 2006). Internode of *Bambusa vulgaris* could be used for the production of engineering composites due to its culms‟ high growth rate, abundantly available, renewable nature, and short maturity period (Qi et al., 2014). Internode distance could indicate higher strength of mechanical properties of engineering composite products due to its continuous fibre length. According to Shahril and Mansur (2009), the fiber length is a good predictor of MOR and MOE and where the shortest fiber at nodes contributed to the lowest mean values of these properties. Qi et al. (2015) also reported that, engineered composite manufactured from bamboo fibre mats without nodes had greater tensile strength, compressive strength, MOE and MOR. Research has shown that internode distance fibre orientation strengthens the engineered composite especially laminated bamboo due to the strip arrangement within the board, and therefore the direction of the radial fibre density is randomly placed within in the board (Sharma et al., 2015). The inherent strength of bamboo is maintained by maintaining the longitudinal fibre orientation (Sharma et al., 2015). It is therefore useful to utilize internode of *Bambusa vulgaris* for the production of engineered composites such as bamboo-ply, laminated boards, (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014).

Table 4.1: Summary of ANOVA on morphological properties of the *Bambusa vulgaris*

Source	df	Internode Distance		Culm Diameter		Culm Thickness	
		Sig.	Var. (%)	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	87.7	0.199ns	10.1	0.001**	53.9
Culm Section (CS)	1	0.001**	84.4	0.001**	93.4	0.001**	99.4
BA×CS	1	0.153ns	12.3	0.874ns	0.2	0.346ns	5.6

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The ANOVA presented in Table 4.1 shows that at 5% level of significance, bamboo age (Mature or Juvenile) and culm section (bottom or top) have significant effect on the internode distance of the bamboo. This suggests that about 87.7% and 84.4% of the variability in the internode distance could be explained by the bamboo age and culm section respectively. This implies that the difference within and across the same bamboo species is significantly important in selecting *Bambusa vulgaris* for industrial utilization.

4.1.1.2 Culm Diameter of *Bambusa vulgaris*

Figure 4.2 shows the culm diameter for the bottom and top portions of mature and juvenile *Bambusa vulgaris.* The culm diameter of the bottom part of the mature bamboo was 87.29 mm whilst that of the top part was 55.90 mm. Similarly, the culm diameter of the bottom part of the juvenile bamboo was 84.80 mm whilst that of the top part was 52.73 mm.

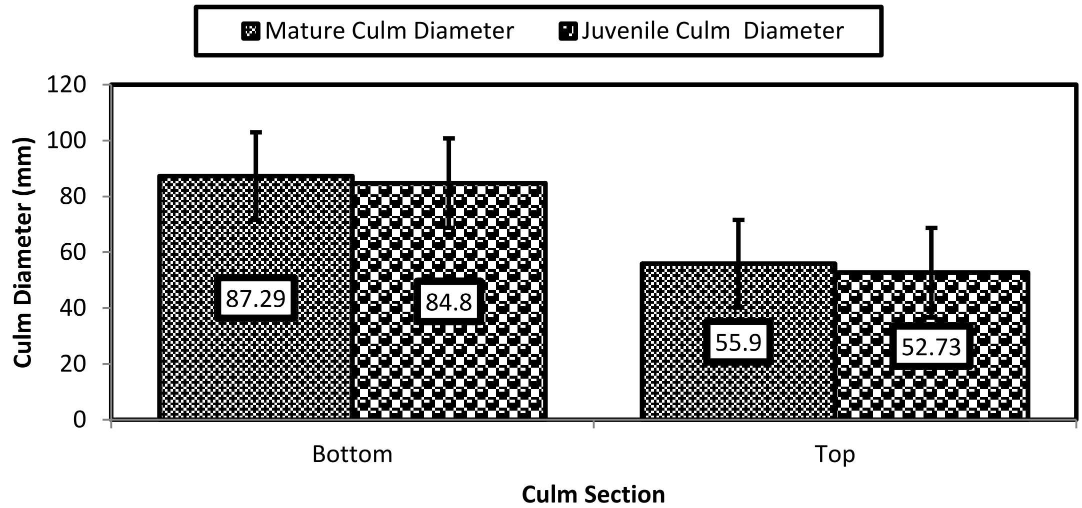

Figure 4.2: Culm diameter of *Bambusa vulgaris*; N= 10

The culm diameter of both the bottom and top sections of the mature bamboo were higher than their corresponding values of the juvenile bamboo. Besides, for both the mature and juvenile bamboos the culm diameter of the bottom sections was greater than their corresponding top sections. The bottom part of the bamboo being bigger than the top part could be as a result of the general structure of the culm that tapered from the bottom portion towards the top portion (Huang et al., 2015). Additionally, the bottom and top part of the mature bamboo being bigger than their corresponding parts of the juvenile ones might be due to the genetic make-up of the species or due to the wide range of rainfall, temperature, altitude, soil type in relation to the habitat (Pathak et al., 2017).

Similar trend of result was reported by Ebanyenle and Oteng-Amoako (2007). Unlike internode distance, which increased until a considerable height from the bottom part, the internode diameter generally decreased gradually towards the tip of the culm (Schulltes & Kurz, 2018). Amada et al. (1997) reported that the diameter and thickness of the bamboo culm decreases as the location of the culm is further from the ground. The outer diameter of the bamboo culm decreased from the bottom to the top portion (Atmawi &Apri, 2018). Culm diameter of *Bambusa vulgaris* could be used for the production of engineering composites due to its culms" availability, renewable nature, and short maturity period (Qi et al., 2014). Liese (1985) reported that in the industrial utilization of bamboo particular for making engineered bamboo composites, bamboo species with large culm diameter are selected. This will contribute significantly due to the higher number of strips produced from large culm diameter in the production of engineering composite products especially with particleboard, laminated board, bamboo scrimber (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014) and this could normally reduced the number of culms selected for the production of these engineered composite products. Studies have shown that, large diameter bamboo had been largely used in the bamboo-based panel, bamboo glue-laminated timber, and bamboo flooring industries as sustainable raw materials of wood (Zhang et al. 2013; Qi et al., 2014). According to Huang et al. (2019), engineered composite products such as bamboo scrimber can be produced using small-diameter bamboo.

The ANOVA in Table 4.1 shows that at 5% level of significant, the bamboo age did not have significant difference on the culm diameter. This implies that the culm diameter differences existing between the matured and juvenile bamboo was not significantly as a result of bamboo age. However, at 5% level of significance culm section had significant effect on the culm diameter of the bamboo and the coefficient of determination was 93.4%. This implies that the sections of the bamboo greatly influenced its culm diameter.

4.1.1.3 Culm Thickness of *Bambusa vulgaris*

Figure 4.3 shows the culm thickness for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The culm thickness of the bottom part of the mature bamboo culm was 21.55 mm whilst that of the top part was 7.71 mm. Similarly, the culm thickness of the bottom part of the juvenile bamboo culm was 20.17 mm whilst that of the top part was 6.83 mm.

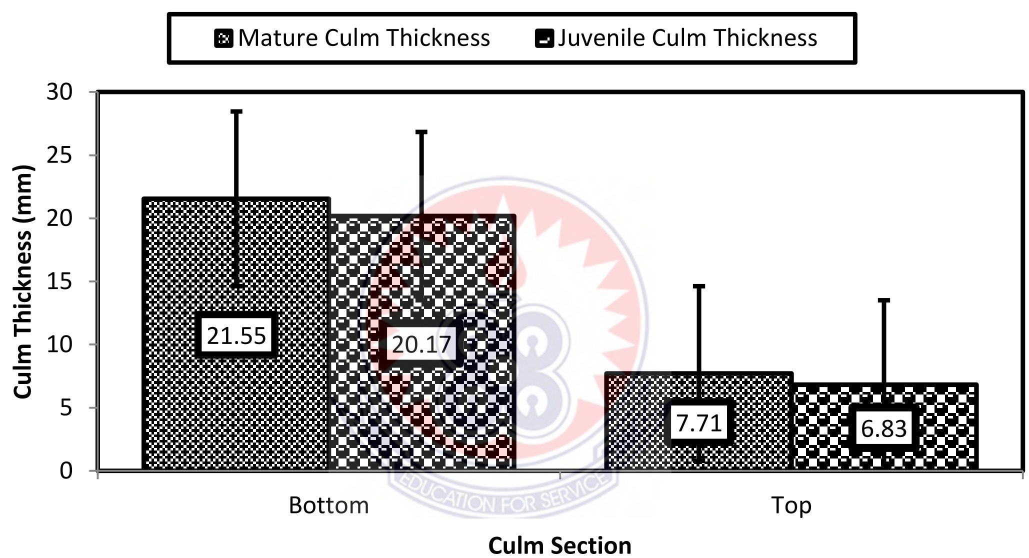

Figure 4.3: Culm thickness of *Bambusa vulgaris*; N= 10

The result further shows that the culm thickness for both the bottom and top portions of the mature bamboo species were higher than their corresponding values for the juvenile bamboo. Additionally, the culm thickness for the bottom portions were thicker than their corresponding top portions for both mature and juvenile bamboo. The variation in thickness between the bottom and top sections could be due to the general structure of the culm that tapered from the bottom portion through to the top that eventually affected the thickness of the culms (Biswas et al., 2011; Maya et al., 2013). Lybeer et al. (2006) reported that, the high variability within one culm and between culms of the same age from one year on is partly masking a clear increased cell wall at higher age. Additionally, the variation in thickness between the matured and the juvenile bamboos studied could be as a result of age. The result of this study is comparable to that of Razak et al. (2010) whose similar study reported that the culm thickness for juvenile bottom culm was 14.6 mm and its top culm was 5.5 mm whiles mature bottom culm was 15.4 mm and its corresponding top culm thickness was 7 mm. This implies that, it is most appropriate to use mature bamboo culm than that of the juvenile bamboo culm for the production of engineering composites products (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014).

The ANOVA in Table 4.1 shows that at 5% level of significance, bamboo age and culm section have significant effect on the culm thickness of *Bambusa vulgaris*. This suggests that both bamboo age and culm section have greater influence on culm thickness.

4.1.2. Basic density

Figure 4.4 shows basic density results for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The basic density of the bottom portion of the mature bamboo culm was 691.80 kg/m³ whilst that of the top portion recorded 660.50 kg/m³. Similarly, the basic density of the bottom portion of the juvenile bamboo culm was 562.26 kg/m³ whilst that of the top portion was 383.53 kg/m³.

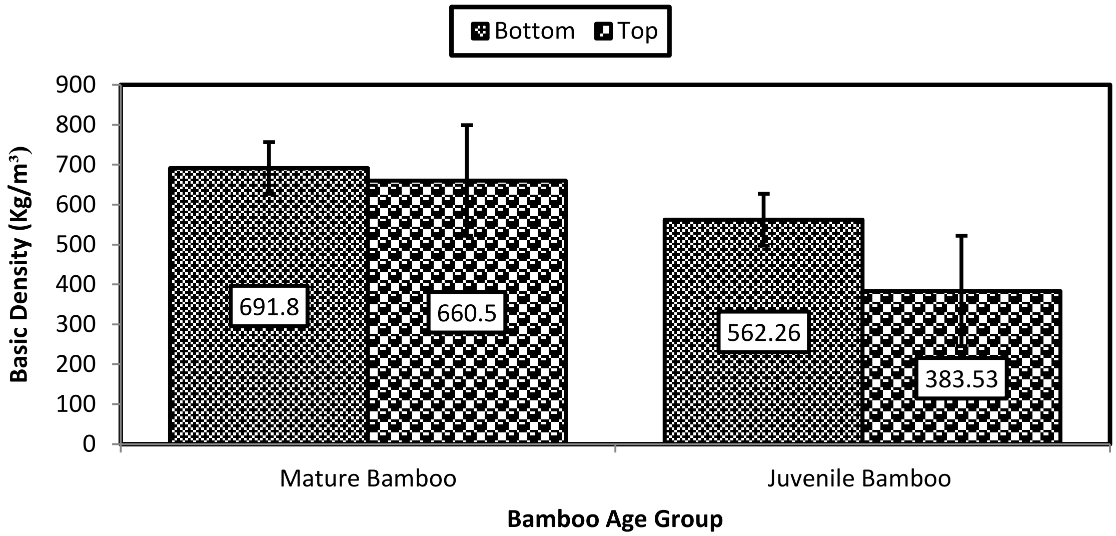

Figure 4.4: Basic density of *Bambusa vulgaris*; N=30

It could be concluded from the study that for both the bottom and the top portions of the bamboo species studied the basic density of the mature bamboo culm was higher than that of the juvenile bamboo culm. These variations could be attributed to the anatomical structure such as fibre proportions around the vascular bundle within the various culm heights (Razak et al., 2010; Vetter et al., 2015; Sulaiman et al., 2018). The anatomical structure such as fibre length is higher for the matured bamboo (4017µm, 3249µm) than that of the juvenile bamboo (2886µm, 2283µm) as indicated in Table 4.15 and this could have accounted for the differences. In addition, the results of this present study show that the anatomical properties like the presence of higher number of vascular bundles and higher proportion of fibrous tissue found in the matured bamboo were different from that of the juvenile bamboo as indicated in the Table 4.9 and 4.17 respectively and this could influenced the difference.

The variations in basic density of the bamboo species could also be due to the level of sections of the culm height for both the mature and juvenile bamboo. Santhoshkumar and Bhat (2015) reported that the density varied with positions of the culm wall and different height levels of the culm in the species whiles Gebremariam and Assefa (2018) also similarly reported that, density of the culm increased with increasing height levels of the culms. However, the result of this present study suggested otherwise. The basic density of the culm rather decreased with increasing height levels of the culms for both juvenile and mature bamboo respectively.

Higher density could indicate higher strength of both physical and mechanical properties for *Bambusa vulgaris* and therefore enhances the utilization of *Bambusa vulgaris* especially in selecting culms for the structural and non-structural applications. This property of mature bamboo having higher basic density has generally influence the acceptability of mature bamboo culm as compared to that of the juvenile bamboo culm as constructional material for both building and wood industry. The mature bamboo culm especially the bottom portions could be utilized for many applications such as furniture, basket, toothpicks, handicrafts products, papers, parquet, bamboo ply, laminated panels (Azmy et al., 2004; Asari & Suratman, 2010; Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014).

Table 4.2: Summary of ANOVA for basic density and moisture content of *Bambusa vulgaris*

		Basic Density		Moisture Content	
Source	df	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	69.5	0.001**	91.2
Culm Section (CS)	1	0.001**	25.3	0.001**	66
BA × CS	1	0.001**	13	0.001**	42.8

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant.

Table 4.2 presented the results of the ANOVA which shows that at P≤0.05 level of significance the bamboo age, culm section and their interaction have significant effect on the basic density of the bamboo. The level of variability was 69.50%, 25.30% and 13% respectively. This could explain by the bamboo age, the culm section and their interactions. This implies that their difference could contribute significantly towards basic density of bamboo species.

4.1.3. Green Moisture Content

The results as presented in Figure 4.5 show MC for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The MC of the bottom part of the mature bamboo culm was 53.2% whilst that of the top part was 71.73%. Similarly, the MC of the bottom part of the juvenile bamboo culm was 111.31% whilst that of the top part was 180.83%.

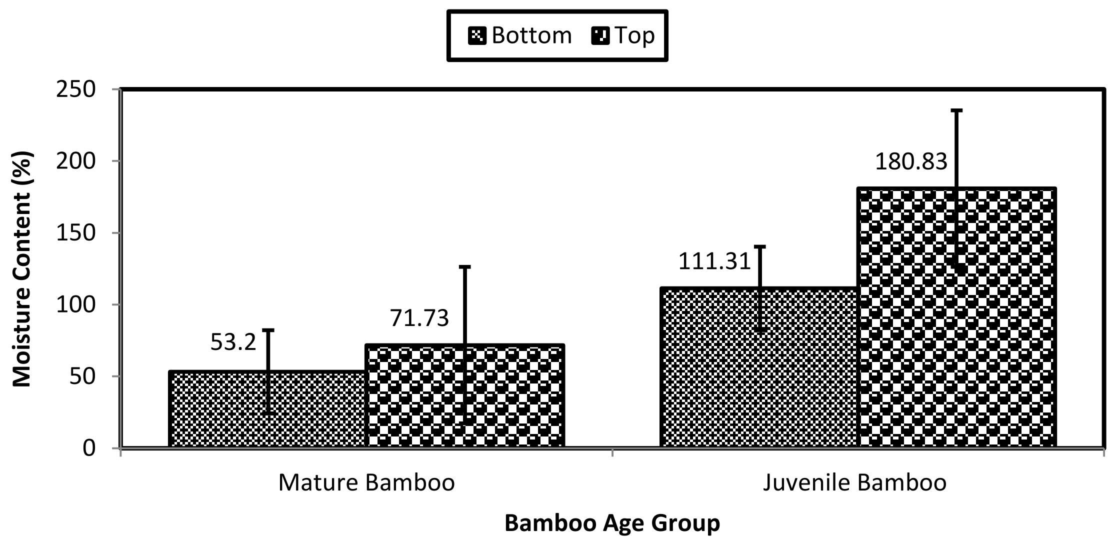

Figure 4.5: Green moisture content of *Bambusa vulgaris*; N=30

The results further show that for both the bottom and the top parts of the bamboo species studied the MC of the juvenile bamboo culm was higher than that of the mature bamboo culm. This result is similar to findings of Razak et al. (2012).

The results again show that the age difference also contributed to the variations in MC. Study by Razak et al. (2010) indicates that the age, height and position in the culms wall thickness influence MC in *Bambusa vulgaris*. This study also shows that the MC decrease as bamboo matures as presented in Figure 4.5. This could explain the rationale involved in the growth of bamboo into its woody material state. This finding is in agreement with the study of Razak et al. (2010), Gebremariam and Assefa (2018) and Sulaiman et al. (2018).

The results further indicate that juvenile *Bambusa vulgaris* has higher moisture content than the mature *Bambusa vulgaris*. This could influence the utilization potential of

Bambusa vulgaris especially on the production of engineering composites products since it affects the dimensional stability of produced engineered composite products such as laminated board, particleboard, bamboo ply. It is therefore preferable to use mature bamboo culm for the production of engineering composites products (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014;) than the juvenile ones since its green moisture content is lower than that of the juvenile bamboo culm.

The results of the ANOVA (Table 4.2) of the MC indicate that at 5% level of significance the bamboo age, culm section and their interaction have significant effect on the MC of the bamboo. The level of variability was 91.20%, 66% and 42.80% respectively and this could explain by the bamboo age, the culm section and their interactions. This implies that their difference could contribute significantly towards MC of bamboo species.

4.1.4. Oven-Dried Shrinkage

The results as presented in Figure 4.6 show shrinkage for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The radial shrinkage of the bottom section of the mature bamboo culm was 4.99 % whilst that of the top section was 7.94 %. Again, the radial shrinkage of the bottom section of the juvenile bamboo culm was 16.68 % whilst that of the corresponding top section was 21.08 %. The tangential shrinkage of the bottom section of the mature bamboo culm was 7.23 % whilst that of the top section was 8.69 %. Similarly, the tangential shrinkage of the bottom part of the juvenile bamboo culm was 23.19 % whilst that of its corresponding top part was 29.78 %. The longitudinal shrinkage of the bottom part of the mature bamboo culm was 0.39 % whilst that of the top part was 0.48 %. Again, for the longitudinal shrinkage of the bottom part of the juvenile bamboo culm was 0.57 % whilst that of its top part was 0.59 %.

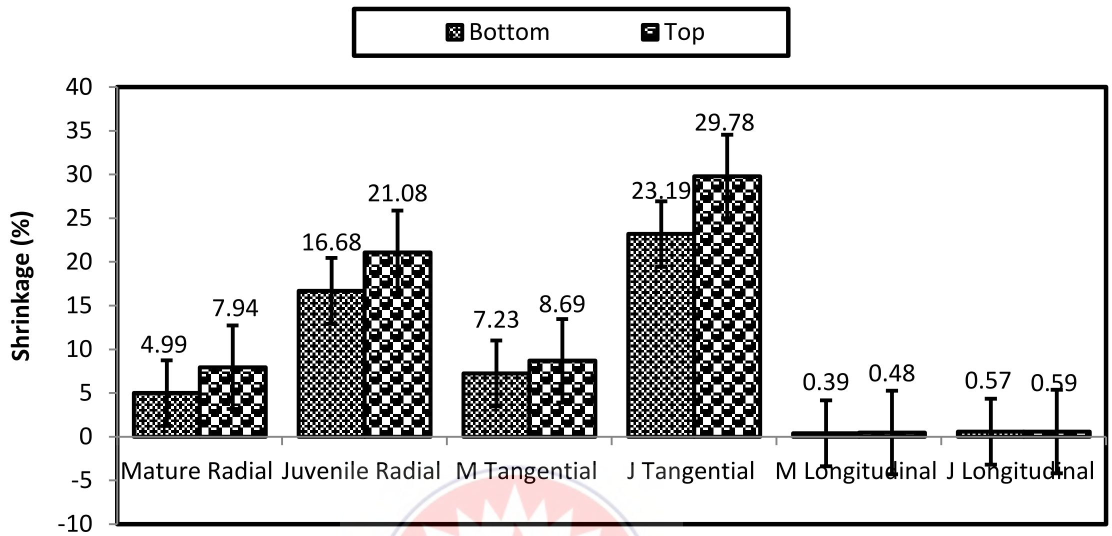

Figure 4.6: Shrinkage of *Bambusa vulgaris*; N=30; M= mature; J= juvenile

The results further show that for both the bottom and top sections of the bamboo species studied the shrinkage in all the directions (radial, tangential and longitudinal) for the juvenile bamboo were higher than that of the mature bamboo. The juvenile bamboo culm shrinks more than that of the mature bamboo culm due to the different amount of water levels in the cells. The possible reason for the shrinkage difference is the anatomical structure of the culm. Unlike wood, shrinkage starts in both cell wall thickness and cell diameter as soon as moisture begins to decrease. This is due to the high amount of parenchyma cells, which lose their moisture first (Vetter et al., 2015). The parenchyma cell proportion of the juvenile bamboo sections (bottom and top) are higher than that of the mature bamboo sections as indicated in Table 4.13 and as a result of that, it shrinks more than the mature bamboo.

For the conventional wood, tangential plane has been accepted as where the greatest dimensional shrinkage occurs while shrinkage along the radial plane is considered less whereas the longitudinal shrinkage has been largely reported to be the least among the three and could be ranged from 0.1 - 0.3% (Desch, 1988; Dinwoodie, 1989). The result of this study was almost in line with the trend of conventions of wood except the longitudinal plane that was observed to be higher. This means that there is proportionality among the increasing shrinkage between these three directional planes and their differences are significant as indicated in Table 4.3.

The shrinkage level could influence the utilization potential of *Bambusa vulgaris* especially on the production of engineering composites. This may enhance in determine the dimensional stability for the production of engineering products such as laminated board, particleboard and bamboo ply. According to Anokye et al. (2014), minimal differential radial and tangential shrinkage of bamboo contributes to its dimensional stability and thus it is most appropriate to use mature bamboo culm for the production of engineering composites since its shrinkage level was lower than that of the juvenile bamboo culm. However, the juvenile bottom culm could also be used for the production of engineering composite products suitable for internal structural applications such as ceiling, bed side cabinet, flooring, and so on (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014). The results further suggest that room temperature could be an ideal means of controlling rate of shrinkage and thereby enhance the dimensional stability of products manufactured from juvenile bottom culm. The moisture content changes with the changes in the relative humidity and temperature of the surrounding environment (Razak et al., 2012). Kishen et al. (1956) reported that the fibre saturation point of bamboo is around 20 - 22%.

From this present study, it is also clear that tangential shrinkage recorded the higher values than radial shrinkage within the same treatment condition of oven drying. Malanit et al. (2008) reported that tangential shrinkage is about one-half as much in radial and much less along the longitudinal direction. However, the result of this present study is different from the conclusions made by Anokye et al. (2014) who reported that shrinkage pattern along the radial direction was slightly more compared to the tangential directions with a ratio of 1.15: 1.

Table 4.3: Summary of ANOVA of shrinkage properties of *Bambusa vulgaris*

		Radial		Tangential		Longitudinal	
Source	df	Sig.	Var. (%)	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	97.2	0.001**	96.1	0.001**	62.3
Culm Section (CS)	1	0.001**	75.4	0.001**	53.8	0.001**	18.7
BA × CS	1	0.001**	10.7	0.001**	32.1	0.007*	6.2

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The results of the analysis of variance for the oven-drying show that at 5% level of significance, the bamboo age, culm section and their interaction have significant effect on the radial shrinkage of the bamboo as shown in Table 4.3. The level of variability was 97.20%, 75.40% and 10.70% and this could be explained by the bamboo age, the culm section and their interactions. Similar trend of results was obtained for tangential and longitudinal shrinkage in oven-dried period. This suggests that the difference within same bamboo species and across age groups could contribute significantly in shrinkage determination.

4.1.5. Volumetric Shrinkage of *Bambusa vulgaris*

Figure 4.10 shows the results of volumetric shrinkage for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The volumetric shrinkage of the bottom portion of the mature bamboo culm was 12.61 % whilst that of its corresponding top portion was 17.11 %. Similarly, the volumetric shrinkage of the bottom portion of the juvenile bamboo culm was 40.44 % whilst that of the top portion was 51.45 %. This result is comparable to the similar trend reported by Thuc and Tuong (2017). Their study reported that volumetric shrinkage of *Dendrocalamus giganteus* bamboo ranges from 9.2–12.1%. Research has shown that volumetric shrinkage of bamboo from different tropical and temperate regions ranges from 7.8 to 36.54% (Wahab et al, 2012; Zhaohua & Wei, 2018).

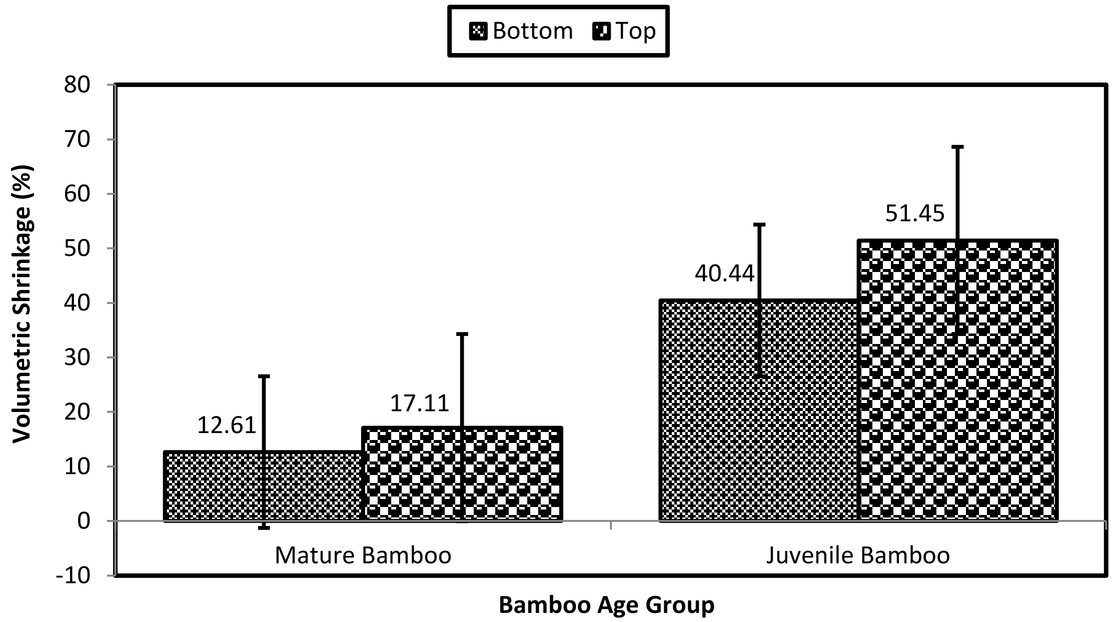

Figure 4.7: Volumetric shrinkage of *Bambusa vulgaris*; N= 30

The results further show that both the bottom and the top portions of the bamboo species studied for the volumetric shrinkage, the juvenile bamboo culm was higher than that of the mature bamboo culm. For the bottom portion, the volumetric shrinkage of the matured one was 12.61% and the juvenile was 40.44% whilst for the top portion, volumetric shrinkage of the matured one was 17.11% and the juvenile was 51.45%.

This was as a result of high value of tangential shrinkage and radial shrinkage which occurred under defined condition of the studied. The volumetric explains the rate at which the moisture of bamboo is being evaporated. The lower percentage of volumetric shrinkage recorded for mature bamboo culm compared to that of the juvenile bamboo culm could means that the dimensional stability of mature bamboo culm was better than that of the juvenile bamboo culm. According to conclusion made by Anokye et al. (2014) indicates that for the dimensional changes, it is clear that the MC and the anatomical characteristics of bamboo influenced the shrinkage behaviour of bamboo. They further stated that the minimal differential radial and tangential shrinkage contributes to the dimensional stability of bamboo. This could promote the general acceptability for the selection of mature bamboo culm rather than that of the juvenile bamboo culm as raw material for the potential utilization for engineered composite products in wood and construction industries (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014).

The results of this study show that the culm section could also influence volumetric shrinkage differences in *Bambusa vulgaris*. Comparatively, mature bamboo culm shrinks less than the juvenile bamboo culm and this could attribute to the moisture differences occurred in the sections of *Bambusa vulgaris*. Liese (1985) and Razak et al. (2010) reported that differences in moisture content might be due to anatomical structure and chemical composition between the culms age and location along the culms. Volumetric shrinkage percentage of various culm section shows that the proportion and maturity of fibre has greater influence on shrinkage properties (Razak et al., 2010). This means that volumetric shrinkage increased along the increasing of culm height section from bottom to the top and these could be directly proportional since the position of culm height section corresponds to the change in volumetric shrinkage as well.

Table 4.4: Summary of ANOVA of volumetric shrinkage of *Bambusa vulgaris*

		Volumetric shrinkage	
Source	df	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	97.6
Culm Section (CS)	1	0.001**	71.6
BA × CS	1	0.001**	31.5

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The ANOVA in Table 4.4 shows that at 1% and 5% level of significance, the bamboo age, culm section and their interaction have significant effect on the volumetric shrinkage. The level of variability was 97.6%, 71.6% and 31.5% respectively and this could be explained by the bamboo age, the culm section and their interactions. This implies that the difference within same bamboo species and across age groups could contribute influence volumetric shrinkage of bamboo species.

4.2 Anatomical Properties

4.2.1 Vascular Bundle

The Figures of 4.8, 4.9, 4.10, 4.11 and 4.12 show the vascular bundles arrangement within the bamboo culm wall thickness of juvenile and mature *Bambusa vulgaris* ranging from inner, middle and outer portions of the culms from the bottom to the top cross-section. The vascular bundles arrangement of *Bambusa vulgaris* was found to be of type III and type IV. These vascular bundles were similar to the classification of vascular bundles presented by Grosser and Liese (1971). The type IV arrangement was found in the bottom culms whilst the type III arrangement was observed in the top culms for both the juvenile and mature bamboo. The type III consists of two parts: the central vascular strand with sclerenchyma sheaths and one isolated fibre bundles whilst the type IV consists of three parts: the central vascular strand with sclerenchyma sheaths, two isolated fibre bundles outside and inside the central strand. This result is similar to what was reported by Liese, (1998). This study reported that type IV vascular bundles contain two fiber sheaths, one above and the other below the main vascular bundle. This study has shown that a full culm of *Bambusa vulgaris* could be a representation of type III and type IV irrespective of the shape and age.

As indicated in Figure 4.9 to 4.12, the vascular bundle consists of one or two smaller protoxylem elements and two large metaxylem vessels and the phloem with thin-walled, unlignified sieve tubes connected to the companion cells (Obataya et al., 2007; Razak et al., 2010; Mustafa et al., 2011; Razak et al., 2012). This study has shown that the vascular bundles for juvenile and mature bamboo culms were larger in the inner portions, but reduced in the middle portions and then becoming smaller and denser in the outer portions of the culm wall. Similar trend of results was reported by Razak et al. (2010) and Mustafa et al. (2011). Their study reported that the vascular bundles of *Bambusa vulgaris* were larger in the inner parts, becoming smaller and denser towards the periphery of the culms wall.

The denser vascular bundle could tend to increase the mechanical strength of the bamboo since the conductive activities are virtually absent within this region (He et al., 2019). The stiffness of vascular bundles varies linearly throughout the culm wall, thus the same longitudinal load applied on different vascular bundle will induce different strain and vice versa (Li & Shen, 2011). The shapes of the vascular bundles change from the outer portion to the inner portion of the bamboo culm wall (Razak et al., 2010; Wang et al., 2011). The vascular bundles affect the physical and mechanical properties (Liese, 1985; Liese, 1998) especially in the outer portions which then influence utilization of the bamboo culm as an important engineering material in the wood and building industries (Obataya et al., 2007; Kumar & Tanya, 2015; Wu & Ho, 2015; Huang et al., 2016).

This study has shown that the inner portion of the culm wall contained more parenchyma cells due conduction activities of storing nutrients and water than that of the outer portion contained more fibres due to high presents of vascular bundles as indicated in Figure 4.9a&c, 4.10a&c, 4.11a&c, and 4.12a&c respectively. Atmawi and Apri (2018) reported that anatomically, bamboo culm comprises vascular bundles and parenchymal base tissue. They further stated that, the gross anatomical structure of a transverse section of any culm internode is determined by the shape, size, arrangement, and number of vascular bundles. According to Chavan and Attar (2013), carbohydrate content of bamboo plays an important role in its durability and service life. They further stated that, durability of bamboo against mold, fungal and borers attack is strongly associated with the chemical composition. The degradation process always starts at the inner portions through to the outer portions of bamboo due to the high amount of parenchyma cells fully filled with starch granules are found in such portions (Fig.4.15 A&B; Fig. 4.25 X). This implies that both juvenile and mature bamboo culms could be susceptible to termite, fungal and beetle attacks since these biodegradable agents feed on the carbohydrates found within the area of parenchyma cells (Chavan & Attar, 2013). The study shows that

4.2.1.1. Vascular Bundle Length

Table 4.9 shows vascular bundle length for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The vascular bundle length of the bottom part of the mature bamboo culm for inner location was 1114.42 µm, middle location 857.78 µm and for outer location was 773.18 µm whilst that of the top part for inner location was 855.19 µm, middle location 776.04 µm and for outer location was 636.39 µm. Similarly, the vascular bundle length of the bottom part of the juvenile bamboo culm for inner location was 986.15 µm, middle location 845.91 µm and for outer location was 746.27 µm whilst that of the top part for inner location was 842.83 µm, middle location 705.39 µm and for outer location was 632.69 µm. The study shows that for both the mature and juvenile bamboo the vascular bundle length decreased as one moves from the inner portion to the outer portion of the culm. The longer vascular bundle length is attributed to the growth of fibre bundle, protoxylem, and phloem as well as the thickness of sclerenchyma sheath within and outer side of the central vascular bundle strand as in Figure 4.9 – 4.12. This result is consistent with that of Mustafa et al. (2011) and Razak et al. (2012) on the vascular bundle length in *Gigantochloa scortechinii*. Their study reported that the vascular bundle length for inner layer position was 853.60 µm, middle layer 882.32 µm and for outer layer was 625.77 µm. On the contrary, this result is different from the study of Mustafa et al. (2011) and Razak et al. (2012) which reported that the vascular bundle length was longer at the middle than its outer and inner peripheries.

Table 4.5: Vascular bundle length and width of *Bambusa vulgaris*

		Juvenile Bamboo Culm		Mature Bamboo Culm	
Culm Section	Location	vascular bundle length (µm)	vascular bundle width (µm)	vascular bundle length (µm)	vascular bundle width (µm)
Bottom	Inner	986.15±64.85	630.77±46.79	1114.42±63.23	706.04 ± 61.41
	Middle	845.91±42.65	480.01±23.79	857.78 ± 84.91	536.71 ± 35.81
	Outer	746.27±31.86	364.80±25.57	773.18 ± 41.09	366.08 ± 26.59
Top	Inner	842.83±59.08	621.55±37.81	855.19 ± 72.05	675.21 ± 46.86
	Middle	705.39±60.28	404.52±30.77	776.04 ± 55.54	529.79 ± 46.46
	Outer	632.69±42.06	338.08±32.25	636.39 ± 54.62	362.65 ± 26.25

± sign represent standard deviation.

For both the bottom and the top portions of the bamboo species studied the vascular bundle length for the mature bamboo was higher than that of the corresponding values for the juvenile bamboo. Furthermore, the vascular bundle length increased from the bottom to the top culm of the for both mature and juvenile *Bambusa vulgaris* and it is consistent with the findings of Atmawi and Apri (2018). The vascular bundle lengths could influence the selection of culms for the structural applications in construction industry. Longer length normally improves the mechanical and physical properties of the culm (Liese, 1985; Liese, 1998).

The vascular bundle type influences the radial length since the involvement of two fibre bundles would be different from only one fibre bundle. The mature bottom culm had higher vascular bundle length than the juvenile bottom culm according to the data presented in Table 4.5 for this study. This could enhance the acceptability of mature bottom culm for the utilization for bamboo-based composites products in construction industry (Bhat et al., 2011; Huang et al., 2013; Sharma et al., 2014; Chen et al., 2020).

This study has shown that the spaces found between these fibre bundles and central vascular strand further contributed to the longer nature of the vascular bundle length. The number of vascular bundles developed in the inner portions of the culms compared to the middle and outer portions respectively could affect the vascular bundle length for both juvenile and mature culms as indicated in Figure 4.9 to 4.12. Vascular bundles were longer and smaller at the outer portion but shorter and larger towards the inner portion (Wang et al., 2011). This makes the outer portion denser and harder than the inner portion. The results of this study show that the shorter vascular bundle length of mature bamboo culm is more compact and denser compared to that of the juvenile bamboo culm (Figure 4.9c, 4.10c, 4.11c, 4.12c) which has made the mature bamboo culm stronger than the juvenile bamboo culm. This tends to improve the mechanical properties of mature bamboo culm than the juvenile bamboo culm. The smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer portions had higher density and mechanical strength than the inner zones (Zhou, 1981; Liese, 1985). This variation could be due to the age difference of the bamboo culms.

Table 4.6: ANOVA vascular bundle length and width of *Bambusa vulgaris*

		Vascular bundle length		Vascular bundle width	
Source	df	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.005**	9.5	0.001**	31.3
Culm Section (CS)	1	0.001**	59.6	0.001**	20.1
Location (L)	3	0.001**	75.5	0.001**	88.9
BA × CS	1	0.400ns	0.9	0.096ns	3.4
BA × L	2	0.454ns	2	0.060ns	6.8
CH × L	2	0.084ns	6	0.441ns	2
BA × CS × L	2	0.042*	7.6	0.071ns	6.4

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The ANOVA in Table 4.6 shows that at 1% and 5% level of significance, the bamboo age, culm section and their interaction as well as location have significant effect on the vascular bundle length of the bamboo. The level of variability was 9.5%, 59.6% and 75.5% respectively. This could be explained by the bamboo age, the culm section, their interaction and the location. Similar trend was observed by the interaction between the bamboo age, culm section and location.

4.2.1.2 Vascular Bundle Width

Table 4.5 indicates the results of vascular bundle width for the bottom and top portions of both mature and juvenile *Bambusa vulgaris.* The vascular bundle widths for juvenile bottom culm were 630.77 μm for inner location, the middle location was 480.01μm and for outer location was 364.80 μm whilst that of juvenile top culm was 621.55 μm for inner location, the middle location was 404.52 µm and for outer location was 338.08 µm. Similarly, the mature bottom culm varied in its vascular bundle width with 706.04 µm for the inner location, 536.71 µm for the middle location and 366.08 µm for the outer location whilst the mature top culm has vascular bundle widths with 675.21 µm for the inner location, 529.79 µm for the middle location and 362.65 µm for the outer location. The results show that vascular bundle widths are wider in the inner portions of the culm wall than that of the middle and outer portions respectively. This variation is resulted, as the metaxylem vessels size reduces at the inner portion through to the outer portion tends to affect the dimension of the vascular bundle width as shown in Figure 4.9 – 4.12. This is consistent with the findings of Mustafa et al. (2011) and Razak et al. (2012). Their study reported that the vascular bundle width for inner layer position was 627.62 µm, middle layer 494.11 µm and for outer layer was 382.41 µm (Razak et al., 2012). The result of this study shows that the vessels are normally bigger at the inner portions of the culm wall compared to that of the middle and outer portions as indicated in Figure 4.9 to 4.12. Zhan et al. (2020) reported that the distribution, size and shape of the bundles change continuously from the periphery towards the center of the culm. They further stated that, the anatomical characteristics of bundles vary from the culm base, middle and top. The vessels contribute significantly to the amount of moisture in the culm due to its conducting activity of transporting water and nutrients that turn to influence the growth of the bamboo culm (He et al., 2019).

The results further show that for both the bottom and the top portions of the bamboo species studied for the vascular bundle width, the mature was higher than that of the juvenile bamboo. The results show that the vascular bundle width varies with the location of culm section for both juvenile and mature culm. It further shows that the vascular bundle width was higher at the bottom culm than the top culm for both the juvenile and mature bamboo and this could have been as a result of influence of vascular bundle type. Liese (1998) reported that Type III vascular bundles typically contain only one fiber sheath at the bottom of the main vascular bundle, whereas type IV vascular bundles contain two fiber sheaths, one above and the other below the main vascular bundle. Li and Shen (2011) reported that the stiffness of vascular bundles vary linearly throughout the culm wall, thus a same longitudinal load applied on different vascular bundle will induce different strain and vice versa. This present study indicates that the mature bottom culm recorded higher vascular bundle width than the juvenile bottom culm and this could enhance the general acceptability of mature bottom culm for the manufacture of engineered composite products (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014). This result is consistent with the similar trend reported by Razak et al. (2010). The results indicated that, the space found between the metaxylem vessels as well as the growth of sclerenchyma sheaths could influence the tangential diameter of vascular bundle.

The ANOVA in Table 4.6 show that at 1% and 5% level of significance the bamboo age, culm section and location have significant effect on the vascular bundle width of the bamboo. Their level of variability was 31.3%, 20.1% and 88.9% respectively and this could be explained by the bamboo age, culm section and location.

4.2.1.3. Metaxylem Diameter

The results on the measurement of the metaxylem vessel diameter in different locations for the bottom and top portions of both mature and juvenile *Bambusa vulgaris* are shown in Table 4.7. The metaxylem vessel diameter of the bottom portion of the mature bamboo culm for inner location was 216.81 µm, middle location 137.70 µm and for outer location was 54.74 µm whilst that of the top portion, inner location was 214.70 µm, middle location 134.90 µm and for outer location was 63.53 µm. Similarly, the metaxylem vessel diameter of the bottom portion of the juvenile bamboo culm for inner location was 214.23 µm, middle location 118.82 µm and for outer location was 73.86 µm whilst that of the top portion, inner location was 144.22 µm, middle location 104.16 µm and for outer location was 87.08 µm. This result implies that the metaxylem vessel diameter show much variation for both juvenile and mature bamboo culm. The results further indicate that, the metaxylem vessel diameter decreased from the inner portion through to the middle and outer portions of the culm wall for both juvenile and mature culms. The variation in metaxylem vessel diameter across the culm wall could be as a result of the anatomical structure of the culm where the inner portion contains more parenchyma cells, fewer fibres and conducting cells with bigger vessels than in the outer portion of the culm wall (Razak et al., 2010). The results of this present study show that the metaxylem vessels decreased from the inner portion to the outer portion of the culm wall for both juvenile and mature bamboo as indicated in Figure 4.9 – 4.12. This further explains the importance of the difference in metaxylem vessels size at each portion (inner, middle and outer) as it functions in transporting water and minerals (Huang et al., 2015; He et al., 2019) for the development of the culm. This result is consistent with the findings of Liese

(1998). The result further indicates that both juvenile and mature bamboo culms recorded decrease trend of variation in culm wall thickness along the culm height from the bottom section to the top section. This result was similar to the finding of Huang et al. (2015) who reported that a slight decrease in trend from bottom to top could be due to the variation in culm wall thickness long the culm height.

Table 4.7: Metaxylem diameter in different locations of *Bambusa vulgaris*

	Mature Bamboo		Juvenile Bamboo	
Location	Bottom (µm)	Top (µm)	Bottom (µm)	Top (µm)
Inner	216.81 ± 8.37	214.7 ± 15.03	214.23 ± 14.02	144.22 ± 8.38
Middle	137.7 ± 4.6	134.9 ± 8.89	118.82 ± 2.78	104.16 ± 4.91
Outer	54.74 ± 2.44	65.53 ± 1.49	73.86 ± 3.34	87.08 ± 2.86

± sign represent standard deviation

The results further show that both the bottom and the top portions of the bamboo species studied for the metaxylem vessel diameter, the mature bamboo was higher than that of the juvenile bamboo. The bottom portion of the metaxylem vessel diameter for the matured inner location was 216.81 µm, 137.70 µm for middle location and outer location was 54.74 µm whilst for the juvenile the inner location was 214.23 µm, 118.82 µm for the middle location and outer location was 73.86 µm. Similarly, the top portions of metaxylem vessel diameter for the matured inner location was 214.70 µm, middle location was 134.90 µm and outer location was 63.53 µm whilst for the juvenile, the inner location was 144.22 µm, middle location was 104.16 µm and outer location was 87.08 µm.

This study has shown that the metaxylem vessels were fully-grown and larger in the inner and middle portions for both juvenile and mature culms. This result is similar to what was reported by Huang et al. (2015). Their study reported that the metaxylem vessels were full-grown in the inner and middle zones. They further stated that this growth in the inner portion might be attributed to the fact that these zones are mainly functioned for water and nutrient transportation. This could have also explained why shrinkage and swelling were very visible at the inner and the middle portions than that of the outer portion. This may be traced to the fact that the vessels at these portions are mainly functioned for water and nutrient transportation (Huang et al., 2015; He et al., 2019).The fibres are ground in sclerenchyma sheath around the metaxylem vessels and phloem (Grosser & Liese, 1971) which then tends to improve the moisture levels of the bamboo. This present study has shown that the metaxylem diameters within the vascular bundle increase in diameter along the sections of the culm. It is further established that the metaxylem vessels diameter also increase across the diameter of the culm wall from the outer portion to the inner portion. Razak et al. (2010) reported that the vessels progressively increased in diameter from the outer to the inner part.

Table 4.8: ANOVA of metaxylem diameter of *Bambusa vulgaris*

Source	df	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	36
Culm Section (CS)	1	0.001**	11.1
Vessel Location (VL)	2	0.001**	94.2
BA × CS	1	0.001**	40.3
BA × VL	2	0.001**	53.2
CS× VL	2	0.001**	27.3
BA × CS× VL	2	0.001**	33.9

Note: ** = Significant at p<0.05; * = significant at p<0.05, ns = Not significant.

Table 4.14 shows the ANOVA results which indicates that at 1% and 5% level of significance, the bamboo age, culm section and vessel location have significant effect on the metaxylem vessel diameter of the bamboo. Their level of variability was 36%, 11.1% and 94.2% respectively. This could be explained by the bamboo age, the culm section and the vessel location. Similar trend of results was observed for all the interactions between bamboo age, culm section and vessel location.

4.2.3 Fibre Characteristics

The results of the fiber characteristics of the *Bambusa vulgaris* culm studied have been presented in Table 4.9.

Table 4.9: Mean values of fibre dimensions of *Bambusa vulgaris* culm

Bamboo Age	Fibre Length (µm)	Fibre Diameter (µm)	Lumen Width (µm)	Wall Thickness (µm)
Mature				
Bottom	4017 ± 97.02	20.54±0.88	13.08 ± 1.50	7.46 ± 1.36
Top	3249 ± 88.53	19.22±1.36	12.76 ± 1.42	6.46 ± 0.88
Juvenile				
Bottom	2886 ± 98.18	19.26±1.33	12.54 ± 1.58	6.72 ± 0.92
Top	2283 ± 89.77	14.03±0.98	8.78 ± 0.42	5.25 ± 0.83

± sign represent standard deviation.

4.2.3.1 Fibre Length

The fibre lengths of the bottom and top portions for both the juvenile and mature *Bambusa vulgaris* are presented in Table 4.9. The longest fibre length was obtained from the mature bottom culm (4017µm) follow by mature top culm (3249µm), juvenile bottom culm (2886µm) and juvenile top culm (2283µm). This result implies that there are significant variations within fibre lengths for both juvenile and mature bamboo culm. This result is consistent with the similar results reported by Razak et al. (2010), Mustafa, et al. (2011) and Razak et al. (2012). The fiber length shows considerable differences between culms as well as variations within one culm (Liese & Grosser, 1972). This difference may be attributed to anatomical structure that influences the growth rate of the culm (Razak et al., 2012). The mature bamboo culm has longer fibre length compared to that of the juvenile bamboo culm that could improve the physical and mechanical properties and thereby influence its utilization potential as constructional material both in the building and wood industries (Obataya et al., 2007; Kumar & Tanya, 2015; Li et al., 2015; Wu & Ho, 2015; Huang et al., 2016). This is because, the longer fibre length, the higher the strength properties of the material (Kumar & Tanya, 2015; Li et al., 2015).

The result further suggests that for both the mature and juvenile bamboo the fibre length of the bottom culm was longer than that of the top culm. Pu and Du (2003) reported that the longer fibre length was located in the bottom culms. This is consistent with the findings of this present study. Additionally, for both the bottom and the top the fibre length of the matured bamboo was longer than juvenile one. The bottom portion for the fibre length of the matured was 4017 µm whilst the juvenile was 2886 µm. Similarly, for the fibre length of the top portions, the matured was 3249 µm whilst the juvenile was 2283 µm. This result is similar to the findings reported by Mustafa et al. (2011), Razak et al. (2010). They reported that the fibre length range between 3500mm – 3700mm for the 2-year-old culms and 3600 mm – 4900 mm for the 4-year-old culms (Razak et al., 2010). Again, the result of this present study could also compared with other bamboo species fibre length for *Bambusa vulgaris* was 3500 – 4900 µm (Razak et al., 2010), *Bambusa vulgaris var.striata* was 2400 – 2600 µm (Kokutse et al., 2013), *Bambusa* *vulgaris Schrad* was 2540 – 2620µm (Kokutse et al., 2013) and *Gigantochloa scortechinii* was 1672.62 – 2074.24 µm (Razak et al., 2012).

The results of the study further indicate that the fibre length difference between the juvenile bottom section and its top section was 603µm whilst the mature bottom section and its top culm was 768µm. Similarly, the mature bottom section was 1131µm longer than that of the juvenile bottom section whilst the mature top section was 966µm longer than that of the juvenile top section. This result shows that the mature bamboo culm has longer fibres and this could play an important role in contributing to its weight and strength properties as a whole. Liese (1992) studied the structure of bamboo in relation to its properties and utilization. The study reported that the fibres contribute 60 – 70% by weight of the total culm tissue. The results of this study indicate that the fibre length of mature bamboo culm can be compared to that of the fibre length of Softwood (3600 µm), hardwood species such as *Gmelina arborea* (1290 µm) (Roger et al., 2007) and other range of *Eucalytus* species (960 – 1040 µm) was a popular as a source of fiber pulp for paper industry (Horn & Setterholm, 1990; Ververis et al., 2004). The results for the juvenile bamboo fibre length was lower than softwood fibre length (3600 µm), but also longer than hardwood species such as *Gmelina arborea* (1290 µm) (Roger et al., 2007). The result of this study further indicates that both mature and juvenile *Bambusa vulgaris* fibres were longer than that was reported by Huang et al. (2015). They reported that, the fibre length of *Bambusa rigida* ranged from 1557.31 to 2114.76 µm and no significant differences were found among the bamboo ages.

The mature bamboo is always utilized for engineered composite products for structural applications due to its fibre length that could better impacted on mechanical properties as compared to that of the juvenile *Bambusa vulgaris* (Kumar & Tanya, 2015; Li et al., 2015; Sumardi et al., 2015; Semple et al., 2015; Wu & Ho, 2015; Huang et al., 2016). This could explain the result of this study as presented in Figure 4.28, 4.29 and 4.30, which shows that the laminated mature *Bambusa vulgaris* has higher mechanical properties such as MOR, MOE and MCS than that of the laminated juvenile *Bambusa vulgaris*.

Table 4.10: ANOVA for measured fibre characteristics of *Bambusa vulgaris*

		Fibre Length		Fibre Diameter		Lumen Width		Wall Thickness	
Source	df	Sig.	Var. (%)	Sig.	Var. (%)	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.001**	36.5	0.040*	8.3	0.010*	6.8	0.028*	4.9
Culm Section (CS)	1	0.001**	19.7	0.040*	8.5	0.020*	5.5	0.005**	7.9
BA ×CS	1	0.560ns	0.4	0.077ns	3.2	0.048*	4	0.589ns	0.3

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

Table 4.10 shows the ANOVA such that at 1% and 5% level of significance, the bamboo age and culm section have significant effect on the fibre length of the bamboo. Their level of variability was 36.5%, and 19.7% respectively. This could be explained by the bamboo age and the culm section.

4.2.3.2 Fibre Diameter

Table 4.9 indicates results of fibre diameter for the bottom and top portions of both mature and juvenile bamboo. The fibre diameter of the bottom portion of the mature bamboo culm was 20.54µm whilst that of the top portion was19.22µm. Similarly, the fibre diameter of the bottom portion of the juvenile was 19.26µm whilst that of the top portion was14.03µm. This report is similar to the findings reported by Abd. Latif (1995), Razak, et al. (2010) and Razak, et al. (2012). They reported that the fibre diameter range between 15.8 – 16.5 µm for the 2-year-old culms and 16.7 – 17.6 µm for the 4-year-old culms (Razak et al., 2010) whiles Razak, et al. (2012) reported that the fiber diameter ranged between 18.3 – 22.36 µm.

The results further show that for both the bottom and the top portions of the *Bambusa vulgaris* studied the fibre diameter of the mature bamboo culm was higher than that of the juvenile bamboo culm. The bottom portion for the fibre diameter of the matured was 20.54 µm whilst the juvenile was 19.26 µm. Similarly, for the top portions fibre diameter of the matured was 19.22 µm whilst the juvenile was 14.03 µm. The difference between the fibre diameter for the bottom and top portion of both the juvenile and matured bamboo could be due to age variation. Xiang et al. (2020) reported that age and height significantly influenced the anatomical characteristics of bamboo culm especially on the fibre properties. The study further shows that fibre diameters vary significantly among the ages (mature and juvenile). This result was similar to the observation made for *Bambusa blumeana* and *Gigantochloa scortechinii* (Abd. Latif & Mohd Tamizi, 1992), *Bambusa vulgaris var. striata* and *Bambusa vulgaris Schrad* (Kokutse et al., 2013). The results of this study compared to that of softwoods and hardwoods show that they are lower than that of softwood (35 μm) and hardwood (25 μm). However, the fibre diameter of the study is bigger than *Eucalytus spp* (15.5 - 16.3μm) and findings reported by Egbewole et al. (2015). Their study reported that the fibre diameter ranged from 14.34 – 14.96 μm. Fibre diameter is one of the fibre characteristics that have been shown in this study to be varied along the culm height of *Bambusa vulgaris*.

The result indicates that the mature bamboo culm has wider fibre diameter compared to that of the juvenile bamboo culm which could improve the physical and mechanical properties and thereby influence the utilization potential of bamboo as constructional material in both building and furniture industries (Kumar& Tanya, 2015; Li et al., 2015; Wu & Ho, 2015; Huang et al., 2016). The wider nature of fibre diameter suggests that both mature bottom section and juvenile bottom section could be used for the production of engineered composite products such as laminated bamboo, particleboards, bamboo ply, etc (Bhat et al., 2011; Wu & Ho, 2015; Huang et al., 2016).

The ANOVA in Table 4.10 shows that bamboo age and culm section have significant effect on fibre diameter at 5% significant level. Their level of variability was 8.3% and 8.5% respectively and this could be explained by the bamboo age and the culm section.

4.2.3.3 Lumen Width

The results on the measurement of the fibre lumen width of *Bambusa vulgaris* are shown in Table 4.9. The highest lumen width was obtained from the mature bottom culm

(15.08µm) follow by the mature top culm (12.76µm), juvenile bottom culm (12.54µm) and juvenile top culm (8.78µm). The fibre lumen obtained for this study was higher than the findings reported by Abd. Latif, (1995), Razak et al. (2010) and Razak et al. (2012). They reported that the fibre lumen width ranged between 2.4 – 2.6 µm for the 2-year-old culms and 2.3 – 2.5 µm for the 4-year-old culms (Razak et al., 2010) whiles Razak et al. (2012) reported that the fiber lumen width ranged between 4.43 – 6.18 µm. Furthermore, the study indicate that the mature bamboo culm has wider lumen width than that of the juvenile bamboo culm which could tend to improve its absorption rate of water and minerals and thereby influence the bamboo properties for better industrial utilization as engineered composite products (Bhat et al., 2011).

The results further show that for both the bottom and the top portions of the *Bambusa vulgaris* studied, the fibre lumen width of the mature bamboo culm was higher than that of the juvenile bamboo culm. Additionally, the lumen widths vary significantly among the ages (mature and juvenile). This result is similar to the observation made for *Bambusa blumeana* and *Gigantochloa scortechinii* (Abd. Latif & Mohd Tamizi, 1992), *Bambusa vulgaris var. striata* and *Bambusa vulgaris Schrad* (Kokutse et al., 2013).

The lumen width for this study is comparable with other findings on the lumen width for *Bambusa vulgaris* culm was 2.3 – 2.6 µm (Razak et al., 2010), *Bambusa vulgaris var.striata* was 2.89 – 3.71 µm (Kokutse et al., 2013), *Bambusa vulgaris Schrad* was 2.79 – 3.01 µm (Kokutse et al., 2013) and *Gigantochloa scortechinii* was 4.43 – 6.18 µm (Razak et al., 2012). The result showed that both mature and juvenile *Bambusa vulgaris* lumen width were wider than that of the findings reported by Egbewole et al. (2015). They reported that the lumen width ranged from 8.80 – 9.34 µm.

At 5% level of significance (Table 4.10) the bamboo age and culm section had significant effect on the fibre lumen width. The level of variability was 6.8% and 5.5% respectively that could be explained by bamboo age and culm section. Similar trend of result was obtained for their interaction. Generally, the fibre lumen width decreased from bottom section to the top section of the bamboo species. It has further shown as one of the fibre characteristics in this study that it varies along the culm section of *Bambusa vulgaris* species.

4.2.3.4 Wall Thickness

The results of the measurement of the double-wall thickness for bottom and top portions of the mature and juvenile *Bambusa vulgaris* have been presented in Table 4.9. The mature bottom culm was 7.46µm whilst the matured top culm was 6.45µm. Similarly, the juvenile bottom culm was 6.73µm whilst the juvenile top culm was 5.25µm. This result is similar to the findings reported by Abd. Latif, (1995), Razak et al. (2010) and Razak et al. (2012). Their study reported that the fibre wall thickness range between 13.4 – 13.9 µm for the 2-year-old culms and 14.4 – 15.1 µm for the 4-year-old culms (Razak et al., 2010) whiles Razak et al. (2012) reported that the fiber fibre wall thickness ranged between 13.87 – 16.18 µm.

Additionally, the fibre wall thickness for the mature bamboo culm was higher for both the bottom and the top portions than that of the corresponding values of the juvenile bamboo culm. For the bottom portions, the fibre wall thickness of the matured was 7.46 µm whilst the juvenile was 6.73 µm. Similarly, for the top portion fibre wall thickness of the matured was 6.45 µm whilst the juvenile was 5.25 µm. The thicker wall fibre walls of the mature bamboo culm compared to that of the juvenile bamboo culm could improve its absorption and retention rate of water and minerals and thereby enhance its properties for better industrial utilization for the production of engineered composite products (Bhat et al., 2011).

Furthermore, the fibre wall at the bottom sections was thicker than that of the top sections. Similar trend of result was obtained by Santhoshkumar and Bhat (2014). Their study reported that the wall thickness at basal height level was higher as compared to other height levels. Comparatively, the results of the fibre wall thickness of *Bambusa vulgaris* is higher than that of the fiber wall thickness of *Eucalyptus spp.* which was 4.3 µm and 3.29 – 3.86 µm (Viane et al., 2009; Dutt & Tyagi, 2011). Additionally, the results of this study show that the wall thickness for both mature and juvenile bamboo species was higher than that of the findings reported by Egbewole, et al. (2015). They reported that the fibre wall thickness ranged from 5.54 to 5.62 µm.

The ANOVA in Table 4.10 shows that at 5% level of significance, bamboo age has significant effect on the fibre double wall thickness of the bamboo and the level of variation was 4.9%. Similar trend of result was obtained for culm section. This implies that fibre wall thickness generally decreased from the bottom section to the top section of bamboo species. This further suggests that there are differences within and across the same bamboo species.

4.2.3.5. Tissues Proportion

4.2.3.4.1 Parenchyma Cell

Table 4.11 shows the parenchyma cell proportion in different locations for the bottom and top portions of both juvenile and mature *Bambusa vulgaris*. The parenchyma cell proportion for mature bottom culm were 14.96 % for inner location, the middle location was 12 % and outer location was 7.52 % whilst for mature top culm were 15.04 % for inner location, the middle location was 12 % and outer location was 7.56 %. Similarly, the juvenile bottom culm varied in its parenchyma cell proportion of 15.28 % for the inner location, 12.08 % for the middle location and 7.72 % for the outer location whilst the juvenile top culm has parenchyma cell proportion of 15.32 % for the inner location, 12.12 % for the middle location and 7.72 % for the outer location. This implies that the proportion of parenchyma cells in the inner portions of both juvenile and mature bamboo culm were significantly higher than that of the middle and outer portions of the culm wall at all levels of culm sections. This trend of result is similar to the findings by Kokutse et al. (2013). Their study reported that parenchyma tissues found in the inner portion and outer portion were 63.73% and 31.76% for *Bambusa* species, 52.82% and 33.62% for *Bambusa vulgaris var. striata,* 54.32% and 33.76% for *Bambusa vulgaris Schrad* and 58.19% and 33.64% *Oxytenanthera abyssinica Munro* respectively. The high content of parenchyma tissues in the inner and middle portions could affect the service life of bamboo since organisms such as molds, fungi and termites do feed on the starch granules found in parenchyma cells (Mwaikambo & Ansell, 2001; Razak et al., 2010). According to Chavan and Attar (2013), carbohydrate content of bamboo plays an important role in its durability and service life. They further stated that, durability of bamboo against mold, fungal and borers attack is strongly associated with the chemical composition that is not adequate. This suggests that promoting bamboo durability and service life solely depend on the preservation chemicals (Liese & Kumar, 2003; Chavan & Attar, 2013).

Table 4.11: Tissue proportions of *Bambusa vulgaris*

		Mature Bamboo Culm		Juvenile Bamboo Culm	
Tissues	Location	Bottom	Top	Bottom	Top
Parenchyma (%)	Inner	14.96 ± 0.36	15.04 ± 0.48	15.28 ± 0.44	15.32 ± 0.18
	Middle	12 ± 0.37	12 ± 0.25	12.08 ± 0.5	12.12 ± 0.63
	Outer	7.52 ± 0.18	7.56 ± 0.26	7.72 ± 0.39	7.72 ± 0.3
Vessel (%)	Inner	0.84 ± 0.09	0.88 ± 0.11	0.92 ± 0.11	0.96 ± 0.09
	Middle	1.5 ± 0.25	1.52 ± 0.18	1.48 ± 0.23	1.48 ± 0.3
	Outer	1.04 ± 0.17	1.04 ± 0.09	1.04 ± 0.17	1.12 ± 0.18
Fibre (%)	Inner	4.08 ± 0.44	3.92 ± 0.39	3.8 ± 0.37	3.72 ± 0.18
	Middle	6.6 ± 0.47	6.44 ± 0.26	6.4 ± 0.49	6.32 ± 0.23
	Outer	11.44 ± 0.41	11.36 ± 0.46	11.24 ± 0.3	11.12 ± 0.42

± sign represent standard deviation.

The results further show that for the parenchyma cell proportions studied for various location of both the bottom and the top portions of the *Bambusa vulgaris*, the juvenile bamboo culm was higher than that of the mature bamboo culm. This could be as a result of age variation between them. The lower parenchyma cell proportion of the mature bamboo could enhance the utilization potential of *Bambusa vulgaris* especially in the production of engineering composites products such as laminated board, particleboard, bamboo ply, etc, (Bhat et al., 2011). It could also contribute significantly in improving the durability and service life of these produced engineered products when treated with preservation chemicals (Liese & Kumar, 2003; Chavan & Attar, 2013) for the use of structural and non-structural applications.

According to Liese (1985) the culm tissue is mostly covered by parenchyma cells and the vascular bundles which are composed of vessels, sieve tubes with companion cells and fibres. Studies have shown that parenchyma cells constitute about 50 – 52% of the total culm tissues (Liese, 1985 &1992; Jiang, 2007; Razak et al., 2009; Shibata, 2012). The result of the study further shows that the parenchyma proportion is slightly higher at the top portion compared to that of the bottom portion for both juvenile and mature bamboo. This implies that parenchyma proportion increase from the bottom portion to top portion of the culms. Another observation is that the parenchyma cells proportion for the juvenile bamboo culm is slightly higher than that of the proportion for the mature bamboo culm and this proportional increase has a significant effect.

The ANOVA in Table 4.12 shows that at 5% level of significant, the bamboo age and tissue location have significant effect on parenchyma cells proportion and their level of variation was 2.9% and 79.3% respectively. This implies that the parenchyma cell proportions are very visible within and across the culm wall thickness of bamboo species. It further suggests that parenchyma cells proportion increased at the juvenile stages of development than at the matured stages.

Table: 4.12. ANOVA for tissue proportion of *Bambusa vulgaris*

Source	df	Parenchyma		Vessel		Fibre	
		Sig.	Var. (%)	Sig.	Var. (%)	Sig.	Var. (%)
Bamboo Age (BA)	1	0.008**	2.9	0.001**	9.6	0.001**	4.3
Culm Section (CS)	1	0.122ns	1	0.678ns	0.1	0.071ns	1.3
Tissue Location (TL)	2	0.001**	79.3	0.001**	17.1	0.001**	86.9
BA× CS	1	0.122ns	0.1	0.593ns	0.1	0.030*	1.9
BA× TL	2	0.572ns	0.5	0.466ns	0.6	0.627ns	0.4
CS× TL	2	0.169ns	1.5	0.757ns	0.2	0.337ns	0.9
BA× CS× TL	2	0.374ns	0.8	0.909ns	0.1	0.544ns	0.5

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

4.2.3.5.2 Vessel Proportion

Table 4.11 shows the result of vessel proportion in different locations for the bottom and top portions of both juvenile and mature *Bambusa vulgaris*. The vessel proportion for mature bottom culm were 0.84 % for inner location, middle location was 1.5 % and outer location was 1.04 % whilst for the mature top culm were 0.88 % for inner location, middle location was 1.52 % and outer location was 1.04 %. Similarly, the juvenile bottom culm varied in its vessel proportion of 0.92 % for the inner location, 1.48 % for the middle location and 1.04 % for the outer location whilst the juvenile top culm has vessel proportion of 0.96 % for the inner location, 1.48 % for the middle location and 1.12 % for the outer location.

Additionally, both the bottom and the top portions of the bamboo species studied for the vessel proportion, the juvenile was higher than that of the mature bamboo in terms of the inner location whilst the mature was higher than that of the juvenile in terms of the middle location. However, both the mature and juvenile are almost the same at the outer location for the bottom portion with slightly increased at the juvenile top outer location.

This result indicates that there are variations in the vessel tissue proportion found in both juvenile and mature bamboo culm. The results further show that vessels are larger and visible at the inner portions of the culms due to the activities of water and nutrient transportation (Huang et al., 2015; He et al., 2019). The results further show that the vessel proportions increase from the inner portion through to the outer portion with slightly reduced at outer portions of both the juvenile and mature bamboo culms. This could be attributed to the inability of vessels to be functioned at the outer portions making the vascular bundles smaller and denser in proportions (Zhan et al., 2020). Liese, (1985) reported that the vascular bundles composed of vessels, sieve tubes with companion cells and fibres. Studies have shown that conducting tissue (vessels and sieve tubes) constitute about 8 – 10% of the total culm tissues (Liese, 1985 &1992; Jiang, 2007; Razak et al., 2009; Shibata, 2012). This implies that the vessel proportions could contribute significantly in the transportation of water and nutrients towards the growth of the bamboo culms. However, the proportions could also enhance the strength properties of bamboo since the vessels progressively decreased in diameter from the inner to the outer portions (Razak et al., 2010).This could contribute to the industrial utilization of bamboo culm especially the bottom portions for the manufacturing of engineered composite products (Bhat et al., 2011) for both structural and non-structural applications.

The ANOVA in Table 4.12 show that at 5% level of significance, the bamboo age and tissue location have significant effect on vessel proportion and their level of variation was

9.6% and 17.1%. This implies that the vessel proportions are very visible within and across the diameter of culm wall thickness of bamboo species.

4.2.3.5.3 Fibre Proportion

The results on the measurement of the fibre proportion in different locations for the bottom and top portions of both juvenile and mature *Bambusa vulgaris* are shown in Table 4.11. The fibre proportion for mature bottom culm were 4.08 % for inner location, middle location was 6.60 % and outer location was 11.44 % whilst for the mature top culm were 3.92 % for inner location, middle location was 6.44 % and outer location was 11.36 %. Similarly, the juvenile bottom culm varied in its fibre proportion of 3.80 % for the inner location, 6.40 % for the middle location and 11.24 % for the outer location whilst the juvenile top culm has 3.72 % for the inner location, 6.32 % for the middle location and 11.12 % for the outer location of the fibre proportion. This result shows that the fibre tissues are progressively increased from the inner portions through to the outer portions for the various sections of the culm for both juvenile and mature bamboo species. This is due to the general structure of bamboo culm wall which reveals that the inner portion contains more parenchyma cells but fewer fibres and conducting cells than in the outer portion of the culm wall (Razak et al., 2010). It further indicates that the fibre proportions were higher and visible in the outer portions for both juvenile and mature bamboo. This high increase of fibre proportion could be due to the diminishing nature of vessels that have caused non-activity of water and nutrient transportation in the outer portions of bamboo (Huang et al., 2015; He et al., 2019).

The results further indicate that the *Bambusa vulgaris* studied for the fibre proportion, the matured bamboo was higher than that of the juvenile bamboo for both the bottom and the top portions of the culm. Studies have shown that fibre tissue constitute about 40% of the total culm tissues (Liese, 1985 &1992; Jiang, 2007; Razak et al., 2009; Shibata, 2012). The results further show that these increased of fibre proportion for the mature bamboo could have greater potential of improving the physical and mechanical properties and thereby enhanced the utilization potential of *Bambusa vulgaris* for the structural applications (Liese et al., 1992). The study further shows that the Fibres within the vascular bundle developed in two different ways one around the xylem and the phloem called the fibre sheaths whiles the one is called the fibre bundles. Razak et al. (2010) reported that the fibres constitute the sclerenchymatous tissue and occur in the internodes as caps of vascular bundles or isolated strands. They further mentioned that the fibres are grouped in bundles and sheaths around the vessels and they are long and tapered at both ends. Studies have shown that in the vascular bundle structure, fibres are supposed to play a key role in providing bamboo material with strength and toughness (Lo et al., 2004; Zou et al., 2009). This implies that the proportions of fibre tissues within the portions of bamboo culm especially the bottom portions could serve as the strength ability of the material to be utilized for the manufacturing of engineered composite products such as fibre-medium board, laminated boards, particleboards, bamboo-ply (Bhat et al., 2011; Huang et al., 2013; Appiah-Kubi et al., 2014; Sharma et al., 2014).

The ANOVA (Table 4.12) indicates that at 5% level of significance, the bamboo age and tissue location have significant effect on fibre proportion. The level of variability was

4.3% and 86.9% respectively. This implies that the fibre proportions are very visible within and across the diameter of culm wall thickness of bamboo species.

4.2.3.6 Scanning Electron Microscopy (SEM) Analysis of *Bambusa vulgaris* Culm

4.2.3.6.1 SEM analysis of raw *Bambusa vulgaris* internode parenchyma cell structure

The results of SEM analysis as presented in Figure 4.13 shows that the parenchyma cells are either partly or fully filled with starch granules or empty. Tekpetey, (2011) made similar observation that the ground parenchyma cells are either partly or fully filled with starch granules in *Bambusa vulgaris* in Ghana. The study further shows that most of the parenchyma cells in mature bamboo culm contain starch granules compared to that of the juvenile bamboo culm as indicated with red arrow. This result is consistent with the similar trend of results reported by Razak et al. (2010). They reported that Starch in the 4-year-old culms was more frequent than in the 2-year-old culms. Mwaikambo and Ansell (2001) reported that the parenchyma cells of older culms is filled with starch grains. Studies have shown that very young culms of 3-month-old do not contain starch since all nutrients are immediately utilized in this developmental stage (Mwaikambo & Ansell, 2001; Razak et al., 2010). The low starch content in most of the culms used in this study could be attributed to the time of the harvesting. The starch content in bamboo has been known to vary with seasons, which are higher in the dry than in the rainy season (Razak et al., 2010).

The result of micrographs further indicates that some of the parenchyma cells in the mature bamboo culm are filled with smaller granules that could be an inclusion. The

elliptical in shape for both mature and juvenile nodes. This result is consistent with the similar trend of results reported by Huang et al. (2015). They reported that metaxylem vessels were not truly circular but rather elliptical in shape with the radial length longer than the tangential diameter.

Furthermore, the two-metaxylem vessels found across the diameter of the node wall thickness, one has bigger diameter than the other for both mature and juvenile bamboo respectively. Additionally, the metaxylem vessels diameter were bigger in the inner portion than the middle and outer portions of both the mature and juvenile node. This could be attributed to the fact that, vessels are actively functioned in the conduction of water and nutrient transportation (Huang et al., 2015; He et al., 2019).

The SEM further indicates that the metaxylem vessels were progressively increased from the outer portion to the inner portion for both mature and juvenile bamboo. In addition, the proto-xylem is more visible in the inner and middle portions for both mature and juvenile bamboo. Furthermore, the proto-xylem is almost dead. Another observation of the micrograph shows that the phloem result is similar to the proto-xylem.

same in both juvenile and mature node regardless of the age difference. It is further observed from the study that the parenchyma cells are found between fibres whiles the vessels are surrounded by the parenchyma cells. Studies show that starch granules are found in parenchyma cells of the old culm (Mwaikambo & Ansell, 2001; Qisheng et al., 2001; Razak et al., 2010). Research shows that very young culms of 3-month-old do not contain starch since all nutrients are immediately utilized in this developmental stage (Mwaikambo & Ansell, 2001; Razak et al., 2010). Qisheng et al. (2001) reported that parenchyma cells are made up of long and short cells of which the long cells contain the starch granules. They further mentioned that short cells do not contain starch, even if their wall thickened. However, this present study shows that the parenchyma cells in the node are made up of smaller cells and these cells do contain starch granules as indicated in Figure 4.15 R. The present study further indicates that the starch granules found in the parenchyma cells are smaller in sizes when compared to that of the starch granules found in long cells of parenchyma at the internodes section. This could be accounted for one of the reasons why biodegradable agents normally attacked the internodes more than the nodes if not treated to prolong the service life of *Bambusa vulgaris*.

Comparatively, the result shows that the fibres within the nodes are thicker and compact in both mature and juvenile. This could be one of the reasons why the strength properties at the nodes are higher and better than that of the internodes of *Bambusa vulgaris*. This could also account for the rigidity at the node sections as compared to the flexibility at the internode sections of the culms. The number of vessels and its sizes at the longitudinal nodes section according to this study are smaller in both the nature and

fibres as well as how the Parenchyma cells around vessel in mature bottom culm node. **R= Mature top culm**; Vessels surrounded by parenchyma cells filled with or without starch granules arranged between fibres in mature top culm node.

4.3. Chemical Properties

4.3.1 Extractives Content

Acetone, ethanol and water extractives solubility content of juvenile and mature bamboo of *Bambusa vulgaris* is presented in Table 4.13. The acetone extractive soluble content for juvenile bamboo culm was 2.5% whilst that of the mature bamboo culm was 2.2%. Additionally, the ethanol extractive content of mature bamboo culm was 1.83% whilst that of juvenile bamboo culm was 1%. In addition, mature bamboo culm recorded higher percentage value of 15.05% for the hot water solubility content which is more than that of 10.48% recorded for the juvenile bamboo culm. The juvenile bamboo culm recorded the average of 8.92% of cold-water solubility whilst that of the mature bamboo culm was 12.23%. This means that the *Bambusa vulgaris* extractives are less soluble in acetone and ethanol but are more soluble in water. Furthermore, the solubility content of acetone was relatively higher than the ethanol content as presented in Table 4.15. The result indicates that acetone solubility content removes more minor constituents find in bamboo culm for both juvenile and mature *Bambusa vulgaris* than that of the ethanol solubility content. However, ethanol extractive soluble content explains that there are other minor constituents found in mature *Bambusa vulgaris* that are more difficult to remove with acetone solubility than that of the juvenile *Bambusa vulgaris*. This means that the mature *Bambusa vulgaris* could have a higher service life than that of the juvenile *Bambusa* *vulgaris* since extractive content influences the natural durability of bamboo material (Shibata, 2012; Chavan & Attar, 2013).

Table 4.13: Chemical composition of *Bambusa vulgaris*

Bamboo Type	Acetone (%)	Ethanol (%)	Cold water solubility (%)	Hot water solubility (%)	Lignin (%)	Holo - cellulose (%)
Juvenile	2.5± 0.04	1.00± 0.01	8.92± 0.83	10.48±1.31	22.98±2.24	63.05 ± 2.84
Mature	2.2± 0.16	1.83± 0.08	12.23±1.1	15.05±0.77	29.11±1.47	51.84 ± 1.22

± sign represent standard deviation

Additionally, the hot water-soluble extractive content was higher than that of the cold-water soluble extractive content for both matured and juvenile *Bambusa vulgaris*. This implies that a lot of minor constituents could only be removed through a high temperature process rather than a cold temperature. It also means that some of the minor constituents could easily be removed as soon as they come in contact with the cold water and this could also affect the colouring and natural durability of bamboo culm (Gritsch & Murphy, 2005; Sun et al., 2006). The extractive content plays major role in enhancing the natural durability of bamboo since it serves as defensive mechanism against termites, fungi and borers with preservation chemicals (Shibata, 2012; Chavan & Attar 2013). Once some of the extractives content could easily leached, the internal defensive ability would be weakened and thereby exposing the material to excessive attack by these deteriorated agents which then affect the utilization potential of the material (Mathew & Nair, 1990; Thapa et al., 1992).

Furthermore, the mature bamboo culm contains more soluble materials than the juvenile bamboo culm and this could improve its density and durability properties. The higher extractive content could be attributed to its anatomical structure that has a complex and larger vascular bundle (Sulaiman et al., 2016). The high extractive content obtained in this study explains that the *Bambusa vulgaris* culms contain more substances like waxes, fats, resins, phytosterols, non-volatile hydrocarbons, low-molecular weight carbohydrates, salts and other water-soluble substances that are soluble in water or neutral organic solvent (Reardon et al., 2013; Ma et al., 2014; Li et al., 2014; Sadiku et al., 2016).

These extractives in general are not considered as the main constituents of bamboo. However, they play an important role in the physiological activity of bamboo since these constituents are normally found in cell cavity (Khalil et al., 2012). The result could be compared to the similar work conducted by Sulaiman et al. (2016). Their study concluded that *Bambusa vulgaris* of the mature age had higher extractive compared to that of the juvenile age. For this reason, the extractive content may be related to density of experimental samples used. A previous study has shown that, the extractive content is affected by cell wall thickness and structure, cell width, the relative proportions of different types of cells, and the amount of extractives present (Espiloy, 1985).

The result for the extractives content of *Bambusa vulgaris* is comparable to other similar extractive content of different species of bamboo. Razak et al. (2013) obtained the extractive content of *Gigantochloa brang, Gigantochloa levis, Gigantochloa scortechinii* and *Gigantochloa wrayi* bamboo with 8.3%, 9.23%, 8% and 8.62% respectively. Norul Hisham et al. (2006) obtained the extractive content of *Gigantochloa scortechinii* bamboo ranging from 3.4 to 5.8%. Mahanim et al. (2008) on their study on *Gigantochloa scotechinii* and *Gigantochloa lagulata* obtained the extractive content ranging from 3.74 to 4.45% and 2.95 to 3.20% respectively.

Extractives content of any fibrous materials are very important element that could positively or negatively influence the material utilization potential for the manufacturing of engineered composite products (Bhat et al., 2011; Wang et al., 2015; Sukmawan et al., 2016). This implies that both mature and juvenile bamboo could be used for the production of engineered composite products such as laminated panels, particleboard, (Bhat et al., 2011; Harries et al., 2012; Wang et al., 2015; Sukmawan et al., 2016) for the structural and non-structural applications (Fu & Fang, 2016; Chen et al., 2020).

Table 4.14: ANOVA for *Bambusa vulgaris* chemical composition

	df	F-value	Sig.
Acetone	1	6.498	0.126ns
Ethanol	1	186.189	0.005**
Hot water	1	18.119	0.051*
Cold water	1	28.132	0.034*
Holocellulose	1	26.379	0.036*
Lignin	1	30.704	0.031*
Alpha cellulose	1	17.074	0.054*
Hemicellulose	1	32.058	0.030*

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The ANOVA on extractives content as presented in Table 4.14 show no significant difference for acetone soluble extractive but significant effect for ethanol soluble extractive ($p \geq 0.05$) for the bamboo age. This means that the quantity of minor constituents extracted with acetone solution were not different from each other. However, there was a significant effect on ethanol extractive for the bamboo age. This means that mature bamboo culm has more minor constituents that are difficult to remove than that of the juvenile bamboo culm. This implies that the extractive content at mature bamboo culm enhances its natural durability properties and thereby advancing its general acceptance for the structural applications. Similar trend of result was observed for the water extractives content.

4.3.2 Lignin Solubility Content

Lignin is considered as cementing material in bamboo that plays an important role as a binding agent to hold the cells together. Lignin is phenolic in nature and is difficult to separate if not with strong acids. Sjostrom (1981) reported that, Klason lignin is obtained after removing the polysaccharides from extractive free wood or bamboo by hydrolysis with 72% sulfuric acid. This acid method for lignin contain preliminary extractive treatments which helps to remove some amount of minor substances like tannins, resins, oils, fats, waxes and so on (Reardon et al., 2013; Li et al., 2014).

Table 4.13 shows that the lignin content of the juvenile bamboo (22.98%) was lower than the mature bamboo (29.11%). However, it was within the range of bamboo species reported in the literature. Comparatively, the juvenile bamboo lignin of 22.98% was similar to some of the findings and conclusions made by the following researchers regarding some bamboo species such as *Bambusa blumeana* of lignin 20.5-22.7% (Latif

&Liese, 1995; Liese & Tang, 2015), *Bambusa heterostachya* of lignin 19.3-23.1% (Latif et al., 1996), *Bambusa stenostachya* of lignin 20.7-25.2% (Chang et al., 2013), *Bambusa vulgaris* of lignin 22.7-23.9 (Latif & Liese, 1995; Liese & Tang, 2015), *Dendrocalamus asper* of lignin 18.5-29% (Prasetya, 1996), *Phyllostachy pubescens* of lignin 22.8% (Li et al., 2007), *Phyllostachy pubescens* of lignin 21.26-23.95% (Li, 2004), *Schizostachyum zollingeri* of lignin 22.1-22.9% (Latif & Liese, 1995; Liese & Tang, 2015). Generally, the lignin content of the juvenile bamboo culm falls within the lignin content range of 20 – 30% reported by Peng and She (2014).

Additionally, the mature bamboo culm has higher lignin content than the juvenile bamboo culm. The presence of the high lignin in the mature bamboo culm will ensure effective bonding structure of the fibre cell walls which could generally influence the rigidity of the material‟s physical and mechanical properties (Li et al., 2010) as compared to that of the juvenile bamboo culm. Research shows that, non-cellulose substances influence the fibre properties such as strength, flexibility, moisture and density significantly (Li et al., 2010). Lignin gives rigidity to the cell within the cell wall and this is the assurance of the bamboo safety in regards to its usage as structural material for constructional industry. Research shows that, the high lignin content of bamboo contributes to its high heating value and its structural rigidity makes it a valuable building material (Scurlock et al., 2000). This implies that the mature bamboo culm could be used for the production of engineered composite products in construction industry (Bhat et al., 2011).

Comparatively, the mature *Bambusa vulgaris* lignin (29.11%) is higher than that of *Gigantochloa brang* (24.83%) and *Gigantochloa levis* (26.50%). However, they are lower than that of *Gigantochloa wrayi* (30.04%) and *Gigantochloa scortechinni* (32.55%) (Wahab et al., 2013). The lignin content of the mature bamboo (29.11%) falls within the generally accepted levels of 20 – 30% (Peng & She 2014).

The ANOVA at 5% level of significance indicates that bamboo age has significant effect on the lignin content $p \leq 0.05$ (Table 4.14). This means that the influence of lignin in the structure of mature bamboo culm will be much higher than that of the juvenile bamboo culm. This implies that the lignin content in mature bamboo culm could enhance its bonding properties and thereby improves its general acceptability for the structural applications in construction industry. Zhan et al. (2016) reported that higher content of lignin made the bamboo culm tougher and stiffer, because it provides plant tissue and individual fibres with relatively greater compressive strength and stiffens the cell wall of the fibres better, so as to protect the carbohydrates from chemical and physical damage.

4.3.3 Holocellulose Content in *Bambusa vulgaris*

The holocellulose in the woody material consist of both the α-cellulose and hemicellulose (Dieguez-Alonso et al., 2015). The result as reported in Table 4.13 indicated that, the holocellulose content of juvenile bamboo culm recorded higher percentage of 63.05 whilst the mature bamboo culm recorded the lower percentage of 51.48. This could be attributed to the high presence of parenchyma cells found in the juvenile bamboo according to Figure 4.9, which could contain starch granules. Qisheng, et al. (2001) reported that the long parenchyma cells, with thickened polylamellated and lignified wall, usually have starch granules in them. They further stated that the starch content of oblong parenchyma cells in bamboo stem of 1 - 2 years of age is abundant.

The results of high holocellulose content of the juvenile bamboo mean that, it contained more carbohydrates than that of the mature bamboo, which could make it more susceptible to biodegradable agent such as termites, fungal and borers‟ attacks (Liese, 1985; Mathew & Nair, 1990; Thapa et al., 1992). Studies have shown that hemicellulose and cellulose are actually made up of carbohydrate polymers which consist of simple sugars of monomer and lignin from phenylpropane (Browning, 1975). This could eventually affect its natural durability and thereby leads to short service life than that of the mature bamboo if no application of preservation chemicals (Liese & Kumar, 2003; Chavan & Attar, 2013) is applied. Peng and She (2014) reported that the holocellulose content in bamboo accounted for 70 – 90% of the chemical composition. The high holocellulose content in juvenile bamboo perhaps could be one of the reasons affected its general acceptance as constructional material in building and furniture industries.

The result is comparable to one reported by Sulaiman et al. (2016). Their study reported that the young *Bambusa vulgaris* recorded higher holocellulose content than the mature *Bambusa vulgaris*. The result of this study is also consistent with the findings of Tamalong et al. (1980) and Chen et al. (1985). They reported that the holocellulose content in bamboo normally consists about 50 – 70%.

The ANOVA indicated that there was a significant effect on the holocellulose content by bamboo age with $p \leq 0.05$ (Table 4.14). This implies that the variation in holocellulose content within mature and juvenile *Bambusa vulgaris* has different proportional values from each other. This means that the impact of holocellulose content in juvenile bamboo culm could be more influential compared to that of the mature bamboo culm.

4.3.4 Alpha Cellulose in *Bambusa vulgaris*

Cellulose is carbohydrate polymers constituents of simple sugars monomers (Browing, 1975). The results as presented in Table 4.15 show the alpha cellulose content of *Bambusa vulgaris* in different ages (juvenile and mature). The alpha cellulose content of the mature bamboo was 55.93% whilst that of the juvenile bamboo was 48.62%. The difference could be attributed to the anatomical structure of the mature bamboo as it has been also reported by Sulaiman et al. (2016). Their study reported that high cellulose in mature *Bambusa vulgaris* might be due to the anatomical structure, whereby the mature age had a larger fibre size and length in the culm of the bamboo species, therefore increasing its alpha cellulose content. The high cellulose content found in mature bamboo could lead to improvement of its mechanical properties (Janssen, 1981).

Peng and She (2014) reported that cellulose content accounted for 45 – 55% of the major constituents of bamboo. Li et al. (2010) in their studies reported that cellulose content accounted for 73.83%. They further reported that cellulose content decreases with increase in age of bamboo. However, the results of this present prove otherwise such that cellulose content turns to increase as the bamboo culm aging. This trend of conclusion was similar to the findings as reported by Sulaiman et al. (2016). Their study reported that the mature *Bambusa vulgaris* has high cellulose content than that of the young *Bambusa vulgaris.*

The alpha cellulose content for the *Bambusa vulgaris* mature culm (55.93%) and juvenile culm (48.62%) as presented in Table 4.15 is comparable to some similar findings in literature. Mahanim et al. (2008) reported that the alpha cellulose contents in bamboo G. scortechinii and G. lagulata consists about 46.14% to 46.53% and 48.4% to 56.45% respectively. Ireana (2010) reported that the alpha cellulose content in *Bambusa blumeana* consist of 58.72%. Li et al. (2007) also reported that alpha cellulose content on *P. pubescens* (Moso bamboo) ranged from 41.71% to 49.02%. The value of alpha cellulose content in this present study could be higher compared to softwood fibre (42%) (Thomas, 1977). However, the mature and juvenile bamboo culms cellulose content values fall within the cellulose content of bamboo in general as reported by Peng and She (2014). Peng and She, (2014) reported that cellulose content accounted for 45 – 55% of the major constituents of bamboo.

The ANOVA indicates that there was a significant effect on the alpha cellulose content by bamboo age with $p \leq 0.05$ (Table 4.14). This implies that the variation in cellulose content among mature and juvenile bamboo species have different proportional values from each other. This means that the impact of cellulose content in mature bamboo could be more influential compared to that of the juvenile bamboo.

Table 4.15: The main chemical composition of *Bambusa vulgaris*

Bamboo Age	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Juvenile Bamboo	48.62 ± 1.99	51.39 ± 1.01	22.98 ± 2.24
Mature Bamboo	55.93 ± 1.52	44.08 ± 1.52	29.11 ± 1.47

± sign represent standard deviation.

4.3.5 Hemicellulose Content in *Bambusa vulgaris*

Hemicelluloses are carbohydrate polymers constituents of simple sugars monomers (Browing, 1975). Table 4.15 shows the hemicellulose content of *Bambusa vulgaris* in different ages (juvenile and mature). The juvenile bamboo species recorded 51.39% which was higher compared to that of 44.08% hemicellulose content for the mature bamboo. This result could be attributed to the anatomical structure of the juvenile bamboo culm as it has been also reported by Sulaiman et al. (2016). They reported that the bottom portion on young age of *Bambusa vulgaris* which has a thick S_1 layer in vascular bundle of the bamboo species. Their study concluded that the bottom portion in young *Bambusa vulgaris* had the higher hemicellulose content, and also had high content of polysaccharides in the primary and secondary walls. Razak et al. (2013) reported that hemicelluloses are amorphous in nature and serve as the lignin to form the matrix, in which the cellulose fibrils are embedded. This means that the high hemicellulose content could influence the natural durability of the juvenile bamboo culm and thereby affects the service life as well as enhancing its general physical property of the culm when treated with preservation chemicals (Liese & Kumar, 2003; Chavan & Attar, 2013).

The result compares favourably with findings reported by Sulaiman et al. (2019). Their study reported that the overall hemicellulose content in two selected bamboo species ranged from 24.66% to 50.93%. The highest average of hemicellulose content was found in *Bambusa vulgaris* (37.54%) and followed by *S. brachycladum* (35.32%). Their study further reported that, *Bambusa vulgaris* had a high average of hemicellulose content in the 2-year-old culms (43.57%) whiles *S. brachycladum* had higher hemicellulose content in the 4-year-old (41.94%). The hemicellulose content for both mature and juvenile *Bambusa vulgaris* are also higher than the hemicelluloses content of *Eucalyptus* species which range from 8.66% - 18.88% (Dutt & Tyagi, 2011).

Peng and She (2014) reported that hemicellulose content accounted for 25 – 35% of the major constituents of bamboo. However, the result of this present study proves otherwise such that hemicellulose content accounted for approximately 44 – 51% in *Bambusa vulgaris* as shown in Table 4.29. This trend of conclusion is similar to the findings as reported by Sulaiman et al. (2016). Their study reported that the mature *Bambusa vulgaris* has hemicellulose content with 32.18%, 29.32% and 33.17% and the young *Bambusa vulgaris* with 48.53%, 41.71% and 40.48% which in all accounted for approximately 29 – 49% in *Bambusa vulgaris*.

Table 4.14 presents the ANOVA that shows that there is a significant effect on the hemicellulose content by the bamboo age with $p \leq 0.05$. This implies that the difference in hemicellulose content across the bamboo species could be explained by bamboo age. This means that the impact of hemicellulose content in juvenile bamboo could be higher than that of the mature bamboo culm. Peng and She (2014) reported that the content of hemicelluloses in bamboo was influenced by the conditions of species, age, climate, harvest and etc. These factors could have accounted for the differences in hemicellulose content for both mature and juvenile bamboo.

4.4. LAMINATED BAMBOO COMPOSITE

4.4.1. Physical Properties

4.4.1.1 Moisture Content of Laminated Bamboo

The moisture content (MC) of laminated mature and juvenile *Bambusa vulgaris* made with 5RL adhesive is presented in Figure 4.16. The juvenile laminated bamboo composite recorded the highest MC of 16.25% whilst the mature laminated bamboo composite recorded the lowest MC of 12.36%.

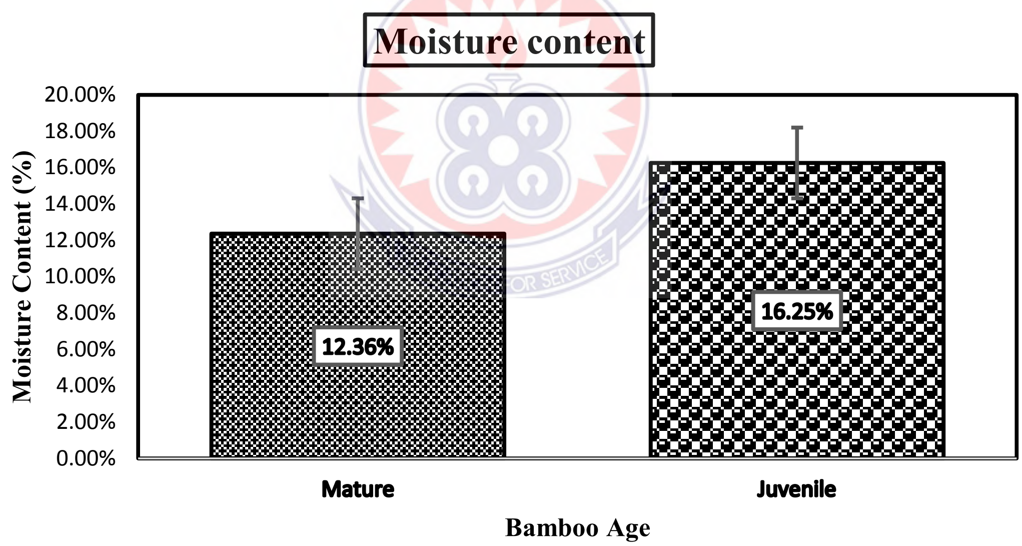

Figure 4.16: Moisture content of laminated bamboo composite; N=10

The difference in MC as being showed in Figure 4.16 could be attributed to the anatomical properties of *Bambusa vulgaris* (Liese, 1985; Razak et al., 2010). Liese (1985) and Razak et al. (2010) reported that differences in moisture content might be due to anatomical structure between the culms age and location along the culms. This implies that the variation in the moisture levels between mature and juvenile bamboo laminate could be as a result of the differences of their anatomical properties. This present study indicates that the proportion of vascular bundle and fibre properties of the matured bamboo was higher than that of the juvenile bamboo as presented in the Table 4.5 and 4.9.

The lower MC of the laminated mature bamboo could enhance its mechanical properties such as compressive strength parallel to grain. Xu et al. (2014) reported that the compressive strength decreases rapidly until the bamboo moisture reached the saturated point. The lower moisture content of the laminated mature bamboo could also improve its dimensional stability and therefore enhance its selection for structural applications especially in building and furniture construction (Chen et al., 2020). The ANOVA in Table 4.16 show that at 5% level of significance the bamboo age has significant effect on the moisture content of the laminated bamboo.

4.4.1.2 Basic Density of Laminated Bamboo

Figure 4.17 shows the basic density of laminated mature and juvenile *Bambusa vulgaris*. The basic density of the mature laminated bamboo composite was 827.93 kg/m³ whilst that of the juvenile laminated bamboo composite was 705.87 kg/m³. This result could be attributed to the fibre wall thickness and lumen width within the various culm heights (Rusch et al., 2019). Rusch et al. (2019) reported that basic density is directly influenced by the cell wall thickness of the fibres. The study further reported that species with lower basic density have fibres with thinner wall. Density is known to influence the strength properties of bamboo. Rusch et al. (2019) reported that density is a variable that influences the mechanical properties. Therefore, the higher basic density of the laminated mature bamboo could contribute significantly to its better mechanical properties that intend influence the general acceptability for its structural applications as constructional material (Rusch et al., 2019; Chen et al., 2020).

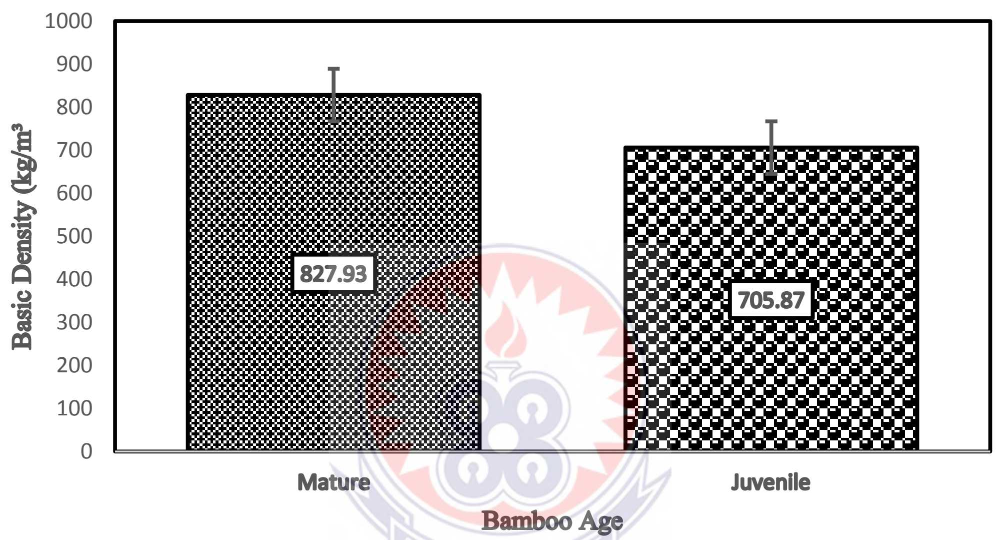

Figure 4.17: Basic density of laminated bamboo composite; N=10

The result is comparable to the findings reported by Sharma et al. (2014), Sharma et al. (2015) and Rusch et al. (2019). Sharma et al. (2015) reported that the laminated bamboo density recorded 686 kg/m^3. Rusch et al. (2019) reported that Glued-laminated bamboo recorded density average of 770 kg/m^3. Sharma et al. (2014) also reported that laminated bamboo density arranged from 577-750 kg/m^3. The high basic density of mature laminated bamboo could be utilized for both external and internal works due to its impact on mechanical properties. This could be used for structural applications like roofing trusts, ceiling joists, ceiling panel, door and window frames, flooring panel, furniture products like bookshelves, carcase construction, and so on. The juvenile laminated bamboo composite could be used for internal works such as bedside cabinet, ceiling panels, and so on (Abd Latif et al., 1990; Xing et al., 2018; Chen et al., 2020).

The ANOVA indicates that there was a significant effect on the basic density of laminated bamboo composite by bamboo age with $p \leq 0.05$ (Table 4.16). This implies that the variation in basic density among mature and juvenile bamboo species have different proportional values from each other.

Table 4.16: ANOVA for physical properties of laminated *Bambusa vulgaris*

Physical Properties	df	F-value	Sig.
Basic Density	1	121.636	0.001**
Moisture Content	1	14.029	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

4.4.1.3 Shrinkage of Laminated Bamboo

The results presented in Figure 4.18 show the radial, tangential and longitudinal shrinkage for both mature and juvenile laminated bamboo composite. The shrinkage of the laminated mature bamboo was 2.47% for radial, 2.8% for tangential and 0.13% for longitudinal. Similarly, the shrinkage of the laminated juvenile bamboo has 6.32% for radial, 6.51% for tangential and 0.22% for longitudinal.

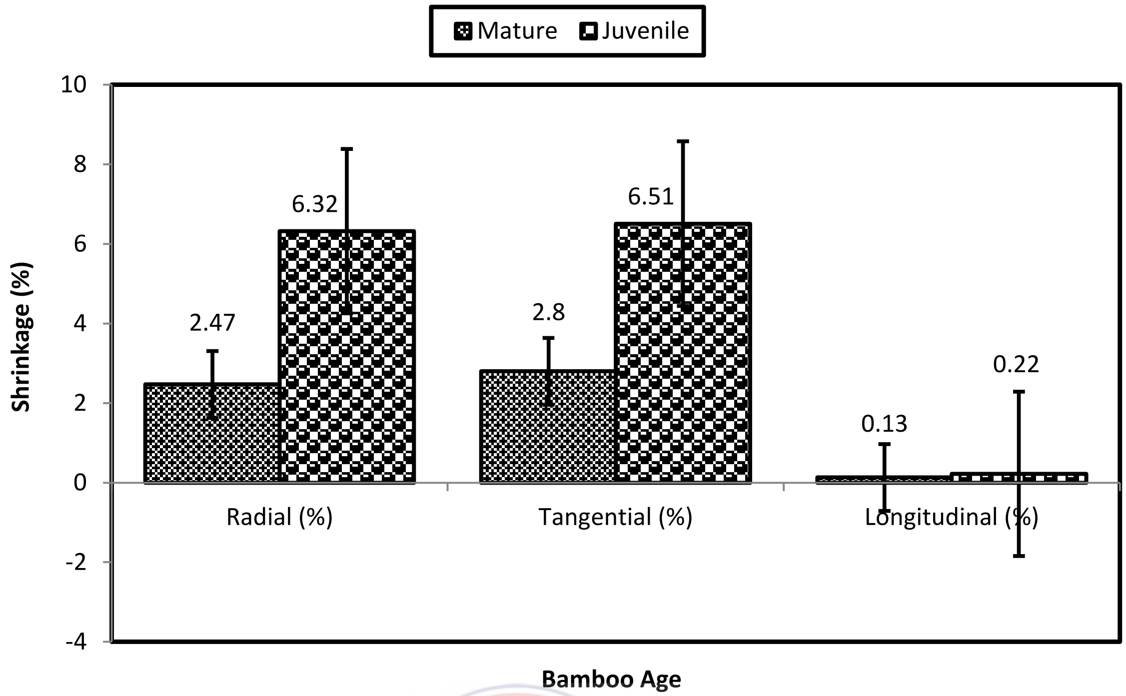

Figure 4.18: shrinkage of laminated bamboo composite; N=10

Additionally, the juvenile bamboo laminated shrinks higher than the mature bamboo laminated. For the radial shrinkage studied, the laminated matured bamboo was 2.47 % whilst that of the juvenile was 6.32 %. Tangentially the shrinkage of the matured bamboo laminate was 2.80 % whilst the juvenile one was 6.51%. Similarly, the longitudinal shrinkage of the laminated matured bamboo was 0.13% whilst the juvenile was 0.22 %.

In addition, both the mature and the juvenile bamboo laminate, shrinkage along the tangential direction was higher followed by the radial and then the longitudinal. Additionally, the radial (6.32%), tangential (6.51%) and longitudinal (0.22%) shrinkage for the juvenile laminated bamboo composite were more than twice that of the mature laminated bamboo composite. This implies that the laminated mature bamboo has a better dimensional stability than that of the juvenile and this could enhance its properties for utilization as constructional material for structural and non-structural applications (Chen et al., 2020; Fu & Fang 2016).

The shrinkage differences in both mature and juvenile bamboo laminate could be attributed to the anatomical structure. The fiber length is often higher at the outer portion through toward the middle and decreases toward the inner portion of the culm wall. The inner portion contains more parenchyma cells but fewer fibers and conducting cells than in the outer portion of the culm wall (Razak et al., 2010). This structure causes the culm to have higher stress at the inner portion, which then causes the outer portion of the culm to shrink toward the inside, resulting in some of the bamboo culm splitting during the drying process (Anokye et al., 2014). The result of this study shows that the anatomical properties such as fibre characteristics of the matured bamboo was higher than that of the juvenile bamboo as presented in the Table 4.9.

The result is comparable to similar findings reported by Ogunsanwo et al. (2019). For the conventional wood, tangential direction has been accepted as where the greatest dimensional shrinkage occurs while shrinkage along the radial plane is considered less whereas the longitudinal shrinkage has been largely reported to be the least among the three and could be ranged from 0.1 - 0.3% (Desch, 1988; Dinwoodie, 1989). Comparatively, the result of this study is in line with the trend of conventions of wood found in the literature (Desch, 1988; Dinwoodie, 1989). However, the tangential and radial shrinkage values were higher than that was stated in the literature (Desch, 1988;

Dinwoodie, 1989). This means that shrinkage occurred in bamboo culm could be different from that of timber.

The mature laminated bamboo composite shrinkage level provides greater assurance that, using laminated bamboo for structural applications especially for external works will be of great benefits due to its quality of dimensional stability (Tumolva et al., 2009). The juvenile laminated shrinkage level also has a good dimensional stability that could promote the utilization potentials of laminated bamboo for structural applications especially for internal works since internal temperature is not as high as the external temperature (Fu & Fang 2016; Chen et al., 2020).

Table 4.17: ANOVA values of shrinkage laminated *Bambusa vulgaris* culm

Physical Properties	df	F-value	Sig.
Radial Shrinkage	1	40.832	0.001**
Tangential Shrinkage	1	38.436	0.001**
Longitudinal Shrinkage	1	11.915	0.003**

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

The ANOVA in Table 4.17 show that at 5% level of significance bamboo age has significant effect on the radial, tangential and longitudinal shrinkage of laminated bamboo composite.

4.4.1.3. Volumetric Shrinkage

Figure 4.19 shows volumetric shrinkage for the laminated mature and juvenile bamboo composite. The volumetric shrinkage of the laminated juvenile bamboo was 13.05% whilst that of the mature was 5.4%. The observed difference in volumetric shrinkage is as a result of shrinkage that are unequal along the three-dimensional planes and that could be largely influenced by the rate of radial and tangential shrinkage respectively. This result is comparable to the outcome of a similar study by Thuc and Tuong (2017). Thuc and Tuong (2017) reported that volumetric shrinkage of *Dendrocalamus giganteus* bamboo culm ranges from 9.2 - 12.1%. Research has shown that volumetric shrinkage of bamboo from different tropical and temperate regions ranges from 7.8 to 36.54% (Wahab et al., 2012; Zhaohua & Wei, 2018).

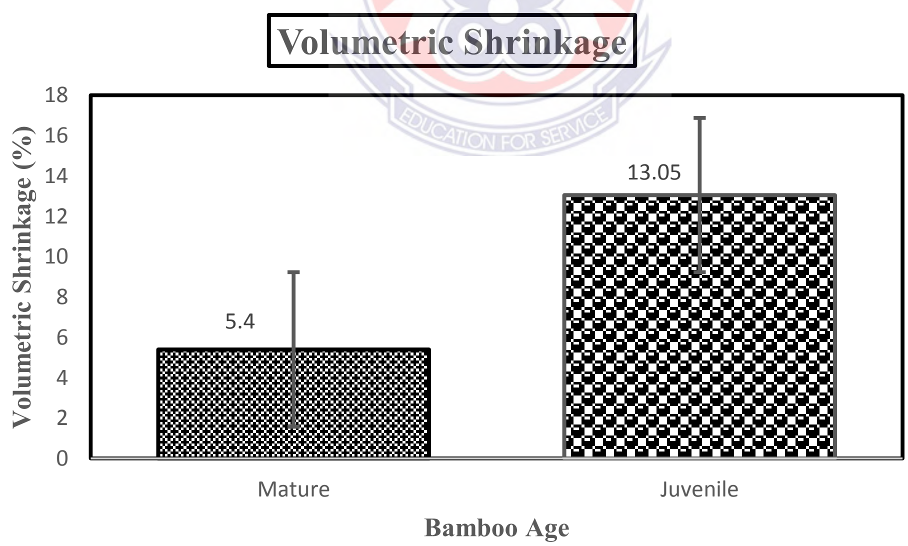

Figure 4.19: Volumetric shrinkage of laminated bamboo composite.

The juvenile laminated bamboo volumetric shrinkage value of 13.05% was more than twice that of the mature laminated bamboo composite. This means that the dimensional stability of mature laminated bamboo was better than that of the juvenile laminated bamboo. This supports the selection of mature laminated bamboo composite rather than juvenile laminated bamboo to be used for structural applications in the furniture and construction industries (Chen et al., 2020). This result is comparable to similar findings by Ogunsanwo et al. (2019).

The ANOVA in Table 4.18 show that at 5% level of significance bamboo age has significant effect on the volumetric shrinkage of laminated bamboo composite.

Table 4.18: ANOVA of shrinkage properties of laminated *Bambusa vulgaris*

Shrinkage Properties	df	F-value	Sig.
Volumetric	1	40.029	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

4.4.2 Mechanical Properties Laminated Bamboo Composite

4.4.2.1 Modulus of Elasticity

Modulus of Elasticity (MOE) is an important property in laminated bamboo composite production that measures its stiffness or resistance to bending when the board is subjected to stress. The MOE of the laminated *Bambusa vulgaris* presented in Figure 4.20 show that the MOE for the laminated mature bamboo was 13379 MPa whiles the of the laminated juvenile bamboo was 5875.7 MPa. This higher variation in MOE could be attributed to the longer fibre length and thicker fibre wall of the mature bamboo culm. This present study reveals that the proportion of vascular bundle and fibre properties of the matured bamboo was higher than that of the juvenile bamboo as presented in the

Table 4.5 and 4.9 respectively. Studies have shown that higher mechanical strength of bamboo is influence by larger fibre length and thick cell wall of bamboo fibres. The fibre proportion occupied by vascular bundles would determine the physical and mechanical properties of a bamboo species (Tomalang et al., 1980; Janssen, 1991; Liese, 1998).

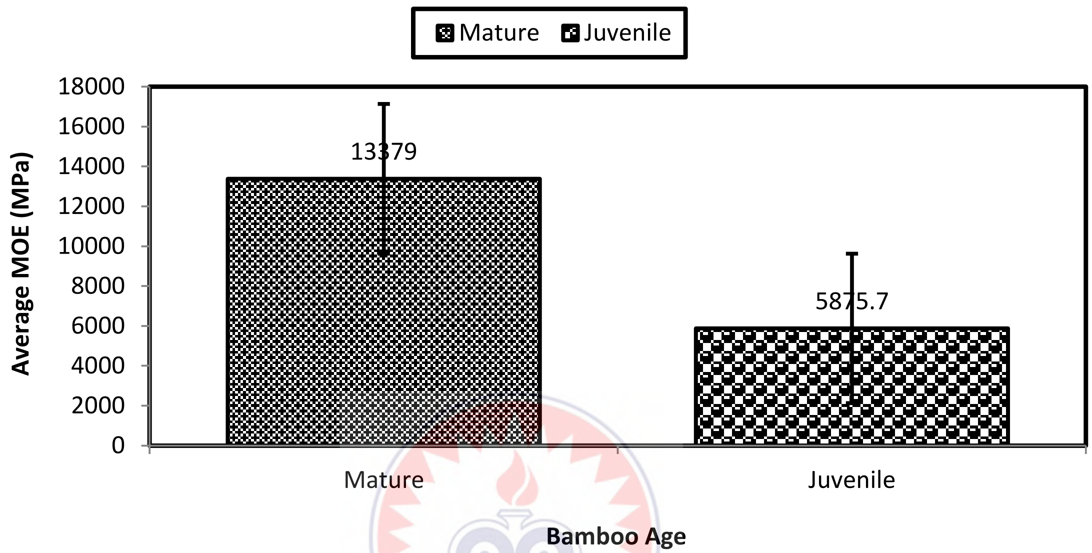

Figure 4.20: Average MOE of laminated bamboo composite; N=10

The vascular bundle could also influence the MOE of mature laminated bamboo composite due to the denser nature found at the outer portions. The smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer portions had higher density and mechanical strength than the inner portions (Zhou, 1981; Liese, 1985). The high MOE of laminated mature bamboo makes it a preferable material for structural applications like roofing trusts, ceiling joists, ceiling panel, door and window frames, flooring panel, furniture products like book shelves, carcase construction, and so on. The juvenile laminated bamboo on the other hand could be used for internal works such as bedside cabinet and ceiling panels (Abd Latif et al., 1990; Xing et al., 2018).

The result is comparable to that of Huang et al. (2013), Appiah-Kubi et al., (2014), and Sharma et al. (2014). Huang et al. (2013) reported that the mean MOE of laminated bamboo arranged from 7000 - 14000 Mpa. Appiah-Kubi et al. (2014) also reported that the mean MOE of laminated *Bambusa vulgaris* board made with three different formaldehyde adhesives ranged from 9794 - 9923 MPa and lastly, Sharma et al. (2014) reported that MOE of laminated bamboo ranged from 1000 - 12000 Mpa.

In addition, laminated mature bamboo composite compares favourably with some of the tropical hardwood species like *Khaya ivorensis* with an MOE of 9113 MPa (Addae-Mensah, 1978; Appiah-Kubi, 2015), *Sterculia rhinopetala* with an MOE of 13382 MPa (Appiah-Kubi et al., 2012; Brunner et al., 2008), *Combretodendron africanum* with an MOE of 9739 MPa (Ofori et al., 2009). According to Appiah-Kubi et al. (2014), the above wood species are used for various forms of construction works in Ghana and the world at large. This implies that the mature laminated bamboo with MOE of 13379 MPa could be used for similar construction works as been mentioned by Appiah-Kubi et al. (2014), since it has similar or higher MOE properties.

Table 4.19: ANOVA for mechanical properties of laminated bamboo

Mechanical Properties		df	F-value	Sig.
Modulus of Rapture (MOR)	Between Groups	1	368.116	0.001**
Modulus of Elasticity (MOE)	Between Groups	1	641.003	0.001**
Compressive Strength (CS)	Between Groups	1	238.440	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

The ANOVA in Table 4.19 shows that at 5% level of significance bamboo age has significant effect on the MOE of laminated bamboo composite. This implies that the difference in MOE could be explained by the bamboo age.

4.4.2.2 Modulus of Rupture

Figure 4.21 shows the modulus of rupture (MOR) of laminated mature and juvenile bamboo composite. The MOR of the mature laminated bamboo was 82.48 MPa whilst that of the laminated juvenile bamboo was 43.42 MPa. The difference in the MOR between that of the laminated mature and juvenile bamboo composite could be attributed to the larger fibre length and thick fibre wall of the mature bamboo culm. Research has shown that the fibre proportion occupied by vascular bundles would determine the physical and mechanical properties of a bamboo species (Liese, 1998; Janssen, 1991). The higher proportions of fibre as reported by Tomalang et al. (1980) have better mechanical properties. Furthermore, the proportion of vascular bundle and fibre properties of the matured bamboo was higher than the juvenile bamboo as presented in the Table 4.5 and 4.9 respectively. Therefore, the mature bamboo is likely to have better MOR.

The vascular bundle could also influence the MOR of mature laminated bamboo composite due to the denser nature found at the outer portions. The smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer portions had higher density and mechanical strength than the inner portions (Zhou, 1981; Liese, 1985). Rusch et al. (2019) reported that density is a variable that influences the mechanical properties. This shows that the mature laminated bamboo composite could be used for structural applications like roofing trusts, ceiling joists, ceiling panel, door and window frames, flooring panel, furniture products like bookshelves, carcase construction, and so on. The juvenile laminated bamboo composite on the other hand could be used for internal works such as bedside cabinet, ceiling panels, and so on (Abd Latif et al., 1990; Xing et al., 2018; Chen et al., 2020).

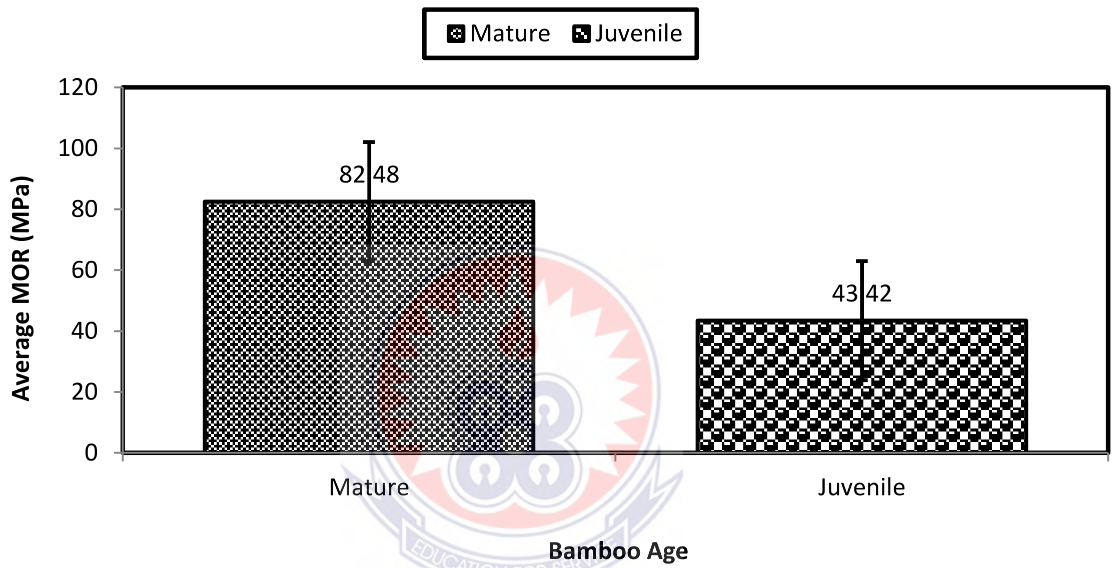

Figure 4.21: MOR of laminated bamboo composite; N=10

The result is comparable to the findings reported by Huang et al. (2013), Appiah-Kubi et al. (2014), and Sharma et al. (2014). Huang et al. (2013) reported that the mean MOR results of laminated bamboo arranged from 39 - 145 Mpa. Appiah-Kubi et al. (2014) reported that the mean MOR results of *Bambusa vulgaris* laminated board made with three different formaldehyde adhesives ranged from 62.58 - 94.3 MPa. Sharma et al. (2014) also reported that the mean MOR results of laminated bamboo arranged from 78 - 88 MPa.

Additionally, mature laminated bamboo composite could also compares favourably with some of the tropical hardwood species like *Khaya ivorensis* with an MOR of 73.9 MPa (Addae-Mensah, 1978; Appiah-Kubi, 2015), *Sterculia rhinopetala* with an MOR of 81.7 MPa (Brunner et al., 2008; Appiah-Kubi et al., 2012;), *Combretodendron africanum* with an MOR of 103.7 MPa (Ofori et al., 2009). According to Appiah-Kubi et al. (2014), the above wood species are used for various forms of construction works in Ghana and the world at large. This implies that the mature laminated bamboo with MOR of 82 MPa could be used for similar construction works as been stated by Appiah-Kubi et al. (2014), since it has similar or higher MOR properties.

The ANOVA (Table 4.19) shows that at 5% level of significance, bamboo age has significant effect on the MOR of laminated bamboo composite. This implies that the difference in MOR could be explained by the bamboo age.

4.4.2.3 Compression Strength Parallel to Grain

Figure 4.22 shows the compressive strength for both the laminated mature and juvenile bamboo composite. The compression strength for the mature laminated bamboo was 62.78 MPa whilst that of the juvenile one was 37.58 MPa. This result shows that the mature laminated bamboo could withstand more loads applied on it than that of the juvenile laminated bamboo. This could be attributed to the larger fibre length and thick fibre wall of the mature bamboo culm. Studies have shown that the fibre proportion occupied by vascular bundles would determine the physical and mechanical properties of a bamboo species (Janssen, 1991; Liese, 1998). The higher proportion of fibre constitutes

40 – 50% of the culm tissue as reported by Tomalang et al. (1980). Furthermore, the proportion of vascular bundle and fibre properties of the matured bamboo was higher than the juvenile bamboo as presented in the Tables 4.5 and 4.9 respectively.

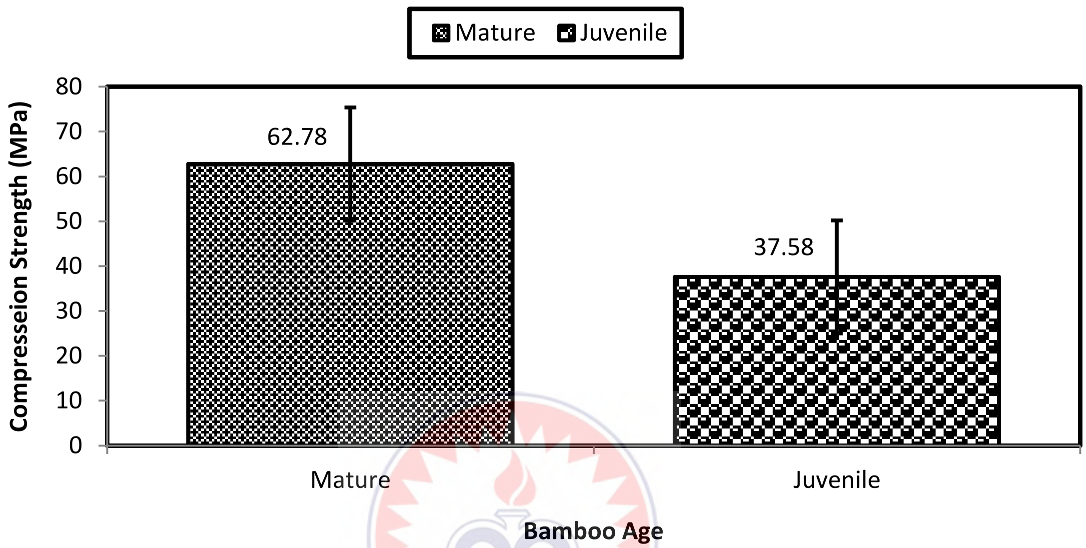

Figure 4.22: Compression strength of laminated bamboo composite; N=10

The vascular bundle could also influence the compression strength of mature laminated bamboo composite due to the denser nature found at the outer portions. The smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer portions had higher density and mechanical strength than the inner portions (Zhou, 1981; Liese, 1985). Rusch et al. (2019) reported that density is a variable that influences the mechanical properties. This study shows that the density of the laminated mature bamboo was higher than that of the juvenile laminated composite as presented in Figure 4.15 and this has resulted in a higher compressive strength for the mature laminated bamboo.

The compressive strength of the laminated *Bambusa vulgaris* composite could be influenced by the adhesive type been used for the manufacturing. This could affect the strength of the laminated composite either positively or negatively depending on the quality adhesive used as bonding material. The performance in service of any adhesives is greatly influenced by its composition (Frihart & Hunt, 2010). The quality of bonding always influences the extent at which the laminated material could withstand the maximum load applied on it. The SEM analysis on the laminated bonding quality after destructive test of this study revealed that the failure of the test occurred through the glue line without the removal of the fibres as shown in Figures 4.23 **Y** and **Z** respectively. This implies that the bonding quality contributed greatly to the failure of the compressive test parallel to the grain for the laminated bamboo composite.

The moisture content could also contribute significantly on the compression strength of the laminated bamboo composite. Xu et al. (2014) reported that the compressive strength decreases rapidly until the bamboo moisture reached the saturated point. The fiber saturation point of bamboo is around 20-22 percent (Kishen, et al. 1956). Perhaps this could have accounted for the decrease in compression strength of the juvenile laminated bamboo composite since its moisture content was produced at 16.25% compared to that of 12.36% for mature laminated bamboo. This could affect the utilization potential for juvenile laminated bamboo regarding it usage as constructional material. The strength quality of 37.58 MPa for juvenile laminated bamboo as against the value of 62.78 MPa for mature laminated bamboo in any structural application evaluation is a clear indication that consumer preference acceptability would be mature laminated bamboo composite.

This shows that the mature laminated bamboo composite could be used for structural applications like ceiling joists, ceiling panel, door and window frames, flooring panel, furniture products like bookshelves, carcase construction, and so on. The juvenile laminated bamboo composite on the other hand could be used for internal works such as flooring panel, ceiling panel, bedside cabinet, ceiling panels, and so on (Abd Latif et al., 1990; Xing et al., 2018;).

The result of this study is comparable to the findings reported by Appiah-Kubi et al. (2014), Sharma et al. (2014) and Sharma et al. (2015). Sharma et al. (2015) reported that the mean compression strength parralell to grain result of laminated bamboo was 77 Mpa. Appiah-Kubi et al. (2014) reported that the mean compression strength parallel to grain results of *Bambusa vulgaris* laminated board made with three different formaldehyde adhesives ranged from 47.71 - 52.41 MPa. Sharma et al. (2014) also reported that the mean MOR results of laminated bamboo arranged from 63 - 64 MPa.

The ANOVA (Table 4.19) shows that at 5% level of significance, bamboo age has significant effect on the compression strength of laminated bamboo composite. This suggests that the difference in compression strength could be explained by the bamboo age. This could also explain that the variation in compression strength among mature and juvenile bamboo composite have different proportional values from each other.

4.4.3. Scanning Electron Microscopy (SEM) Analysis for Destructive Test of Laminated Bamboo Composite Glue Line

Figure 4.23 shows the glue lines in the cross-section of the *Bambusa vulgaris* laminated composite indicated with white arrows after destructive test. It is further observed that the bamboo strips were well bonded during lamination. This implies that RL 5 minutes" wood adhesive used for the production was good to hold the bamboo strips together. It also means that the glue line could be free from deformation before the destructive test was carried out.

The study further reveals that after destructive test was conducted, the failure occurred along the glue line of the laminated specimens as indicated with white arrow in Figure 4.23 Y and Z. It was further observed that the failure along the glue line did not affect the fibres as shown in Figure 4.23 Z. This could mean that the bonding quality of RL 5 minutes wood adhesive was not good enough due to its inability to remove the fibres after the failure of destructive test and this could be traced to poor penetration of the adhesive (Kol et al. 2009). According to Kol et al. (2009), the adhesion between the material and adhesive depends on several factors, such as the penetration of the adhesive, the wettability of the surface, the roughness, and the water content (Kol et al., 2009). Kamke and Lee, (2007) also reported that, bonding quality is influenced by the amount of adhesive penetration into the bamboo strips during the manufacture of composites products.

The Figure 4.23 Z further shows that the RL 5 minutes wood adhesive was removed along the edges of the bamboo strips, showing the thickness of the glue and this could be

4.5.1 Durability of Laminated Bamboo Composite

4.5.1.1 Absorption of Preservative

The results of preservative absorption have been presented in Figure 4.24. The laminated juvenile bamboo sample had the least absorption value of 142.13kg/m^3 as compared to that of the laminated mature bamboo sample which had the highest absorption value of 149.42kg/m^3. It was observed that there was a variation in preservative absorption for the laminated mature bamboo and the laminated juvenile bamboo and this difference could be attributed to the anatomical differences in the bamboo samples. According to Das (2010), the cross-section of the bamboo fibre is filled with various micro-gaps and micro-holes, which have much better moisture absorption. This implies that micro-gaps and holes could enhance the penetration of the boron compound since the solution uptake is strongly dependent on bamboo permeability (Lee et al., 2018).

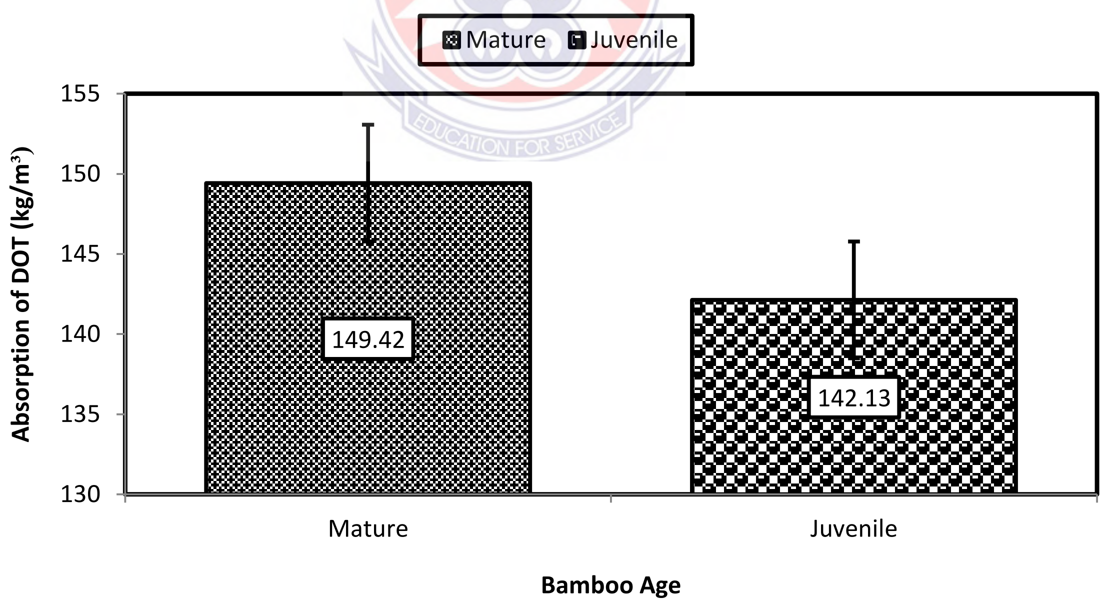

Figure 4.24: Absorption of preservative of laminated bamboo composite; N=10 DOT=disodium octaborate tetrahydrate.

The treatment of laminated bamboo composite is about allowing an adequate amount of preservative to be absorbed by the material in order to achieve some form of protection. Morrell (2018) reported that treatment is the amount of chemicals deposited in a specific area of the wood/ bamboo. Treatment of laminated bamboo composite enhances its service life in order to improve the durability of the material. This is the surest way in controlling the actions of bio-degrading organisms on wood/bamboo (Sen et al., 2002).

The result of this study is comparable to the similar results reported by Gauss et al. (2019). Their study reported that *Dendrocalamus asper* bamboo were treated in a vacuum/pressure process with disodium octaborate tetrahydrate (DOT) solutions and had retentions of 14.79 kg/m^3 and 21.79 kg/m^3. The preservative absorption in this study is considerably higher than that reported (45.1kg/m^3) by Venmalar and Nagaveni (2005) for rubber wood treated in a cold bath of neem oil for 24 hours. The ANOVA shows that there was no significant difference ($p > 0.05$) in the effect of absorption level between the two laminated bamboo samples on preservative absorption as presented in Table 4.20.

4.5.1.2 Weight Loss of Laminated Bamboo Composite

The results of percentage weight loss of the mature and juvenile laminated bamboo samples exposed to *Coriolopsis polyzona* (white rot fungi) after twelve (12) weeks has been presented in Figure 4.25. The percentage weight loss of the control (non-treated) samples for both laminated mature and juvenile bamboo was 52.34% and 54.94% respectively. This variation could be attributed to the presence of extractives content in the *Bambusa vulgaris*. The mature bamboo contained higher extractives content than that of the juvenile bamboo as presented in Table 4.15 and this could have affected the natural durability outcomes of the control sample specimens.

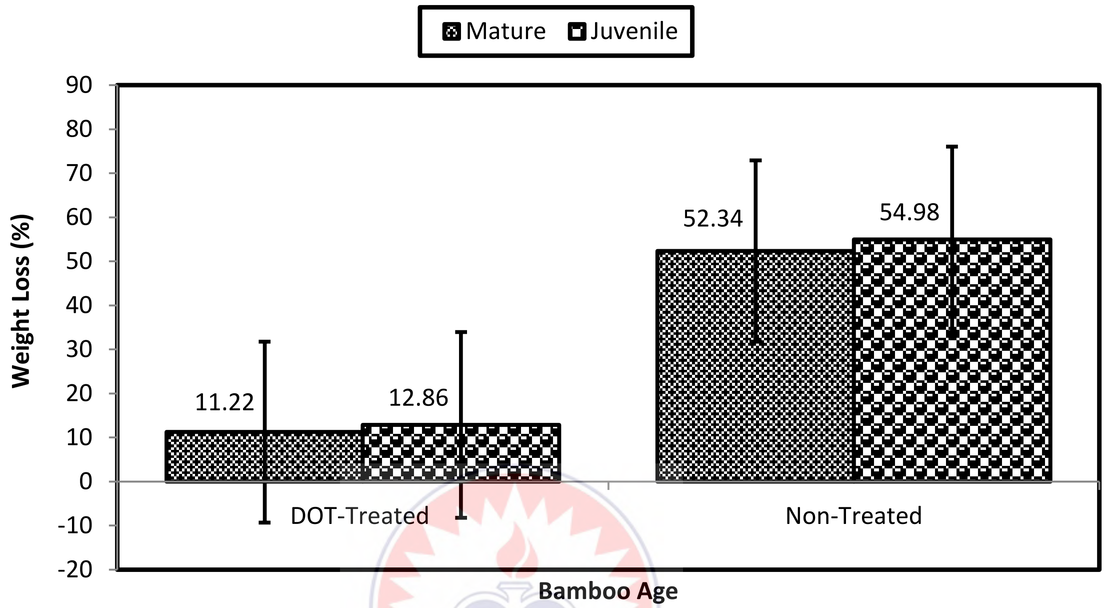

Figure 4.25: Weight loss of laminated bamboo composite; N=10; DOT=disodium octaborate tetrahydrate.

Additionally, the control samples of laminated bamboo composites fall within class IV as presented in Table 4.22. This implies that laminated *Bambusa vulgaris* products cannot be used in areas that are characterized with fungi due to its susceptibility to fungal attacks. This bio-degradable agent always feed on the carbohydrates found on *Bambusa vulgaris* which are naturally noted for such. This present study confirmed that *Bambusa vulgaris* contains a lot of starch granules fully or partially filled in parenchyma cells after SEM analysis had been done (Fig. 4.13 A&B).

Percentage loss in weight for both laminated mature and juvenile bamboo samples treated with disodium octaborate tetrahydrate (DOT) was 11.22% and 12.86%. The treatment of laminated *Bambusa vulgaris* composites with disodium octaborate tetrahydrate (DOT) preservative has shown an improvement in its decay resistance performance to white rot fungi after meeting classification standard of Class II in evaluating the weight loss assessment as presented in Table 4.22. The laminated mature bamboo composite performed better in decay resistance assessment with approximately weight loss value of 11% as compared to that of the laminated juvenile bamboo composite of approximately 13%.

This could be attributed to the efficacy of the treatment preservative used for the study. The preservative absorption for laminated mature bamboo was 149.42 kg/m^3 whilst the laminated juvenile bamboo was 142.13 kg/m^3. This implies that the higher absorption of disodium octaborate tetrahydrate (DOT) preservative plays a major role in preserving the laminated *Bambusa vulgaris* composite which turns to improve its decay resistance performance to white rot fungi. Although, the preservation absorption difference was not significant according to ANOVA in Table 4.20. It is however important to note that the treatment of *Bambusa vulgaris* laminated composite could enhance its usage especially in fungi invested zones. The durability performance of this study shows that both juvenile and mature laminated bamboo composites were improved with DOT could be used for external and internal works in building and furniture industries.

The ANOVA presented in Table 4.21 shows that at 5% level of significance the bamboo age did not have significant effect in the percentage of weight loss. This implies that the percentage weight loss differences existing between the matured and juvenile laminated bamboo were not significant as a result of bamboo age. However, at 5% level of significance treatment conditions had significant effect on the percentage weight loss for both the mature and juvenile laminated bamboo and the coefficient of determination was 92.6%. This implies that the treatment conditions (Treated and Untreated) for both the juvenile and mature laminated bamboo greatly influenced its percentage weight loss.

Table 4.20: ANOVA of absorption of laminated *Bambusa vulgaris*

	df	F-value	Sig.
Absorption	1	0.305	0.588ns

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

Table 4.21: ANOVA of percentage weight loss of laminated *Bambusa vulgaris*

		Weight Loss	
Source	df	Sig.	Var. (%)
Bamboo Age (BA)	1	0.285ns	3.2
Treatment Condition (TC)	1	0.001**	92.6
BA ×TC	1	0.808ns	0.2

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

Table 4.22: Natural durability of laminated bamboo exposed to *C. polyzona* classification.

Laminated Sample Type	**Weight loss (%)**	**Decay Resistance Class**
Mature control	52.34 ± 2.91	Susceptible (Class IV)
Mature Treated	11.22 ± 1.03	Resistant (Class II)
Juvenile control	54.94 ± 2.13	Susceptible (Class IV)
Juvenile Treated	12.86 ± 1.12	Resistant (Class II)

± sign represent standard deviation.

CHAPTER FIVE

5.0. SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATION

5.1. Introduction

This chapter summarises the key findings of the study, draws conclusions and suggests recommendations. It also gives the indication on the areas of the study that could be replicated or further research.

5.2. Summary of Findings

- The internode length for both the juvenile and mature bamboo culms ranges from 300.60mm to 442.20mm whilst the culm diameter and culm thicknesses range from 52.73mm to 87.29mm and 6.83mm to 21.55mm respectively.
- The oven-dried shrinkage at the radial, tangential and longitudinal direction, juvenile *Bambusa vulgaris* shrinks more than the mature culm and their difference was significant ($p<0.05$).
- The oven-dried volumetric shrinkage values for mature bamboo was lower than that of the juvenile bamboo and their difference was significant ($p<0.05$).
- The mature bamboo obtained higher basic density ranges from 660.50 kg/m^3 to 691.8 kg/m^3 compared to that of the juvenile bamboo ranges from 383.53 kg/m^3 to 562.26 kg/m^3 and their difference was significant ($p<0.05$).
- The juvenile bamboo demonstrated higher value of MC compared to that of the mature bamboo and their difference was significant ($p<0.05$).
- The cross-section vascular bundles arrangement within the juvenile and mature *Bambusa vulgaris* was in Type III and Type IV.

- Similarly, the vascular bundle length (636.39µm to 1114.42µm) and width (362.65µm to 706.04µm) for mature bamboo was higher than the vascular bundle length (632.69µm to 986.15µm) and width (338.08µm to 630.77µm) of juvenile bamboo.
- The metaxylem vessels were slightly elliptical in shape rather than truly circular. Additionally, mature bamboo obtained higher metaxylem vessels diameter (65.53µm to 216.81µm) than the juvenile bamboo (87.08µm to 214.23µm) and their difference was significant ($p<0.05$).
- The mature bamboo obtained higher fibre length ranges from 3249µm to 4017µm compared to that of the juvenile bamboo ranges from 2283µm to 2886µm and their difference was significant ($p<0.05$).
- Similarly, the mature bamboo obtained higher fibre diameter ranges from 19.22µm to 20.54µm than that of the juvenile bamboo ranges from 14.03µm to 19.26µm and their difference was significant ($p<0.05$).
- Additionaly, the mature bamboo obtained higher lumen width ranges from 12.76µm to 13.08µm than that of the juvenile bamboo ranges from 8.78µm to 12.54µm and their difference was significant ($p<0.05$).
- In addition, mature fiber thickness (6.46µm to 7.46µm) obtained was thicker than the juvenile (5.25µm to 6.72µm) and their difference was significant ($p<0.05$).
- The mature bamboo contained 31.18% higher extractives content than the juvenile *Bambusa vulgaris*.
- The mature bamboo contained better chemical properties of cellulose (55.93%), hemicellulose (44.08%) and lignin (29.11) than the juvenile cellulose (48.62%),

hemicellulose (51%) and lignin (29.98%) and their difference was significant ($p<0.05$).

- The juvenile laminated shrinks in radial, tangential and longitudinal more than the mature laminated bamboo and their difference was significant ($p<0.05$).
- The volumetric shrinkage of the juvenile laminated was higher than that of the mature laminated bamboo and the difference was significant ($p<0.05$).
- The mature laminated bamboo contained lower MC than that of the juvenile laminated *Bambusa vulgaris* and their difference was significant ($p<0.05$).
- Additionally, the mature laminated obtained higher MOE (13379MPa), MOR (82.48MPa) and compression strength (62.78MPa) than the juvenile laminated of MOE (5875.7MPa), MOR (43.42MPa) and compression strength (37.58MPa).
- The Percentage weight loss for both mature and juvenile laminated bamboo composite was 11.22% and 12.86% respectively.

5.3. Conclusion

From the experimental investigations conducted, the following conclusions were drawn:

1. The morphological properties of *Bambusa vulgaris* vary depending on the age and section along the culms. The internode length increases from the bottom portion to the top portion with a decrease in the culm diameter and culm wall thickness. Therefore, it is more suitable to use bottom section for both juvenile and mature *Bambusa vulgaris* for the production of engineered bamboo composite.

2. The physical properties of *Bambusa vulgaris* vary depending on the age and section. The mature and the bottom section had better physical properties than the juvenile and the top section respectively. Consequently, it is always necessary to consider the age and section before selecting *Bambusa vulgaris* for work.
3. The moisture content influenced shrinkage percentage as the juvenile bamboo shrinks higher than that of mature bamboo. The higher shrinkage occurred along the tangential plane and the lower along the longitudinal plane. Therefore, it is always appropriate to consider mature bamboo culm for industrial utilization especially the bottom section due to its lower level of MC that has produced lower shrinkage.
4. The density for oven-dry was higher in the mature bamboo than in the juvenile bamboo. The differences in their densities were significant. Therefore, mature *Bambusa vulgaris* culms are suitable to be used as engineering composite material as higher density gives stronger mechanical properties.
5. The mature and the bottom section of *Bambusa vulgaris* possess higher vascular bundle properties than that of the juvenile and the top section respectively. The arrangement of vascular bundle types between juvenile and mature bamboo culms was the same as their bottom culms are found in type IV whiles their top culms are in the type III. Consequently, it is more useful to consider the mature bottom section for structural and non-structural application since higher vascular bundle improves physical and mechanical properties of bamboo material.

6. The fibre characteristics were higher in the mature bamboo culm compared to that of the juvenile bamboo culm. Higher fibre properties always resulted in better physical and mechanical properties and these make mature bamboo culm more useful as engineering material.
7. The increase in the cells wall thickness in fibres is a part of the maturing process in the bamboo culms. There was a significant difference in vessel diameter between the juvenile and mature bamboo culms. Therefore, both juvenile and mature *Bambusa vulgaris* species are suitable material for engineering composite especially their bottom sections.
8. The mature *Bambusa vulgaris* possess overall better extractives composition than the juvenile bamboo culm. The extractives content was higher in the mature culm than the juvenile culm and their difference was significant. Consequently, it is more useful to consider mature culm for industrial utilization since high extractives content always contributes to the natural durability of bamboo culm.
9. The holocellulose content exhibited significant difference between the juvenile and mature bamboo culm. However, their proportionality in cellulose and hemicellulose content was not different from each other and therefore, both *Bambusa vulgaris* species are suitable material for engineering composite.
10. Lignin content showed significant diference between the mature and juvenile bamboo culm. Higher lignin content always improves the bonding and mechanical properties of bamboo and therefore, mature bamboo culm is suitable material for engineered composite.

11. The mature laminated of *Bambusa vulgaris* possess better physical properties than that of the juvenile laminated bamboo composite. The mature laminated has better basic density, moisture content and shrinkage properties than the juvenile laminated bamboo composite and their differences were significant. Consequently, these make mature bamboo laminate more useful as engineering material.
12. The mature laminated had better MOR, MOE and compression strength than that of the juvenile laminated bamboo composite and their differences were significant. Therefore, both juvenile and mature *Bambusa vulgaris* species are suitable for engineering composite material.
13. The mature laminated bamboo composite had better dimensional stability than the juvenile laminated bamboo. Therefore, it would be more useful to consider mature bamboo culm for engineering application that requires stable material.
14. Treatment of the laminated bamboo composite with DOT improved its decay resistance from a decay class of susceptible to that of resistance. Therefore, it would be useful to treat bamboo culms before its utilization for structural and non-structural applications.

5.4. Recommendations

From the findings of experimental investigations conducted, the following recommendations are made below:

1. Based on the results obtained for chemical, anatomical and physical properties, the bottom section of mature *Bambusa vulgaris* culm is recommended to be used as constructural material for both building and furniture applications.
2. From the results obtained, both the juvenile and mature *Bambusa vulgaris* culm could be used as raw material for engineered composite products such as glued laminated board, fibreboards and particleboard especially the bottom section.
3. Based on the results of the physical, mechanical and durability properties the mature laminated bamboo composite is recommended to be used as building materials for housing, ceilling and flooring.
4. Based on the results of the physical, mechanical and durability properties the mature laminated bamboo composite is recommended to be used for external and internal furniture works.
5. The physical, mechanical and durability properties of the juvenile laminated bamboo composite is recommended to be used for internal furniture works.
6. Its also recommended that bamboo culms should be treated in order to improve its durability to withstand external conditions.
7. For future studies, it is recommended that the utilization of laminated bamboo composite for the production of artefacts as well as examine the sanding, tensile and shear properties.

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