STUDY ON POTENTIAL MAHANG OF LOCAL WOOD AS A CORE IN FIBERGLASS REINFORCED POLYMER SANDWICH COMPOSITE IN NAVAL STRUCTURE

by

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DECLARATION

I declare that this thesis entitled "**Study on potential of local mahang wood as a core in fiberglass reinforced polymer sandwich composite in naval structure**" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Balsa wood is commonly used as core materials in sandwich structures for weight critical applications such naval structures. The present study evaluates the physical and mechanical properties on the different arrangement of mahang wood (parallel-to-grain and perpendicular-to-grain) on middle and bottom part for sample of mahang tree as core of sandwich composite. These four specimens were tested their water absorption, moisture content, and density for physical testing. Meanwhile, for mechanical properties the samples were tested on compression, three-point bending and tensile tests. In parallel compression, bending and tension, the strength increase linearly with density (based on mahang wood parts; middle and bottom). Meanwhile, in perpendicular, the strength varies nonlinearly.

ABSTRAK

Kayu balsa biasanya digunakan sebagai bahan teras dalam struktur sandwic bagi aplikasi kritikal seperti struktur navi. Kajian ini menilai sifat-sifat fizikal dan mekanikal pada susunan kayu Mahang yang berbeza (selari dengan ira dan serenjang dengan ira) pada bahagian tengah dan bawah sampel pokok mahang sebagai teras komposit sandwic. Keempat-empat spesimen diuji sifat serapan air, kandungan kelembapan, dan ketumpatan untuk ujian fizikal. Sementara itu, bagi sifat mekanikal sampel-sampel telah diuji pada ujian mampatan, ujian lenturan tiga-pin dan ujian tegangan. Dalam uijan mampatan selari, lenturan dan ketegangan, peningkatan kekuatan berkadar langsung dengan ketumpatan (berdasarkan bahagian kayu mahang; pertengahan dan bawah). Sementara itu, dalam ujian mampatan serenjang, kekuatan berbeza dalam kadaran songsang dengan ketumpatan.

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LIST OF ABBREVIATIONS

Al_2O_3	Aluminum Oxide
ANOVA	Analysis of Varience
ASTM	American Society for Testing and Materials
B_2O_3	Barium Oxide
BSE	Backscattered Electron
CaO	Calcium Oxide
CMC	Ceramic Matrix Composite
GFRP	Glass Fiber Reinforced Polymer
K_2O	Potassium Oxide
MgO	Magnesium Oxide
MMC	Metal Matrix Composites
MOE	Modulus of Elastic
MOR	Modulus of Rupture
Na_2O	Sodium Oxide
PMC	Polymer Matrix Composite
SEM	Scanning Electron Microscope
SE	Secondary Electron
SiC	Silicone Carbide
SiO_2	Silica

LIST OF SYMBOLS

ρ	Density
W1	Weight of Sample
W2	Volume of Sample
mm	Milimeter
cm	Centimeter
C	Celsius
H	Hour
Mm/min	Rotation rate
Kg/m^3	Kilogram per meter cube
TM	Timber middle
TB	Timber bottom
CM	Core middle
CB	Core bottom

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Composite are the combination of two or more materials (*e.g.*, matric and reinforced, or dispersed phase) to form a new material system with enhanced material properties. There are three types of composite which are polymer matrix composite, ceramic matrix composite and metal matrix composite. They are considered as multiphase material. The multiphase materials are the combination of various metal alloy, ceramics, polymers and plant fibers to produce new, advance and extraordinary materials which able to exhibit great mechanical, physical characteristics such as stiffness, toughness and high temperature strength.

In recent years, many researches have been carried out on wood-fiber composite. The wood-based composite are encompass a range of products which used for number of nonstructural and structural applications (Mohammadi & Nairn, 2013). The composite structure has been fall into two types *(e.g.*, laminar and sandwich). The sandwich composite structure is widely used because of its advantages such as lightweight, relatively high stiffness and strength (Callister & Rethwisch, 2011). The structure consists of three parts which are two outer sheets as faces and had been separated by a thicker core. The core material used in load carrying sandwich constructions have been divided into three categories (*e.g.*, rigid polymeric foams, wood, and honeycombs) and they structurally serves several function like provide support for the faces (Callister & Rethwisch, 2011). Their function of the sandwich such as thermal and acoustical insulation depends mainly in the core material and its thickness. The properties of primary interest for the core are density, shear modulus, shear strength, stiffness perpendicular to the faces, thermal, and acoustical insulation (Kim *et al.*, 2008).

Balsa wood known with having ultra-low weight and considerable stiffness and other advantages, it is enough to make Balsa (*Ochroma pyramidale*) woods as a core of composite materials (Mohammadi & Nairn, 2013). However, due to its availability and high cost in transportation, Mahang (*Macaranga spp.*) woods have been studied as a competitive alternative composite wood core. In this study, Mahang wood will be characterized based on its fiber orientations (*e.g.*, parallel-to-grain, perpendicular-to-grain and random orientation). Instead of hundreds of studies carried out since 1990's based on the balsa wood as the main core, this study attempts to explore and study more about the wood core that can be make from our local materials that will give many benefits to nation's economy.

1.2 Problem Statement

The Balsa (*Ochroma pyramidale*) woods are one of popular core choices because of its properties such as high compression and shear strength and have excellent fatigue performance and also able resemble a honeycomb under a microscope (Osei-Antwi *et al.*, 2013). Balsa trees are native overseas which is native to southern Mexico to southern Brazil forests. However, due to its origin, balsa showed some drawbacks which high costly in supplying it because of its availability and transportation. In addition, the wood manufacturers in Malaysia are facing problems in getting the supply of wood and manufacturers tend to use alternative core materials (Vural & Ravichandran, 2003).

In Malaysia, there are several lesser-known tropical species which have potentials to be developed as core material (Srivaro *et al.*, 2014). Mahang wood is now being study as the alternative materials (Rahman *et al.*, 2012) to be applied as core materials in sandwich composites in composite industry with having fast growing characteristics.

Studies on the performance of wood composite core made of species from temperate countries have been carried out and the specifications on the appropriate use of this material have been established (Srivaro *et al*., 2014). Since local wood core of sandwich composite is new in Malaysia, there is lack of published information on wood core composite made from tropical species and no study on wood core composite from *Mahang (Macaranga sp)* wood been conducted. The study is needed to produce great composite core properties using local materials and able to operate as well as balsa wood.

1.3 Research Objectives

This research was conducted based on a two different aims or objectives that to be achieved which are:

1. To study the effect of different arrangement of mahang wood (parallel-to-grain and perpendicular-to-grain) between middle and bottom part of mahang tree as core composite.

2. To characterize the samples by their physical and mechanical testing as water absorption, strength, toughness, and fracture.

1.4 EXPECTED OUTCOMES

In this study, we expected be able to produce the wood core of the sandwich composite from local tree species which is *Mahang (Macaranga spp.)* wood. The wood core is expected to be used as naval structure. There are three types of fiber orientations (*i.e.*, perpendicular-to-grain and parallel-to-grain also mixed fiber orientation) from three different types of tree part (*i.e.*, top, middle, and bottom) that are being use in this study. In addition, the samples will be characterized based on physical and mechanical testing such as water absorption, tension, compression, and flexural.

CHAPTER 2

LITERATURE REVIEW

2.1 Composite Materials

Most materials used in engineering structures are combinations of distinctly different materials. Material properties are fundamentally average quantities obtained from tests on bulk materials. Composite materials are composed of two or more phases which basically presumed to consist of a matrix such as epoxy or polyester and one or more reinforcing phases. Typically both (matrix and reinforcing phase) are isotropic. The reinforcing phases (*e.g.*, fiberglass, carbon and aramid) are further classified as particulate, discontinuous fiber or continuous fiber and for the matrix phase has been classified into three types; polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs) (Courtney, 1990). They are considered as multiphase material. The multiphase materials are the combination of various metal alloy, ceramics, polymer and plant fibers to produce new, advance and extraordinary materials which able to exhibit great mechanical, physical characteristics such as stiffness, toughness and high temperature strength.

For the purpose of discussion, the reinforcing phase need not be in the shape of fiber to impart desired properties. The continuous fibers has length are as long as the dimension of the component of which they are part while the discontinuous fiber (*e.g.*, glass fiber) can provide significant composite strengthening although the strength of these type of composites are always less (slightly less) than the continuous fibers (Callister & Rethwisch, 2011). Furthermore, different types of materials can be used as composite matrix such as polymer, metal and ceramic. Polymer matrix composites are the most common for Mahang wood producing sandwich structure (Courtney, 1990). For the examples include ordinary fiber glass used as sporting goods and other applications. The primary drawback to PMCs is the low maximum temperature at which they can be used (Callister & Rethwisch, 2011).

One simple scheme for the classification of composite materials (Callister & Rethwisch, 2011) is shown in Figure 2.1, which consists of three main divisions; particle-reinforced, fiber-reinforced and structural composites. The dispersed phase for particle-reinforced composites is equiaxed (*i.e.*, particle dimensions are approximately the same in all directions) while fiber-reinforced composites, the dispersed phase has the geometry of a fiber (*i.e.*, a larger length-to-diameter ratio). In addition, the structural composites are combinations of composites and homogenous materials.

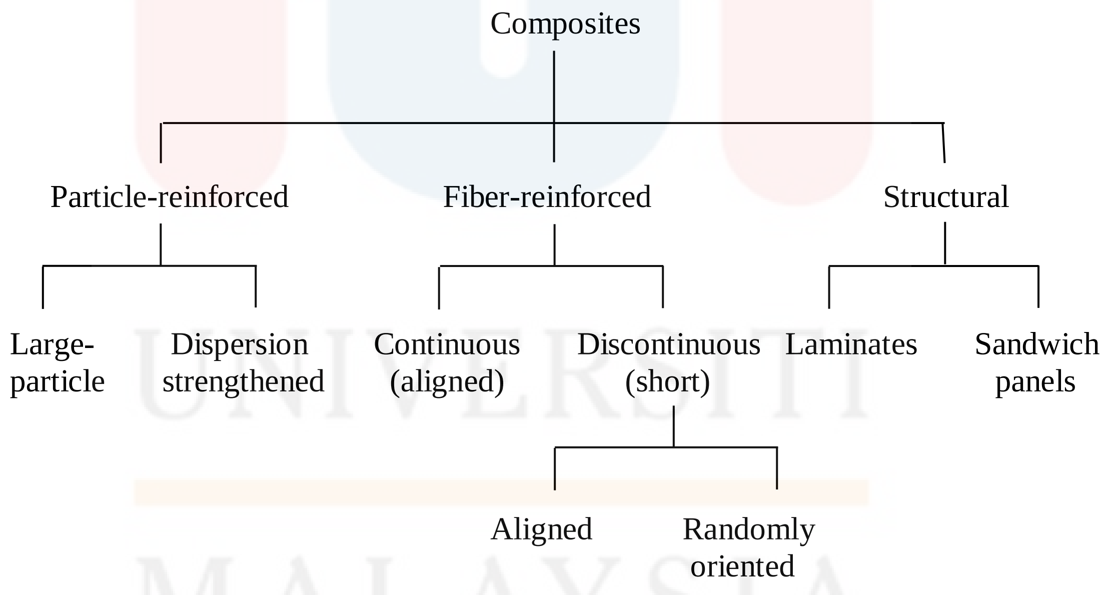


Figure 2.1: A classification scheme for the various composite types

2.2 Polymer Matrix Composites

Polymer Matrix Composites (PMCs) are popular due to their low cost and simple fabrication methods (Masuelli, 2013). It is consists of polymer resin as its matrix and combined with fibrous reinforcing dispersing phase. Strength and modulus of the fiber are much higher than the matrix material normally. This makes fibers the main load-bearing component. However, there must be a matrix material with good adhesion properties to firmly bond fibers together. At the same time, the matrix material can serve to uniformly distribute the applied load, and transfer the loads to fiber. In addition, some properties of composite materials mainly depend on the characteristics of the matrix material. As a result, in composite materials, the performance of fiber, matrix and the interface between them directly impact on the performance of composite materials (Wang *et al.*, 2009). PMCs permits properties such as high tensile strength, high stiffness, high fracture toughness, good abrasion resistance, good puncture resistance, good corrosion resistance, and the most important is low cost.

These materials are used in the greatest diversity of composite applications, as well as in the largest quantities, in light of their room-temperature properties, ease of fabrication, and cost (Courtney, 1990). The PMCs are widely used for manufacturing in secondary load-bearing aerospace structures, boat bodies, vehicles, sport goods and other armor parts. The popularity of PMC in manufacturing field is having related with its properties. The properties of PMCs are determined by properties of the fibers, orientation of the fibers, concentration of the fibers, and the properties of the matrix (Kim *et al.*, 2008).

The PMCs are often classified into two categories; reinforced plastics, and so-called advanced composites. Relatively, both are being differ based on the level of mechanical properties which usually strength and stiffness (Princeton, 1988). The reinforced plastics typically inexpensive and consist of polyester resins reinforced with low-stiffness glass fibers (E-glass) and have been used up to 40 years in applications (*e.g.*, automotive panels, boat hulls and sporting goods). Besides that, advanced composites consists of fiber and matrix combinations that yield superior strength and stiffness, relatively expensive, and typically contain a large percentage of high-performance continuous fibers for example S-glass, graphite, and aramid (Wang *et al*., 2009).

Basically, there are two types of polymers that uses as matrix materials used for fabrication composites which are thermosets and thermoplastics (Princeton, 1988). For the thermosets types, examples are epoxies and phenolic while the thermoplastics are polyethylene (*e.g.*, low density and high density), polypropylene, nylon, and acrylics. The thermoplastic matrix is a material that able cure reversibly and softens when heated above the glass transition temperature, T_g or melting point, T_m and becomes hard after cooling. In the other hand, the thermoset is a material that made up by polymer joined together chemical bonds that acquire a high cross-linked polymer structure which it is cure irreversibly and become permanently hard and rigid after curing (Mohammed *et al.*, 2015; Stark *et al.*, 2010). Table 2.1 shows comparison of general characteristics between thermoset and thermoplastics matrix. Moreover, the PMC can also be classified into three types according to reinforcement types such as glass, carbon and aramid (Callister & Rethwisch, 2011).

Table 2.1: Comparison of general characteristics of thermoset and thermoplastic matrix (Stark, 2010)

Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughness thermoset	↓	↑	↑	↑	↓
Lightly crosslinked thermoplastic	↓	↑	↑	↑	↓
Thermoplastic	High	Low	Low	Low	High

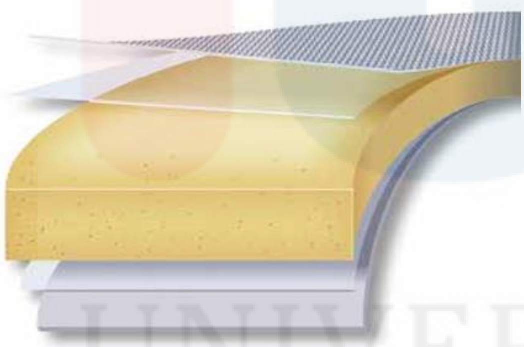
2.3 Sandwich Composite Structures

The properties of composite materials are not depend only on the properties of constituent materials but also on the geometrical design of the structural elements (Callister & Rethwisch, 2011). Commonly, it has two types of composite structures which are laminar and sandwich panels. Both of them are having their own special characteristics that being applied in the industry. The sandwich structure concept described by the American Society of Testing and Materials (ASTM). A structural sandwich is a special form of composite comprising of a combination of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly (Nallagula, 2006).

A sandwich panel is a panel made up of a lightweight and thick core overlaid with two thin facings. Usually, the thin facings are made of strong and dense materials because they have to bear nearly all of the applied edgewise-loads and flatwise-bending moments (Srivaro *et al.*, 2014). The face sheets are able to impart high stiffness and strength to structure and must thick enough to withstand tensile and compressive stresses. In the other hand, the core is made of weak and low density materials, separates and stabilizes the thin facings and provides most of the shear rigidity of the sandwich construction.

The sandwich composite can be compared to an I-beam, which can be regarded as optimized with regard to the cross sectional geometry (Nallagula, 2006). This comparison was shown in Table 2.2. However, in the I-beam and in the sandwich composite, most of the normal stresses will be carried through out by flanges or faces and the shear stresses by the web or the core in the sandwich respectively. In addition to these, the core should provide sufficient stiffness to avoid local buckling.

Table 2.2: The comparison between sandwich composite and I-beam structure

Sandwich Composite	**I-Beam Structure**
	
- Analogous in the sense when subjected to bending. - High stiffness-to-weight ratio.	- Endless I-beam. - More proportional stiffness.

Basically, sandwich composites materials have been classified based on the type of facing sheets and also the type of core used. Based on the core type classification of sandwich materials, there are foam-type core sandwich composites, honeycomb core sandwich composites and corrugated core sandwiches (Courtney, 1990). The honeycomb core is usually manufactured from an aluminum foil. The ordinary honeycomb tends to bend anti-elastically and might not fit in a given shape but improved version of it is available, which has a flexible core and can provide good formability (Wiernicki *et al.*, 1991). Facing sheets can be made from aluminum, stainless steel or other alloys. Some facings like hardboard, plywood, glass reinforced cement, plaster board, and resin impregnated paper are being used for construction purposes. These are also called fiber-reinforced laminates. Depending on the use of the sandwich composite and the application, different cores can be glued to different facings. The major flexibility is that almost any core can be glued to any facing sheets. Typically the core materials are made of metallic and metallic honeycombs, cellular foams, and balsa woods (Daniel, 2009). In this study, glass fiber-reinforced polymer (GFRP) will be study as facing sheets while mahang (*Macaranga sp.*) woods as the core of sandwich composite structure.

2.4 Glass Fiber-Reinforced Polymer (GFRP) Composites

Fiberglass is a composite consists of glass fibers which it can be in either continuous or discontinuous of fibers that contained within a polymer matrix (Callister & Rethwisch, 2011). The fiber diameters are normally in range between 3 too 20 μm.

Glass is commonly used as fiber reinforcement material due its properties (Qi *et al.*, 2015). It is easily drawn into high-strength fibers from molten state, it is readily available and economically fabrication. Besides that, it is relatively strong as a fiber and it produced a composite having a very high specific strength when embedded in plastic matrix. In addition, it possesses a chemical inertness when coupled with various plastics and this property is very useful for composite materials when applied in variety of corrosive environments (Callister & Rethwisch, 2011).

The main ingredient of glass fiber is silica (SiO_2) and contains smaller portions of barium oxide (B_2O_3) and aluminum oxide (Al_2O_3) added to the silica to modify the structure and progress the workability of the fiber. E-glass and C-glass fibers have low sodium oxide (Na_2O) and potassium oxide (K_2O) content. They are attributes to its corrosive resistance to water and high surface resistivity. Other ingredients include calcium oxide (CaO) and magnesium oxide (MgO) (Mallick, 2008).

The surface characteristics of glass fibers are extremely important because even minute surface flaws can deleteriously affect the tensile properties. Surface flaws are easily introduced by rubbing or abrading the surface with another hard material (Callister & Rethwisch, 2011). Also, glass surfaces that have been exposed to the normal atmosphere for even short time periods generally have weakened surface layer that interferes with bonding to the matrix. Newly drawn fibers are coated during drawing with a size, a thin layer of substance that protects the fiber surface from damage and undesirable environmental interaction. Glass fiber-reinforced polymer (GFRP) is usually familiar in applications such as automotive and marine bodies. Besides that, in transportation industries there are using increasing amounts of GFRPs in order to decrease vehicle weight and boost fuel efficiency.

Furthermore, the fiberglass reinforced plastic is having superior electric insulation performance and high frequency dielectric properties. GFRP is a superior insulating material in power frequency. Besides insulation property, GFRP has good high-frequency dielectric properties as well. It can thus be used as the high-frequency wave-transparent materials for radome. In addition the GFRP has excellent chemical corrosion resistance and good friction property and anti-friction properties.

Fiberglass refers to a group of products made from individual glass fibers combined into a variety of forms. Glass fibers can be divided into two major groups according to their geometry: continuous fibers used in yarns and textiles, and the discontinuous (short) fibers used as batts, blankets, or boards for insulation and filtration. Fiberglass can be formed into yarn much like wool or cotton, and woven into fabric which is sometimes used for draperies. Fiberglass textiles are commonly used as a reinforcement material for molded and laminated plastics. Fiberglass wool, a thick, fluffy material made from discontinuous fibers, is used for thermal insulation and sound absorption. It is commonly found in ship and submarine bulkheads and hulls; automobile engine compartments and body panel liners; in furnaces and air conditioning units; acoustical wall and ceiling panels; and architectural partitions (Grabovac, 2005). Fiberglass can be tailored for specific applications such as Type E (electrical), used as electrical insulation tape, textiles and reinforcement; Type C (chemical), which has superior acid resistance, and Type T, for thermal insulation (Kazemahvazi, 2010).

2.5 Core of Sandwich Composite Structures

The sandwich composites structures are widely used because of its advantages such lightweight, relatively high stiffness and strength (Callister & Rethwisch, 2011). The structure consists of three parts which are two outer sheets as faces and been separated by a thicker core. The faces technically bearing almost loads applied, however, the cores materials also play as an important role in this structure which it is functioning in provide continuous support for the faces

(Tagariell *et al.*, 2007). It also must thick enough to provide high shear stiffness to be able withstand with transverse shear stresses. However, the tensile and compressive stress on this part is much lower than on the faces. Commonly used materials for face sheets are composite laminates and metals, while cores are made of metallic and nonmetallic honeycombs, cellular foams, and balsa wood (Daniel, 2009). The Figure 2.2 shows balsa wood as core material in the sandwich composite.

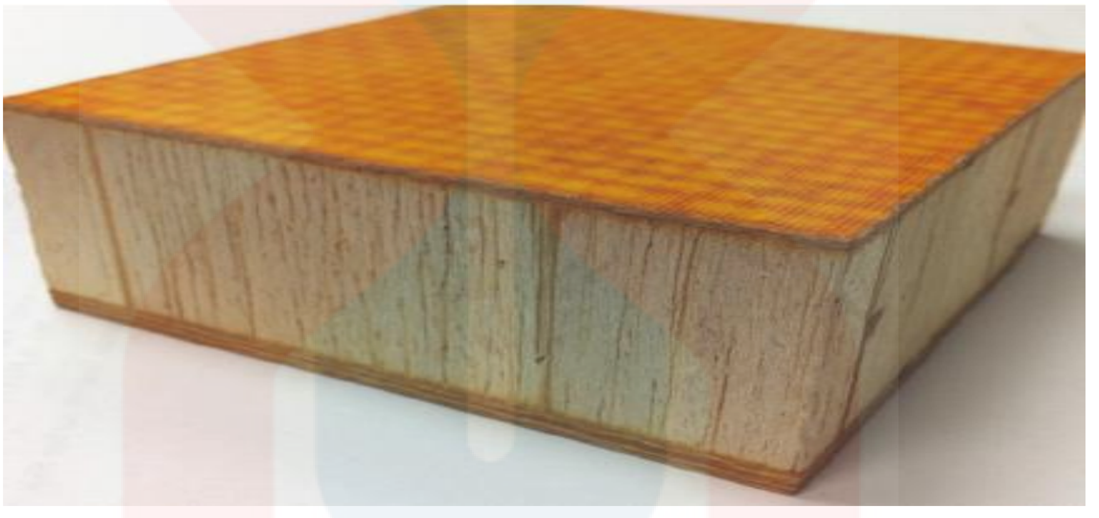


Figure 2.2: Balsa wood as core material in sandwich structure composite

In recent years, many researches have been carried out on *Balsa* (*Ochroma pyramidale)* woods as core composite. Balsa was introduced and the plentiful import of balsa into the United States began. It is first became readily available in the United States near the end of the 1920’s, with the model building market taking particular interest it’s lightweight, ability to absorb shock and vibration, and ease of cutting, shaping and gluing (Green, 2001). Balsa is commonly used as core because its properties that being softest, lightest and considerable stiffness (Mohammadi & Nairn, 2013) such an interesting natural materials made it mostly preferred as wood core (Osei-Antwi *et al.*, 2013). However, balsa trees grow naturally in the humid rain forests of Central and South America. Table 2.3 shows the differences of mechanical properties between five wood species. From this table, balsa wood is shown that it having 340 in weight/Bending Modulus Elasticity with the lowest 10 Ibs√ft^3 weight. In addition, it is also having the lowest value of compression parallel to grain (14.9 MPa) and value in bending compared to another wood species.

Table 2.3: Mechanical properties for five wood species at 12% moisture content (Green, 2001)

		Bending		Compression		Shear	Tension			
	Weight (lbs./ft^3)	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)	Parallel to Grain (MPa)	Perpendicular to Grain (MPa)	Parallel to Grain (MPa)	Parallel to Grain (MPa)	Perpendicular to Grain (MPa)	*Side Hardness (kN)	Weight / Bending Modulus Elasticity
Red Oak	48	99	12500	46.6	7	12.3	101.4	5.5	5.7	260.42
Loblolly Pine	32	88	12300	49.2	5.4	9.6	88	3.2	3.1	384.38
Sitka Spruce	28	70	10800	38.7	4	7.9	75.8	2.6	2.4	385.71
Yellow Poplar	26	70	10900	38.2	3.4	8.2	154.4	3.7	2.4	419.23
Balsa	10	21.6	3400	14.9	-	2.1	-	-	-	340

The composite manufacturers in Malaysia are facing problem in getting the supply of wood due to its availability and high cost for the transportation. Mahang (*Macaranga spp*) wood is being study to use it as alternative materials for the core sandwich composites. Mahang is in the family of *Acacia wood* and which has fast growing characteristic. Balsa wood has density varying over a wide range between 40 and 380 kg/m^3, depending on the average size and the wall thickness of cells (Vural & Ravichandran, 2003), while mahang has density ranging in 100-300 kg/m^3 (Ang *et al.*, 2014) which in the range as balsa wood. The heaviest of the wood shown, red oak, and other woods make balsa be as extremely light weight. This comparisons show mahang has tendencies to be applied as core production which will replace the balsa wood. Figure 2.3 shows matured tree species of balsa and mahang trees.

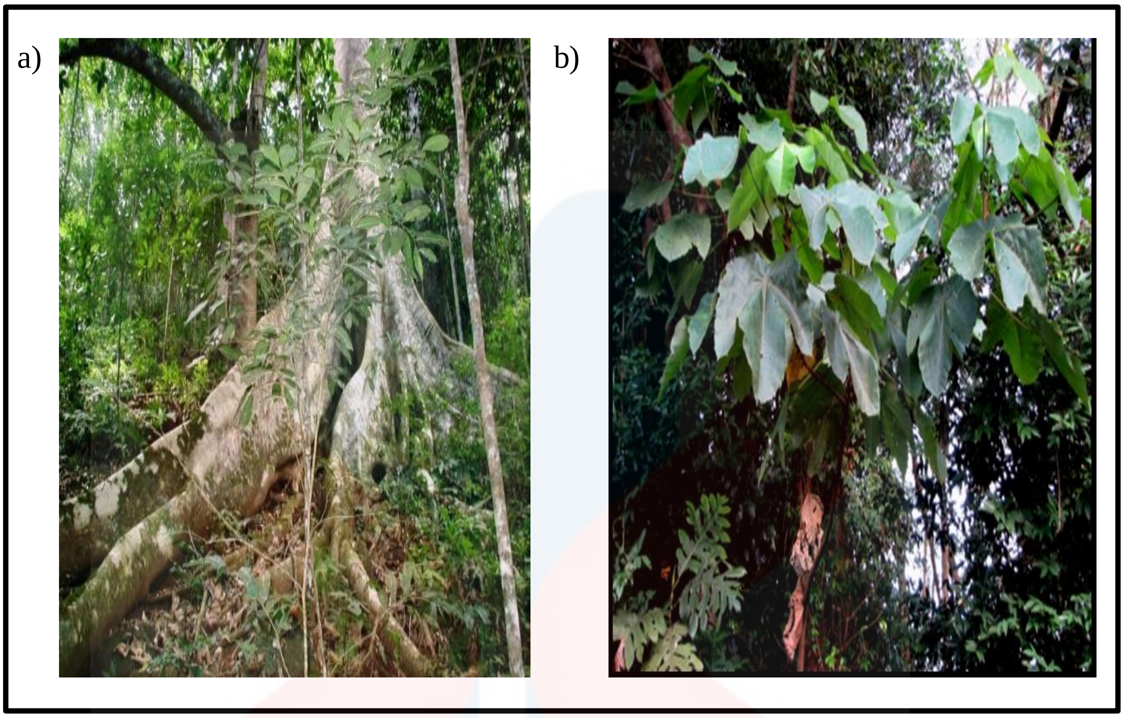


Figure 2.3: Matured tree species; a) balsa tree (Osei-Antwi *et al*., 2013) and b) mahang wood (Hadi, 2012)

2.6 Applications of Sandwich Composite

Composite materials are becoming prevalent in many industries like aerospace, sporting goods and the construction industry. The focus in this study more on the polymer matrix composite on the naval structure. Currently there is a wide range of naval structures being developed using fiber-reinforced polymer composites (Mouritz *et al*., 2001). This development is driven by the need to enhance the operational performance (*e.g.*, increased range, stealth, stability and payload) of warships and submarines. The applications examined include large patrol boats, hovercraft, mine counter measure vessels and corvettes that are built completely of composite materials.

Composites were firstly used after the Second World War in the construction of small personnel boats for the US Navy (Hayman *et al.*, 2001). Figure 2.4 shows La Fayette (US Navy ship) was using composite superstructure with sections. These boats proved to be stiff, strong, durable and easy to easy to repair, and these attributes led to a rapid expansion of composite use in other types of US naval craft.

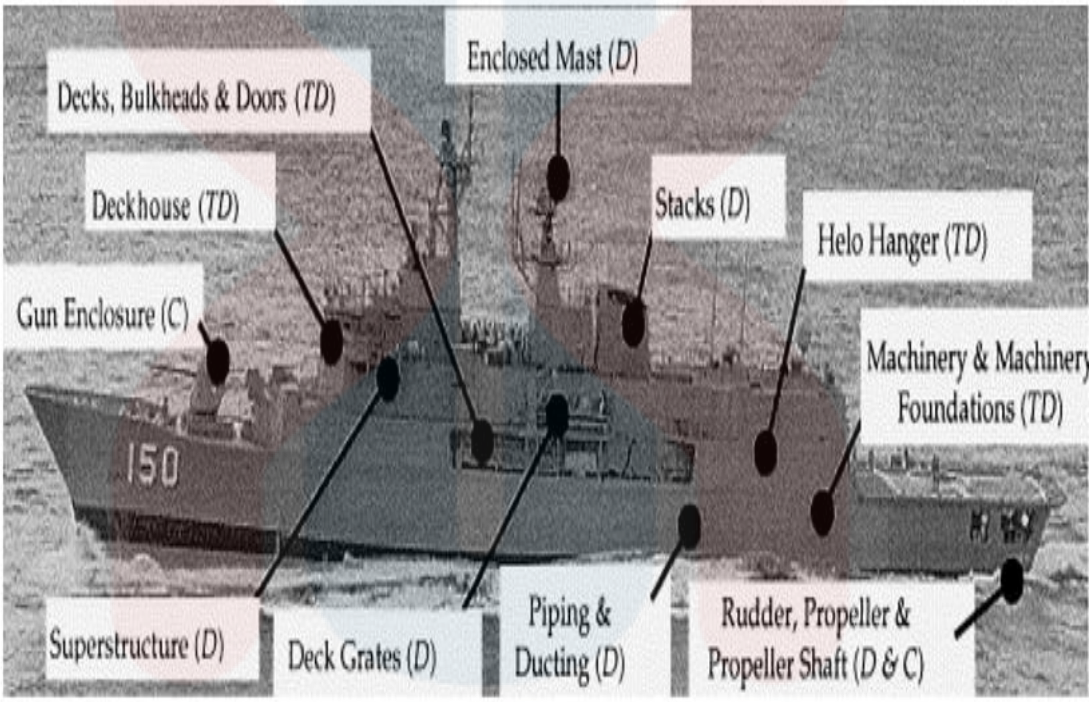


Figure 2.4: La Fayette frigate with the composite superstructure section (Grabovac, 2005)

The composite materials help navies overcome their major problems (*i.e.*, corrosion and high topside weight) with a weight-saving up to 65% is achieved by replacing steel with composite materials. Cracking has become so persistent and widespread in many warships that expensive repairs are regularly required (Kazemahvazi, 2010). Reinforcement of crack-prone regions with composite has been used to suppress cracking, although this is an expensive solution. Because of these problems many navies are now assessing the feasibility of building large ship superstructure with composite. The GOST watercraft shows in Figure 2.5 is one of the new US Navy creations by using a combination of aircraft and boat technology to “fly” on water using two buoyant tubular foils and a gas turbine. The watercraft named by GHOST because the boat is intended to have no radar signature. The boat uses supercavition techniques that surround the tubular foils with a bubble of gas to eliminate drag. Built from aluminum and stainless steel, the vessel is nonmagnetic and difficult to target using sonar.

Figure 2.5: The GOST watercraft (Grabovac, 2005)

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study, *Mahang (Macaranga spp.)* will be tested its physical and mechanical characteristics and the fully steps has been concluded in flow chart at Figure 3.2.

3.2 Materials

In this study, *Mahang (Macaranga spp.)* woods were obtained from Agriculture Park of Universiti Malaysia Kelantan and were used as core of sandwich panel. Mahang sawn timber were dried in the laboratory oven (forced convection) at temperature of 103 $\pm$ 2℃ for 24 hours. The density expected was in the range 100 – 300 kg/m^3. Four types of mahang wood core panels were prepared in this experiment according to the grain direction, namely, parallel-to-grain and perpendicular-to-grain and with dimensions of 100 x 100 mm from two parts of Mahang tree (three parts of middle to five parts of bottom). Both sides of the flat planed mahang wood pieces were abraded with rough 400 grit sandpaper (SiC paper). Residual sanding dusts on the wood surface were removed by blowing with dry compressed air. The adhesive epoxy was used to bind the core layer and it was commercially available and supplied by a local adhesive company with ratio 10 parts epoxy to 2.7 parts hardener. The core panels were prepared in dimensions 300(length) x 300(width) mm which thickness were cut followed for each testing. Core specimens were pre-dried at 103℃ $\pm$ 2℃ for 24 hours, bonded and were cured at room temperature for overnight. A post 4 hours post-cure at 65℃ was subsequently accomplished to enhance adhesion. All specimens will be placed in a conditioning room at a temperature of

20°C and relative humidity of 65% to achieve a final average moisture content of 12% at the time core panel fabrication.

In order to know the properties of mahang wood and the mahang wood core, they were tested on their mechanical and physical properties. The results were compared with balsa properties that have been used as primary source for core production. The specimens were prepared according to their testing by following the suitable standard test method by American Society for Testing and Materials (ASTM).

The testing were conducted as follows:

I. Density
II. Moisture contents
III. Water absorption
IV. Compression
V. Tensile
VI. Three-point static bending

3.3 Fabrication of Sandwich Core (Shaping)

In general, the shaping of wood composite core process started from cut the logs the specific length then dried it. Mahang wood pieces are having similar grain direction bonded together side by side with epoxy adhesive used to achieve a 300 mm (width) x 300 mm (length) of dimension core. Epoxy resin blended according to the supplier's suggestion and spread onto surface of the mahang wood using a hand brush. The resin mixed 10 parts epoxy to 2.7 parts of hardener by weight was used in this study. The core specimens were pre-dried at 103°C ± 2°C for 24 hours, bonded and allowed a room-temperature cured overnight. A 4 hours post-cure at 65℃ was subsequently accomplished to enhance adhesion. The readily core will be ground using silicon carbide (SiC paper) to get smooth surface. Four types of core were fabricated in this experiment according to grain direction of mahang wood, namely with core parallel-to-grain and perpendicular-to-grain from two parts of mahang tree (middle and bottom). Three replications were performed in each testing. In this study, 16 core panels were produced in the end.

3.4 Characterization (Physical and Mechanical Properties)

The characterizations were done on samples which; mahang timber (T) and mahang wood core (C) of sandwich composite. The specimens were prepared in two different orientations according to the grain direction, namely, parallel-to-grain, perpendicular-to-grain that were took from two parts of mahang tree which middle stated as M and bottom stated as B part. On the other hand, test specimens were labeled, namely with TM for timber middle, TB for timber bottom specimens, CM for core middle and CB for core bottom. Three replications will be performed in each treatment.

3.4.1 Density

Density measured from specimens with dimensions of 30 mm (length) × 30 mm (width) × 30 mm (thickness) by followed ASTM D2395 for mahang timber specimens while for mahang core specimens were followed ASTM C272 with dimensions of 50 mm (length) × 50 mm (width) × 15 mm (thickness). This test was used the Archimedes’s principle to calculate density. Each specimen was identified, dimensionally measured and weighed. The test specimens (for saturated weight) used for the present study are shown in Figure 3.1 and the data collected were attached in appendices.

The density was calculated for each test piece by applying the following equation:

$$\text{Bulk Density (g/cm}^3\text{)} = \left[\frac{Mo}{Mw - Ms}\right] \times \rho_w \tag{3.1}$$

Where

M_O = Masses of dry sample

M_S = Masses of suspended sample

M_W = Masses of saturated sample

ρ_w = Density of water

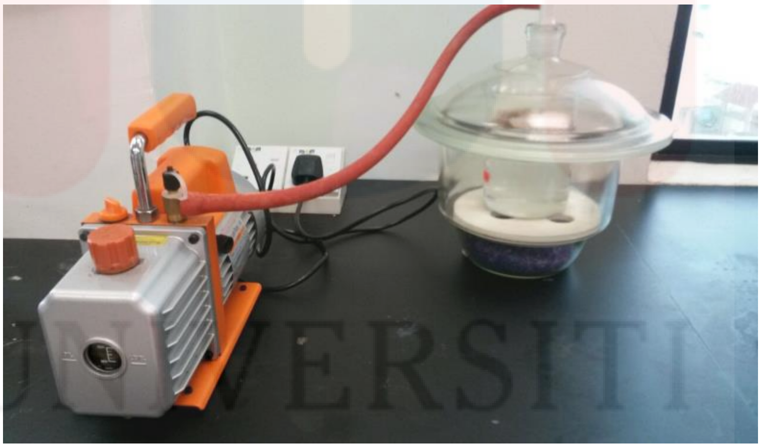


Figure 3.1: Sample prepared for saturated weighing.

3.4.2 Moisture Contents

Moisture content measured the amount of water contained in the wood, usually expressed as a percentage of the mass of oven-dry mass of the sample. It also provides means of assessing variability contributed by the oven or specimen hygroscopicity, or both. The specimens were cut in dimension of 50 x 100 mm in cross section and 25 mm along the grain will attain “constant mass” within 24 h when dried in a forced convection oven. The specimens were weighed using balance consistent with the sensitivity shall be a minimum of 0.1% of the nominal oven-dry mass of the specimen. This testing was done accordance with ASTM D4442-07. This method provided the average moisture content for the test pieces. The Figure 3.2 had shown the samples in oven-dry condition. The data collected was attached in the appendices. The moisture contents were calculated for each test piece by applying the following equation:

$$\text{Moisture Content (\%)} = \frac{(\text{Initial mass} - \text{oven dry mass})}{\text{Oven dry mass}} \times 100\ \% \qquad (3.2)$$

Figure 3.2: Oven-dry condition.

3.4.3 Water Absorption Test

Water absorption measured from the thickness swelling of specimens. The moisture uptake was measured from specimens with dimension of 200 mm (length) × 50 mm (width) × 6 mm (thickness). It was done by the samples were immersed in two types of water for 24 hours in accordance with ASTM C272 for wood core specimens and ASTM D4442-07 for the wood specimens. In this experiment, sea water and tap water were used. The seawater used for this study was collected from Pantai Sri Tujuh, Tumpat, Kelantan and the tap water was from Materials Science laboratory at Jeli campus of Universiti Malaysia Kelantan. The seawater was boiled before use to eliminate living organisms. Four beakers were filled with the test liquids (1400 ml) whereas two were filled with seawater and another two filled with tap water. Since all the specimens were less dense than water, they floated on the top of the water. Wire gauze was used to maintain the specimens beneath the surface of surface of water shows in Figure 3.3. There were three specimens in each beaker. The immersion beakers were closed to minimize the evaporation losses. After immersion period, each specimen was removed from beakers and patted dry with an absorbent towel then measured for weight and weight. To determine the percentage of water absorption and swelling, the sample were weighed and their thickness was measured before and after immersion using a digital vernier caliper with having 0.01 accuracy.

The water absorption (WA) was calculated using the following equation:

$$WA\ (\%) = \left[\frac{M1 - Mo}{Mo}\right] \times 100\ \% \qquad (3.3)$$

where

M_o = Masses of sample before immersion in water

M_1 = Masses of sample after immersion in water

The effect of four hours water immersion on swelling characteristics expressed as percentage of weight and volume change.

Figure 3.3: Sample in immersion media.

3.4.4 Compression Fixture

The compression test was conducted to compare the compression properties between mahang wood and mahang core specimens. This test allows for two approaches accordance to the grain direction of specimens (parallel and perpendicular) from two parts of mahang tree (middle and bottom) were tested. All the specimens were prepared by followed ASTM D143-14 for wood samples and ASTMC365 for wood core samples. Rectangular mahang wood specimens with dimension 50 x 50 x 200 mm^3 (wood specimens) and 76.2 x 76.2 x 76.2 mm^3 (core specimens) were tested in compression. The specimens were compressed in the Testometric M500-50CT, equipped with a 5kN load-cell, under displacement control. The displacement rate of the cross-head was set to 0.076 mm/min and 0.50 mm/min for timber and core specimens respectively in compression. The load and deflection were recorded, and the Young's modulus was also calculated. The specimens were weighed before test, and after test a moisture section approximately 25 mm in length cut adjacent to the part under load. A total of six specimens were tested with three replications were performed in each testing.

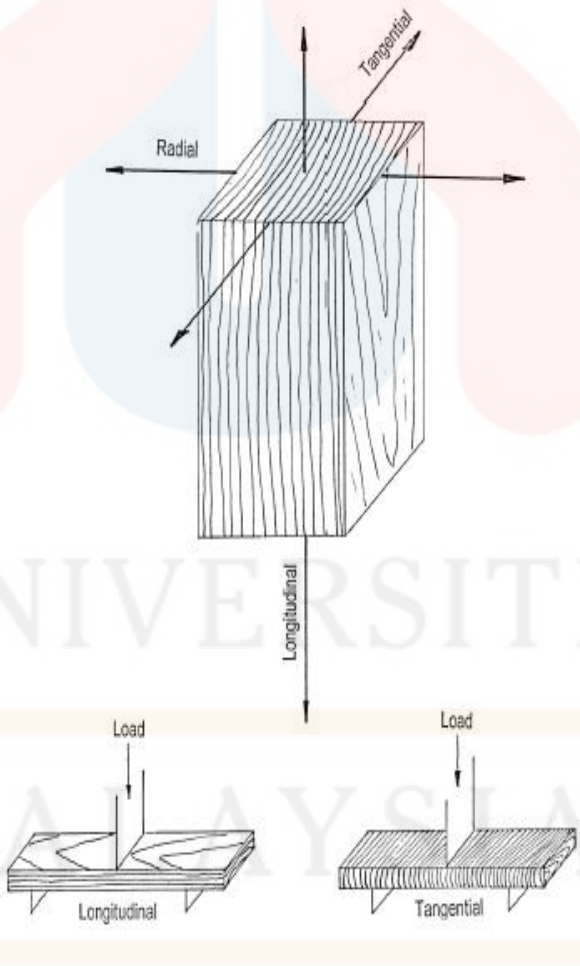


Figure 3.4: Orthotropic structure of wood (Hiziroglu, 2010).

In this study, the samples were tested on two different (parallel and perpendicular accordance to grain orientations) for two parts of mahang wood and it had shown on Figure 4.6.

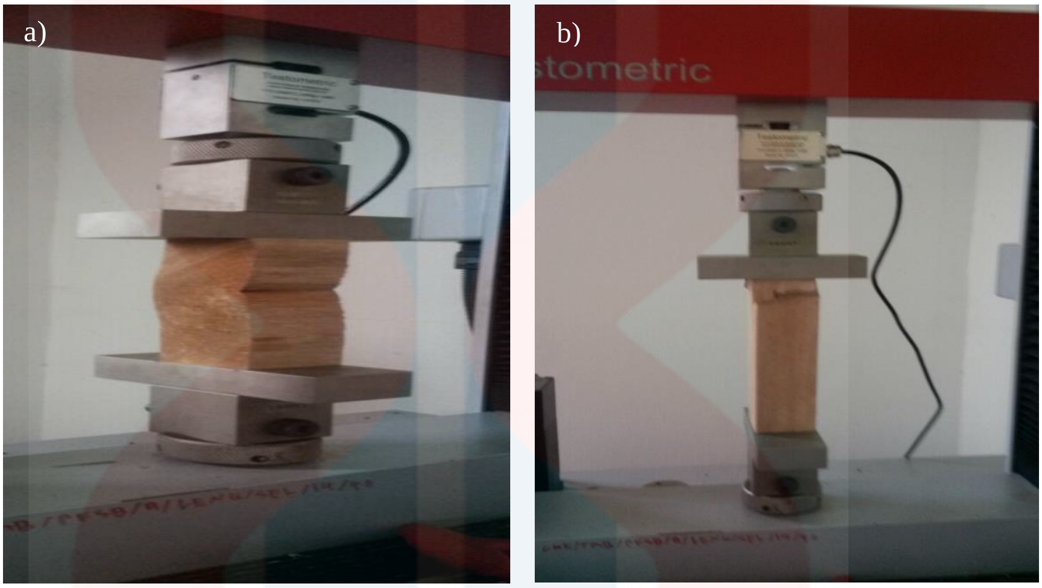


Figure 4.6: Test on; A) parallel-to-grain and B) perpendicular-to-grain of mahang wood.

3.4.5 Three-point Static Bending Test

In this test, the flexural strength will be measured by using static three-point bending test. This test allows for two approaches accordance to the grain direction of specimens (parallel and perpendicular) and mahang timber from two parts of mahang tree (middle and bottom) were tested. All the specimens were prepared by followed ASTM D143-14 for wood samples and ASTMC393-11 for wood core samples. Mahang beams with dimensions 50 x 50 x 490 mm^3 for wood specimens and for core specimens were 50.8 x 18.9 mm^2 in cross-section and 244 mm in length were tested in three-point bending with a loading span of 204 mm. The bending tests were conducted in Testometric M500-50CT, equipped with a 5kN load-cell, under displacement control. The displacement rate of the cross-head was set to 2.5 mm/min for wood specimens and 7.62 mm/min for core specimens. A schematic of a three-point bending test was illustrated in Figure 3.5 (Nallagula, 2006). From the recorded force and deflection data, the modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated. The MOR is a measure of the bending stress at fracture, calculated by assuming linear elasticity up to fracture.

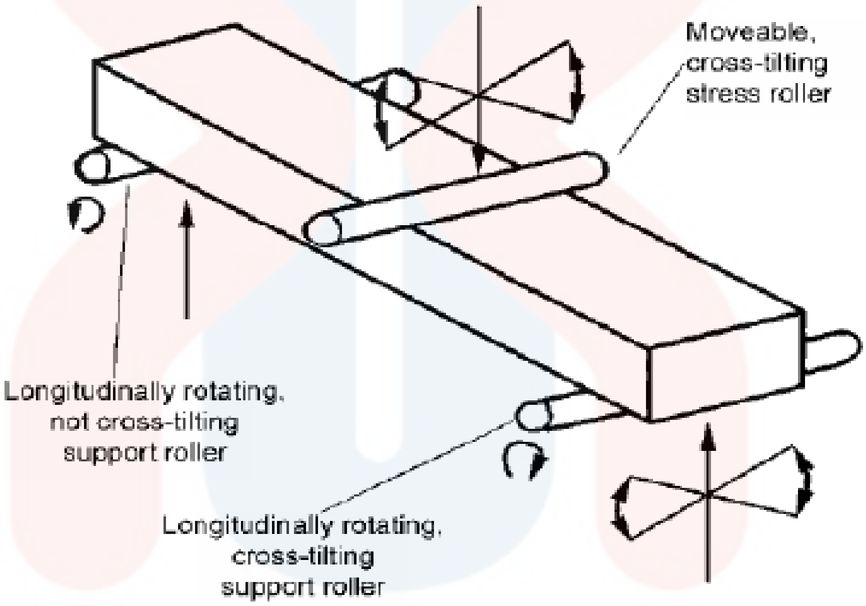


Figure 3.5: Three-point bending schematic.

A total of 8 specimens will be tested with three replication were performed in each testing. The data collected was attached in the appendices. The following two equations were used to calculate MOE and MOR of the samples:

$$\text{MOE} = \frac{\text{P L}^3}{48 \text{ I D}} \tag{3.5}$$

where

P = load below proportional limit (Ib.)

L = test span (in.)

I = moment of inertia, which is the inertia of a rigid body with respect to its rotation and in the case of a rectangular cross section (in.)

D = center deflection (in.)

$$\text{MOR} = \frac{\text{P}_{max}\text{L}}{\text{b d}^2} \tag{3.6}$$

$$\text{I} = \frac{(\text{b d}^3)}{12} \tag{3.7}$$

where

P_{max} = failure load (Ib.)

L = test span (in.)

b = width of the sample (in.)

d = thickness of the sample (in.)

I = moment of inertia (in.)

3.4.6 Tensile Test

Evaluation of the tensile strength of wood and core specimens was accomplished by ASTM D143-14 for wood and ASTM D3039 for core materials. This test allows for two approaches accordance to the grain direction of specimens (parallel and perpendicular) and mahang timber from two parts of mahang tree (middle and bottom) were tested. Using a double-gimbeled yoke arrangement, the extensometer was drawn apart at the rate 1 mm/min on a universal test machine. The maximum load is normalized for the sample face area to obtain strength:

$$\text{Tensile Strength, TS} = \frac{P}{ab} \qquad (3.8)$$

Where

TS = Tensile strength (psi)

P = Load at failure (Ib.)

a = Sample width (in.)

b = sample length (in.)

Figure 4.13: Tensile test; a) wood specimen and b) for core specimen.

Figure 4.13 had shown the samples on extensometer of Universal Testing Machine for timber and core specimens. From the recorded force and elongation, stress, strain and modulus were calculated. A total of 24 mahang specimens (timber and core), nominally measuring 200 x 24 x 35 mm^3 and 250 x 25 13 mm^3, respectively were prepared and preconditioned for timber and core specimens and three replications were done for each testing. The data collected was attached in the appendices.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the physical and mechanical tests on mahang wood core and mahang timber specimens. The study was attempted to explore and study the mahang wood properties in order to operate as well as balsa wood as a core of sandwich composite structure. The panels were fabricated into small square specimens according to American Society for Testing Materials (ASTM) as illustrated in Figure 4.1. Each of testing was followed to different ASTM as attached in the appendices.

Figure 4.1: Mahang core

4.2 Density

Density is one of the main physical properties that were crucial for any materials in naval applications. Three samples for each parts of wood and core materials were measured for density properties. Each specimen was identified, dimensionally measured and weighed. The density variation between mahang timber and core specimens were illustrated in Figure 4.2. It was clear from Figure 4.2 that the density of mahang timber samples showed lower density than the core specimens with an average value between 346 kg/m^3 and 431 kg/m^3 for middle and bottom samples respectively. Meanwhile, the mahang core samples showed the highest density with an average value of 575 kg/m^3 and 808 kg/m^3 for middle and bottom parts, respectively. For instance, by comparing with other mahang species, the density timber specimens that have been used in this study were in the middle range 346 – 431 kg/m^3 between mahang species were compared. Where the green density for *Macaranga hosie* from Malaysia with an average 618 kg/m^3 and *Macaranga triloba* from Kalimatan, Indonesia with an average value of 350 kg/m^3 (Killmann, 1989) and *Macaranga hypoleuca* with density value of 431 kg/m^3 (Sailana, *et al.*, 2000). The different results could be attributed to differences in species, age or collected area of sample.

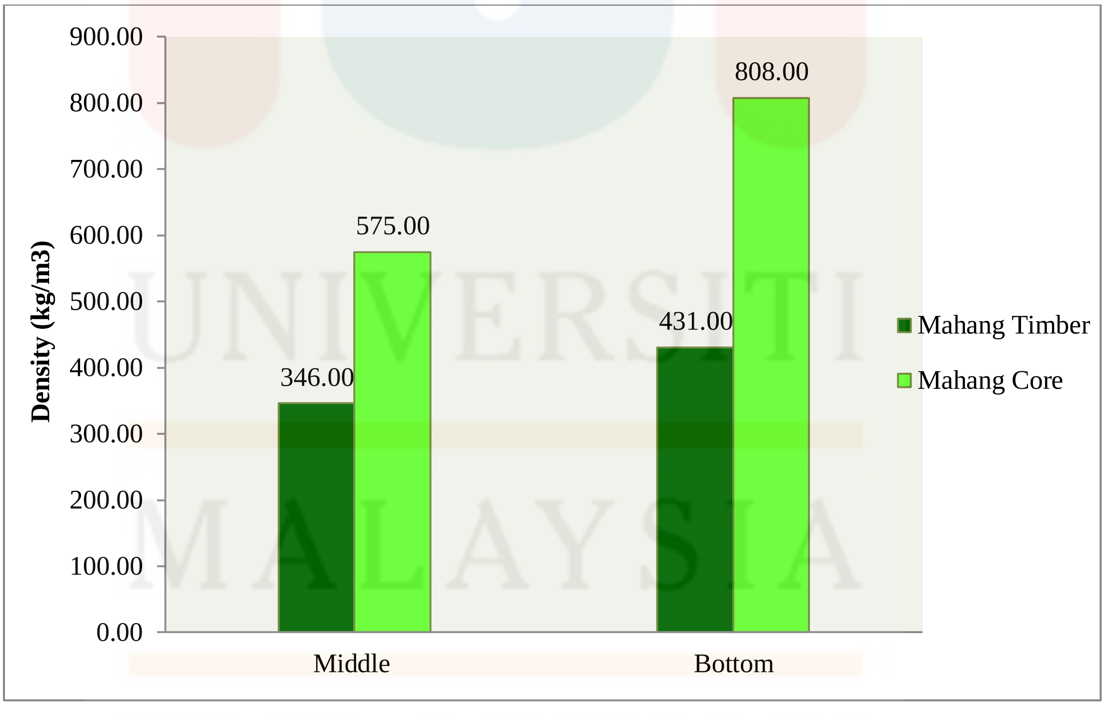


Figure 4.2: Density for mahang wood.

In this study, balsa wood (*Ochroma pyramidale*) properties were made as control value compared with mahang wood. Balsa wood is one of the common core materials in structural sandwich panels in naval applications because its having ultra-low density (Mohammadi & Nairn, 2013). The wood density of balsa typically in range between 100 to 250 kg/m^3 and also it is can vary from 60 to 380 kg/m^3 (Borrega & Gibson, 2015). Wood-based panels with density below 500 kg/m^3 are classified as lightweight materials (Srivaro *et al.*, 2014). From this comparison, the densities of mahang samples that have been used in this study rather high compared to balsa wood. With this result, Mahang wood could not be considered as well as balsa wood as the lightest commercial timber.

4.3 Moisture content

Moisture content is the mass of moisture present in wood divided by the mass of the wood with no moisture in it, expressed as a percentage. It was important to know the moisture content because it had significant effect on width and thicknesses of the specimens. In general, wood is dried to 15 - 20% moisture content for typical structural application rather than using it in green condition (Hiziroglu, 2010). The moisture in the wood affects the dimensional movement of wood and wood products (Carll & Wiedenhoeft, 2009) because it causes the wood to shrink and expand. Particularly, the strength of adhere wood products can be compromised by swelling-induced stresses that accompany wetting. In addition, wood products and wood construction can be degraded by elevated moisture levels or by greatly fluctuating moisture conditions. Consequently, wooden products constructed without consideration of moisture control were suffered moisture-induced damage and lead to excessive repair and maintenance costs.

Figure 4.3 had shown the differences percentage of moisture contents between four types of specimens. It was clear that mahang core samples show the highest moisture content with value of 15.04% (CM) and 15.39% (CB). In addition, the bottom specimens were showed higher percentage of moisture content compared to the middle specimens which differs by 0.17% (T) and 0.35% (C).

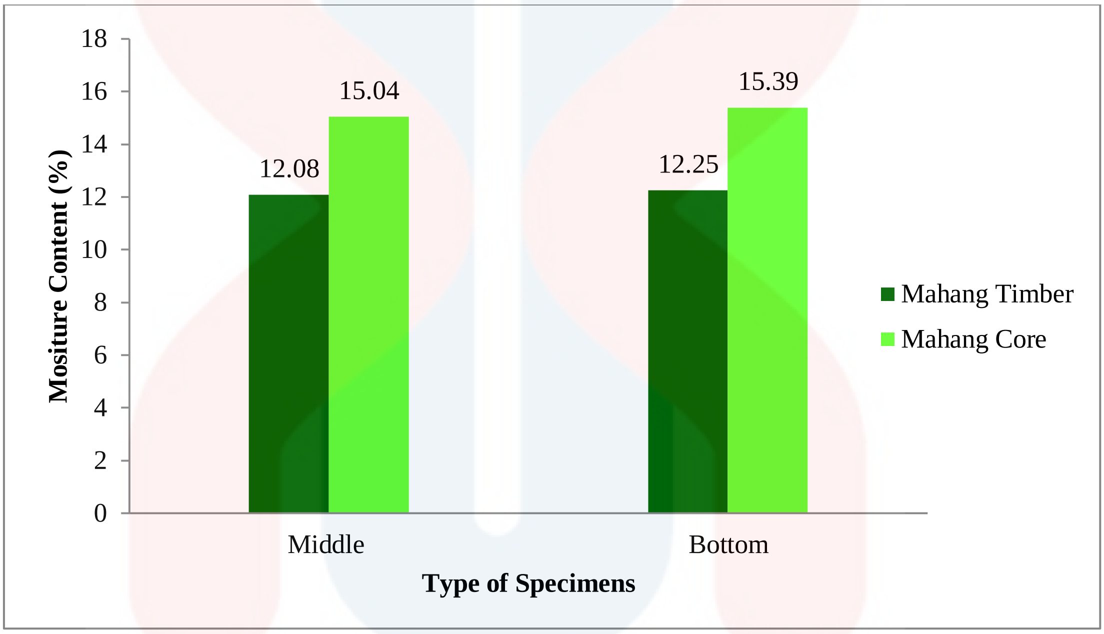


Figure 4.3: Comparative percentage of moisture content by middle and bottom samples for mahang timber and core.

By referring to the technical data sheet that mostly referred for moisture content of timber in naval applications (Table 4.1), the maximum moisture content of timber is 15% (Limited, 2014). The table had shown that the moisture content of timber was differed based on the end-product. On the other hand, moisture content of mahang wood was in the range of 12% to 15%. It shows that mahang wood has high tendency for naval application. Therefore, the moisture content of wood was vital in naval application because it affects the strength of wood (Gerhards, 1982). In addition, as the wood dries, the strength properties improve. For instance, the tensile strength of wood at its highest by 6-12% of moisture content, while the compression and bending strength of wood increase and been at their greatest in 12-15% moisture content range.

Table 4.1: Species, products, moisture content and applicable standards (CORe, 2013).

Species Group	**Seasoned Product**	**Moisture Content Bounds**	**Number of the applicable standard**
Hardwood	Flooring, lining, dressed boards	9% -14%	AS 2796
	Decking	10% to 18% *	AS 2796
	Framing	- 90% of pieces less than 15% - All pieces less than 18%	AS 2082

4.4 Water absorption

Water absorption by the core material is a major concern in naval structures. It would affect the mechanical, electrical and thermal insulation properties in case of damage to the face sheet of sandwich structure. In this study, the data recorded based on color change, weight change (%), and volume change (%) were collected from all specimens which the specimens immersed in seawater and distilled water as immersion media for 4 hours.

The color of mahang core and timber specimens change from light brown to dark brown whereas compared to reported balsa wood specimens which the color transformed from white to dark brown (Sadler *et al.*, 2009). This color changes clearly depicts high water absorption nature of balsa wood and mahang wood specimens.

Figure 4.4 shows the effect of 4 hours water immersion on weight gain, expressed as percentage of initial weight of core and timber materials. It was clear from Figure 4.5 that TB specimen shows the highest percentage of weight gain which was around 47.6% and 37.53% after immersed in distilled water and seawater, respectively. On the contrary, the weight gain percentage of TM, CM and CB specimens were lower and differ marginally between four specimens. In this test, timber specimen shows higher percentages weight gain compared to core specimens. The TB specimen showed higher percentage weight gain with value 47.6% which differs by 19.53% with CB specimen after immersed in distilled water and for the immersion in seawater, the CB have much lower value of weight gain compared to TB and TM with differ by 18.94% and 12.58%, respectively. Besides that, CM sample showed the lowest percentage of weight gain with 25.57% of weight change percentage after immersed in the distilled water and 16.29% after immersed in the seawater.

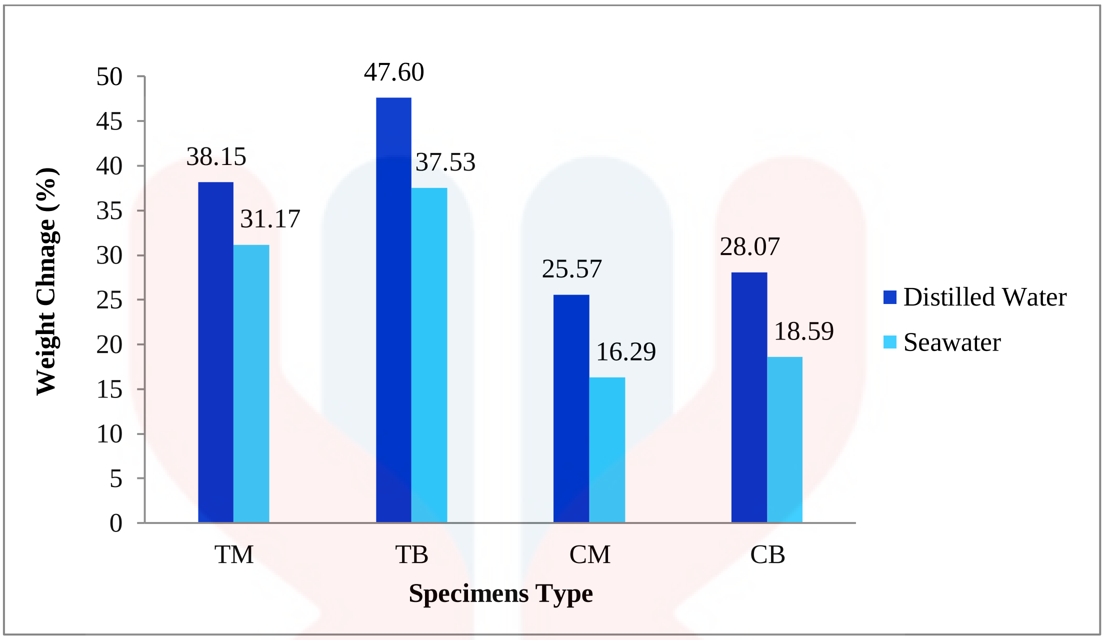


Figure 4.4: Comparative percentage of weight gain by Mahang (core and timber) specimens after immersed for 4 hours.

Figure 4.5 shows the effect of 4 hours water immersion on swelling characteristics (volume change) for all specimens tested. It was clearly show that the percentage of volume change varies between specimens tested. The volume change of CM specimen is the lowest during immersion period. The TB quickly expanded and reached as high as 21.30% swelling when immersed in distilled water and 19.79% after immersed in seawater during testing period. On the other hand, middle specimens were showed a reduction percentages volume change between timber and core specimens. The percentage volume gained of TM specimen reduced from 18.15% to 16.00% for CM specimen after immersed in the distilled water for four hours. All the specimens show the volume change percentage after immersion period.

The samples which immersed in the distilled water show higher change than immersed in seawater. This is due to the fact that moisture absorption of specimens immersed in sea water is less than immersed in distilled water because the attribution of salt ionic species in water interferes with the diffusion of water in timber and core specimens (Yin *et al.*, 2015).

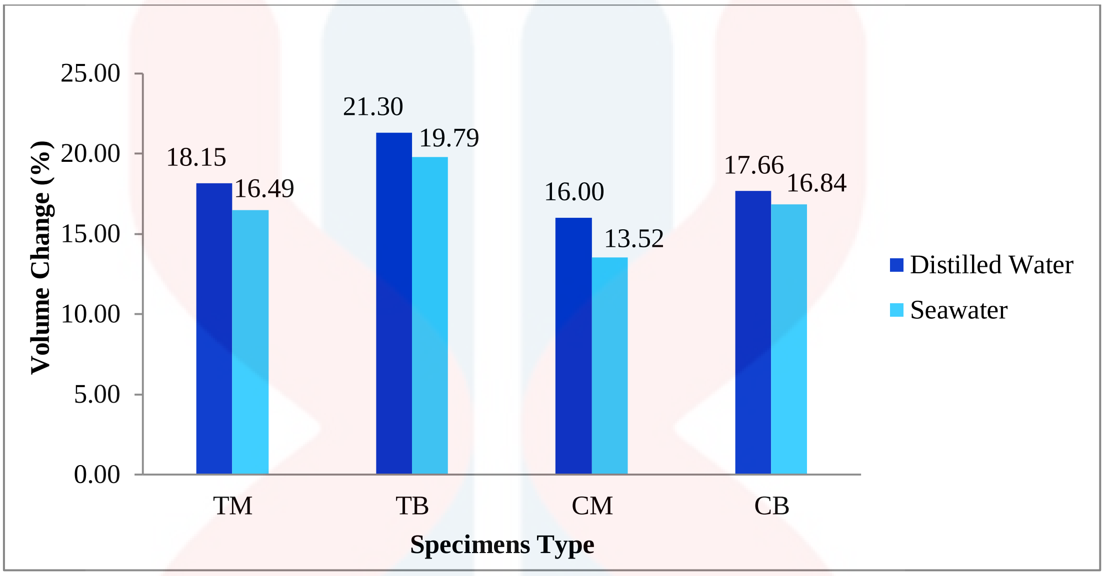


Figure 4.5: Comparative percentage of volume gain by mahang (core and timber) specimens after immersed for 4 hours.

One possible reason for greater water ingression in timber specimens is the more hydrophilic nature of its constituent cellulose fiber and lignin (Exploitation & Killmann, 1989, Saad & Kamal, 2012). It was reported in the past research that balsa wood samples showed significantly different amount of water absorption in seawater (67%) and tap water (74%) increased in weight after it has been immersed for 4 hours (Sadler *et al.*, 2009) and it marginally different with mahang specimens. Timber specimens show only 47.6% as the highest weight gained after immersed in the distilled water and 37.53% after immersion in the seawater. The absorption rate was greater for distilled water exposed conditions compared to seawater (D'Almeida, 1991). Besides that, the dimensional change is the same in all specimens direction which is true for both sea and distilled water (Sadler *et al.*, 2009).

In conclusion, mahang wood show good properties with having lower volume and weight gained after test period compared to balsa wood. On top of that, mahang wood show high tendacy in replacing balsa as core in naval application.

4.5 Compression Strength

Compression of wood and wood-based materials plays an important role in almost any construction projects. If the compression strength of wood beam is not known, not only deflection due to bearing load may cause significant deformation but also could even lead to its failure during service life.

Figure 4.7 demonstrates the compressive strength variation between mahang timber and core specimens. It was clearly show that core samples indicated higher compressive strength compared to timber samples. In this study, CB sample had shown the highest compressive strength with an average value which 21.46 MPa and 20.76 MPa for parallel and perpendicular-to-grain, respectively. Meanwhile, TM sample illustrated the lowest compressive strength compared to the other samples with 8.39 MPa (parallel-to-grain) and 8.10 MPa (perpendicular-to-grain). Other than that, timber samples differed marginally with core samples which deviating by 12.51% (B) and 12.25% (M) for perpendicular of grain orientation. Moreover, parallel orientation also show the huge different of compressive strength between core and timber sample with 12.86% and 12.65% for bottom and middle samples, respectively.

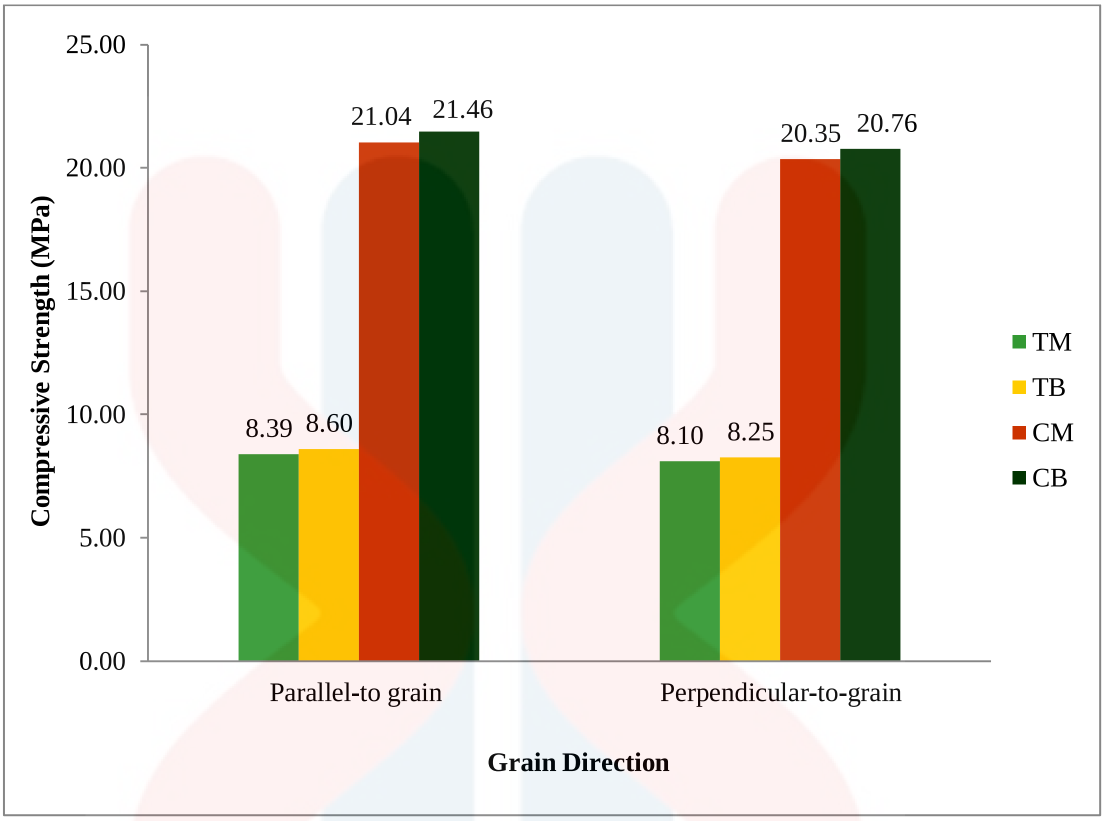


Figure 4.7: Compressive strength of mahang wood at different orientations.

Figure 4.8 and 4.9 illustrated the significant between load and deflection for timber and core samples. The graphs pattern have slightly different which the deflection of core specimens much lower than the timber specimens. The core specimens deflected on forces applied less than 1.2 mm while the timber samples were deflected more higher and achieved not more than 4 mm. Technically, the mechanical strength (compressive strength) significantly increased linearly with the wood density.

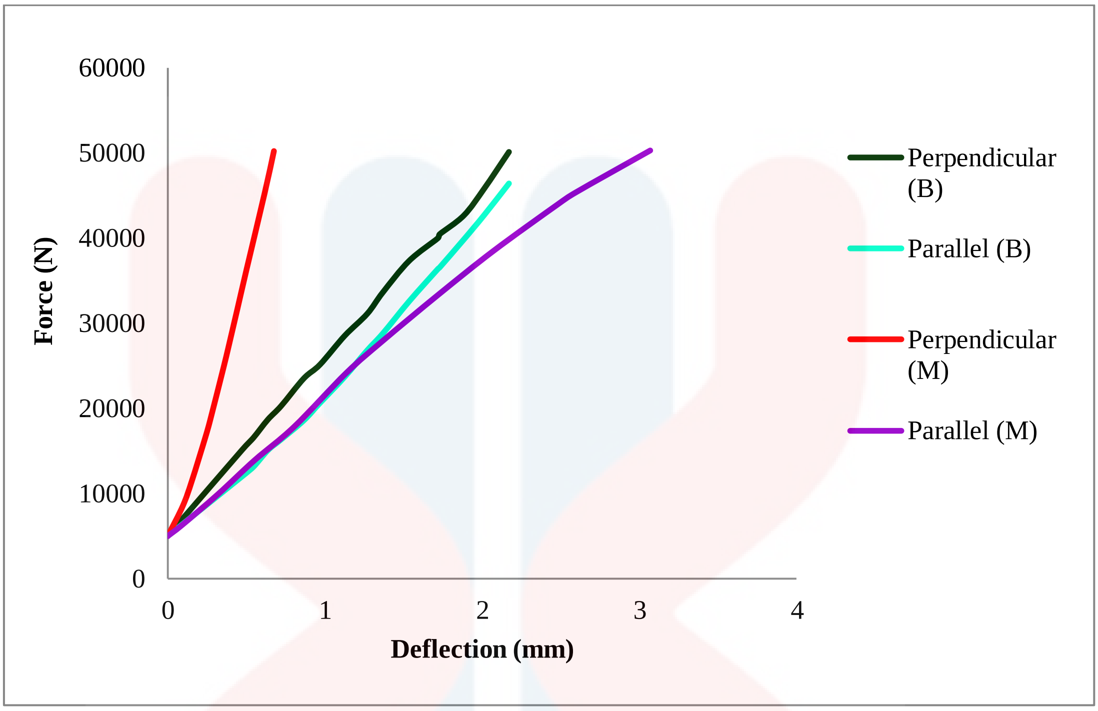


Figure 4.8: Force-deflection curves for mahang wood (timber) specimens at different orientations.

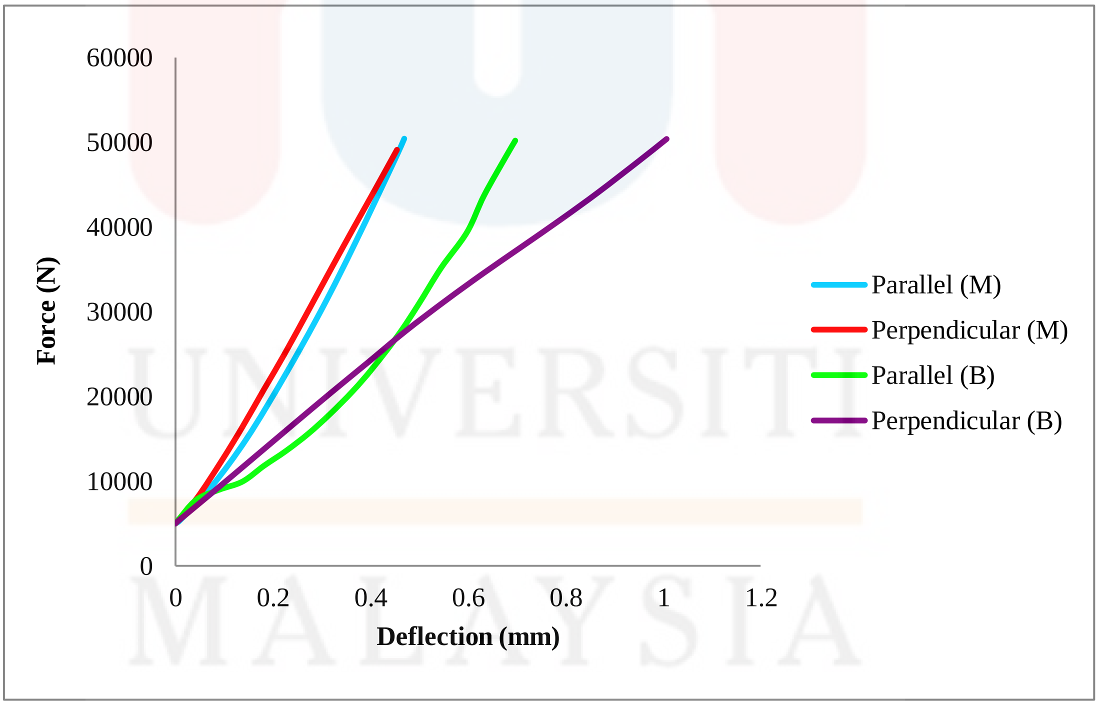


Figure 4.9: Force-deflection curves for mahang wood (core) specimens at different orientations.

Balsa wood has been referred as control sample for this study. The compressive strength of balsa wood in ranged of 4.7 MPa to 19.5 MPa for balsa timber (Gurit, 2010) and 10.1 MPa to 17.5MPa for balsa core (Auszac, 2007). With this values, mahang wood show slightly different with balsa wood. The compressive strength of mahang wood was stated in the range of 8.10 MPa to 8.60 MPa and 20.35 MPa to 21.46 MPa for timber and core, respectively. It shows that, mahang timber sample has in range of balsa timber, meanwhile mahang core sample it stated more higher than balsa core sample in terms of compression strength.

The different occurred not only due to samples taken from different parts of the mahang tree but also the grain directions of samples also affected the compressive strength of mahang wood. It was proved that the axial direction (parallel-to-grain) exhibited (Sadler et al., 2009) much stiffer and stronger than in-plane directions. By contrast, the strength in the radial (perpendicular-to-grain) and tangential directions show much lower than axial direction (Da Silva & Kyriakides, 2007). However, the radial modulus is stiffer than the tangential one even for denser wood.

4.6 Flexural strength

Researches to determine flexural strength and stiffness of wood have been done for a number of species (Qi *et al.*, 2015) and generally conducted as an alternative to tension tests. There were many structural wood products are subjected to bending due to the easier preparation of test specimens and data obtained from tests can be directly related to service conditions (Borrega & Gibson, 2015). There are two mechanical properties typically reported in bending test which the modulus of elasticity (MOE) and modulus of rupture (MOR). Furthermore, the MOR was computed under the assumption of linear elastic behavior and it cannot be used to predict the ultimate failure stress of composite (Bodig & Jayne, 1982). Nevertheless, the MOE and MOR are widely known used in characterizing the mechanical properties of wood in bending.

Figure 4.10 depicts the variation of MOR value for four types of mahang wood specimens. In this study, the tests were conducted on all specimens excepted for timber samples (parallel-to-grain). Firstly, timber sample (TB) shows the higher value of MOR compared to another samples with 37.02 MPa. Meanwhile, CM sample shows the lowest value (3.06 MPa) and followed by TM (32.22 MPa). Besides that, the graph shows a slump pattern between timber and core samples tested on perpendicular orientation. The MOR of TB differs around 27.85 MPa with CB sample. Similarly to middle samples which TM with 32.22 MPa of MOR, while CM only stated 3.06 MPa of MOR mahang wood.

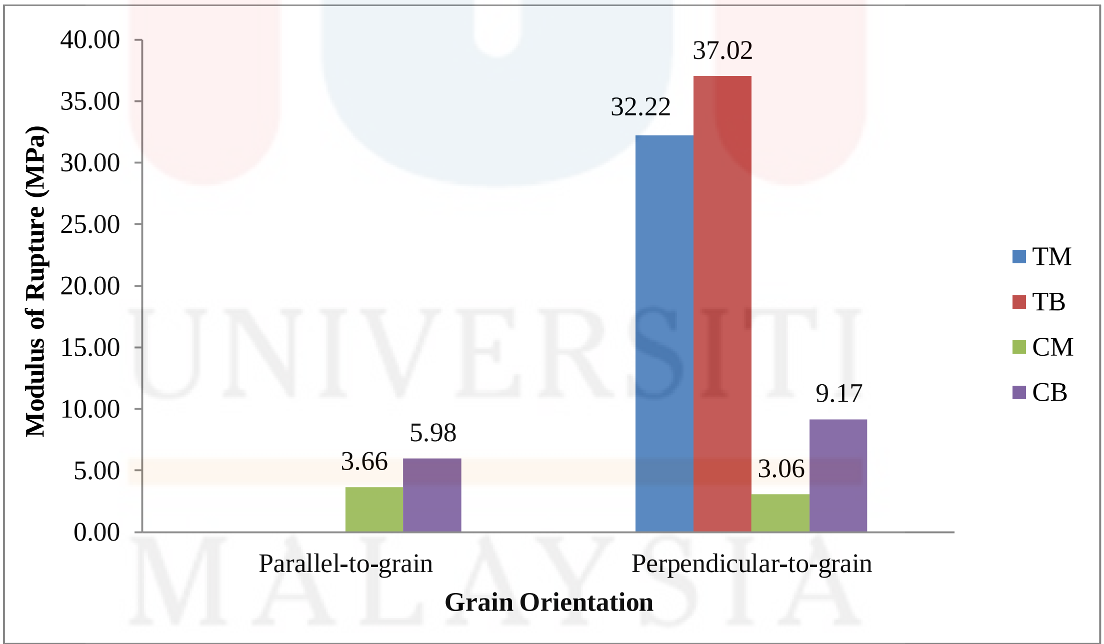


Figure 4.10: Modulus of rupture (MOR) of Mahang wood.

On the Figure 4.11, it shows the value of modulus of elasticity (MOE) of mahang wood specimens. In this study, the TM sample shows the highest value of MOE with 4982.56 MPa and followed by TB as the second highest with 3294.20

MPa of MOE. Conversely, CM indicates the lowest value of MOE compared to other samples with 628.84 MPa. The CB sample shows a slightly different between parallel and perpendicular specimens. The CB for parallel-to-grain, it shows 1032.89 MPa while 1290.87 MPa for perpendicular-to-grain.

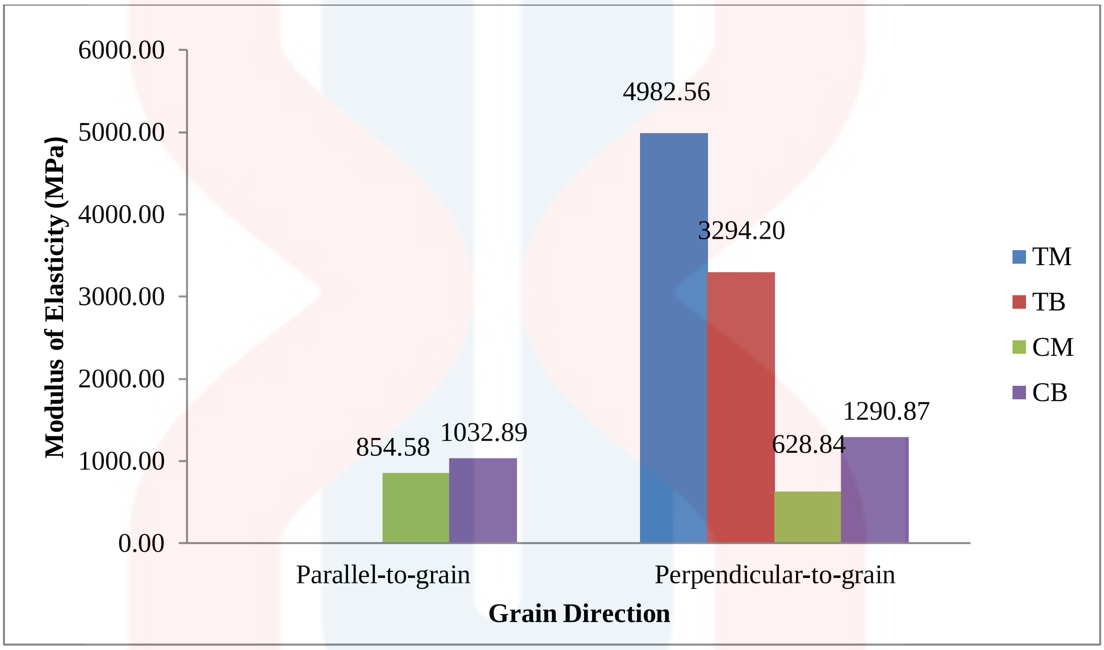


Figure 4.11: Modulus of elasticity (MOE) of mahang wood.

As comparison, the MOR and MOE of balsa were studied. The MOE and MOR of balsa wood increased linearly with density, with values up to 8000 MPa for MOE and 70 MPa for MOE at density of 240 kg/m^3. Moreover, the values of MOE and MOR can be up to 36 000 MPa for MOE and 320 MPa for MOR with 1557 kg/m^3. Mahang wood indicates with MOE range in 628.84 MPa to 4982.56 MPa while MOR value of mahang in the range of 3.06 MPa to 37.02 MPa. The linear dependence of MOE and MOR properties on density because in bending, wood fibers on the lower part of the beam are axially extended until eventually fails due to tension stresses. Furthermore, at given density, the fibers must carry higher share of the load than if they were sole cell type and also the rays and vessels contribute more to the flexural modulus than to strength (Borrega & Gibson, 2015). On top of that, failure of wood specimens in bending due to flexural stress corresponded to the MOR was reached the bottom of the beam samples, then subjected to tension and fractured (Green *et al.*, 1999). The propagation of the crack it was often hard to see the crack with a naked eyes once the bending test had terminated (Borrega & Gibson, 2015). The Figure 4.12 shows the crack pattern of mahang wood (timber sample).

Figure 4.12: The crack pattern on mahang wood (timber sample).

4.7 Tensile Strength

Wood exhibits highest strength in tension parallel-to-grain according to grain direction. From the past research, tensile strength parallel-to-grain of small clear specimens 2 to 3 times greater than compressive strength of parallel-to-grain and also about 1.5 times greater than static bending strength (Kultikova, 1999). The mechanical performance of wood is strongly dependent on its density (Borrega & Gibson, 2015). In this study, a tension parallel-to-grain test was performed for timber specimens and evaluation for core specimens; the tests were performed on both parallel and perpendicular accordance to the grain orientations.

The result of mahang timber and core tensile strength data were illustrated in Figure 4.14. The trend indicates the higher tensile strength on the timber samples for mahang wood, and the corresponding declined in the value of tensile strength for core samples. The TB sample show the highest value of tension strength with 40.22 MPa while CM sample was the lowest with 16.99 MPa compared to the other samples for parallel-to-grain specimens. However, CM and CB samples have been relatively stable, differs with only 2.87 MPa for perpendicular specimens meanwhile, 4.44 MPa was recorded for perpendicular specimens. For comparison, the literature tensile strength data for balsa wood was attached on appendices. Balsa wood depicted tensile strength in the range between 9.40 MPa to 13.80 MPa (Da Silva & Kyriakides, 2007) for core samples and 7.60 MPa to 32.20 MPa range of tensile strength for balsa timber. The data on the tensile strength and stiffness of balsa wood in the literature are limited in the number and reliability.

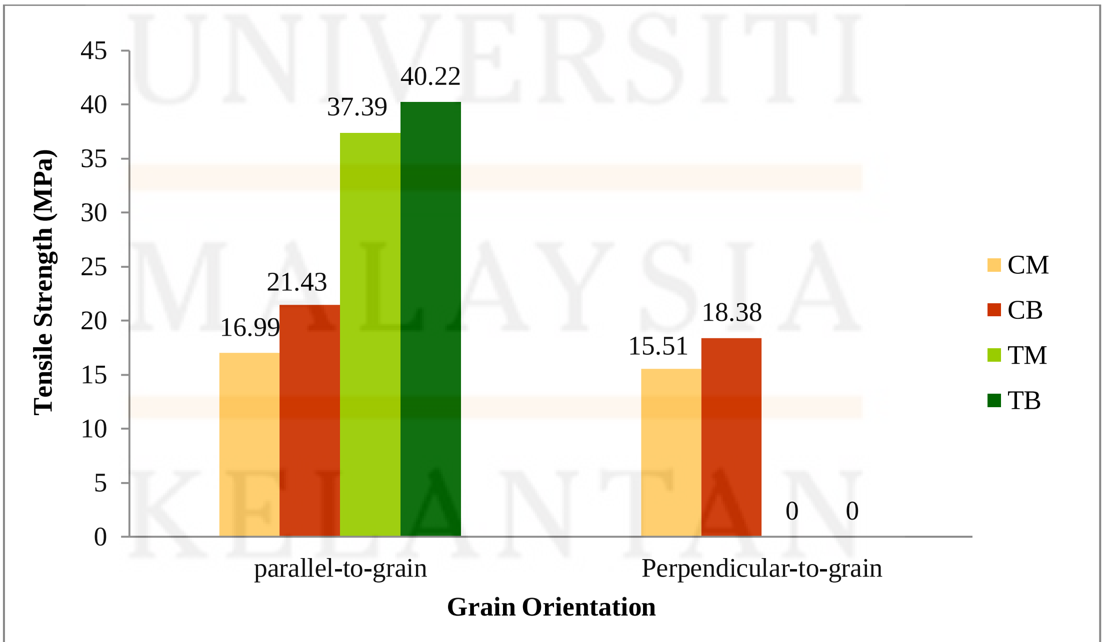


Figure 4.14: Tensile strength of mahang wood.

Figure 4.15 depicts the tensile modulus (Young's Modulus) for mahang wood. Generally, the overview shows the variation in tensile modulus values between the different samples tested. In this study, parallel-to-grain samples recorded higher value of tensile modulus compared to perpendicular samples. TB sample shows the highest value of tensile modulus with 1698.77 MPa for parallel-to-grain but it plunged to 450.73 MPa for perpendicular samples. Besides that, TM sample also shows a reduction of tensile modulus with 1228.97 MPa differed between parallel and perpendicular specimens. On top of that, TM (406.08 MPa) and CM (854.58 MPa) samples show the lowest value of tensile modulus for perpendicular and parallel orientations samples, respectively. Comparatively, balsa wood was reported having tensile modulus in the range between 2234 MPa to 3930 MPa for balsa wood as core sample (Auszac, 2007) and there was no data reported for balsa wood as timber sample.

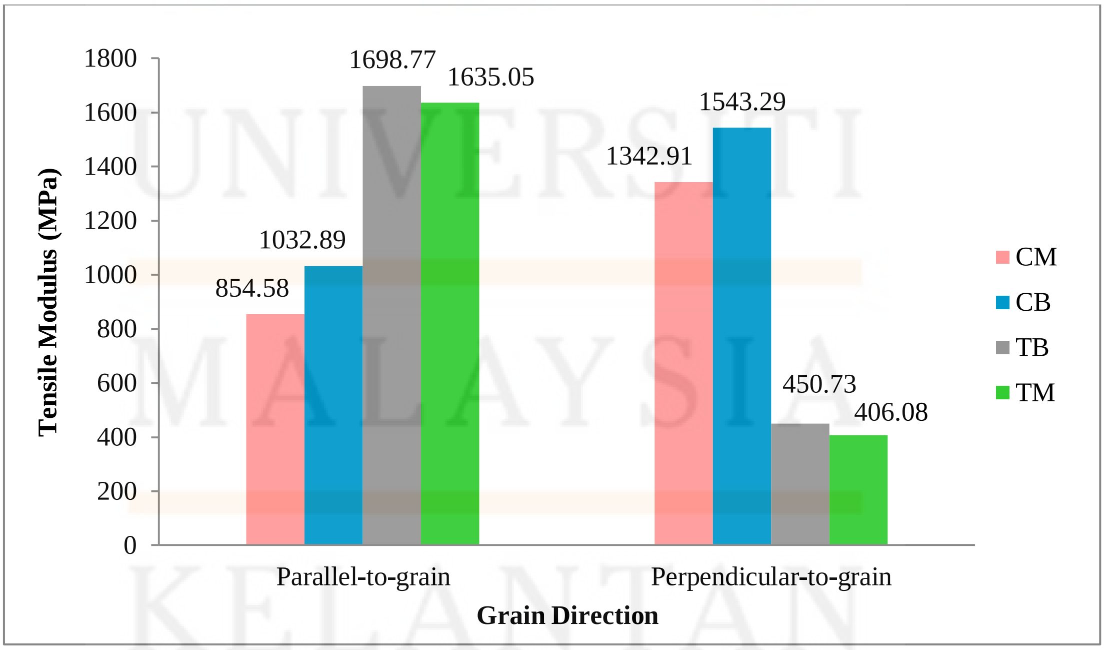


Figure 4.15: Tensile modulus for mahang wood.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The physical and mechanical properties in middle and bottom parts of mahang wood were investigated accordance to parallel and perpendicular-to-grain. The density of mahang varied roughly from 346 to 808 kg/m^3. In moisture content, mahang wood able to reach 12 -15% of moisture contents level followed the standards. In both axial and radial (parallel and perpendicular) compression, the strength increased linearly with density which 8.10 MPa to 8.60 MPa and 20.35 MPa to 21.46 MPa for timber and core, respectively. The radial (perpendicular) mechanical properties were dependent on the fibers, which were subjected to bending and on the rays which were axially compressed during perpendicular loading. In bending the modulus of elasticity (MOE) and modulus of rupture (MOR) increased linearly with part of mahang wood (middle and bottom) as function as density different. The value reached up to 4982.56 MPa for MOE and 37.02 MPa for MOR. The failure occurred on the upper side of the beam on the first, and it subjected to compression, however the wood fractured ultimately on the lower side of the beam due to increased tensile stresses. The compressive failure in mahang occurred as the fibers buckled and were laterally displaced. The mechanical behavior of mahang wood was modeled by considering its density resemble and similar to balsa wood. In physical tests, mahang wood showed a good agreement to the balsa wood data. However, the MOR, MOE and tension strength were slightly lower from the expected value, possibly due to the fact that cellular structure in mahang does not same with balsa. In load-bearing application, the fibers were vital because it likely to carry a higher share of the load.

APPENDICES:

Appendix A:

Table A.1: Mass and density of Mahang wood specimens

Sample	Mass in air (g)	Mass in water (g)	Saturated mass (g)	Density (g/mm^3)
M1	8.14	9.03	11.60	3.17
M2	8.11	9.07	11.59	3.23
M3	8.14	9.14	11.18	3.99
B1	8.07	10.38	12.12	4.66
B2	7.60	9.00	10.63	4.70
B3	8.61	9.81	12.23	3.57

Appendix B:

Table B.1: Volume and weight of Mahang timber specimens for water absorption test.

Sample	Distilled water					
	Middle			Bottom		
	Before immersion	After immersion	Gain %	Before immersion	After immersion	Gain %
Vol. (m^3)	114.743	130.184	13.46	116.017	134.090	15.58
	114.542	130.089	13.57	117.513	138.776	18.09
Weight (g)	38.129	47.892	25.61	35.371	45.837	29.58
	37.863	47.527	25.52	36.025	45.594	26.56
Sample	**Seawater**					
	Middle			**Bottom**		
	Before immersion	**After immersion**	**Gain %**	**Before immersion**	**After immersion**	**Gain %**
Vol. (m^3)	114.381	130.531	14.12	117.867	138.639	17.62
	119.805	141.210	17.87	117.729	138.565	17.70
Weight (g)	35.553	42.348	19.11	39.462	46.065	16.73
	37.591	44.383	18.07	37.893	43.899	15.85

*M is stands for middle part and B is for bottom part of Mahang tree.

Table B.2: Volume and weight of Mahang core specimens for water absorption test.

Sample	**Distilled water**					
	Middle			**Bottom**		
	Before immersion	**After immersion**	**Gain %**	**Before immersion**	**After immersion**	**Gain %**
Vol. (m^3)	72.829	86.048	18.15	84.891	98.889	16.49
Weight (g)	42.703	63.029	47.60	30.037	41.495	38.15
Sample	**Seawater**					
	Middle			**Bottom**		
	Before immersion	**After immersion**	**Gain %**	**Before immersion**	**After immersion**	**Gain %**
Vol. (m^3)	73.239	87.607	19.62	49.198	55.667	13.15
	75.989	91.155	19.96	33.773	37.720	14.65
Weight (g)	80.561	120.546	49.63	88.166	125.124	41.92
	33.695	42.265	25.43	45.853	55.213	20.41

Appendix C:

Table C.1: Moisture content of mahang wood specimens.

Sample	Initial mass (g)	Oven-dry mass (g)	Moisture content (%)
M1	71.27	64.19	11.03
M2	74.57	66.02	12.95
M3	62.83	55.97	12.26
B1	90.64	81.54	11.02
B2	90.47	80.16	12.86
B3	90.49	80.17	12.87

Table C.2: Moisture content of mahang core specimens.

Sample	Initial mass (g)	Oven-dry mass (g)	Moisture content (%)
M1	51.71	45.08	14.71
M2	44.59	38.51	15.79
M3	48.34	42.17	14.63
B1	79.29	69.04	14.85
B2	74.76	64.78	15.41
B3	84.85	73.21	15.90

Table C.3: Moisture content between the mahang timber and the core specimens after oven-dry for 24h at 103ºC ± 2ºC.

Sample	Moisture content (%)	
	Timber Specimens	Core Specimens
Middle	12.08	15.04
Bottom	12.25	15.39

Appendix D:

Table D.1: Compression properties of (50 x 50 x 200) mm Mahang wood specimens.

	Num.	Parallel-to-grain		Perpendicular-to-grain	
		Middle	**Bottom**	**Middle**	**Bottom**
Youngs Modulus (N/mm^2)	1.	1640.238	1789.185	1342.913	1406.386
	2.	1446.336	1608.347	Null	1279.440
Force @ peak (N)	1.	50392.000	50299.000	50225.000	50489.000
	2.	50296.000	46376.000	Null	50499.000
Stress @ break (N/mm^2)	1.	20.988	24.370	1.640	7.778
	2.	20.529	12.491	Null	2.110
Stress @ peak (N/mm^2)	1.	20.988	20.557	6.613	21.040
	2.	20.529	22.370	Null	21.032
Strain @ peak (%)	1.	1.311	1.468	1.409	10.435
	2.	1.535	1.692	Null	9.180
Def. @ break (N)	1.	2.622	2.936	2.863	22.102
	2.	3.069	15.639	Null	19.078

*Def. is stands for deflection.

Table D.2: Compression properties of (76.2 x 76.2 x 76.2) mm Mahang core specimens.

	Num.	Parallel-to-grain		Perpendicular-to-grain	
		Middle	**Bottom**	**Middle**	**Bottom**
Youngs Modulus (N/mm^2)	1.	809.312	523.419	447.128	333.433
	2.	1024.934	1228.451	404.282	385.489
	3.	729.480	1346.790	366.816	633.277
Force @ peak (N)	1.	50455.000	50479.000	50490.000	50483.000
	2.	50476.000	50497.000	50498.000	50499.000
	3.	50490.000	50455.000	50497.000	50492.000
Stress @ break (N/mm^2)	1.	3.215	0.915	0.897	0.895
	2.	2.640	0.885	0.893	0.900
	3.	0.916	0.976	0.879	0.877
Stress @ peak (N/mm^2)	1.	8.689	8.694	8.696	8.694
	2.	8.693	8.697	8.697	8.697
	3.	8.696	8.689	8.697	8.696
Strain @ peak (%)	1.	0.660	0.919	1.816	1.652
	2.	0.616	0.608	1.429	1.606
	3.	0.759	0.614	1.871	1.325
Def. @ break (N)	1.	1.217	0.726	1.427	1.286
	2.	1.085	0.470	1.110	1.262
	3.	0.597	0.524	1.445	1.018

*Def.is stands for deflection.

Table D.3: Compression strength of mahang wood.

Sample	Parallel-to grain	Perpendicular-to-grain
TM (N/mm^2)	8.70	8.39
TB (N/mm^2)	8.70	8.40
CM (N/mm^2)	21.04	20.35
CB (N/mm^2)	21.46	20.76

Appendix E:

Table E.1: Flexural properties of (50 x 50 x 200) mm mahang core specimens.

	Num.	Parallel-to-grain		Perpendicular-to-grain	
		Middle	**Bottom**	**Middle**	**Bottom**
Def. @ Break (mm)	1.	5.766	4.026	0.531	1.809
	2.	2.001	3.195	3.563	5.817
	3.	3.155	2.540	3.271	1.373
Average Force (N)	1.	225.587	302.014	179.300	1054.300
	2.	159.443	188.805	170.265	290.908
	3.	164.182	416.005	158.879	514.800
Young's Modulus (N/mm^2)	1.	232.403	375.520	1308.231	1705.352
	2.	399.941	336.464	305.298	317.602
	3.	272.788	807.400	272.986	1849.648
MOR (N/mm^2)	1.	4.418	6.186	2.479	14.574
	2.	3.280	3.861	3.446	5.827
	3.	3.286	7.896	3.257	7.116

Table E.2: Bending data of mahang wood (timber specimens)

	Num.	Middle	Bottom
Bending Strength @ Break (N/mm^2)	1.	32.223	33.275
	2.		39.554
Young's Modulus (N/mm^2)	1.	4982.561	3766.738
	2.		2821.657
MOR (N/mm^2)	1.	32.223	34.484
	2.		39.560

Appendix F:

Table F.1: Tension properties of mahang wood (core specimens).

	Num.	Parallel-to-grain		Perpendicular-to-grain	
		Middle	Bottom	Middle	Bottom
Stress @ Break (N/mm^2)	1.	-0.985	-1.545	-3.317	-1.809
	2.	-0.812	-1.806	-4.314	-1.114
	3.	-3.255	-0.871	-1.363	-3.618
Force @ Peak (N)	1.	4525.000	5046.000	6285.000	10560.000
	2.	7556.000	8198.000	3015.000	798.000
	3.	4491.000	7651.000	5823.000	6561.000
Elong. @ Break (mm)	1.	2.664	3.017	-0.004	4.204
	2.	4.169	4.566	1.414	0.694
	3.	2.326	3.885	4.617	1.520
Stress @ Peak (N/mm^2)	1.	13.923	15.526	19.338	32.492
	2.	23.249	25.225	9.277	2.455
	3.	13.818	23.542	17.917	20.188
Strain @ Break (%)	1.	1.066	1.207	-0.002	1.682
	2.	1.668	1.826	0.566	0.278
	3.	0.930	1.554	1.847	0.608
Young's Modulus (N/mm^2)	1.	3347.274	2710.303	2425.685	2514.763
	2.	1993.207	2037.749	5279.667	1536.266
	3.	2294.989	2060.066	1225.989	4250.881
Stress @ Yield (N/mm^2)	1.	4.197	3.474	4.305	7.852
	2.	4.726	5.218	5.812	0.535
	3.	3.585	5.055	3.628	9.363

Table E.2: Tension properties of mahang wood (timber specimens).

	No.	Middle	Bottom
Force @ Peak (N)	1.	38389.000	32668.000
	2.	16681.000	34749.000
	3.	29900.000	37783.000
Elong. @ Break (mm)	1.	14.598	6.642
	2.	0.790	9.189
	3.	11.795	10.830
Stress @ Peak (MPa)	1.	533.181	388.905
	2.	184.895	398.919
	3.	293.595	428.348
Strain @ Break (%)	1.	6.347	3.005
	2.	0.343	4.158
	3.	5.128	4.900
Young's Modulus (MPa)	1.	15492.679	62882.580
	2.	71544.742	53179.136
	3.	58287.916	54158.194
Stress @ Yield (MPa)	1.	112.306	201.143
	2.	170.142	151.054
	3.	122.662	147.076

Table E.3: Tensile strength of mahang wood.

Sample	Parallel-to-grain		Perpendicular-to-grain	
	Middle	Bottom	Middle	Bottom
Core (MPa)	16.99	21.43	15.51	18.38
Timber (MPa)	337.22	405.39	/	/

Table E.4: Tensile modulus of mahang wood.

Sample	Parallel-to grain	Perpendicular-to-grain
TM (MPa)	1635.05	1342.91
TB (MPa)	1698.77	1543.29
CM (MPa)	854.58	406.08
CB (MPa)	1032.89	450.73

Table E.5: Balsa wood properties guide (Auszac, 2007).

Density	
1. Low density	75 kg/m^3 (0.0027 Ib/in^3)
2. Medium density	150 kg/m^3 (0.0054 Ib/in^3)
3. High density	225 kg/m^3 (0.0081 Ib/in^3)
Tensile Strength	
1. Low density	7.6 MPa
2. Medium density	19.9 MPa
3. High density	32.2 MPa

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