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DEVELOPMENT AND MECHANICAL TESTING OF WOOD PLASTIC COMPOSITE (WPC) MADE OF RECYCLED POLYMER AND RECYCLED WOOD FLOUR

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REPORT ORGANIZATION

This report consists of two parts which contributed to the main research topic. Part 1 is reporting on the "Production and characterization of Enviro-Recycled-Wood Plastic Composites (ER-WPC) for the structural application" and Part 2 is reporting on the "The effect of coupling agent addition to the mechanical of wood plastic composite (WPC) made of recycled high density polyethylene wood flour (RWF)".

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PART 1

Production and characterization of Enviro-Recycled-Wood Plastic Composites (ER-WPC) for the structural application

ABSTRACT

Composites of polymer reinforced with natural fibres have been widely received great attention by the entire engineering community. Natural fibers that explored such as hemp, sisal, jute and wood fibers provide greater reinforcing capabilities when it perfectly compounded with the polymers matrix. Thus, the potential from the induction of wood flour fibers in the thermoplastics Polypropylene (PP) for the structural application required the materials which can up stand the load in a prolonged duration with unpredictable service environment. This research aims to study and analyze the effects of different fiber loading on the mechanical properties and its relationship to the microstructural behavior of the wood flour fiber reinforced polypropylene composites. The major raw materials used in this project is polypropylene (PP) as matrix materials which based on two type which is the virgin and the recycle resin and wood flour fiber as reinforcement materials for the composite fabrication. The composite plate were fabricated by using an extruder and compression molding machine and were then cut into the specific dimension according to the specific ASTM standard of testing. The specimens primarily were tested for the Critical Properties Analysis -Tensile Test. The best compounding formulation of composite was found at the weight percentage (wt%) of 60wt% of PP matrix and 40wt% of the wood flour fibers for both of virgin and recycle. Further analyses for various mechanical properties of the composite were done accordingly to all composites formulation. The microstructures of tested specimens fracture surface were observed by using an optical microscope as to understand the fracture behavior, the fiber distribution and the surface morphology and its significant correlation to the mechanical properties studied. The results showed that the increasing of fiber loading had significantly increased the mechanical properties of the fabricated composite. Through the study, the enhancement of fabricated composite could be applied to the structural engineering applications through the advantage of the mechanical properties performance of tensile, flexural and impact properties. Conclusively, it is hope that the research will contribute to the development of newly environmental friendly advance material specifically for the structural application.

INTRODUCTION

In this new era, the technologies of developing and designing a new material are rapidly growth. This phenomenon is actually a tradition since in primitive or ancient epoch, entire human being were adapting their daily live by implicated all material surrounds them to become better and practical (Stark *et al*., 2003). The applications of the engineering materials in human life were started with the stone edge then evolved to the wood and after that metal, followed by the polymer and composite era. The latest invention of material is the combination of the polymer (non-biodegradable) with some of biodegradable natural fiber such as jute, hemp, ramie, flax, coconut and sugar cane dregs.

As we know, the thermoplastic resins, such as polypropylene, polyethylene, polystyrene, and polyvinyl chloride, soften when heated and harden when cooled. This property allows other materials, such as wood, to be mixed with the plastic to form composite products. The resulting wood-flour-filled polymer composites can be easily processed into various shapes and can be recycled (Richardson *et al*., 2006). In WPCs, a polymer matrix forms the continuous phase surrounding the wood component. These matrix polymers are typically low-cost commodity polymers that flow easily when heated, allowing for considerable processing flexibility when wood is combined with them. These polymers tend to shrink and swell with temperature but absorb little moisture and can be effective barriers to moisture intrusion in a well-designed composite (Rowland, 2002). Wood itself contains polymers such as lignin, cellulose, and various hemi-celluloses but have very different properties from the synthetic polymers with which it is most often combined. Wood is less expensive, stiffer, and stronger than these synthetic polymers, making it a useful filler or reinforcement (Stark and Clemons, 1997). Even though wood does not shrink and swell much with the temperature, it readily absorbs moisture, which alters its properties and dimensions and can lead to degradation if not well protected.

The primary advantages of using a biodegradable filler in plastic are low density, non abrasive, high filling levels that possible resulting in high stiffness properties, easily recyclable, low energy consumption and low cost of production (Kahraman *et al*.,2005). Thus, the main purpose of using the filler in composite is to improve the mechanical properties of existing polymeric material for the structural application.

In the structural application, the material is desired to have greater stability to withstand the load or stresses applied in a prolonged duration. Due to the outdoor used; it also requires vast resistivity of external environmental influence such as weather, fungal growth and etc; which may lead to degradation. Throughout the performances of wood flour as filler for plastic, this tends to increase the stiffness and its strength. In principle, it is expected WPCs should display superior mechanical properties, dimensional stability, greater resistance to chemical and biological degradation, and less moisture absorption.

Therefore, the development of this research is to characterize all related engineering properties which mandatory for the structural application. This research works focused on the study of the mechanical properties of the fabricated composite emphasizing on the impact, tensile and flexural properties at the laboratory scale. There are several processing stage involved in the fabrication of the samples. The internal mixer was utilized extensively in this research to produce good compounding of resulted composites. After that, the compounded materials are designed into the practical shape by using hot and cold compression molding. This followed by testing stage in order to investigate the mechanical properties and others. The analysis of data was further compare the performance of the fabricated WPC to the existing materials used in order to verify that this new developed composites has great potential to be used as the substitution or alternative materials in the structural application.

Problem Statement (Part 1)

WPCs can be labeled as true composite materials, possessing properties of both major ingredients. The key mechanical property such as strength and stiffness of these composite materials lies between those for polymer and wood. The structural morphology plays a vital role in defining most of the functional attributes of the fabricated WPC. The excellent moisture resistance of polymers compared with wood directly related to the molecular structure of plastic material that being used, making WPC more durable and attractive. Environmental, biological, chemical, mechanical, and/or thermal modes of degradation are all contributes to the degradation of WPCs. Outdoor durability, by its nature, exposes WPCs to degradation modes that can act synergistically (Stark *et al*., 2003). The major drawback of wood flour composites is probably their propensities to swell on water uptake since wood flour are hygroscopic. The hydrophilicity and swelling of the polymer matrix are usually limited for the matrix materials. Thus, the overall focus of this research is on reducing the effects of major drawbacks mentioned by investigating the effects of various loading of wood flour addition to the final properties of the fabricated WPC.

Research Objectives (Part 1)

The purposes of this research were as followed:

(a) To study the effects of different loading percentages of wood flour to the mechanical properties of the fabricated composites develop from virgin Polypropylene (PP) and recycled PP.

(b) To further investigate the structural integrity of the fabricated WPC through the water absorption and thickness swelling study.

(c) To understand the failure mechanism of the tensile fractured composites through the microstructural observation by using Optical Microscope (OM).

Research Scope (Part 1)

The main raw material that will be used during the research is basically a virgin and recycled Polypropylene (PP) which will be combined with the wood-flour. Internal mixer and hot press compression molding set up will be used to fabricate the intended composite. Then, the samples were tested destructively by using the tensile test (ASTM D638), impact test (ASTM D256), flexural test (ASTM D790) and weathering test (ASTM D570). All of the test procedures are in accordance to the American Standard Testing Method (ASTM) as to ensure the accuracy and reliability of the testing data.

In line with the purposes of this research, the weight percentage of wood flour to the fabricated composite will be varied. The percentages of wood flour which employed in this study are 0 %, 10 %, 20 %, 30 %, 40% and 50%. The optimum formulation of wood flour in the fabricated composites will be recommended. As the percentage of wood flour increase, the mechanical properties are expected to be escalating as well.

Report Hypotheses (Part 1)

In this research, the different filler weight percentages of wood flour in the fabricated composites will influences the mechanical properties. This expectation is basically according to the rule of mixture (ROM) which explaining the more reinforcement in composite will provide better resulted properties. The extended properties of this fabricated composite are very useful to be applied in a structural application where

the material is forced to withstand higher load and stress in an outdoor environmental atmosphere.

Importance of the Research (Part 1)
This research is conducted with determination to fully utilized the recycled polypropylene and to value add the wood by-product that is wood flour which significance in term of the economical consideration. Apart from that, the utilization of recycled PP is to appreciate the important of environmental concern which can reduce the pollution due to the uncontrolled disposal. By the end of this research, it is hope that it will produce novelty to the material application especially in the structural field. It is also expected that this development may contribute to the enhancement of the advance material.

LITERATURE REVIEW

Introduction

The review will be given on the composites material base on its history, classification, major properties, application and the fabrication processes. This chapter also covers the manufacturing technologies involved from the raw material during material preparation and samples fabrication until the experimental testing that undertakes as to achieve the objectives of the research project. Comprehensive reviews related to wood polymer composites and the theories involved will be covered extensively.

Composite Material

Composites are hybrid materials made of a polymer resin reinforced by fibers, combining high mechanical and physical performance of the fibers and the physical properties of polymers refer to the Figure 2.1a.

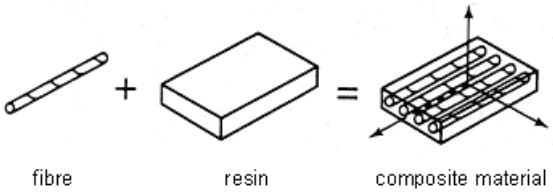


Figure 2.1a: Composite composition

According to Matthew and Rawling (2002), each of material (i.e, matrix and reinforcement) must exist of more than 5 wt% to be classified as composite material. The purposed of introducing the composite material is to improve the properties that have been performed by monolithic materials. Thus, the composite is expected to improve the mechanical characteristics such as the stiffness, toughness as well as ambient and high temperature resistance (Callister, 2003). The short and discontinuous fiber composites are responsible for the biggest share of the successful applications, whether measured by the number of parts or quantity of the material used. Less visible but growing enormously since the last decade, are the applications of continuous fibre reinforced polymers. By changing the direction of the fibers in

the resin, the material properties can be tailored to the external loads. To optimize the performance of the composite, the construction of the multiple adjusted layers (laminae) can be used to form a laminate (refer to Figure 2.2a). Typical fibers used are glass, carbon, aramid and natural fibres. Epoxy, polyester and polypropylene is a common resins used in the composite fabrication.

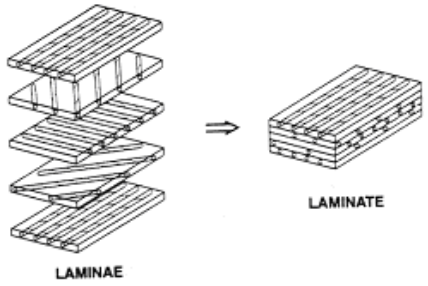


Figure 2.2a: Tailored composite

By this joining, poor capabilities and drawbacks of the individual components will be disappeared. For instance, composites will have a high stiffness and strength with a low weight and their corrosion resistance is often excellent (Callister, 2003). Composites have worked their way up amongst wood and metal due to their outstanding price performance ratio during a lifetime. A powerful approach in improving this ratio is to minimize the steps required from the raw material to the end product fabrication. Additional economic benefits are the inexpensive raw materials (e.g. when using reinforcements of glass fiber or natural fiber) and the little to none required maintenance during service. Composites are now a part of everyday life, and have entered nearly all major industrial sectors, including aerospace, ground transport, packaging, sports industry and civil engineering. Most current applications are modern; however, some are in fact quite ancient (Kaw, 1997).

Composite Classification

According to Callister (2003), a classification scheme for the various composites types can be illustrated as in the following Figure 2.3a. The composites materials are classified by the geometry of reinforcement and the types of matrix materials used in its constituent. As a result, there are three main types of geometries of the reinforcement which are particle-reinforced, fiber-reinforced and structural composite (Callister, 2003). Types of matrix used in composites are also can be divided into four types, namely as polymer matrix composite (PMC), metal matrix composite (MMC), ceramic matrix composite (CMC) and carbon carbon composite (CCC) (Callister, 2003; Matthew and Rawlings, 2002). Despite, fiber based reinforced composites will be emphasized in this study, whereby the wood flour was used as reinforcement filler for the thermoplastics Polypropylene (PP) matrix (Lee *et al*., 2007; Stark *et al*., 2002). Thus, PMC system which utilized the wood flour as filler reinforcement material will be developed and further emphasizes in this study.

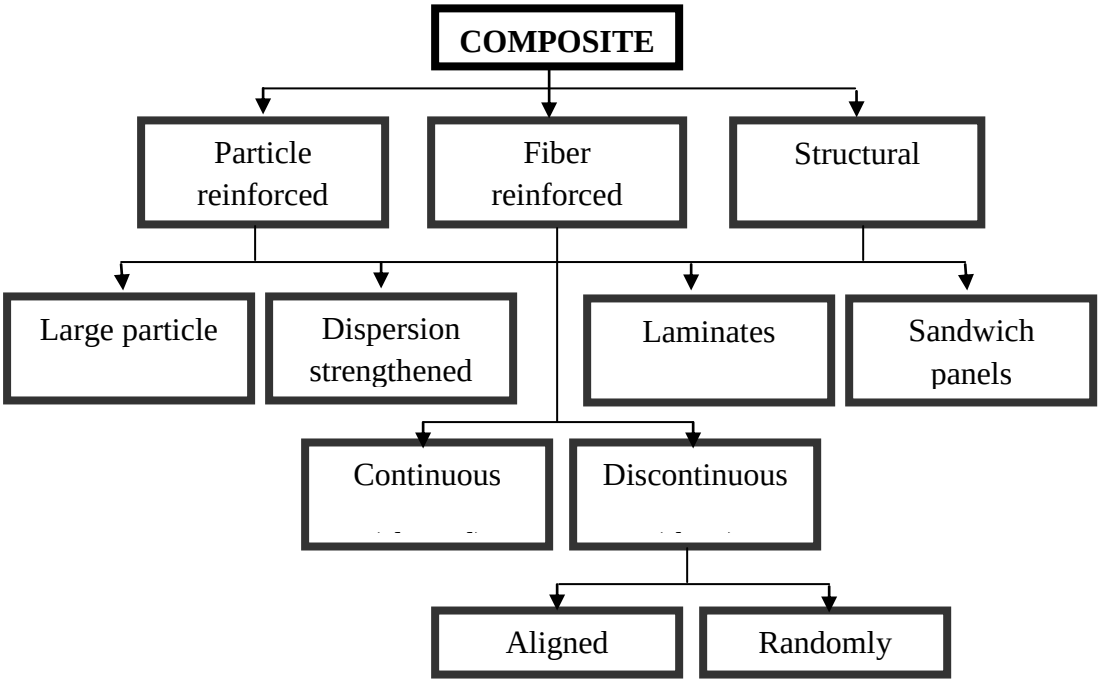


Figure 2.3a: A classification scheme for various composites types.

(Callister, 2003)

Polymer Matrix Composite

Polymer Matrix Composites (PMC) is also known as Fibre Reinforcement Polymers (FRP). The most common matrix materials for composites are polymeric materials. The reason for this is two-fold. First, in general the mechanical properties of polymers are inadequate for much structural purpose. In particular their strength and stiffness are low compared to the metals and ceramics. This meant that the reinforcement at least, initially did not have to have exceptional properties. Secondly, the processing of polymer matrix composite (PMCs) need not involve high pressures and does not required high temperatures as well as utilize the sample fabrication development. For these reasons polymer matrix composites developed rapidly and soon become accepted for the structural applications. Today glass-reinforced polymers are still by far the most popular composite materials in terms of volume advantages with the exception of concrete (Matthews *et al*., 1994).

There are also disadvantages in PMCs. The main disadvantages are their low maximum working temperatures, high coefficients of thermal expansion, dimensional instability, and sensitivity to radiation and moisture. Absorption of water from the environment may cause harmful effects which degrade the mechanical performance, including swelling, formation of internal stresses and lowering of the glass transition temperature (Matthews *et al*., 1994).

Matrix

There are three major components in composites; which are the matrix, filler reinforcement and the interface phase. The matrix phase of composite may be a metal, polymer or ceramic. In general, metals and polymers are used as matrix when some ductility is desirable (Matthews and Rawlings, 2002; Callister, 2006). Matrix should be good in their mechanical properties, good dimensional stability at the elevated temperature and good resistance to moisture and solvent. There are four major roles of matrix in the fiber reinforced composites. Principally it binds the fiber together in a composite material and separates the fiber due to its distribution in composite. It also importance to provide the required shape for the composites and to transfer stresses evenly between the fibers while carrying the load, as well as to protect the fibers against the physical damage and environment reaction (Callister, 2006; Kalpakjian, 2006). The matrix adds toughness to the composite while fibers have good tensile strength. The matrix gives compression strength to the composite. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mold cavity or onto the mold surface. The compounding of matrix and reinforcement were prepared by utilizing the internal mixer machine before proceed to the compression process (Stark *et al.*, 2002)

Polypropylene (PP)

The monomer propene (propylene), CH_2 = CH- CH_3, is related to ethane and like ethane, processes a double covalent bond that may split to allow addition polymerization to occur. Polypropylene is a highly crystalline olefinic polymer and the presence of CH_3 groups attached to the linear chain molecules gives polypropylene a greater strength and stiffness than HDPE although its density is similar to that of LDPE (John, 2003).

Polypropylene has a higher T_g and melting point than polyethylene. Service temperature is increased, but PP needs to be processed at higher temperatures. The melting temperatures are generally in the range of 210^{o}C to 250^{o}C (Harper, 2002).

It has a higher softening point than HDPE and can be used to make bottles that may be boiled or steam sterilized without softening. It has a good resistance to most forms of chemical attack and excellent fatigue. One very useful property of polypropylene is its excellent fatigue resistance and its ability to be bent repeatedly without fear of cracking. An example of how this property has been utilized by designers is the integrally molded hinge. Many small boxes and components such as car accelerator pedals are produced as one-piece moldings in polypropylene with an integrally molded hinge (John, 2003).

Reinforcement

Matthews and Rawlings (2002), claimed that the mechanical properties of composites are a function of shape, dimensions and orientations of filler reinforcement and also the quality interactions among them. Reinforcements can be both natural and man-made. Many materials are capable of reinforcing polymers. Some materials, such as the cellulose in wood are naturally occurring products. There have numerous advantages over the glass fibers including low cost, biodegradability, processing easiness and the absences of toxic byproducts (Lee *et al*., 2007).

Nature Fiber

Natural fibers can be subdivided into vegetable, animal, and mineral fibers. Mineral fibres are no longer or only in very small amounts applied in new technical developments because of their carcinogenic effect (Riedal, 1999).

Based on the Figure 2.4a, there are some properties of natural reinforcing fibers. For comparison purposes, the breaking length or tenacity and elongation at failure for both natural and synthetic fibers are presented in the Figure 2.4a, making clear that hemp, flax and ramie fibers can compete with some frequently used synthetic engineering fibers. The breaking length marks the length of the fiber fixed at one end, at which it breaks due to its own weight.

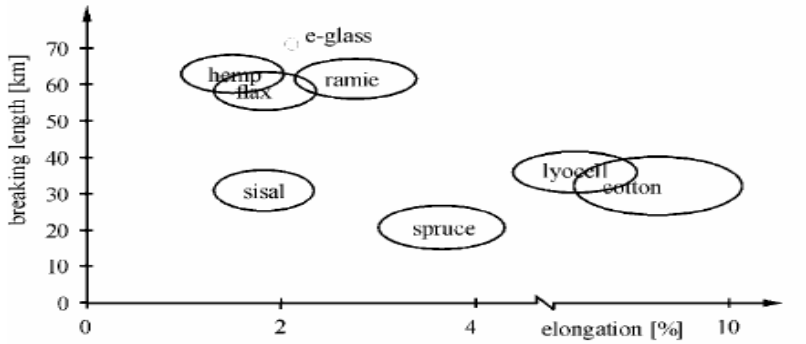


Figure 2.4a: Properties of different natural reinforcing fibers. (Riedal, 1999).

According to Figure 2.5a, the cellulose based fibers can be classified into wood fibers and non-wood fibers. In non-wood fibers, they can be further classified into straw, plant (such as bast, leaf and seeds) and grass. Both of the fiber categories are quite important in the composite industries as reinforcement.

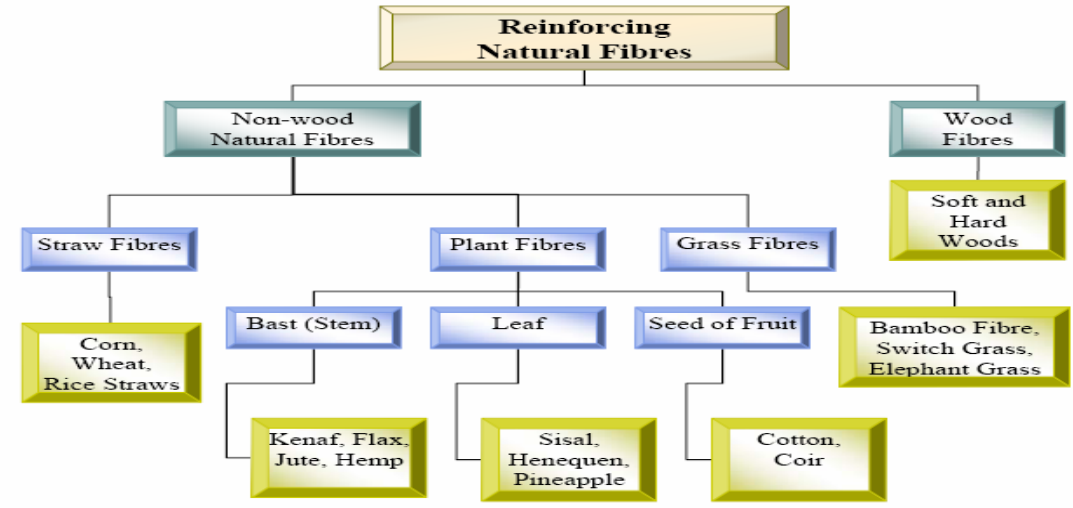


Figure 2.5a: Diagram for reinforcing natural fibers. (Felix *et al*., 1994).

Table 2.1a indicates the comparison between natural fiber and glass. Carbon dioxide neutrality of natural fibres is particularly attractive. Burning of substances derived from the fossil products (e.g. petroleum), releases enormous amounts of carbon dioxide into the atmosphere. This phenomenon is believed to be the root cause of the greenhouse effect that caused the critical world's climatic change (Riedal, 1999).

Table 2.1a: Comparison between natural and glass fibers. (Wambua *et al.*,2003)

	Natural fibre (NF)	Glass fibre
Density	Low	Twice that of natural fibres
Cost	Low	Low, but higher than NF
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	Wide
CO_2 neutral	Yes	No
Abrasion to machines	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not Biodegradable

Wood Polymer Composite

To understand wood plastic composites (WPCs), we must first understand the two major constituents. In WPCs, polymer matrix forms the continuous phase surrounding the wood component. These matrix polymers are typically low-cost commodity polymers that flow easily when heated, allowing considerable processing flexibility when wood is combined with them. These polymers tend to shrink and swell with temperature but absorb little moisture and can be effective barriers to moisture intrusion in well-designed composite.

As claimed by the Lee *et al*., 2007, wood itself contains polymers such as lignin, cellulose, and various hemi-celluloses but has very different properties from the synthetic polymers with which it is most often combined. Wood is less expensive, stiffer, and stronger than these synthetic polymers, making it a useful filler or reinforcement. Though wood does not shrink and swell much with temperature, it readily absorbs moisture, which alters its properties and dimensions and can lead to bio-degradation if not well protected (Lee *et al*.,2007).

In this chapter, the basic structure and properties of polymers and wood will be explored individually to lay a strong foundation of greater understanding for the composites made from them.

Polymers: Structure and Properties

The word polymer comes from the Greek poli, which means many, and meros, which means parts (Osswald and Menges, 1996). Polymers can be natural (e.g. cellulose, collagen, keratin) or synthetic (e.g. polypropylene, polyethylene) in origin. A polymer is called a plastic when it has other materials such as stabilizers, plasticizers, or other additives within it. Owing to the low thermal stability of wood flour, plastics

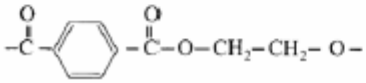
that can be processed at the temperatures lower than about 200 °C are usually used in WPCs (Stark *et.al*., 2002).

In North America, the great majority of WPCs use polyethylene as the matrix, though polypropylene, polyvinyl chloride, and others are also used (Morton *et al*., 2003).

Molecular Structure

Much of how the polymer performs is determined by its molecular structure. This structure is developed during the polymerization process where low molecular weight monomers are reacted to form long polymer chains. Table 2.2a shows the basic chemical structural units of several common polymers as well as their common abbreviations.

Table 2.2a: Structural units for selected polymers with approximate glass transition (Tg) and melting (Tm) temperatures. (Osswald and Menges, 2003)

Structural unit	Polymer	T_g (°C)	T_m (°C)
$-CH_2-CH_2-$	Polyethylene (PE)	−125	135
$-CH_2-CH(CH_3)-$	Polypropylene (PP)	−20	170
$-CH_2-CH(C_6H_5)-$	Polystyrene (PS)	100	—
$-CH_2-CH(Cl)-$	Polyvinyl chloride (PVC)	80	—
	Polyethylene-terephthalate (PET)	75	280

Properties

The properties of thermoplastic polymers are often highly dependent on the temperature at which they are measured and the speed at which they are tested. Generally speaking, when the temperature of a polymer melt is reduced below the melt temperature, the material behaves as a leathery solid. If a polymer is semicrystalline, a crystal structure develops. As the temperature is further reduced below its glass transition, the amorphous portions solidify and form a glassy, stiff and in some cases, brittle material (Osswald and Menges, 2003).

While polymers have solid-like properties such as elasticity and dimensional stability, they also have liquid-like characteristics such as flow over time that depends on temperature, stress, and pressure. This tendency of a polymer to behave as it were a combination of a viscous liquid and an elastic solid is generally referred to as visco elasticity (Carley, 1993). For example, most polymers have higher moduli when stress is rapidly applied versus when it is applied slowly. Also, some polymers tend to sag over time (i.e. creep) when bearing sustained loads, an important consideration in structural applications. Typical room temperature properties of

commonly used polymers in WPCs are summarized in the Table 2.3a. These values are provided to give a general indication of the polymer properties.

Though these polymers tend to have considerably lower mechanical performance than the so-called engineering plastics, the commodity plastics listed have reasonably good mechanical performance for many applications and low price. The polyethylenes are by far the most common polymers used in WPC fabrication in the North America. Polypropylene is common in other parts of the world. They absorb little moisture and act as effective moisture barriers. This is because PP are hydrophobics and we can assumed that the hydrophilic wood flour absorbed the water (Stark, 2001).This is important since moisture sorption in WPCs can negatively affect the performance of the composite.

Table 2.3a: Typical room temperature properties of common polymers.
(Osswald and Menges, 2003)

Polymer	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Water absorption in 24 h (%)	Coefficient of thermal expansion ($K^{-1} \times 10^6$)
LDPE	0.91-0.93	8-23	0.2-0.5	300-1000	<0.01	250
HDPE	0.94-0.96	18-35	0.7-1.4	100-1000	<0.01	200
PP	0.90-0.92	21-37	1.1-1.3	20-800	0.01-0.03	150
PVC	1.4-1.6	50-75	1.0-3.5	10-50	3-18	70-80

Wood: Structure and Properties

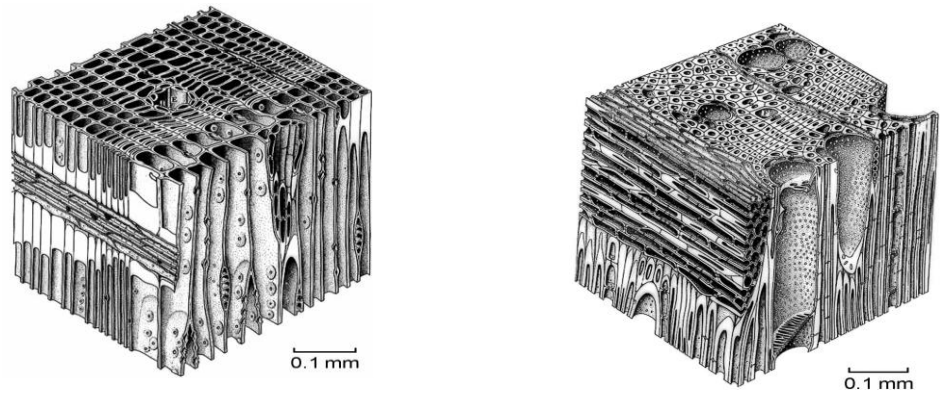
Wood contains natural polymers such as lignin, cellulose, and various hemicelluloses but has very different properties from the synthetic polymers with which it is most often combined. The efficient structure and anatomy make it a stiff, strong, tough, and lightweight material that can efficiently perform functions such as for the moisture transport that are critical for survival of the tree. Its excellent material performance and low cost have made it a useful structural material for millennia (Pentti, 2006).

From a polymer composite standpoint, wood is less expensive, stiffer, and stronger than many commodity synthetic polymers, making it a suitable candidate for filling or reinforcing them. However, moisture sorption characteristic that serves it well in nature can be problematic in a composite material application. Therefore, to effectively use wood as a filler or reinforcement in polymers, an understanding of its material behavior is important (Pentti, 2006). Discussion on the structure and anatomy of wood and its behavior as the fillers or reinforcements made from them will be reviewed

Wood Anatomy

As with the most natural materials, the anatomy of wood is more complex. Wood is porous, fibrous, and anisotropic. Wood is often broken down into two broad classes: softwoods and hardwoods, which are actually classified by botanical and anatomical features rather than wood hardness. Figures 2.6a(a) and 2.6a(b) are schematics of a

softwood and hardwood, showing the typical anatomies for each wood classification. Softwoods (or gymnosperms) include such species as pines, firs, cedars, and spruces; hardwoods (or angiosperms) include species such as the oaks, maples, and ashes (Rowell, 2005).



(a) (b)

Figure 2.6a: Schematic of a wood; (a) Softwood, (b) Hardwood (Pennti, 2006)

Wood is primarily composed of hollow, elongated, spindle-shaped cells (called tracheids or fibers) that are arranged parallel to each other along the trunk of the tree (Pentti 2006; Rowell, 2005). The lumen (hollow center of the fibers) can be completely or partially filled with deposits, such as resins or gums, or growths from neighboring cells called tyloses (Miller, 1999). These fibers are firmly cemented together and form the structural component of wood tissue. The length of wood fibers is highly variable but average about 1mm (1/25 in.) for hardwoods and 3-8mm (1/8 to 1/3 in.) for softwoods (Miller, 1999). Fiber diameters are typically 15-45 μm.

Properties

Owing to its commercial importance, the properties of common wood species are readily available. However, the properties of fibers and particles derived from the wood can be significantly different from the wood from which it is derived (Rowell, 2005). Methods for producing wood-derived fillers and fibers as well as the high temperatures and pressures often found during the composite processing that influence the attributes such as surface chemistry, density, and moisture content of the wood component in the final composite. For example, wood fibers produced by thermomechanical means lead to lignin-rich surfaces while those produced by the chemical means lead to carbohydrate-rich surfaces (Stokke and Gardner, 2003). These changes in surface chemistry can affect adhesion with polymers. Important properties of wood fillers and fibers derived from them are discussed below.

Moisture sorption

The major chemical constituents of the wood cell wall contain hydroxyl and other molecular groups that attract moisture. Absorbed moisture interferes with and reduces hydrogen bonding the between cell wall polymers and alters its mechanical

performance (Rowell, 2005). However, the interior of the crystalline cellulose is not accessible to moisture, which is important in maintaining rigidity in the tree even at high moisture contents (Tarkow, 1981).

The equilibrium moisture content of wood is affected by temperature and humidity and can vary as much as 3-4% depending on if the higher or lower humidity (i.e. wood exhibits a moisture sorption hysteresis). The moisture sorption of fillers and reinforcements derived from wood are affected by the methods used to produce them. However, wood flour is produced mechanically and its moisture sorption properties are similar to that of solid wood. Wood flour usually contains at least 4% moisture when delivered, which must be removed before or during the processing with thermoplastics. Even if dried, wood flour can still absorb moisture quickly. Depending on ambient conditions, wood flour can absorb several percent of moisture within hours. Moisture of up to about 30% can be adsorbed by the cell wall with a corresponding reversible increase in an apparent wood volume. Volume changes of the wood component due to moisture sorption, especially repeated moisture cycling, can lead to interfacial damage and matrix cracking (Peyer and Wolcott, 2000). As a result, many manufacturers of WPCs limits wood flour content to 50-65% by weight in the composite formulation and rely on the partial encapsulation of the wood by the polymer matrix to prevent major moisture sorption and subsequent negative effects to the fabricated composite.

Durability Properties

The surface of wood will undergo the photochemical degradation when exposed to UV radiation. This degradation takes place primarily in the lignin component and results in a characteristic of the color change (Rowell, 2005). Wood is degraded biologically because organisms will attack the celluloses and hemicelluloses in the cell wall and can hydrolyze them into digestible units using specific enzyme systems (Rowell, 2005).

Mechanical Properties

The mechanical properties of wood are quite anisotropic with the largest values are found parallel to the grain that corresponds to the direction of alignment of the wood fibers (Pentti, 2006). The strength of wood flour would be expected to be less than that of wood fiber at the same conditions since it is easier to separate the fibers than to break them. Also, the low aspect ratio of the flour and limited adhesion between the wood flour and plastic often lead to incomplete stress transfer that prevents optimal reinforcement of matrix. However, sufficient useful property improvements (e.g. increased modulus, heat deflection temperature, and dimensional stability with changes in temperature), ease of processing, and low cost make wood flour desirable as filler in composite application.

Manufacturing Technologies

In this section, it will cover the processing involved during manufacture the wood polymer composite. Wood flour and polymers are among the most important materials used in composite fabrication. Both materials have advantages as well as disadvantages, especially with respect to the durability, mechanical properties, swelling, thermal resistance and their potential availability. Firstly, discussion on the process involved in the material preparation (compounding) will be made. The compounding process offers the opportunity to combine these materials, although the compounding system must comply with special requirements in order to obtain

excellent properties. After that, it will cover the sample preparation (moulding) process. The technology that is used is Hot Compression Molding. This forming technique is the simultaneous application of the external pressure and temperature to enhance densification of the product made.

Compounding Technologies

Various systems are currently used for the compounding of WPCs. Typical machines come from the plastics industry and the extruder is the most important system used in the production of WPC. As stated by S. Y. Lee *et al*.,(2007), the compounding of this composite were prepared by an extruder. A compounding temperature of 190°C was used to prevent the thermal degradation of the wood flour (Starks *et al*., 2002). Sgriccia *et al*., (2008) and Sanadi *et al*., (1995), pointed out that most natural fibers have low degradation temperature i.e around 200°C in consideration with the melting point of polypropylene, the mixing process of wood polymer composite was handled at a range of 170°C to 190°C which proposed by Lee *et al*.,(2007). The compounding process will be undertaken by using the extruder machine in order to produce the compounded stage of wood flour polypropylene composite.

Moulding Technologies

The fabrication of composite samples was done by using the compression moulding process. The process is directly involved the controlled temperature in order to prevent fiber degradation. Based on Kalpakjian (2006) and Xun Xu *et al*., (2007), compression moulding process, a preshaped charge of fiber, premeasured volume of powder, or viscous mixture of liquid-resin or filler material is placed directly into a heated mold cavity that typically is around 200°C but can be much higher. Liu *et al.,* (2007) proposed that this fabrication technique is widely used to process the natural fiber reinforced composites.

Rules of Mixtures (ROM)

The mechanical properties of composites such as elastic modulus can be calculated by using the prediction theory of the Rules of Mixture (RoM) (Mirbagheri *et al*., 2007).

Elastic Modulus

Most of the fiber-reinforced composite are anisotropic, whereby these materials will have at least five or six independent elastic moduli (Callister, 2003). Thus, their properties are different at various directions. Often all the fibers are aligned in one direction to give an uniaxial oriented materials. Among the five or six moduli, two are considered as the most important moduli in most situations:

a) The longitudinal Young Modulus (YM) of composites, E_{cL} in which the load is applied parallel to the direction of the fibers.
b) The transverse Young Modulus (YM) of composites, E_{cT} in which the load is applied perpendicular to the direction of the fibers.

According to the Mirbagheri *et al.,* (2007), a tensile force tends to stretch the fiber and matrix to the same extent in the longitudinal direction. Therefore, on the assumption that fiber, matrix and composite will experience the equal strain, the longitudinal Young Modulus in tension can be calculated as:

$$E_{cL} = E_m V_m + E_f V_f \quad (2.1)$$

Where Em and Ef are the modulus of matrix and fibers, and Vm and Vf are the corresponding volume fractions of the two phases, respectively. In the transverse direction on the assumption that fiber, matrix and composite are experienced equal stresses. Thus, the Young Modulus in tension can be approximated as follows:

$$1 / E_{cL} = V_m / E_f + V_f / E_m \quad (2.2)$$

Density

The density of the composite material can be easily obtained by using this equation:

$$\rho_c = \rho_m V_m + \rho_f V_f \quad (2.3)$$

where Vf and Vm are the volume fraction of fiber and matrix, and ρ_c , ρ_f and ρ_m are the densities of composite, fiber and matrix respectively (Matthews and Rawlings, 2002).

Fiber Loading

As revealed by Bledzki *et al*., (2002), the mechanical properties of fiber-reinforced polymer composites such as creep resistance increased with the increasing of wood flour content. Increases in tensile strength, flexural strength and modulus of the wood flour composite found to correspond with the increases in the wood flour aspect ratio (Stark *et al*., 2002). In addition, Stark *et al*.,(2002), claimed that the decrease in strength may be due to the degradation of the interface between the Polypropylene (PP) and wood flour (WF), while the decreases in modulus could be a result of the decrease in modulus of the wood upon moisture absorption. This also supported by Bledzki *et al*., (2002) which proved that the creep modulus of wood fiber-PP composites increased around 165 % with the increasing of wood flour content at about 40 – 60 wt %. The suggested fraction of wood flour used in this study are varied in the range of 0 % to 50 % by weight (wt %).

As cited by Sgriccia *et al*., (2008) the variation in the experimental results may caused by the different of fiber and matrix loading composition and also due to the possibility of void present in the fabricated composites. Thus, by varying the fiber loading in the fabricated composite, it tends to exhibit the difference composition or formulation used in this research. The more fiber loading will also result in significant material cost savings as these natural fibers are much cheaper compared than the pure PP resin and far less expensive than the glass fiber. The increasing of fiber loading will decrease the usage of polymer matrix significantly.

Tensile and Flexural Properties

According to Callister (2006), the tensile strength TS (MPa or psi) gives a mean which the stress is at the maximum on the engineering stress-strain curve. The tensile strength and tensile modulus for PP are 20 to 35 Mpa and 0.7 to 1.2 Gpa as mentioned by the Kalpakjian. Therefore, the tensile of the fabricated composites is expected to be much higher due to match the properties to the projected application. The mechanical properties of wood fiber reinforced polymer composites are comparable with the properties of the conventional ones (e.g. glass fiber reinforcement) (Kocsis *et. al.,* 2005). As captured in the Figure 2.7a, the tensile strength and modulus increase simultaneously with the fiber content. However, this excellent result only will be gathered if consider the important of coupling agents. In

line with this research scope which eliminated the used of any coupling agent and additives, the tensile strength was believed to be decreased as pictured in Figure 2.7a.

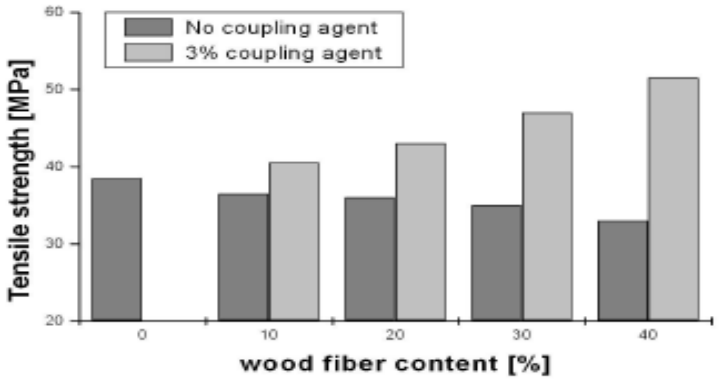


Figure 2.7a. The relationship between tensile strength and filler loading with and without coupling agent (Kocsis *et. al.,* 2005).

Mechanical properties important for the application of recycled polymers include not only tensile and flexural strength but also modulus and elongation (Yeh *et al*., 2009). Yeh *et al*., (2009) also claimed that the absence of the coupling agents, the tensile strength is 41.5 Mpa when virgin polymer is used, and this number is higher than that obtained with the use of the recycled ABS. The statement was proved in the Figure 2.8a which shows the tensile strength versus the amount of coupling agent for WPCs made with both kinds of ABS resins and with three different coupling agents; the wood content is 50%, and the percentage of coupling agent quoted is based on the amount of wood flour. This is not unexpected since the recycled polymer contains impurities, and its tensile strength is lower than that of the virgin polymer.

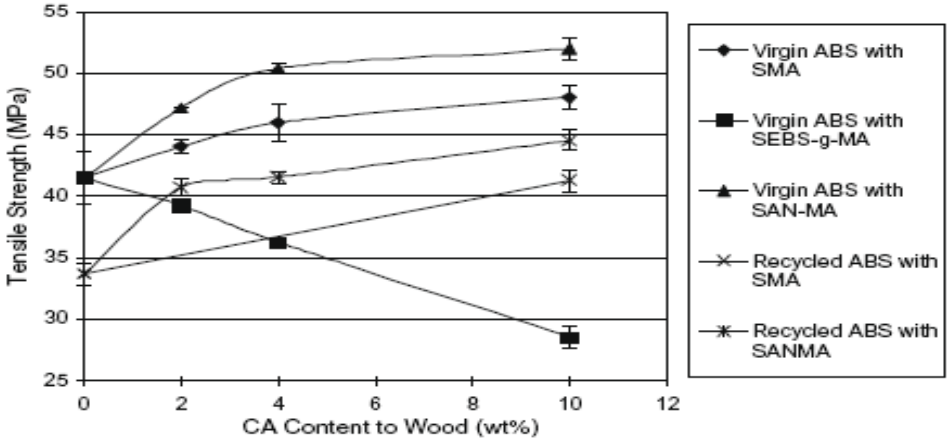
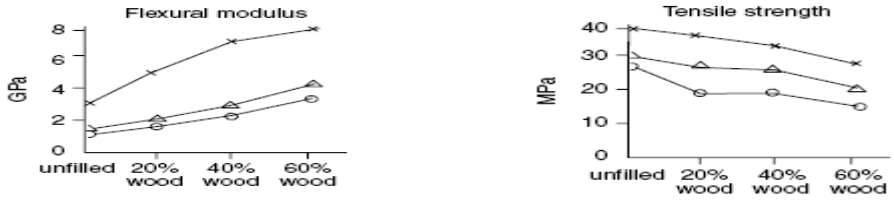


Figure 2.8a: Tensile strength of ABS–WPCs containing 50 wt.% wood as a function of amount of different coupling agents used (Yeh *et al*., 2009).

Adding the wood to plastics can increase the stiffness sufficiently for certain building applications. As shown in Figure 2.9a(a), addition of wood fiber can cause 2-3 fold increase in bending stiffness as compared to unfilled plastics. However, even with these improvements, most WPCs have moduli of elasticity less than half that of solid wood other effects of adding wood to plastics can be stated as follows. With increasing content of wood in WPCs product, the tensile strength decreases (Figure 2.9a(b), flexural strength increases (up to a maximum), melt index decreases and notched impact energy increases.



(a) (b)

Figure 2.9a: Effect of plastic type (polyethylene o, polypropylene Δ, polystyrene x) and wood loading levels on properties of wood plastic composites.

Impact Properties

The energy needed to cause dynamic failure of wood flour composites was measured using Izod impact tests. Stark *et al.,* (2002) reveled that the impact strength of the PP/wood flour composite were depending with the particle size and the type of impact testing i.e., whether the samples were notched or un-notched. The energy required for crack propagation was measured with a notched Izod specimen, and the energy required for crack initiation was measured with the un-notched Izod specimen. Crack propagation occurred at the wood flour/PP interface as a result of the poor interface between the hydrophilic wood flour and the hydrophobic PP. Consequently, composite made from larger wood flour particles had higher notched impact capacity (higher critical crack propagation energy) as a result of the increase in fracture surface area. Conversely, un-notched impact energy (minimum energy needed to initiate a crack) decreased with increasing particles sizes. The wood flour in the PP matrix provided stress concentrations, therefore providing sites for crack initiation. The larger the wood flour particle, the larger the stress concentration along the naturally weak interface of the hydrophilic wood flour and the hydrophobic PP, and the un-notched impact energy (Stark *et. al*., 2002).

In accordance to the research made by Yeh *et. al*., (2009), the reversed-notch Izod impact strength of virgin ABS based WPCs as a function of added coupling agent amount is shown in Figure 2.10a. it is evidence that the impact strength of these WPCs is low, and in the absence of any coupling agent, it is about 63 J/m. This is despite the fact that the notched Izod impact strength of ABS itself is more than 200 J/m. The impact strength of WPCs, however increases with coupling agent amount because it improving ductility. None the less, as in the case of ductility, large impact strength differences between the virgin and recycled polymers show up as small differences in the corresponding mechanical property of the wood-reinforced ABS (Yeh *et. al*., 2009).