

พอลิเมอร์ของพอลิ(เมทิลเมทาคริเลต-โค-อะคริลาไมด์)  
และพอลิ(เมทิลเมทาคริเลต-โค-2-เอทิลเฮกซิลอะคริเลต)ที่มีไม้ยางพาราประกอบ



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RUBBERWOOD-POLYMER COMPOSITES CONTAINING  
POLY(METHYL METHACRYLATE-CO-ACRYLAMIDE) AND POLY(METHYL  
METHACRYLATE-CO-2-ETHYLHEXYL ACRYLATE)



Miss Supuksorn Rungsri

วิทยาลัยวิศวกรรมบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

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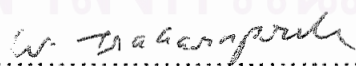
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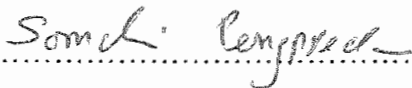
THESIS COMMITTEE

.....Chairman  
(Professor Patarapan Prasassarakich, Ph.D.)

.....Thesis Advisor  
(Associate Professor Amorn Petsom, Ph.D.)

.....Member  
(Associate Professor Sophon Roengsumran, Ph.D.)

.....Member  
(Associate Professor Wimonrat Trakarnpruk, Ph.D.)

.....Member  
(Assistant Professor Somchai Pengprecha, Ph.D.)

ศุภกตสรณ์ รุ่งศรี : พอลิเมอร์ของพอลิ(เมทิลเมทาคริเลต-โค-อะคริลาไมค์)และพอลิ(เมทิลเมทาคริเลต-โค-2-เอทิลเฮกซิลอะคริเลต)ที่มีไม้ยางพาราประกอบ

RUBBERWOOD-POLYMER COMPOSITES CONTAINING POLY(METHYL METHACRYLATE-CO-ACRYLAMIDE) AND POLY(METHYL METHACRYLATE-CO-2-ETHYLHEXYL ACRYLATE) อ. ที่ปรึกษา : รศ. ดร.อมร เพชรสม, 91 หน้า ISBN 974-13-1224-5

งานวิจัยนี้เป็นการเตรียมพอลิเมอร์ไม้ยางพาราประกอบ ด้วยวิธีการอิมเพกนชันภายใต้การลดความดัน โดยใช้มอนอเมอร์ผสม 2 ชนิด คือ เมทิลเมทาคริเลต/อะคริลาไมค์ (MMA/AM) และ เมทิลเมทาคริเลต/2-เอทิลเฮกซิลอะคริเลต (MMA/2-EHA) แล้วทำการศึกษา ภาวะที่เหมาะสมในกระบวนการเตรียมตัวอย่าง คือ เวลาที่ใช้ดึงอากาศออกจากช่องว่างในเซลล์ไม้ และเวลาที่ใช้แช่ขึ้นตัวอย่างในส่วนผสม รวมทั้งศึกษาผลของปริมาณเบนโซอิลเปอร์ออกไซด์ (BPO) ที่ใช้เป็นสารริเริ่ม และอัตราส่วนของมอนอเมอร์ผสมทั้ง 2 ชนิด ที่จะมีผลกระทบต่อสมบัติความเสถียรทางกายภาพและสมบัติทางกลของตัวอย่างที่เตรียมขึ้น แล้วนำมาเปรียบเทียบกับไม้ยางพาราธรรมชาติและไม้เนื้อแข็ง 2 ชนิดคือ ไม้สัก และ ไม้แดง

ผลการศึกษาพบว่า พารามิเตอร์การเตรียมที่เหมาะสมเป็นดังนี้ เวลาที่ใช้ในการดึงอากาศออกจากช่องว่างในเซลล์ไม้ 2 ชั่วโมง และเวลาที่ใช้ในการแช่ขึ้นตัวอย่าง 4 ชั่วโมง ปริมาณเบนโซอิลเปอร์ออกไซด์ ที่เหมาะสมคือ 2 เปอร์เซ็นต์ ไม้ที่มี MMA/AM จะให้ค่าโพลีเมอร์โลดคิงต่ำ อยู่ในช่วง 22.04-30.56 เปอร์เซ็นต์ แต่ MMA/2-EHA จะให้ค่าโพลีเมอร์โลดคิงสูงกว่าคืออยู่ในช่วง 56.68-60.00 เปอร์เซ็นต์ ค่าการดูดซับน้ำเพิ่มเมื่อเพิ่มอัตราส่วนของ AM และ 2-EHA สำหรับสมบัติเชิงกลของไม้ที่มี MMA/AM ค่ามอดูลัสยืดหยุ่น ความทนแรงบิดงอ และการทนต่อแรงอัด จะให้ค่าสูงสุดที่อัตราส่วน 80:20 คือ 7992.7 เมกกะปาสคาล 125.25 เมกกะปาสคาล และ 70.99 นิวตันต่อตารางมิลลิเมตร ตามลำดับ เมื่อใช้ MMA/2-EHA จะให้ค่ามอดูลัสยืดหยุ่น ความทนแรงบิดงอ และการทนต่อแรงอัด สูงสุดที่อัตราส่วน 20:80 20:80 และ 80:20 คือ 8699 เมกกะปาสคาล 130.24 เมกกะปาสคาล และ 77.36 นิวตันต่อตารางมิลลิเมตรตามลำดับ

หลักสูตร ปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่อนิสิต สุภัทสรณ์ รุ่งศรี  
 สาขาวิชา ปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่ออาจารย์ที่ปรึกษา อมร เพชรสม  
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KEY WORD : RUBBERWOOD / IMPREGNATION / COMPOSITE

SUPUKSORN RUNGSRI : RUBBERWOOD-POLYMER COMPOSITES CONTAINING POLY(METHYL METHACRYLATE-CO-ACRYLAMIDE) AND POLY(METHYL METHACRYLATE-CO-2-ETHYLHEXYL ACRYLATE). THESIS ADVISOR : ASSO. PROF. AMORN PETSOM, Ph.D. 94 pp. ISBN 974-13-1224-5

This research involved the preparation of rubberwood-polymer composites by impregnation under reducing pressure with 2 types of monomer mixtures, which were methyl methacrylate/acrylamide (MMA/AM) and methyl methacrylate/2-ethylhexyl acrylate (MMA/2-EHA). Impregnation conditions such as evacuating time and soaking time were studied. The effect of benzoyl peroxide used as an initiator and the ratio of monomers that would have some effects on the physical and mechanical properties of impregnated samples were investigated. The results were compared to those of untreated rubberwood and two hardwoods including teak and redwood.

The results showed that the optimum preparation parameters were 2 hours evacuating time, 4 hours soaking time, and 2% benzoyl peroxide. Impregnated samples containing MMA/AM gave low polymer loading at 22.04-30.56%, but MMA/2-EHA gave higher polymer loading at 56.68-60.00%. Water absorption was increased with increasing the ratio of AM and 2-EHA. For the mechanical properties of WPC with MMA/AM, the MOE, flexure stress, and compression were highest 80:20 ratio, which were 7992.7 MPa, 125.25 MPa, and 70.99 N/mm<sup>2</sup>, respectively. When MMA/2-EHA was used, the MOE, flexure stress, and compression were highest at 20:80, 20:80, and 80:20 ratios which were 8699 MPa, 130.24 MPa, and 77.36 N/mm<sup>2</sup>, respectively.

Program Petrochemistry and Polymer Science Student's signature SUPUKSORN RUNGSRI  
Field of study Petrochemistry and Polymer Science Advisor's signature [Signature]  
Academic year 2000 Co-advisor's signature -

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## LIST OF ABBREVIATIONS

WPC	-	wood-polymer composite
MMA	-	methyl methacrylate
2-EHA	-	2-ethylhexyl acrylate
AM	-	acrylamide
MMA/2-EHA	-	methyl methacrylate-co-2-ethylhexyl acrylate
MMA/AM	-	methyl methacrylate-co-acrylamide
BPO	-	benzoyl peroxide
ASE	-	ant swell efficiency
MOE	-	modulus of elasticity
SEM	-	Scanning Electron Microscopy
HLT	-	half-life time
% w/w	-	% weight by weight
S.D	-	standard deviation
MPa	-	Mega Pascal
hrs.	-	hours

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## CHAPTER 1

### INTRODUCTION

Wood materials have been used in the area of building, transportation, papermaking, textiles, and people's daily lives for a long time. It is difficult to suggest another material possessing such diverse properties and basic utilities. Although modern technology has been successful to substitute wood in many ways with light metals and plastics, it has never been possible to supercede the versatile utility of wood because wood is strong and stiff with respect to bulk density, cheap, durable, beautiful appearance, naturally available, and easy to work with. Though the versatility of wood is well recognized, there are some inherent characteristics that tend to restrict its versatile and potential applications. The most important drawback is the dimensional instability at variations of moisture contents, resulting in contractions and expansions in some anatomical directions of wood. Several approaches have been taken in the past in attempts to avoid such defects and to enhance the quality and enlarge the dimension of wood as a raw material, therefore wood composites or wood-based materials are developed.

Thailand has a lot of planted rubber trees (*Hevea brasiliensis*), a softwood species, that produce latex for tires, adhesives, and other products. Rubber plants have been a major economic plant in the southern and the eastern part, including some part of the north-eastern part. At present, Thailand has about 11.6 million rais rubber plantation area . The rubber plantations in Thailand tend to continue increasingly every year, particularly in the north-eastern part. [1]

Since the role and the important of rubber have increased, the government has encouraged the replantation of the uneconomic rubber trees with the high yielding varieties one. In the beginning, most of cut down rubber trees were burnt away. The rest, just a few proportion was used for fuel, which caused much of economic loss.

After the government has banned forestry concession in 1989, the lack of hardwood occurred. Therefore, Thailand must imported sawlogs and sawntimber from neighbouring countries. The import values increase, as a result, Thailand must loose the hard to gain foreign currency. Moreover, the import of wood from neighbouring countries has been uncertain in quantities, more difficult, and not enough for the demand of industry. Consequently, the rubber wood becomes more important and more demand.

As a result of forestry concession banning in 1989, the furniture manufacturers have lacked of materials from hard wood. Therefore, the manufacturers turned to develop the utilization of softwood which is rapid growth tree and non-reserved wood species, particularly rubber wood as a substituted material in large quantities. The manufacturers found that it can substitute the hard wood from natural forest in certain applications. Moreover, the export market prefers furniture made from rubber wood. Today, rubber wood products have been increasing in values and bring not lower than 10,000 million baht a year income to the country.

After the economic life of a rubber tree which was estimated to be 25 years, it produces too small amount of latex, and the tree must be replaced with a new one. The rubber trees can be used to substitute import sawlogs and sawntimber from the neighbouring countries. Around the country, there are uneconomic rubber trees which are cut down at about 200,000 rais for annum, equivalent to the volume of wood at

about 9.8 million cubicmeter. If all of the wood could be used, it would be very useful and make strong impact to the economy of the country. [2]

### **1.1 Objective of the research work**

1. To study the process for the preparation of the rubberwood-polymer composites prepared by impregnation of rubberwood with methyl methacrylate/acrylamide and methyl methacrylate/2-ethylhexyl acrylate

2. To study the physical and mechanical properties of rubberwood-polymer composites obtained under various conditions.

### **1.2 Scopes of the research work**

In this research work, the wood-polymer composites were prepared from methyl methacrylate/acrylamide, methyl methacrylate/2-ethylhexyl acrylate and rubberwood. Suitable monomer mixtures and various impregnation conditions such as initiator content, evacuating time, soaking time, and monomer ratios were investigated. The physical and mechanical properties of specimens such as polymer loading, density, water absorption, antismell efficiency, modulus of elasticity, flexure stress, compression parallel to grain, resistance to termite, and SEM of the microstructure of WPC would be studied.

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## CHAPTER 2

### THEORY AND LITERATURE REVIEW

Wood reserve of the world forest is diminishing very fast. All this has necessitated for the development of good quality wood, as well as the improvement of low grade wood either by genetic changes or by chemical treatments of the low grade wood to transform it to work as a substitute for the higher grades. One way to improve the physical and mechanical properties of low grade wood is by combination of wood and plastic. Plastic, unlike wood, has high resistance to water absorbability and is hydrophobic. It is also durable in various weather conditions and resistant to pest attack. The combination also makes the product more resistant to abrasion, biological attack, and weather conditions. The best way to make the combination is alloyed or reinforced with plastic, that is, monomer molecules are forced into the void spaces of wood and then they are polymerized among the fibers of wood and even the saturated cell walls.

#### 2.1 Formation and structure of wood

##### 2.1.1 Chemical composition of wood [3]

Wood consists of a cell wall made up of biopolymer and a cell cavity regarded as a void. Main components of the cell wall are cellulose (40-50%), hemicellulose (5-20%), and lignin (20-30%), and the rest is extractives (more than 2%).

Cellulose, the major constituent, comprises approximately 50% of wood substance by weight. It is a high-molecular weight linear polymer consisting of chains of bonded glucose monomers. During growth of the tree, the cellulose molecules are arranged into ordered strands called fibrils, which in turn are organized into the larger structural elements comprising the cell wall of wood fibers.

Lignin comprises 23-33% of softwoods, and 16-25% of hardwoods. It occurs in the wood throughout the cell wall, but is concentrated toward the outside of the cells and between cells. Lignin is a three-dimensional phenylpropane polymer.

The hemicelluloses are associated with cellulose and are polymers built from several different kinds of sugar monomers. The relative amounts of these sugars vary markedly with species. The hemicelluloses play an important role in fiber-to-fiber bonding in the papermaking process.

The extractives may range from roughly 5-30%, depending on such factors as species, growth conditions, and time of year the tree is cut. The extraneous materials are both organic and inorganic. The organic component contributes to such properties of wood as color, odor, taste, decay resistance, density, hygroscopicity, and flammability. Extractives include tannins and other polyphenolics, coloring matters, essential oils, fats. This component is termed extractive because it can be removed from wood by extraction with such solvents as water, alcohol, acetone, benzene, and ether.

The inorganic component of the extraneous material generally comprises 0.2-1.0% of the wood substance, although higher values are occasionally reported. Calcium, potassium, and magnesium are the more abundant element constituents.

The cell wall polymers (cellulose, hemicellulose, and lignin) have many hydroxyl group, functioning as sites with chemicals during the chemical modification of wood.

The cell cavity is filled with air, and the ratio of void volume varies with wood species or wood density, being 13-93%. The voids function as passage and reservoirs of chemicals during the chemical modification of wood.

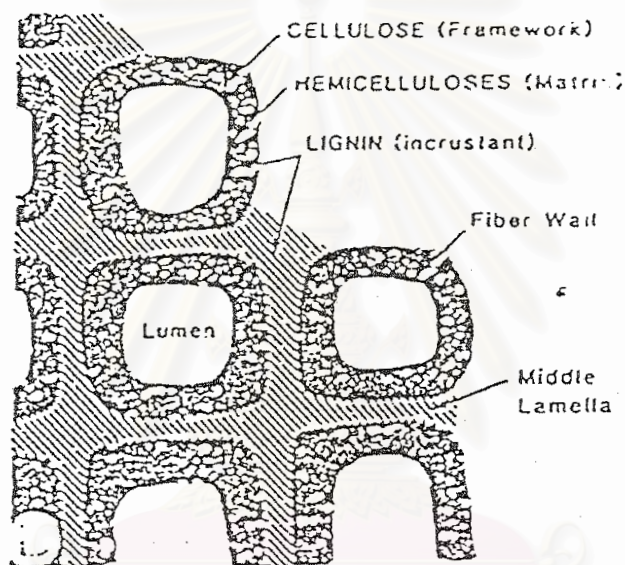


Figure 2.1 Schematic diagram showing the location of major constituents of wood

### 2.1.2 Anatomy of wood [4]

A cross section of a tree (Figure 2.2) shows the following well-defined features in succession from the outside to the center:

Bark, which may be divided into the outer, corky, dead part that varies greatly in thickness with different species and with age of trees, and the thin, inner living part.

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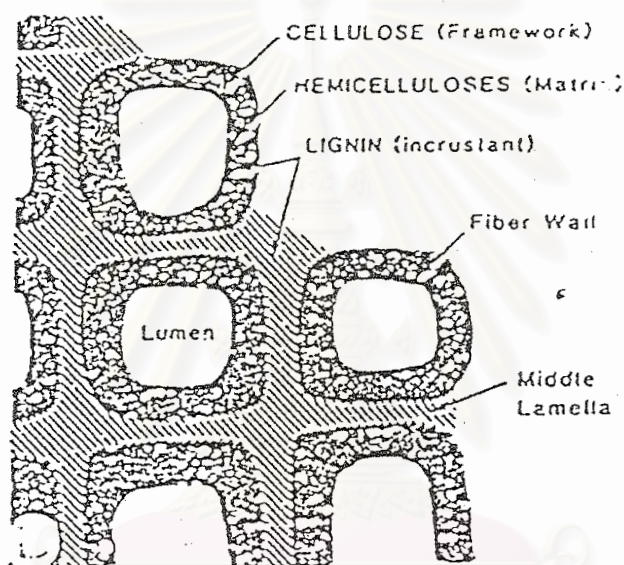


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Bark, which may be divided into the outer, corky, dead part that varies greatly in thickness with different species and with age of trees, and the thin, inner living part.

Wood, which in merchantable trees of most species is clearly differentiated into sapwood and heartwood.

Pit, the small core of tissue located at the center of tree stems, branches, and twigs.

Sapwood is located between the bark and the heartwood. The sapwood contains both living and dead cells and functions primarily in the storage of food and the mechanical transport of water or sap. The sapwood layer may vary in thickness and in the number of growth rings contained in it. Sapwood commonly ranges from 1-1/2 to 2 inches in radial thickness. Sapwood of all species, however, is not resistant to decay.

In general, heartwood consists of inactive cells that do not function in either water conduction or food storage. The transition from sapwood to heartwood, however, is accompanied by an increase in the extractive content. Heartwood extractives in some species such as black locust, western redcedar, and redwood make the wood resistant to fungi or insect attack.

The age of a tree at any cross section of the trunk may be determined by counting the growth rings. The inner part of the growth ring formed first in the growing season is called earlywood and the outer part formed later in the growing season, latewood. Earlywood is characterized by cells having relatively large cavities and thin walls. Latewood cells have smaller cavities and thicker walls. [5]

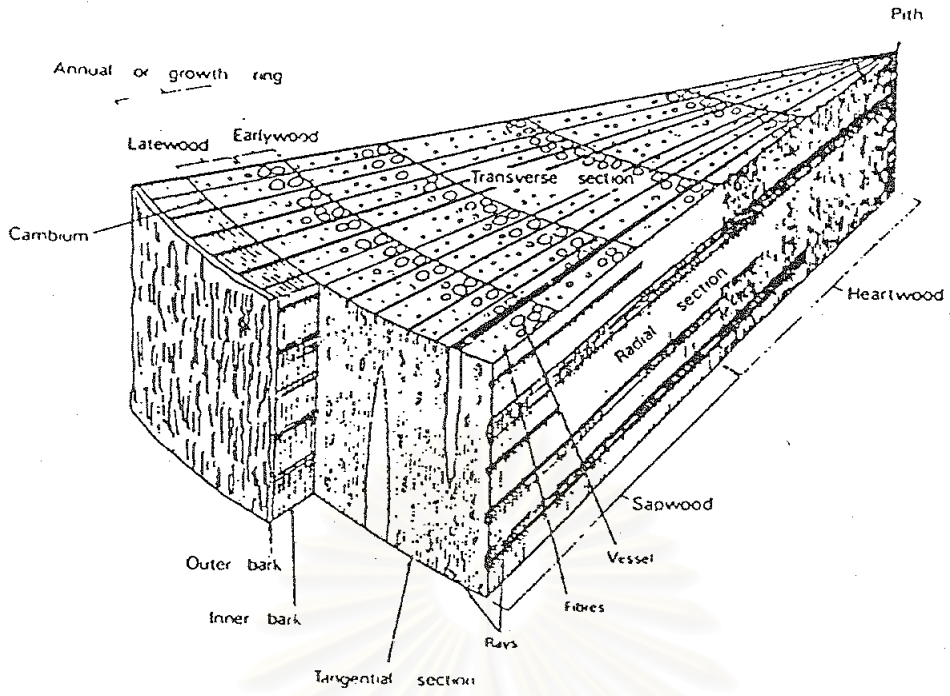


Figure 2.2 Diagrammatic wedge section of wood

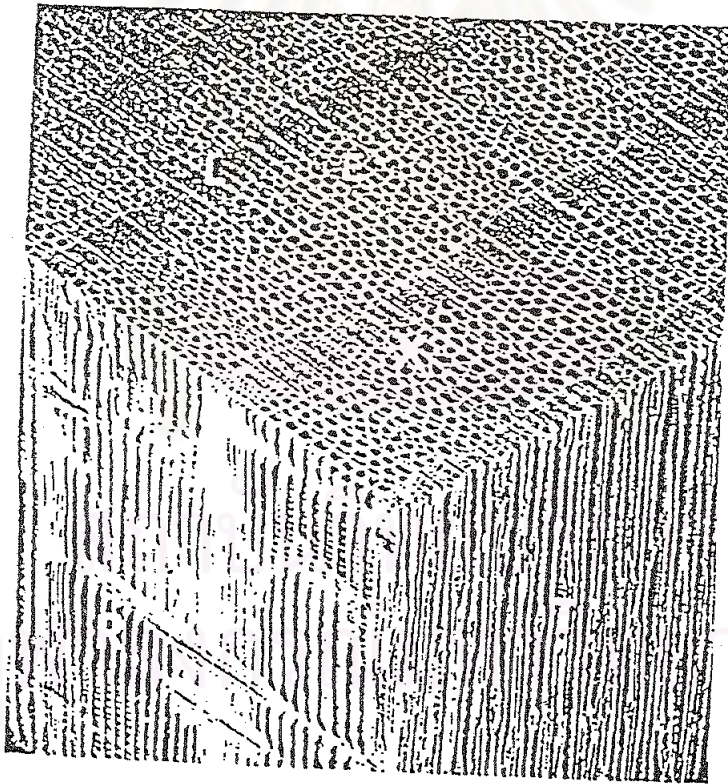


Figure 2.3 Cross-section view (X) of wood. (E) earlywood, (L) latewood, (R) radial surface, and (T) tangential surface

### 2.1.3 Softwood and hardwood

Woods are divided into hardwoods and softwoods. Hardwood trees (angiosperms) generally have broad leaves, are deciduous in the temperate regions of the world, and contain a special cell called a vessel element. Softwood trees (conifers or gymnosperms) are cone-bearing, generally have scalelike or needlelike leaves, are not deciduous, and do not contain vessel elements. The terms hardwood and softwood have no direct application to the hardness or softness of the wood.

#### 2.1.3.1 Softwood [6]

Figure 2.4 illustrates the cell structure of white pine, an example of a softwood. The three planes, TT, RR, and TG, represent the same three planes described for hardwoods. The rectangular units that make up the transverse surface (TT) are sections through long vertical cells called tracheids (TR). Because softwoods do not contain vessel cells, the tracheids serve the dual function of transporting sap vertically and giving strength to the wood. The wood rays (WR) store and distribute sap horizontally. Fusiform wood rays (FWR) are rays with horizontal resin ducts (HRD) at their centers. The large hole in the center of the end grain is a vertical resin duct (VRD). Some softwoods, such as cedar and the true fir, do not have resin ducts. The annual ring (AR) is often divided into an earlywood zone (S) composed of thin-walled cells and a latewood zone (SM) composed of thicker walled cells. The symbol SP indicates a simple pit, an unthickened portion of the cell wall through which sap passes from ray parenchyma cells to tracheids or vice versa. Bordered pits (BP) have their margins overhung by the surrounding cell walls but still function as a passageway for sap to move from one cell to another.

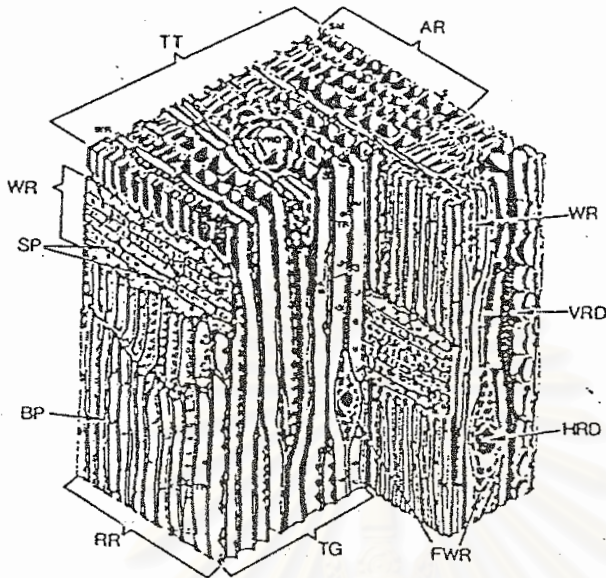


Figure 2.4 Cellular structure of a softwood. (AR) annual rings, (BP) border pit, (FWR) fusiform wood rays, (HRD) horizontal resin duct, (RR) edge grain, (S) earlywood, (SM) latewood, (SP) simple pits, (TG) flat grain, (TR) trachied, (TT) end grain, (VRD) vertical resin duct, and (WR) wood rays

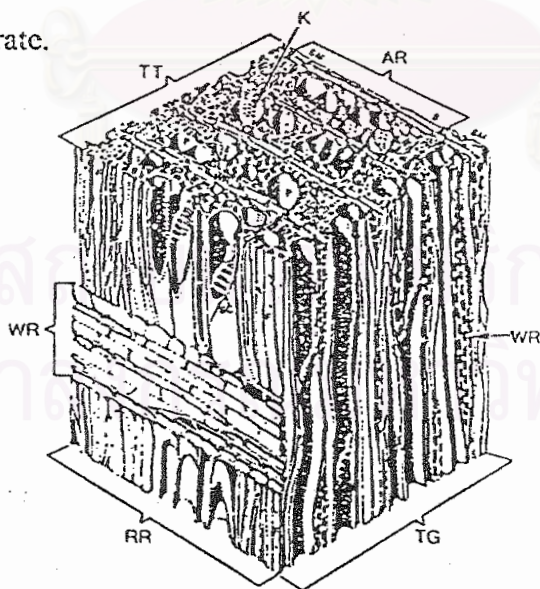
### 2.1.3.2 Hardwood

Figure 2.5 illustrates the cellular structure of a yellow Poplar, an example of a hardwood. The horizontal plane (TT) of the block corresponds to a minute portion of the top surface of a stump or end surface of a log, called the transverse surface. The vertical plane (RR) corresponds to a surface cut parallel to the radius and parallel to the wood rays (WR), called the radial surface. The vertical plane (TG) corresponds to a surface cut a right angles to the radius and the wood rays (WR) and is called the tangential surface. In temperate climates, trees often produce distinct growth layers called growth rings or annual rings (AR). These rings vary in width according to environmental conditions.



Where there is visible contrast within a single growth ring, the first formed layer is called earlywood (S) and the remainder latewood (SM). Hardwoods have specialized structures called vessels for conducting sap upward. Vessels are a series of relatively large cells with open ends set one on top of the other and continuing as open passage for long distances. In most hardwoods the ends of the individual cells are entirely open, whereas in others they are separated by a grating, as indicated at SC. On the end grain, vessels appear as holes and are termed pores (P). Most of the smaller cells on the end grain are wood fibers (F), which are the strength-giving elements of hardwoods. They usually have small cavities and relatively thick walls. Thin places or pits (K) in the walls of the wood fibers and vessels allow sap to pass from one cavity to another. Wood rays (WR) are strips of short horizontal cells that extend in a radial direction. Their function is food storage and lateral conduction.

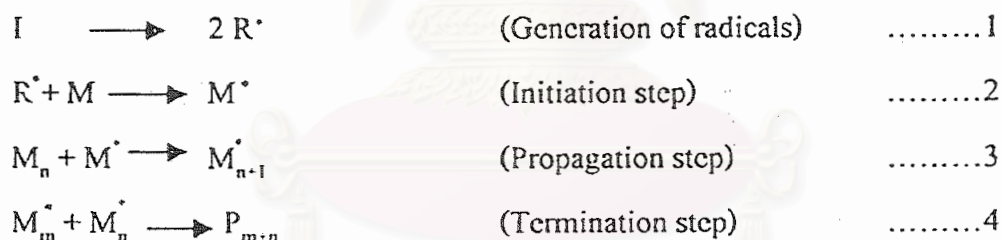
All cells in wood, including vessel cells, fibers, and ray cells, are cemented together by a thin layer, the middle lamella. This thin, intercellular layer is composed of lignin and carbohydrate.



**Figure 2.5** Cellular structure of a hardwood. (AR) annual rings, (F) fiber, (K) pits, (P) pores, (RR) edge grain, (S) earlywood, (SM) latewood, (TG) flat grain, (TT) end grain, and (WR) wood rays

## 2.2 Wood-polymer composites [7]

Quite a number of studies have been carried out to improve the quality of timber of low-grade wood normally used for fuel. The improvement is done through the formation wood-polymer composites using suitable monomers which are impregnated into the wood bulk. Wood-polymer composite (WPC) is a wood impregnated with polymers in order to strengthen the properties of the natural wood. WPC is a composite made by impregnating wood with a polymerizable monomer (mainly vinyl-monomer) or prepolymer, and polymerizing them to a solid. The initiation of polymerization is done by generation of free radicals with irradiation of radiant ray or heating with catalyst (initiator). Formulation of polymerization by free range radicals is (Equations 1-4):



Where I is initiator,  $R^{\bullet}$  is free radical from initiator, M is monomer,  $M^{\bullet}$  is growing radical, P is polymer, and m, n are the degree of polymerization. The impregnated monomers are polymerized within the wood cells by exposure to radiation or heat-catalyst. The polymers form a netlike texture created from the impregnated monomers within the wood cellulose. The wood sample preserves its aesthetic look but its physicochemical properties are greatly enhanced. These materials, called wood-polymer composites (WPC), are suitably used in place of high-quality timber of teak, mahogany, oak, etc.

## 2.3 Impregnation Process

Prior to the impregnation stage, water and air must be removed from the wood to provide a space for the treating fluid. Water is removed by a drying process in an oven. After drying, wood is placed in a pressure vessel and a vacuum process is applied to remove air. After the wood is placed in a vessel, air is first evacuated from the vessel and wood cell lumen in evacuation chamber, and next the monomers, with or without catalyst, are introduced into the vessel under the vacuum. After atmospheric pressure is regained, the impregnated wood is taken out of the monomer liquid. In the case of low permeable wood, air pressure is applied to the liquid prior to taking out the wood. The pressure and time of evacuation and compression depend upon the wood species used. Next, to polymerize the monomer, the impregnated wood is heated or irradiated. The amount of monomer loading depends upon the monomer composition, the period of impregnation, and the structure and species of wood.

### 2.3.1 Thermal polymerization [8]

This method requires a catalyst to be incorporated into the impregnation solution in order to thermally create free-radicals that initiate the entire polymerization process to ultimately prepare wood-polymer composites. The mechanism of production of the composite is once the free radicals are generated out of the impregnating bulk monomer with the help of the added catalyst.

Among many different vinyl monomers used during the 1970s and 1980s, methyl methacrylate (MMA) appears to be the preferred monomer for the thermal (catalyst-heat) process. However, all types of vinyl monomers can be thermally polymerized in the presence of a catalyst, such as a peroxide.

### 2.3.2 Peroxide initiators [9]

Peroxide initiators (peroxides) are chemical substances that possess one or more oxygen-oxygen bonds and have the general structures ROOR' or ROOH where R and R' are inorganic or organic group. Under the influence of heat or light, the weak oxygen-oxygen bond cleaves to produce a pair of free radicals (radicals) as follows:



#### 2.3.2.1 Applications of Peroxides

Because they produce highly reactive radicals, peroxides are used in many commercial radical reactions. In the various polymer industries they are used as radical sources for polymerizing and copolymerizing vinyl monomers, curing unsaturated polyester resins and elastomers, crosslinking olefin polymers and copolymers, grafting vinyl monomers onto polymers, modifying polypropylene, and compatibilizing polymer blends and alloys.

The effectiveness of a peroxide in a given application depends on its thermal decomposition rate and the efficiency of the radicals generated in carrying out the desired reaction. The first step in selecting a peroxide for use in an application is to choose a peroxide having half-life characteristics best suited to the temperature and time of the application. In applications, for example, requiring a reaction time of  $\sim 5$  hr, the peroxide selected should have a 1-hr half-life time (HLT) from  $\sim 5^\circ\text{C}$  below to  $\sim 15^\circ\text{C}$  above the temperature of the application.

The second step in picking a peroxide for use in an application is to choose a peroxide that is the most effective in the application. In applications such as vinyl monomer polymerization and copolymerization to give unbranched (linear) polymer, peroxide should be selected that generate alkyl radicals having lower energies than methyl radicals.

#### 2.4 Monomers for wood-polymer composites

Representative types of monomers and prepolymers have been used to make WPC during the past 30 years, and some of them are listed in Table 2.1. The most widely used industrial monomers, such as methyl methacrylate (MMA) and styrene (St) are the cheapest WPC base chemicals and are easy for engineering. The lower the viscosity of monomer is the easier the impregnation becomes. To a monomer solution, soluble, light-stable dyes can be added to color the final WPC. The color emphasizes the grain structure of the particular species. The third component, chemicals such as a crosslinker, an absorbent of ultraviolet rays, a flame retarder, and preservatives can be added to improve the properties of WPC and the organic solvent for swelling the cell wall to control the impregnation area of monomers. In the catalyst-heat process, the catalyst can be added in the amount of 0.2-2% weight percent to monomers.

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**Table 2.1** Some monomers and prepolymers used for making WPC

---

Methyl methacrylate (MMA)
Di-, tri-methacrylate
Glycidyl methacrylate (GMA)
Hydroxyethyl methacrylate (HEMA)
Hydroxyethyl acrylate (HEA)
Acrylonitrile (AN)
Styrene (St)
Unsaturated polyester (UP)

---

In this study, three types of monomers were used to copolymerize including methyl methacrylate (MMA), acrylamide (AM), and 2-ethylhexyl acrylate. The details of each monomer when they are polymers and mechanisms of copolymerization of MMA/AM and MMA/2-EHA are expressed below:

#### 2.4.1 Polymethyl methacrylate

Polymethyl methacrylate is an atactic, amorphous, thermoplastic material, and has a high transparency. Resins are used to produce cast sheets or other shapes. It is produced by free radical polymerization of methyl methacrylate using the usual peroxide or azo initiators, or by thermal or photochemical initiation.

Polymethyl methacrylate have excellent optical, thermal, electrical, and chemical properties. They have poor resistance to ketones and chlorinated solvents. Outstanding weatherability makes them an excellent choice for exterior applications.

### 2.4.2 Polyacrylamide

Polyacrylamides are readily water soluble over a broad range of conditions. Initially designed for applications involving separation and clarification of liquid-solid phases, the polymers are now used for binding, thickening, and film formation.

Acrylamide,  $\text{CH}_2=\text{CHCONH}_2$ , is unique in its ability to produce very high molecular weight linear polymers which exhibit strong hydrogen bonding. Solid polyacrylamide is a hard glassy polymer and has good thermal stability when compared with other polyelectrolytes; however, degradation occurs upon prolonged heating at elevated temperatures.

Acrylamide copolymerizes easily with many vinyl monomers. Reaction rates and molecular weights tend to be lower than those obtained in acrylamide homopolymerization, and the acrylamide content of copolymers is often higher than that of the feed. Some of the most widely used comonomers are weak acids, acrylic and methacrylic acids.

### 2.4.3 Poly2-ethylhexyl acrylate

Acrylic esters are represented by the generic formula  $\text{CH}_2=\text{CH-COOR}$ . The nature of the R group determines the properties of each ester and the polymers it forms. 2-Ethylhexyl acrylate,  $\text{CH}_2=\text{CH-COOCH}_2(\text{C}_2\text{H}_5)\text{CH}(\text{CH}_2)_3\text{CH}_3$ , is in this class.

To a large extent, the properties of acrylic ester polymers depend on the nature of alcohol radical and the molecular weight of the polymer. Poly(methyl acrylate) has little or no tackiness at room temperature; it is a tough, rubbery, and moderately hard polymer. Poly(ethyl acrylate) is more rubberlike, considerably softer

and more extensible; whereas Poly(butyl acrylate) is softer still and much tackier. In the *n*-alkyl acrylate series, the softness decreases through *n*-octyl acrylate. Unless subjected to extreme conditions, acrylic polymers are durable and degrade slowly.

The combination of durability and versatility, and the ability to tailor molecules relatively easily to specific applications, have made acrylic polymers prime candidates for numerous and diverse applications. The ease of handling acrylic ester monomers and the ease of copolymerizing the softer acrylates with the harder methacrylates, styrene, acrylonitrile, and vinyl acetate allow products to be manufactured which range from soft rubbers to hard nonfilm-forming polymers.

## 2.5 Mechanisms of copolymerization of MMA/AM and MMA/2-EHA

Both two types of copolymers were produced via heat-catalyst polymerization which benzoyl peroxide was used as initiator or catalyst to generate free radicals.

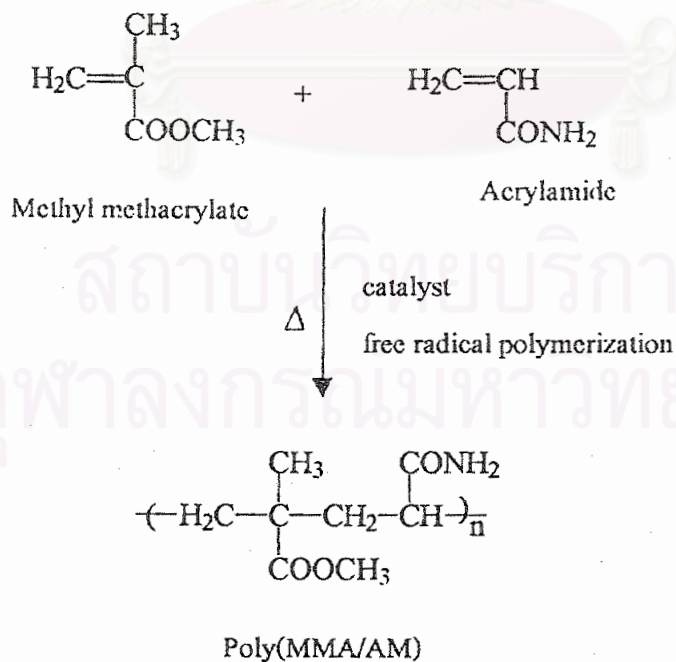
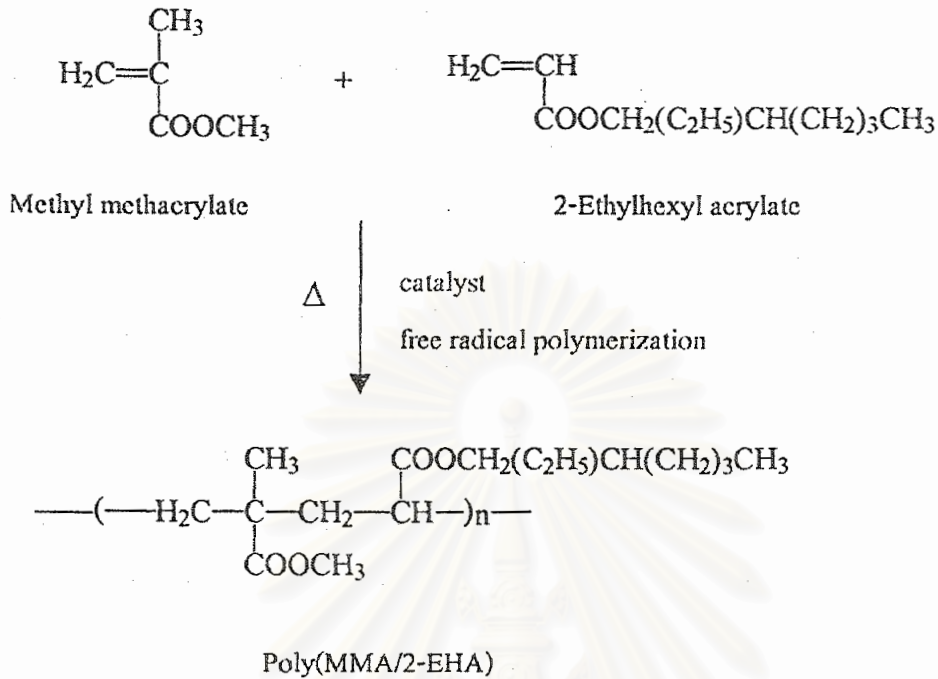


Figure 2.6 Copolymerization mechanism of poly(methyl methacrylate/acrylamide)





**Figure 2.7** Copolymerization mechanism of poly(methyl methacrylate/2-ethylhexyl acrylate)

## 2.6 Properties of WPC [10]

WPC has changed and improved in many areas, compared with the untreated wood. Its notable advantages are an increase in the static strength, surface hardness, abrasion resistance, dimensional stability, fine-finishing, and attractive grain.

### 2.6.1 Mechanical properties

The most pronounced mechanical properties improved by WPC are compression strength and hardness. These properties are improved 4 to 5 times that of untreated samples, if attentive selection is made to the wood species and monomers.

The properties of WPC are improved 1.5 to 2 times for tension, bending, and impact strengths, compared to the untreated wood.

### **2.6.2 Dimensional stability**

Polymers generally reduce swelling and shrinkage from water, and promote dimensional stability. WPC especially, shows more resistance to water absorption because of the resistance of water vapor-diffusion from polymer in the cell lumen. Otherwise, antismelling efficiency (ASE) depends on the volume-effect after WPC treatment, i.e., bulking effect. The larger the volume of bulking is, the more has dimensional stability. Regarding ASE of WPC with polymer loading, it shows the maximum value between from 30 to 70% of polymer loading.

### **2.6.3 Biological deterioration of wood [11]**

The biological causes of wood deterioration, during its processing or when it is in service, are of great concern to wood technologists. The economic importance of wood losses due to attack by decay fungi, wood-boring insects and marine borers demands that consideration be given to methods of conserving wood through a better understanding of these biological agencies.

#### **2.6.3.1 Deterioration by microorganisms**

All microorganisms have four fundamental requirements for growth: air, water, a favorable temperature, and food. Exclusion of any one of its requirements will prevent a microorganism from growing. It follows that the most effective and permanent way of preventing biodeterioration is to deprive the target organism of at least one of its requirements.

The most important deterioration of wood by microorganisms is caused by fungi. Fungi are primitive plants which lack chlorophyll and, therefore, cannot manufacture their own food like green plants do, but must rely instead on the products of the photosynthesis of green plants to provide them with already-manufactured organic substances. Two classes of fungi, called the Ascomycetes and Fungi Imperfecti, usually live on low-molecular weight carbohydrates, such as sugars and starch, stored in wood, without attacking the wood cell wall substance and, therefore, cause discolorations without affecting wood strength. Most deterioration of wood by microorganisms can be prevented, or at least minimized, by proper design, construction, and choice of materials.

#### **2.6.3.2 Biodeterioration by insects**

The primary insects that are capable of initiating attack in dry wood in service are termites, powderpost beetles, carpenter ants, and carpenter bees. Of these, the termites cause by far the greatest structural damage. In this research, only dry wood termites are studied.

Dry wood termites cause significant damage in aboveground portions of structures, principally attics, in warm climates. They are a more severe problem in subtropical and tropical regions around the world. Under the caste system in the termite society, only the workers are involved in chewing tunnels and chambers in the wood. The worker termites are creamy-white, soft-bodied, maggot-like, wingless, sterile, blind and usually eyeless insects.

Termites actually break down wood cell wall substances as their food source, but they need help with the process. Protozoan symbionts, living in the gut of each termite, enzymatically break down the wood, which the termite has mechanically pulverized, into soluble substances which the termite can use as food.

## 2.6 Literature review

Impregnation of wood with suitable chemicals that can react with cell wall components has been extensively reported to improve dimensional stability towards moisture and some mechanical properties. Impregnation of wood to produce wood-polymer composite (WPC) which can be carried out with suitable chemicals, such as liquid-borne preservative or monomers that can be polymerized in situ either by using a catalyst-heat technique or irradiation method are summarized as follows:

Deubzer, B. and Brunner, E. [12] studied impregnated wood containing a polymer which is produced in the wood matrix from the polymerization of a monomer and/or prepolymer having aliphatic multiple bonds and crosslinked organopolysiloxanes. The polymer impregnated wood is prepared by impregnating the wood with a mixture containing a monomer and/or prepolymer containing aliphatic multiple bonds which is capable of free radical polymerization and a crosslinkable organopolysiloxane and thereafter the monomer and/or prepolymer is polymerized and the organopolysiloxane is crosslinked in the wood.

Igarashi, I., Ota, H., and Mizoguchi, Y. [13] investigated a curing composition and a method for impregnating wood using the curing composition obtained by reacting an alkylene oxide adduct of a hydrocarbon polyol and (meth)acrylic acid providing easily cures on irradiation using active energy rays, such as ultraviolet rays,

or heating impregnation of wood by this method with those ingredients which have low volatility and easy to handle, exhibits less problem with offensive odor upon cutting or polishing after curing. Moreover, it shows excellent properties of wood and high reactivity. Therefore, it is capable of improving moisture resistance and dimensional stability to wood.

Rozman, H.D., Kumar, R.N., Abusamah, A. and Saad, M.J. [14] prepared wood-polymer composites (WPC) of rubberwood (*Hevea brasiliensis*) by impregnating the wood with glycidyl methacrylate (GMA), combinations of glycidyl methacrylate and diallyl phthalate (GMA-DAP), or diallyl phthalate (DAP) alone. Polymerization was carried out by catalyst-heat treatment. The results showed that WPC based on GMA exhibited about five times greater dimensional stability (results of antishrink efficiency after six days of soaking) than those based on DAP alone. Flexural [Modulus of Elasticity (MOE), Modulus of Rupture (MOR), and toughness], compressive, and impact properties for all the samples tested are improved, especially for those with higher chemical loading.

Khan, M.A. and Idriss, K.M. [15] prepared wood plastic composites (WPC) with low density wood simul under Co-60 gamma radiation using acrylamide (AM), butyl methacrylate (BMA), and styrene (ST) as the bulk monomers at different compositions with methanol used as swelling agent. The effects of additives, e.g., polyfunctional monomers and oligomers, used by 1% v/v or w/v, on the polymer loading and tensile strength of the composites are investigated. Polyfunctional monomers are *N*-vinyl pyrrolidone (NVP), tripropylene glycol diacrylate (TPGDA), and trimethylol propane triacrylate (TMPTA). Oligomer additives are urethane acrylate (UA), epoxy acrylate (EA), and polyester acrylate (PEA). When polymer loading (PL) was increased, the tensile strength (TS) of the composite was enhanced.

Incorporation of a small amount (1% v/v or w/v) of coadditives like sulfuric acid ( $H^+$ ), lithium nitrate ( $Li^+$ ), copper sulfate ( $Cu^{2+}$ ), and urea (U) into the impregnation solutions containing the additives has significantly influenced the PL and TS values of the WPC.

Solpan, D. and Guven, O. [16] impregnated oak and cedar with acrylonitrile (AN), methyl methacrylate (MMA), and mixtures of allyl glycidyl ether (AGE) with AN and MMA to conserve and consolidate the wood. After impregnation, these monomer mixtures were polymerized by gamma irradiation. The dimensional stability and the resistance against the biodegradation of the wood (oak and cedar)/(co)polymer composites were determined. The water uptake capacity of the wood/(co)polymer composites is up to 50% lower than that of the original wood, for P(AGE/ MMA) and P(AGE/AN) copolymers. They are also lower than those of PAN and PMMA. Artificial raining does not change the structure of wood/(co)polymer composites and no biodegradation are observed.

Witt, A.E. [17] studied a wear-resistance wood product such as a wood flooring material having a white or bleached appearance which is obtained by impregnating wood with a solution of a polymeric resin containing whitening agent in a polymerizable monomer such as methyl methacrylate. After uniform distribution of the monomer solution throughout the wood was obtained, the monomer was polymerized and the whitening agent precipitated in situ in the polymer matrix as a material having a refractive index sufficiently different from the refractive index of said matrix to impart a bleached or white appearance to wood flooring material.

Rungvichaniwat, C. [18] impregnated para rubberwood with epoxy resin mixture under reduced pressure. The effect of diluent type, diluent content, hardener content related to the viscosity and curing time of prepolymer mixture were studied. Impregnation conditions such as soaking times, evacuating time, evacuating pressure were varied to various conditions in the preparation process. Para rubberwood-epoxy resins composites gave significant lower water absorption, higher antishrink efficiency than natural para rubberwood. Modulus of elasticity, flexure stress, compression parallel to grain were improved and specific gravity was higher than natural para rubberwood.

Kasamchainanta, B. [19] prepared durianwood-polyester resins composites by impregnation under reduced pressure. The effect of diluent content, initiator types, initiator content that related to viscosity and cure time of prepolymer mixtures were studied. Impregnation parameters such as evacuating time, soaking time were varied to various conditions in preparation process. Impregnated samples obtained from the optimum conditions gave significant lower water absorption, higher antishrink efficiency, higher density than natural durainwood. Modulus of elasticity, flexure stress, compression parallel to grain were also improved.

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## CHAPTER 3

### EXPERIMENTAL PROCEDURES

#### 3.1 Materials

##### 3.1.1 Rubberwood

The small pieces of rubberwood were obtained from Bangkok Shuttle Industry Co.,Ltd. Dimension of them are 2.5×2.5×0.5 cm (width×length×thickness), 1×3×1 cm (width×length×thickness), 2.5×10×0.5 cm (width×length×thickness), and 2×2×1 cm (width×length×thickness).

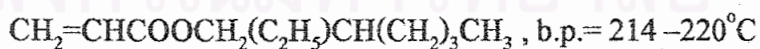
##### 3.1.2 Monomers and initiator

###### 3.1.2.1 Monomers

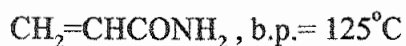
Methyl methacrylate (MMA)



2-Ethylhexyl acrylate (2-EHA)



Acrylamide (AM)

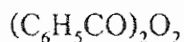


All of these monomers were supplied by Siam Chemical Industry Co., Ltd.



### 3.1.2.2 Initiator

Benzoyl peroxide (BPO)



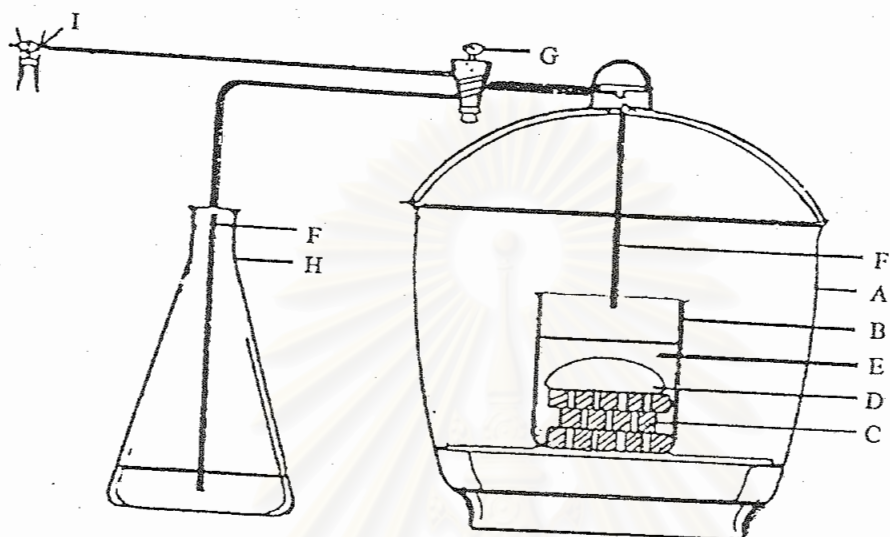
It was supplied by Siam chemical Industry Co.,Ltd. Its trade name is NYPER BO, 50% white paste.

### 3.2 Apparatus and equipments

1. Vacuum Chamber : modified from 8 inches diameters desiccator
2. Vacuum pump : SUPER POWER 1/2HP, Type SM-1/2 R
3. Vernier : MITUTOYO, Japan
4. Sandpaper : WATER PROOF NO.80
5. Universal testing machine : HOUNDFIELD 1000N, England
6. Electric saw : PEHAKA, England
7. Vacuum oven : MUTTER, Germany
8. Weighting : METTLER, England
9. Desiccator

Apparatus for vacuum impregnation is shown in Figure 3.1

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- A- Vacuum desiccator
- B- Plastic or glass treatment beaker
- C- Test wood blocks
- D- Glass or suitable weight
- E- Treating solution
- F- Polyethylene tubing
- G- Three-way stopcock
- H- Flask containing treating solution
- I- Line to source of vacuum

Figure 3.1 Apparatus for vacuum impregnation

### 3.3 Experimental Procedures

#### 3.3.1 Preparation of rubberwood-polymer composites

##### 3.3.1.1 Preparation of wood specimen

The wood specimens used for testing were prepared from clear, defect-free rubberwood. Test specimens were sawed in the dimension in 3.1.1 and oven dried at 105°C for 24 hours prior to treatment.

##### 3.3.1.2 Determination of moisture content and density of specimens

Each specimen was weighed and then reweighed after drying over night in oven at 105°C. Moisture content was calculated as the percentage of moisture based on the weight of wood.

$$\text{Moisture Content (\%)} = \frac{W_o - W_1}{W_1} \times 100$$

where  $W_o$  = weight before drying

$W_1$  = weight after drying

The volume of each sample was determined. Density was calculated using equation below.

$$\text{Density} = W_1 / V \text{ (g/cm}^3\text{)}$$

where  $V$  = volume of specimen after drying

### 3.3.1.3 Preparation of impregnation monomer mixtures

The monomer mixtures were prepared with methyl methacrylate/2-ethylhexyl acrylate (MMA/2-EHA) and methyl methacrylate/acrylamide (MMA/AM) which were mixed by weight in the ratio shown in Table 3.1 and used appropriate content of benzoyl peroxide to catalyze the polymerization reactions.

**Table 3.1** Monomer solutions for rubberwood-polymer composites

Ratio of (% w/w)	
MMA:2-EHA	MMA:AM
100:0	100:0
80:20	80:20
70:30	70:30
60:40	60:40
50:50	50:50
40:60	40:60
30:70	30:70
20:80	20:80
0:100	0:100

### **3.3.1.4 Preparation of rubberwood-polymer composites**

All wood specimens for impregnation or testing were first oven dried at 105°C for 24 hours and placed in a vacuum chamber at room temperature for desired time. The monomer mixture and benzoyl peroxide as a catalyst, were introduced into the vacuum chamber until the wood samples were covered. After the desired soaking time was reached, the vacuum was released. Finally, wood samples were removed and wiped out to remove excess monomer mixture from wood surface (polymerization was usually begun during the impregnation process). The wood samples were wrapped in aluminium foil and thermally polymerized at 90°C for 24 hours. The apparatus for vacuum impregnation was shown in Figure 3.1.

### **3.3.2 The study of appropriate conditions for rubberwood-polymer composites**

#### **3.3.2.1 Effect of evacuating time on properties**

Rubberwood-polymer composites were prepared from monomer mixtures containing materials as follows: 100% by wt. MMA, 2% initiator content. The impregnation parameters were as follows: 4 hours soaking time, and various evacuating times at 0.5, 1, 2 hours.

#### **3.3.2.2 Effect of soaking time on properties**

Rubberwood-polymer composites were prepared from monomer mixtures containing materials as follows: 100% by wt. MMA, 2% initiator content. The impregnation parameters were as follows: 2 hours evacuating time, and different soaking time at 2, 4, 6 hours.

### 3.3.3 Study of factors effecting in the preparation of rubberwood-polymer composites

#### 3.3.3.1 Initiator contents

Benzoyl peroxide content as 1%, 2%, and 3% by weight was added to the monomer mixture. The impregnation parameters were as follows: evacuating time was 2 hours, soaking time was 4 hours.

#### 3.3.3.2 Monomer ratio

Two types of monomer mixtures, MMA/2-EHA and MMA/AM, were prepared in the same ratio as follows: 100:0, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80, and 0:100 % w/w. The initiator at 2% content was added into each monomer mixture.

The impregnation parameters were as follows: evacuating time was 2 hours, soaking time was 4 hours.

### 3.3.4 Characterization of rubberwood-polymer composites

#### 3.3.4.1 Physical properties

##### 3.3.4.1.1 Polymer loading

Before impregnation, the specimens were dried in an oven at 105°C overnight and weighed. After impregnation, the wood composites specimens were obtained. They were weighed again and the polymer loading were calculated as follows:

$$\text{Polymer loading (\%)} = \frac{W_t - W_0}{W_0} \times 100$$

where  $W_t$  = weight of treated wood  
 $W_0$  = weight of untreated wood (oven dry)

#### 3.3.4.1.2 Density of specimens

The weight and dimension or volume of wood composite specimens were determined. Density was calculated using the following formula:

$$\text{Density} = W / V \text{ (g/cm}^3\text{)}$$

where  $W$  = weight of specimens  
 $V$  = volume of specimens

#### 3.3.4.1.3 Water Absorption (WA)

All samples, both control and treated, were immersed in water at room temperature for 7 days. After that period, the samples were wiped of excess water and weighed. The water absorption was determined on the basis of oven-dry measurements.

$$\text{Water absorption (\%)} = \frac{[W_1 - W_0]}{W_0} \times 100$$

where  $W_1$  = weight of specimens after water soaking  
 $W_0$  = weight of specimens before water soaking

#### 3.3.4.1.4 Antiswell efficiency (ASE)

The dimensional stability of impregnated wood samples, cut from longitudinally, was evaluated with antiswell efficiency (ASE) values using changes in tangential, radial, and longitudinal dimensions after 7 days of soaking in water. Dimensional stability was expressed as ASE and determined as follows:

$$\text{Volumetric swelling coefficient (S)} = \frac{V_1 - V_0}{V_0}$$

where  $V_1$  = wood volume after water soaking  
 $V_0$  = wood volume before water soaking

$$\text{Volumetric antiswelling efficiency (ASE)} = \frac{S_1 - S_0}{S_0} \times 100$$

where  $S_1$  = volumetric swelling coefficient for untreated wood  
 $S_0$  = volumetric swelling coefficient for treated wood

#### 3.3.4.2 Mechanical Properties

Mechanical properties are measured as follows:

##### 3.3.4.2.1 Flexure stress and modulus of elasticity (MOE)

[ASTM D3043-87]

This method is applicable to material that is uniform with respect to elastic and strength properties. Total deflection, and modulus of elasticity were calculated from it. A conventional flexure testing machine is used to apply and measure a load at mid-span of a small flexure specimen; and the resulting deflection at

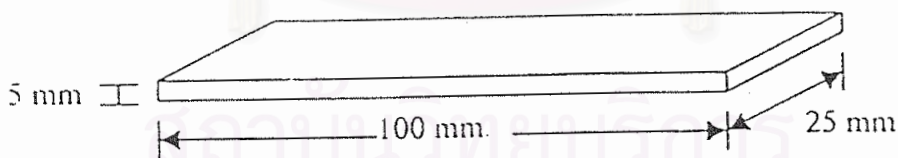


mid span is measured or recorded. The test proceeds at a constant rate of head motion until either sufficient deflection data in the elastic range have been gathered or until specimen failure occurs.

$$\text{Modulus of elasticity (MOE)} = \frac{L^3 \Delta W}{4bd^3 \Delta S}$$

- where
- $L$  = the span between the centers of supports (m)
  - $\Delta W$  = the increment in load (N)
  - $b$  = the mean width (tangential direction) of the sample (m)
  - $d$  = the mean thickness (radial direction) of the sample (m)
  - $\Delta S$  = the increment in deflection (m)

The dimension of testing specimen is shown in Figure 3.2



**Figure 3.2** Dimension of specimen for flexure stress and MOE testing

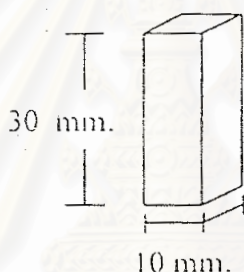
#### 3.3.4.2.2 Compression parallel to grain [ASTM D3501]

Compression strength parallel to grain was measured by a universal testing machine using samples of 10x10x30 mm for rubberwood as control and treated wood. The compression parallel to grain was calculated from the formula below:

$$\text{Compression parallel to grain} = \frac{P_{\max}}{a \times b}$$

where  $P_{\max}$  = the maximum load (N)  
 $a, b$  = the cross section dimension of the test piece (mm)

The dimension of testing specimen is shown in Figure 3.3 as follows:



**Figure 3.3** Dimension of a specimen for compression parallel to grain testing

#### 3.3.4.2 Evaluation of WPC specimens for the resistance to termites

[ASTM D3345]

Prepare five replicate blocks for each variable under test. Use five untreated blocks as controls for each separate study. Wash all containers rinsed in the surface antiseptic solution, and dry. Place the test block in the bottom of the container with one edge of the block up against the side of the containers. Add 200 g of oven-dry sand and add sufficient distilled water. Calculate the water content as follows:

$$\% \text{ water to add} = \% \text{ saturation} - 7.0$$

Calculate the percent saturation as follows:

$$\% \text{ saturation} = (\text{weight of water} / \text{oven dry weight of sand}) \times 100$$

After addition of water, the container was left overnight. The termites was weighed at  $1 \pm 0.05$  g and added into prepared container with loosely closed tops. The container was maintained at room temperature for 4 weeks. After 4 weeks, disassembled the containers, removed and cleaned the blocks. The test blocks were examined visually at each block using the following rating system:

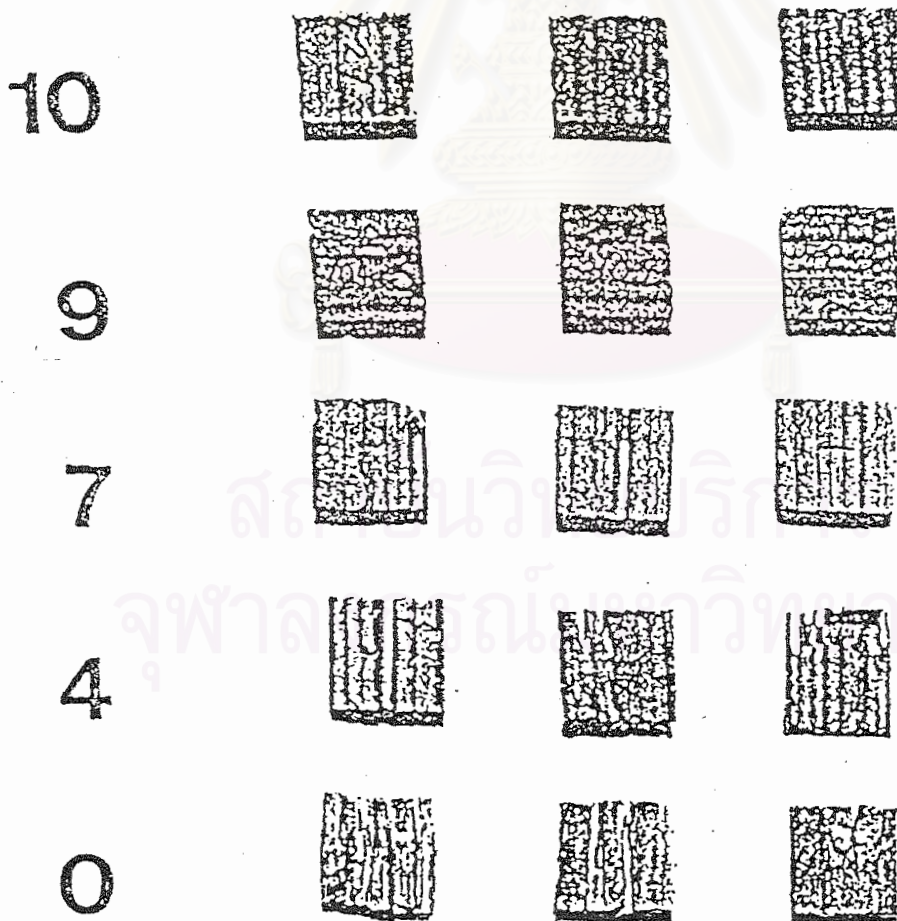


Figure 3.4 Typical ratings of termite attack on test blocks

10 = Sound, surface nibbles permitted

9 = Light attack

7 = Moderate attack, penetration

4 = Heavy

0 = Failures

#### 3.3.4.4 Microstructure of WPC specimens

Scanning electron microscopy was used to examine microstructure of the specimens. The extent to which the polymer filled the cells and the empty wood cells was investigated.



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## CHAPTER 4

### RESULT AND DISCUSSION

Wood could provide better service in some applications if it was harder and more dimensionally suitable. In this study, rubberwood-polymer composites made by impregnation of rubberwood with different monomer mixtures and impregnation parameters were investigated. Dimensional stability and mechanical properties of specimens were tested and compared to those of natural rubberwood and other hardwoods.

#### 4.1 Characteristic of natural rubberwood materials

The natural rubberwood was characterized for their mechanical properties before study. The results of characterization (average value from two separated determinations with five specimens each) are presented in Table 4.1.

**Table 4.1** Characteristic of natural rubberwood materials

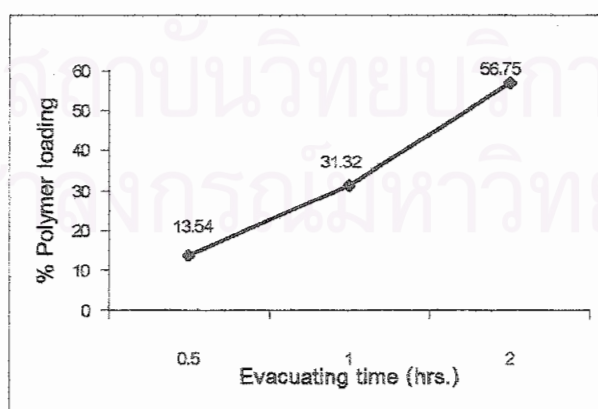
Properties	Rubberwood
Density ( $\text{g/cm}^3$ )	0.63
MOE (MPa)	6596
Flexure stress (MPa)	93.0
Compression ( $\text{N/mm}^2$ )	40.08

#### 4.2 Effect of evacuating times on the polymer loading of impregnated samples

As the evacuating time increased, the void space free of air was correspondingly increased. So the more amount of monomer mixtures penetrated into the wood cells was obtained. In this study, the evacuating time was varied from 0.5, 1, and 2 hours. The monomer mixtures containing 100% MMA, and 2% initiator content were used. Results of these experiments are shown in Table 4.2 and illustrated in Figure 4.1.

**Table 4.2** Polymer loading of rubberwood-MMA composites prepared from various evacuating times

Physical properties	Evacuating times (hrs.)		
	0.5	1	2
Polymer loading (%)	13.54	31.32	56.75



**Figure 4.1** Effect of evacuating time on polymer loading of impregnated samples

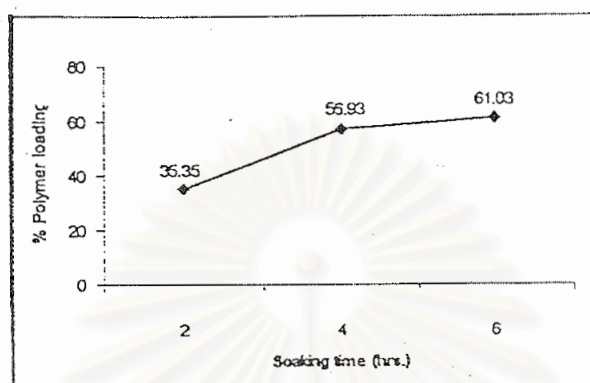
In this experiment, the results showed that 2 hours evacuating time samples gave the highest polymer loading values. The long evacuating time gave the ability to evacuate air from the wood cells. Thus, it was allowed for more opportunity of monomer mixture to penetrate into empty wood cells and retained in there. Therefore, the evacuating time of 2 hours was used to study for the next experiment. These results agreed well with those reported in the literature [18]. According to the literature [18], it was pointed out that at 2 and 3 hours evacuating time, the rubberwood samples gave higher polymer loading than 1 hour evacuating time. Moreover, MOE and flexure stress of treated samples at 2 and 3 hours showed significant improvement at about 55-100% when compared to untreated sample. From all of results, it was found that at 2 hours evacuating time the rubberwood polymer composite gave the best dimensional stability and mechanical properties.

#### 4.3 Effect of soaking times on the polymer loading of impregnated samples

Soaking time is the periods used to soak the specimens in the polymerizable mixtures. The soaking times were varied from 2, 4, and 6 hours. Another impregnation parameter was fixed at 2 hours evacuating times. The monomer mixtures containing 100% MMA, and 2% initiator content were used. Properties of the impregnated samples are shown in Table 4.3 and illustrated in Figure 4.2.

**Table 4.3** Polymer loading of rubberwood-MMA composites prepared from various soaking times

Physical properties	Soaking times (hrs.)		
	2	4	6
Polymer loading (%)	35.35	56.93	61.03



**Figure 4.2** Effect of soaking time on polymer loading of impregnated samples

The results from Figure 4.2 showed that the polymer loading was increased accordingly with soaking time. However, there was no significant different of polymer loading between specimens obtained after 4 hours soaking time. Thereby, soaking time at 4 hours is enough period that treated samples showed high polymer loading and it was used to study for other effects.

#### 4.4 Effect of initiator content on the properties of impregnated samples

It was expected that, the higher concentration of initiator, the better the properties of impregnated wood. The initiator contents were varied from 1, 2, and 3 percents. Parameters of impregnation process were as follows: 2 hours evacuating time and 4 hours soaking time. Impregnated samples gave the properties which presented in Table 4.4, Figures 4.3, and 4.4.



**Table 4.4** Properties of rubberwood-MMA composites prepared from various initiator contents

Physical properties	Initiator content (%)		
	1	2	3
Polymer loading (%)	45.82	55.77	56.76
Density (g/cm <sup>3</sup> )	0.96	0.98	0.98
Water adsorption (%)	37.99	36.81	33.97
Antiswell efficiency	35.40	42.22	42.21

Mechanical properties	Initiator content (%)		
	1	2	3
Polymer loading (%)	40.76	45.42	48.54
MOE (MPa)	8472.7	9610.9	9612.3
Flexure stress (MPa)	142.35	168.35	176.22

Polymer loading (%)	36.72	43.43	49.13
Compression (N/mm <sup>2</sup> )	86.09	93.46	97.89

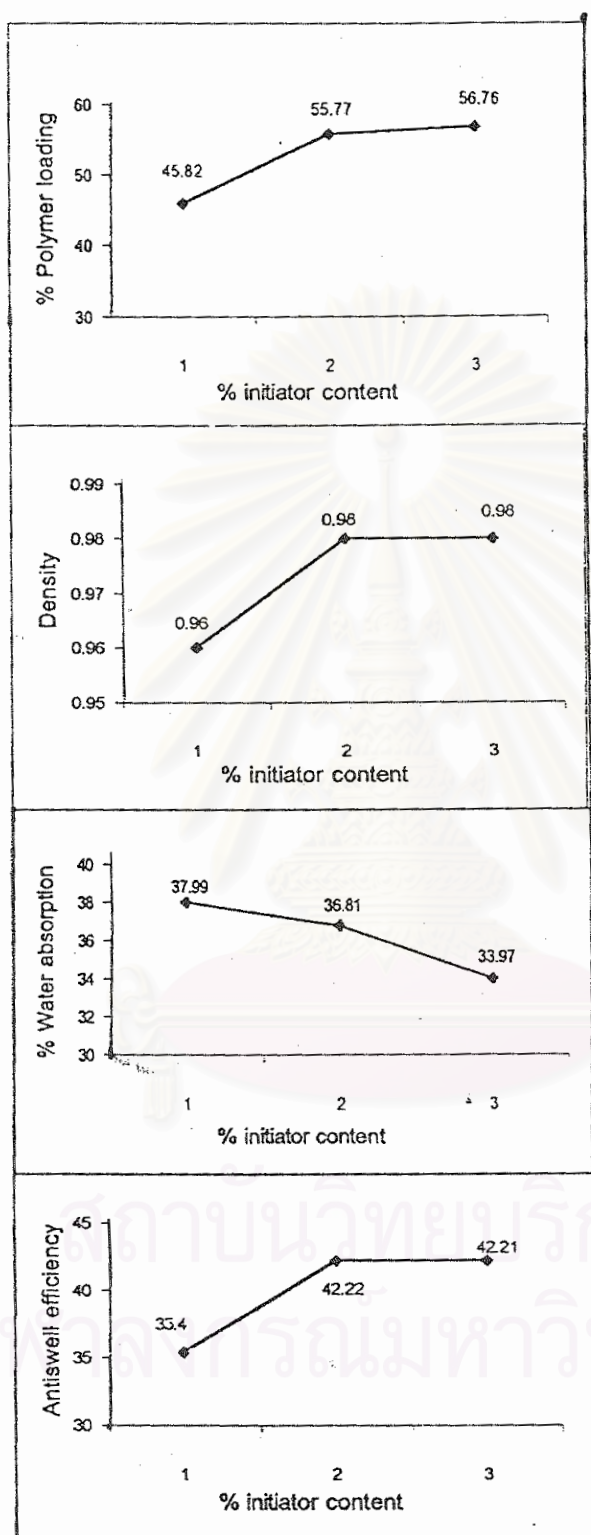
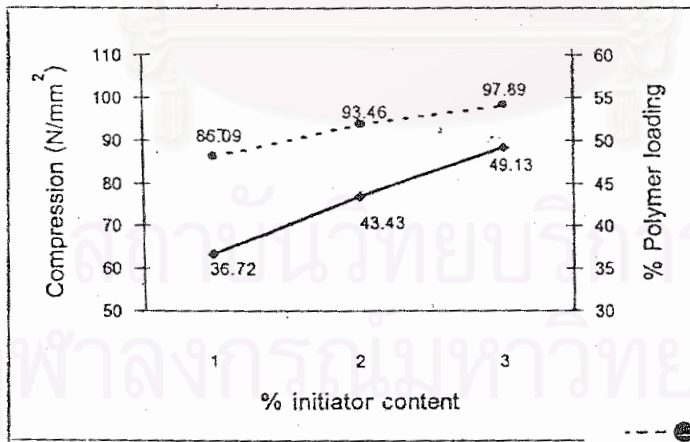
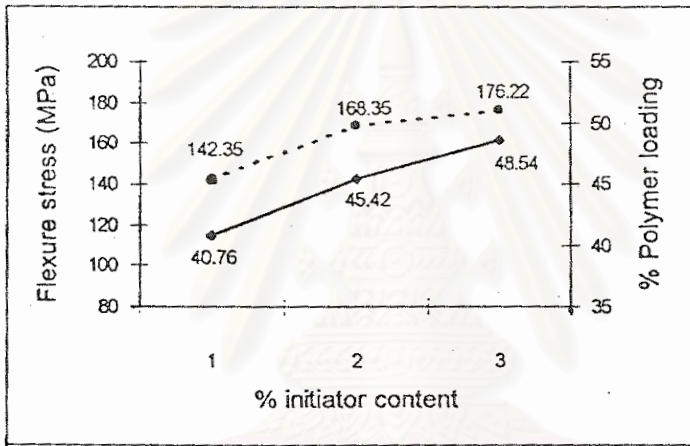
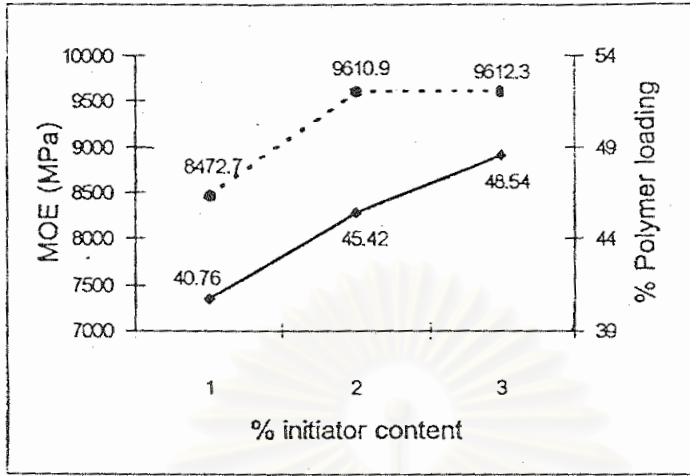


Figure 4.3 Physical properties of rubberwood-MMA composites prepared from various initiator contents



Mechanical properties

Polymer loading

Figure 4.4 Mechanical properties of rubberwood-MMA composites prepared from various initiator contents

Physical properties of impregnated sample with various initiator contents showed that the polymer loading was increased with increasing initiator contents but they were not significantly difference at 2% and 3% initiator contents, resulting in similar value of density in such initiator contents.

The water absorption and antiswell efficiency (ASE) were found to be in the same trend which could be explained that the increasing amount of polymer could fill up the lumen of wood, resulting in the reduction of hydroxy groups of wood cell wall and prevented the absorption of moisture which consequence in improving ASE.

Results of mechanical properties were shown in dash line and polymer loading of each sample was shown in smooth line. They showed that higher initiator contents gave higher polymer loading, but they are not much different at 2% and 3% initiator contents like in MOE, flexure stress, and compression.

#### **4.5 Effect of monomer ratio on the properties of impregnated samples**

Impregnated wood containing monomer mixtures offers an effective way of modification of the physical and mechanical properties to different degrees. In this present work, 2 types of copolymers such as MMA/2-EHA and MMA/AM were selected. The monomer ratio of MMA : 2-EHA and MMA : AM were varied from 100:0, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80, and 0:100. Parameters of impregnation process were as follows: 2 hours evacuating time, 4 hours soaking time, and 2% initiator content. Specimens exhibited the properties which were presented in Table 4.5, 4.6 and Figures 4.5, 4.6, 4.7, and 4.8.

**Table 4.5** Properties of rubberwood-MMA/2-EHA composites prepared from various monomer ratios

Physical properties	Ratio of MMA : 2-EHA (% w/w)								
	100:0	80:20	70:30	60:40	50:50	40:60	30:70	20:80	0:100
Polymer loading (%)	55.77	60.00	60.89	59.36	57.11	58.12	58.01	56.68	47.82
Density (g/cm <sup>3</sup> )	0.98	0.99	0.98	0.98	0.97	0.96	0.96	0.94	0.96
Water absorption (%)	36.81	22.04	25.98	26.43	26.51	29.94	34.03	37.82	30.31
Antiswell efficiency (%)	42.22	49.28	47.34	44.89	42.51	40.35	35.42	30.10	41.37

Mechanical properties	Ratio of MMA : 2-EHA (% w/w)								
	100:0	80:20	70:30	60:40	50:50	40:60	30:70	20:80	0:100
Polymer loading (%)	45.42	47.58	48.69	49.91	48.75	48.75	48.07	48.65	46.02
MOE (MPa)	9610.9	7234.6	7424.9	7584.9	7730.5	7770.8	8025.8	8699	9047.3
Flexure stress (MPa)	168.35	106.77	111.26	112.91	117.58	117.99	120.51	130.24	137.92

Polymer loading (%)	43.43	55.44	55.27	52.98	51.86	50.31	51.13	52.17	49.95
Compression (N/mm <sup>2</sup> )	93.46	77.36	69.29	69.15	66.30	58.46	59.56	50.82	62.90

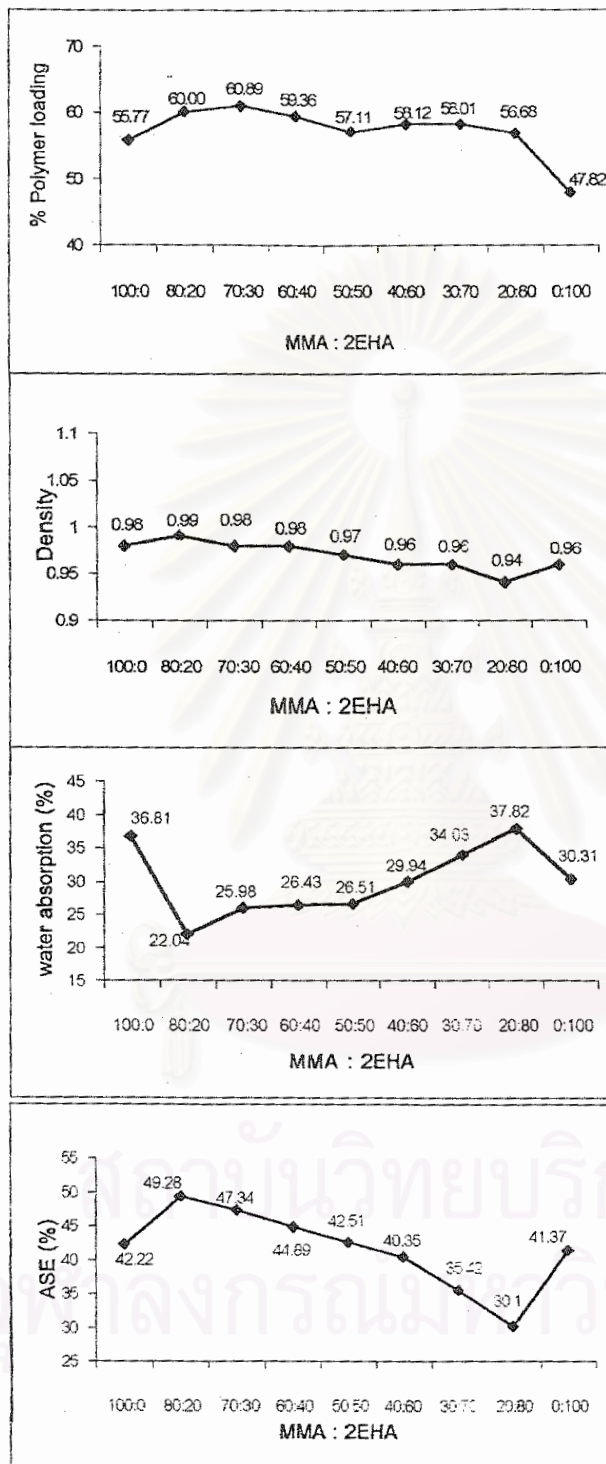
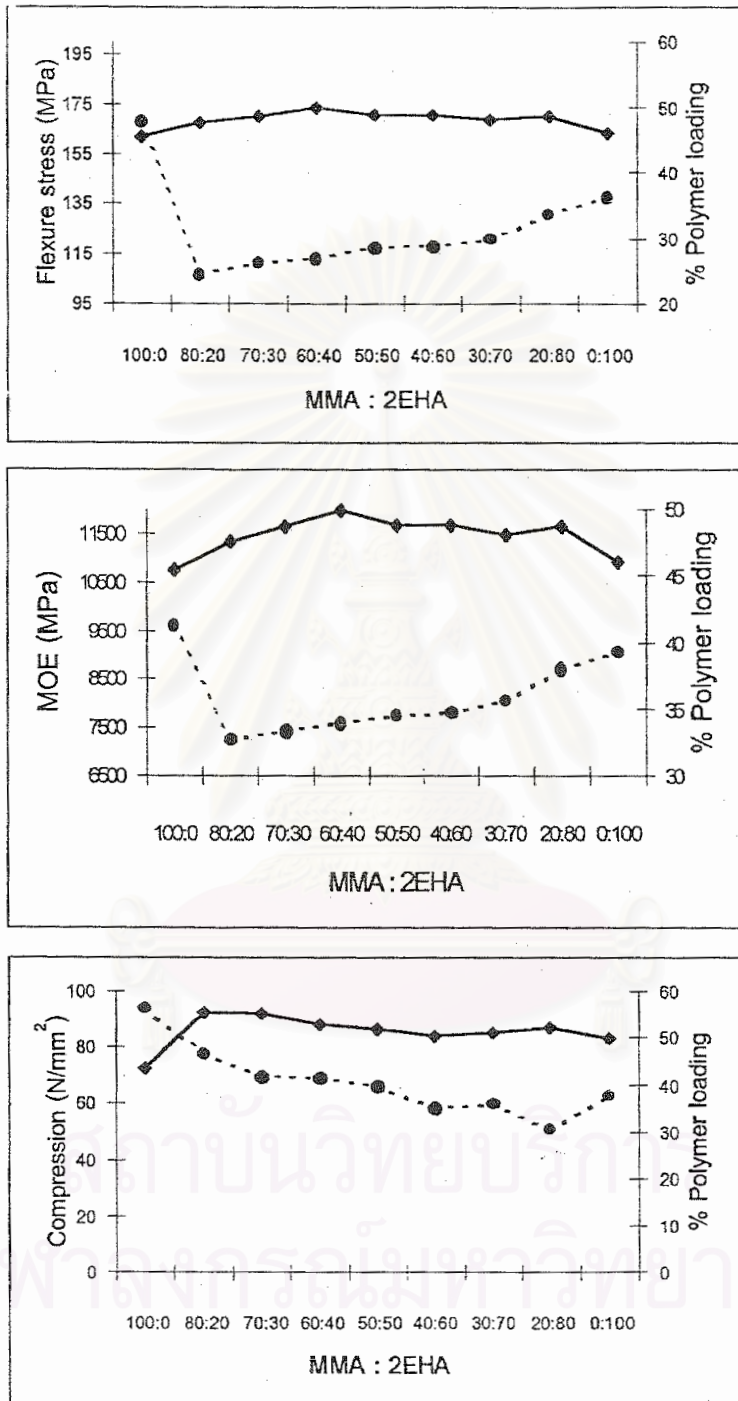


Figure 4.5 Physical properties of rubberwood-MMA/2-EHA composites prepared from various MMA/2-EHA ratios



**Figure 4.6** Mechanical properties of rubberwood-MMA/2-EHA composites prepared from various MMA/2-EHA ratios

As a result in Figure 4.5, dimensional stability comparison of impregnated samples with varied MMA : 2-EHA ratio showed that polymer loading and density were decreased slightly with increasing 2-EHA contents. The resistance to moisture as shown in term of ASE decreased because there was less resin filled in cell cavities which allowed more water absorption, resulted in decreasing of ASE accordingly. On the other hand, the retarding or preventing of the movement of moisture in wood was decreased.

The mechanical properties are increased because the cell cavities in wood are filled with hard polymer as expected. Interesting results obtained by copolymerizing MMA with monomer having bulky alkyl group such as 2-EHA were revealed. Although MMA has major advantages such as excellent transparency, weatherability, and hardness, it is also has some disadvantages including brittleness and low service temperature. As mentioned above, the bulky alkyl group of 2-EHA could improve the flexibility of MMA compositions.

From Figure 4.6 the results showed that the more 2-EHA content, the better MOE and flexure stress. Thereby, the stiffness of rubberwood-MMA/2-EHA composites decreased with increasing 2-EHA contents.



**Table 4.6** Properties of rubberwood-MMA/AM composites prepared from various monomer ratios

Physical properties	Ratio of MMA : AM (% w/w)								
	100:0	80:20	70:30	60:40	50:50	40:60	30:70	20:80	0:100
Polymer loading (%)	55.77	30.56	28.90	28.00	26.16	25.25	25.20	22.04	23.32
Density (g/cm <sup>3</sup> )	0.98	0.74	0.73	0.73	0.72	0.71	0.71	0.68	0.71
Water absorption (%)	36.81	51.93	55.01	60.22	61.82	62.00	62.27	64.07	64.86
Antiswell efficiency (%)	42.22	27.37	26.49	25.26	23.90	22.37	21.50	17.64	18.62

Mechanical properties	Ratio of MMA : AM (% w/w)								
	100:0	80:20	70:30	60:40	50:50	40:60	30:70	20:80	0:100
Polymer loading (%)	45.42	22.03	16.59	14.15	13.85	13.27	12.78	12.67	22.99
MOE (MPa)	9610.9	7992.7	7975.7	7614.0	7557.9	7537.2	7523.4	6380.5	6511.2
Flexure stress (MPa)	168.35	125.25	122.15	118.02	117.05	105.48	104.40	100.42	106.16

Polymer loading (%)	43.43	23.19	15.85	15.28	14.91	14.57	13.72	12.30	20.36
Compression (N/mm <sup>2</sup> )	93.46	70.99	69.35	67.73	65.78	57.82	55.97	53.64	58.03

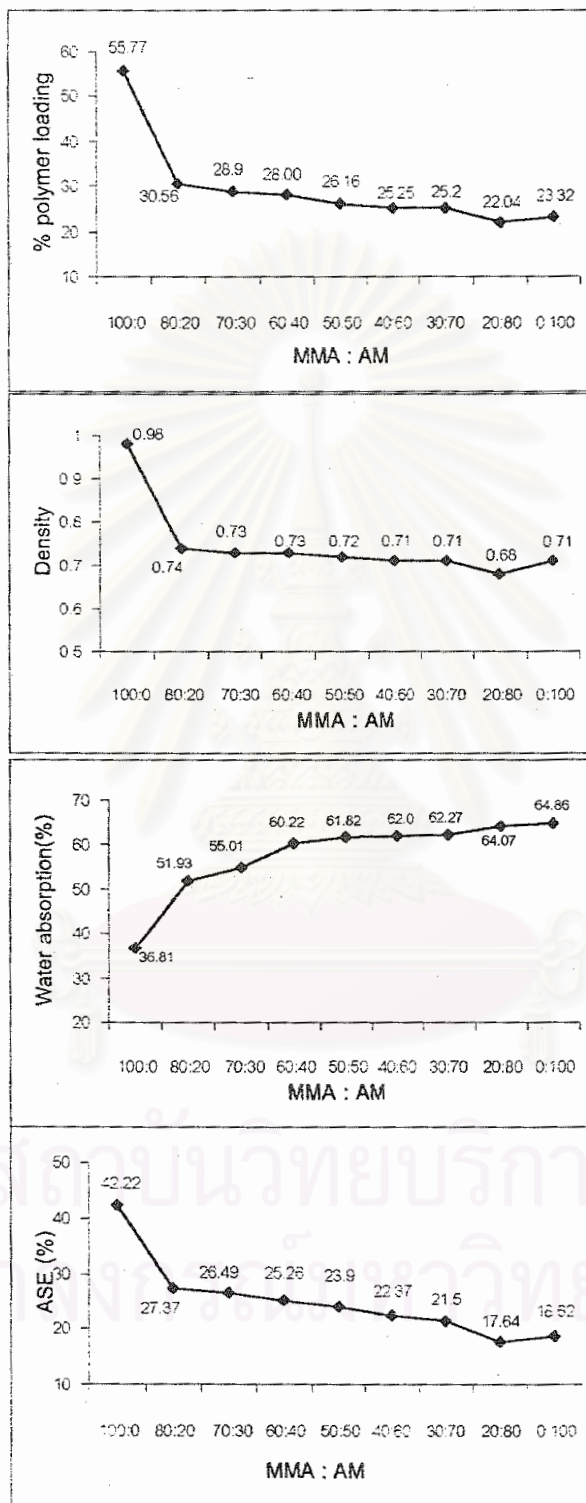


Figure 4.7 Physical properties of rubberwood-MMA/AM composites prepared from various MMA/AM ratios

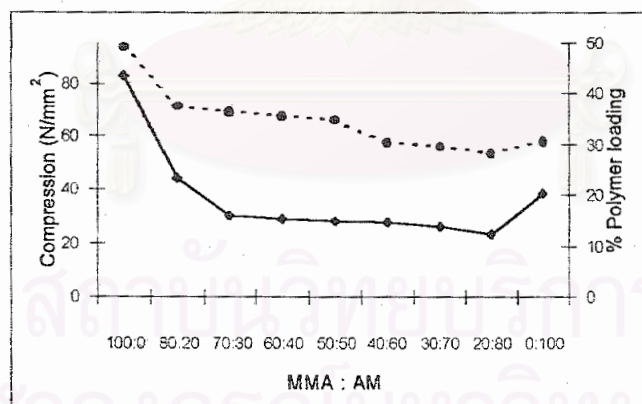
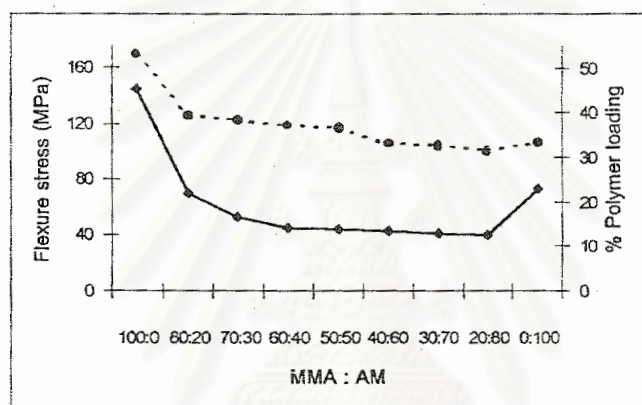
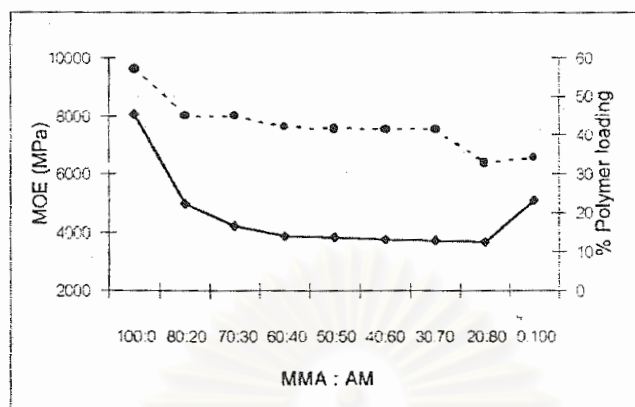


Figure 4.8 Mechanical properties of rubberwood-MMA/AM composites prepared from various MMA/AM ratios

From Figure 4.7 physical properties in part of polymer loading and density showed that there were no significant difference in the ratio of MMA : AM from 20:80 to 0:100, but when there was no AM, the polymer loading and the density were the highest.

Differences in solubility in water of the two monomers used (MMA having poor solubility, AM being highly soluble) caused the effect of swelling in water. Higher proportions of AM would act as a physical barrier for the approach of the hydrophobic monomer MMA to the water swollen radicals. On the other hand, with increasing AM proportions, water absorption increased, and ASE followed a falling trend as in Figure 4.7. Especially, for no MMA case, exclusively present of the hydrophilic monomer (AM) has made water absorption values to be the highest.

Figure 4.8 revealed how the mechanical properties such as MOE, flexure stress, and compression changed with the subsequent change of MMA : AM ratio. Progressive increase in AM content apparently led to no significant difference in MOE up to 70% AM, but MOE started to fall from 80% AM and above. However, for the use of AM in an amount of more than 50%, flexure stress and compression was decreased with increasing the contents of AM.

#### 4.6 Evaluation of WPC specimens for resistance to termites



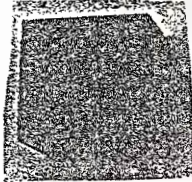
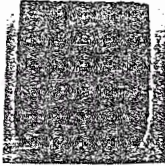

The rubberwood is utilized for firewood, sawn timber, and also furnitures. Unfortunately, rubberwood belongs to the lowest durability class, so it is easily attacked by termites or other fungi. The WPC making is an alternative way to prevent damage from deterioration.

In this research, five types of woods including untreated rubberwood, 2 types of treated rubberwood, teak, and redwood were tested under the same condition. The results are shown in Table 4.7.

From the data, it was found that termites preferred to attack untreated rubberwood more than others. Furthermore, rubberwoods were also attacked by fungi. Like teak and redwood, both of the treated rubberwoods showed more resistant to fungal attack than untreated rubberwood. Thus, the rubberwoods impregnated with MMA/2-EHA and MMA/AM were proved to be more resistant to attack by termites and fungi.

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**Table 4.7** The result of rating of termite attack

Types of wood	Rating of termite attack
 <p>Rubberwood</p>	7
 <p>MMA/2-EHA-rubberwood</p>	10
 <p>MMA/AM-rubberwood</p>	10
 <p>Teak</p>	10
 <p>Redwood</p>	10

#### 4.7 Scanning Electron Microscopy (SEM) of WPC

The scanning electron microscopy (SEM) was employed to investigate transverse sections of the specimens. The microstructure of untreated rubberwood cells, impregnated wood cells of rubberwood-MMA/2-EHA composites, and rubberwood-MMA/AM composites are shown in Figures 4.9, 4.10 and 4.11 respectively.

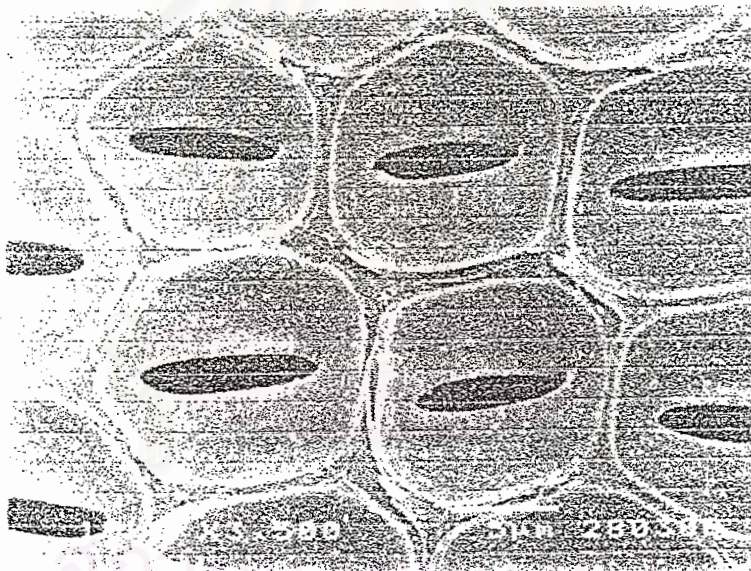


Figure 4.9 SEM micrograph of transverse section of empty wood cells (3,500 x)

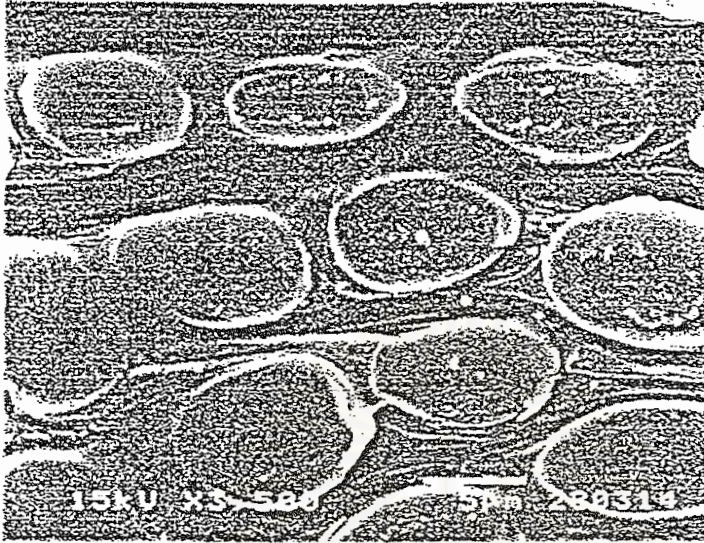


Figure 4.10 SEM micrograph of transverse section of rubberwood-MMA/2-EHA composites wood cells (3,500 x)

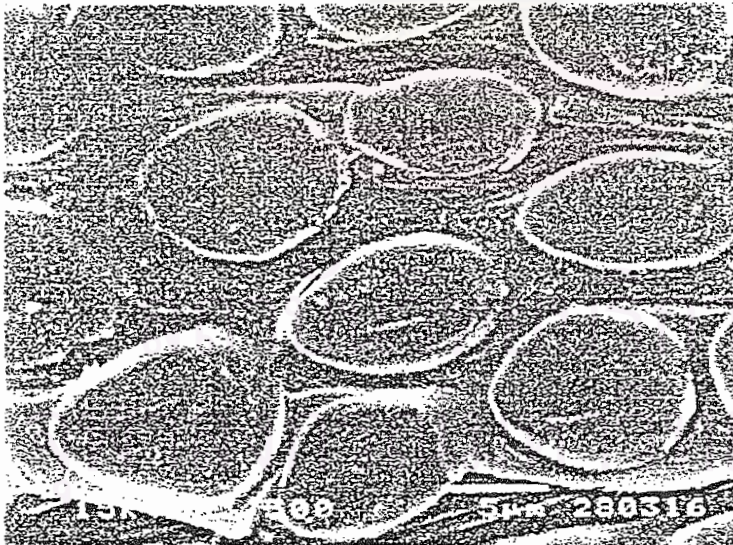


Figure 4.11 SEM micrograph of transverse section of rubberwood-MMA/AM composites wood cells (3,500 x)



From Figure 4.9, the microstructure of untreated rubberwood cells showed the empty void spaces. In impregnation process, Figure 4.10 and 4.11, showed the empty wood cells filled with polymer, which were important consequence on the improvement of physical properties and mechanical properties of natural wood.

#### 4.8 Application of rubberwood-polymer composites

The rubberwood-polymer composites had better physical and mechanical properties and some other properties than those of some hardwoods. The comparisons of wood properties are shown in Table 4.9.

**Table 4.8** Comparison of the properties of MMA/ZEHA-rubberwood and MMA/AM-rubberwood with other woods

Properties	Types of wood		
	Rubberwood	MMA/2-EHA-rubberwood composites	MMA/AM-rubberwood composites
Density	0.630	0.940-0.990	0.68-0.74
MOE (Mpa)	6596	7234.6-8699.0	6380.5-7992.7
Flexure stress (Mpa)	93.0	106.77-130.24	100.42-125.25
Compression (N/mm <sup>2</sup> )	40.08	50.82-77.36	53.64-70.99

**Table 4.8** Comparison of the properties of MMA/2EHA-rubberwood and MMA/AM-rubberwood with other woods (continued)

Properties	Types of woods			
	UPR-durianwood composites	Epoxy-rubberwood composites	Teak	Redwood
Density	0.841	0.860	0.650	0.87
MOE (Mpa)	11790	9271	6398	5790
Flexure stress (Mpa)	180	154	98	82
Compression (N/mm <sup>2</sup> )	75.90	72.00	86.30	82.30

From Table 4.9, it was shown that rubberwood impregnated with MMA/2-EHA could improve the mechanical properties of untreated rubberwood. The MMA/AM made rubberwood had better flexure stress and compression. Some MOE of MMA/AM-rubberwood composites were improved, some were not. That depended on the ratio of MMA : AM as mentioned in section 4.5. When comparing with UPR-durianwood composites and epoxy-rubberwood composites though they had higher mechanical properties than those of MMA/2-EHA and MMA/AM-rubberwood composites, the procedures in preparing wood-polymer composites of this research is much easier. However, the properties of these treated rubberwood were all higher than those of teak and redwood. Therefore, treated rubberwood could have good potential to be applied in the applications that use teak or redwood such as flooring material, furnitures, household items, etc.

#### 4.9 The cost of specimens

The cost of MMA/AM and MMA/2-EHA rubberwood composites can be evaluated as follow:

The prices of materials			The dimensions of specimens	
Methyl methacrylate	60	baht / kg	Water absorption : 2.5x2.5x0.5 cm <sup>3</sup>	
Acrylamide	130	"	MOE and flexure stress : 2.5x10x0.5 cm <sup>3</sup>	
2-Ethylhexyl acrylate	55	"	Compression	: 1x1x3 cm <sup>3</sup>
Benzoyl peroxide(BPO)	400	"	Termite resistance	: 2x2x1 cm <sup>3</sup>
Rubberwood	70	baht / ft <sup>3</sup>		

In each batch, 20 pieces of each dimension of wood were impregnated all in monomer mixtures 50 g and 2% BPO. Thus, the example of calculating cost of impregnated samples is exhibited below:

The volumes of all specimens are

$$= \frac{20 \times [(2.5 \times 2.5 \times 0.5) + (2.5 \times 10 \times 0.5) + (1 \times 1 \times 3) + (2 \times 2 \times 1)]}{30 \times 30 \times 30} \text{ ft}^3 = 0.0167 \text{ ft}^3$$

In case of MMA-rubberwood composites, 50 g of monomer mixtures containing MMA and BPO 2% were used. Thus, MMA 49 g and BPO 1 g were used for rubberwood 0.0167 ft<sup>3</sup>, which were 176.05 baht of MMA and 0.4 baht of BPO. Therefore the net price of MMA-rubberwood composites is 176.05 + 0.4 + 70(price of natural rubberwood) or equal to 246.45 baht/ft<sup>3</sup>.

**Table 4.9** The cost of MMA/AM and MMA/2-EHA rubberwood composites

	Monomer-rubberwood composites				
	MMA	AM	2-EHA	MMA/AM	MMA/2-EHA
Price (Bh/ft <sup>3</sup> )	246.45	451.84	161.38	287.53	243.52

## CHAPTER 5

### CONCLUSION

Wood-polymer composites (WPC) of rubberwood (*Hevea Brasiliensis*) were prepared by impregnating the rubberwood with 2 mixtures of two monomers such as methyl methacrylate/2-ethylhexyl acrylate (MMA/2-EHA) and methyl methacrylate/acrylamide (MMA/AM). Polymerization was carried out by catalyst-heat treatment. The optimum conditions for rubberwood-polymer composites preparation are as follows:

Benzoyl peroxide	2% by weight
Evacuating time	2 hours
Soaking time	4 hours

MMA/2-EHA-rubberwood composites displayed relatively higher polymer loading and density than those of MMA/AM-rubberwood composites. Thus, dimensional stability in water of MMA/2-EHA-rubberwood composites could be better than that of MMA/AM-rubberwood composites.

However, both types of copolymers behaved in the same trend that the higher polymer loading, the less water absorption they were. When the content of 2-EHA and AM increased, the water absorption also increased.

For the mechanical properties, the incorporation of 2-EHA could improve the brittleness of MMA resulting in better MOE and flexure stress which corresponded well with the ratio of 2-EHA due to the flexibility of the bulky alkyl group. Moreover, compression was improved as well.

The sample impregnated with MMA/AM showed the highest compression and flexure stress at the ratio of 50:50. There were no significant difference in MOE up to 30:70, but it exhibited lower value after that.

Most samples showed improvement in mechanical properties as compared to the untreated rubberwood, however, there is no statistically difference. Untreated rubberwood probably fails in compression due to the buckling or relatively thin cell walls because of a long-column type of instability. The addition of polymer resulted in a coating on the cell walls, which thickening them, thus greatly increased their mechanical properties.

Resistance to termites was compared among untreated rubberwood, teak, and redwood. The results showed that impregnation wood with MMA/2-EHA and MMA/AM completely resisted the damage from termites as well as teak and redwood.

The investigation of microstructure of impregnated rubberwood showed that the lumen of wood were filled with both MMA/2-EHA and MMA/AM compared with untreated rubberwood resulting in highly improving of physical and mechanical properties.

## 5.1 Suggestion and future work

1. From the results of termite resistance testing, it was found that the mortality of termites was 100% died before 4 weeks. Therefore, the treated samples should be baked at 90°C in an oven until the untreated monomers were completely removed from the samples before testing.

2. Investigation of the properties of MMA/AM and MMA/2-EHA rubberwood composites containing crosslinking agent, such as divinyl benzene on the physical and mechanical properties should be further studied. It is anticipated that the properties should be improved.

3. The large scale for impregnation, the modification of impregnation process, and the change of monomer types are worthwhile to investigate.

## REFERENCES

1. สว่าง วรรณสุภผล. "การศึกษาความเป็นไปได้ในการจัดตั้งโรงงานผลิตเชื้อกระดาษจากไม้ยางพารา", วิทยานิพนธ์ปริญญามหาบัณฑิต ภาควิชาวิศวกรรมอุตสาหกรรม บัณฑิตวิทยาลัย จุฬาลงกรณ์มหาวิทยาลัย, 1983, 14-15.
2. พงศ์ โสโน. "ผลิตผลป่าไม้และการใช้ประโยชน์", เอกสารกองวิจัยผลิตผลป่าไม้ กรมป่าไม้ กระทรวงเกษตรและ สหกรณ์ เลขที่ ต. 1-2516 หน้า 27
3. Rowell, R.M. The chemistry of solid wood., Washington: Copyright, 1984, 150-152.
4. Miller, R.B. "Structure of wood", Wood engineering handbook., New Jersey: Prentice Hall, 1990, 2-3.
5. Wilcox, W.W., Botsai, E.E., Kubler, H. "Relation of functions, structure, and properties", Wood as a building material. A Wiley-Interscience publication, 1991, 7.
6. Hunt, M.G., and Garratt, A.G. "Factors affecting penetration and absorption", Wood preservation. USA: McGraw-Hill Book Company, 1967, 843-847.
7. Ohkoshi, M. "Wood(Chemical modification)", Polymeric materials encyclopedia. 1996, 8714.
8. Idriss Ali, K.M., and Khan, M.A. "Wood-plastic composites", Polymeric materials encyclopedia. 1996, 8475-8476.
9. Sanchez, J., Myers, T.N. "Peroxide initiators", Polymeric materials encyclopedia. 1996, 4927.
10. Taniguchi, T., Okamura, K. "Wood-polymer composites", Polymeric materials encyclopedia. 1996, 8755.

11. Wilcox, W.W., Botsai, E.E., Kubler, H. "*Wood deterioration and its prevention*", Wood as a building material. A Wiley-Interscience publication, 1991, 121-124.
12. Deubzer, B. and Brunner, E. "*Polymer impregnated wood and process for preparing the same*", U.S. Patent No. 4,304,820 1981.
13. Igarashi, I., Ota, H., and Mizoguchi, Y. "*Curing composition and method for impregnating wood*", U.S. Patent No. 5,496,589 1996.
14. Rozman, H.D., Kumar, R.N., Abusamah, A., and Saad, M.J. "*Rubberwood-polymer composite based on glycidyl methacrylate and diallyl phthalate*" J. Appl. Polym. Sci. 1998, 67, 1221-1226.
15. Khan, M.A. and Idriss Ali, K.M. "*Wood plastic composite using different monomers*", J. Appl. Polym. Sci. 1993, 49, 1989-2001.
16. Solpan, D., and Guven, O. "*Comparison of the dimensional stabilities of oak and cedar wood preserved by in situ copolymerization of allyl glycidyl ether with acrylonitrile and methyl methacrylate*", Angewandte makromolekulare chemie. 1998, 33-37.
17. Witt, A.E. "*Impregnated wood product having a bleached or white appearance and process for making the same*", U.S. Patent No. 4,568,564 1986.
18. Rungvichaniwat, C. "*Para rubberwood-epoxy resins composites*", Master's Thesis, Program of Petrochemistry and Polymer Science, Faculty of Science, Chulalongkorn University, 1998.
19. Kasamchainanta, B. "*Mechanical property improvement of durianwood with polyester resin*", Master's Thesis, Program of Petrochemistry and Polymer Science, Faculty of Science, Chulalongkorn University, 1999.





**APPENDICES**

สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

Table A The parameters for preparation of rubberwood-polymer composites

WPC	Initiator content (%)	Evacuating time (hrs.)	Soaking time (hrs.)	MMA : AM ratio (% w/w)
A	2	0.5, 1, 2	2, 4, 6	100:0
B	1	2	4	100:0
C	2	2	4	100:0
D	3	2	4	100:0
E	2	2	4	0:100
F	2	2	4	80:20
G	2	2	4	70:30
H	2	2	4	60:40
I	2	2	4	50:50
J	2	2	4	40:60
K	2	2	4	30:70
L	2	2	4	20:80

สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

Table A The parameters for preparation of rubberwood-polymer composites (continued)

WPC	Initiator content (%)	Evacuating time (hrs.)	Soaking time (hrs.)	MMA : 2-EHA ratio (% w/w)
M	2	2	4	0:100
N	2	2	4	80:20
O	2	2	4	70:30
P	2	2	4	60:40
Q	2	2	4	50:50
R	2	2	4	40:60
S	2	2	4	30:70
T	2	2	4	20:80

สถาบันวิทยบริการ  
จุฬาลงกรณ์มหาวิทยาลัย

Table A-1 Testing properties of natural rubberwood

Physical properties				Mechanical properties		
Sample/piece (unit)	Density (g/cm <sup>3</sup> )	Water absorption (%)	Swelling Coefficient	Modulus of elasticity (MPa)	Flexure stress (MPa)	Compression (N/mm <sup>2</sup> )
1/1	0.66	87.08	0.08	5127	72.6	32.00
1/2	0.63	85.44	0.08	6801	95.6	39.30
1/3	0.70	83.66	0.08	6635	100.2	39.00
1/4	0.64	85.13	0.09	6972	96.3	41.00
1/5	0.54	86.27	0.08	7601	78.0	44.00
Average.	0.63	85.52	0.08	6627	92.6	39.06
2/1	0.60	85.55	0.08	7538	107.1	36.40
2/2	0.61	80.74	0.08	6214	84.1	49.40
2/3	0.59	89.98	0.09	6604	108.8	44.20
2/4	0.71	86.68	0.08	7203	92.4	33.50
2/5	0.66	88.68	0.08	5262	74.8	42.00
Average.	0.63	86.33	0.08	6564	93.4	41.10
Average.	0.63	85.92	0.08	6596	93.0	40.08
S.D.	0.05	2.56	0.00	852.07	13.04	5.25

Table A-2 Testing properties of rubberwood-polymer composites A

Sample / piece (unit)	Evacuating times (hrs)			Soaking times (hrs)		
	0.5	1.0	2.0	2.0	4.0	6.0
	Polymer loading (%)	Polymer loading (%)	Polymer loading (%)	Polymer loading (%)	Polymer loading (%)	Polymer loading (%)
1/1	10.12	30.67	56.12	35.46	57.17	61.11
1/2	15.85	28.45	56.47	33.81	60.65	60.85
1/3	13.58	31.64	57.23	34.57	54.96	58.34
1/4	13.64	30.59	58.37	36.57	56.18	62.74
1/5	14.97	33.74	59.76	35.94	55.37	61.77
Average	13.63	31.02	57.59	35.27	56.87	60.96

2/1	13.09	32.74	55.47	34.12	55.71	63.42
2/2	12.13	31.52	58.22	36.44	56.62	61.57
2/3	14.75	33.19	55.41	37.15	59.32	60.08
2/4	15.36	30.64	58.25	34.42	57.43	59.14
2/5	11.87	29.99	52.18	35.03	55.82	61.25
Average	13.44	31.62	55.91	35.43	56.98	61.09

Average	13.54	31.32	56.75	35.35	56.93	61.03
S.D.	1.79	1.60	2.14	1.14	1.81	1.54

Table A-3 Testing properties of rubberwood-polymer composites B

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	45.74	0.85	42.24	32.18	33.33	8730	140.3	42.19	97.30
1/2	44.15	0.87	40.78	33.12	34.64	8310	134.0	27.37	93.10
1/3	46.29	0.88	35.57	35.97	41.86	8610	132.1	35.53	74.60
1/4	47.76	0.86	34.97	37.74	45.23	8460	142.8	32.64	64.70
1/5	44.87	0.86	33.51	38.55	43.67	7740	162.2	40.51	100.00
Average.	45.76	0.86	37.42	35.51	39.75	8370	142.28	35.65	85.94
2/1	40.58	0.88	42.26	34.15	35.56	8878	159.9	41.12	99.87
2/2	45.98	0.87	40.25	34.26	40.44	8489	145.6	35.46	65.48
2/3	48.35	0.85	40.18	35.27	44.12	8877	130.2	35.89	75.46
2/4	46.75	0.84	35.12	36.08	46.55	7865	135.1	34.89	92.89
2/5	47.67	0.85	35.01	36.65	42.18	8768	141.3	41.59	97.46
Average.	45.87	0.86	38.56	35.28	41.77	8575.4	142.42	37.79	86.23
Average.	45.82	0.86	37.99	35.40	40.76	8472.7	142.35	36.72	86.09
S.D.	2.26	0.01	3.43	2.01	4.67	399.03	11.02	4.70	14.38

Table A-4 Testing properties of rubberwood-polymer composites C

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	47.53	0.98	39.52	40.66	43.05	8711	150.7	46.46	96.00
1/2	57.54	0.96	37.85	41.59	43.39	10020	157.2	46.70	96.10
1/3	58.72	0.99	36.36	41.71	44.63	9809	179.5	57.79	91.40
1/4	58.74	0.99	36.19	42.52	46.62	9321	166.0	35.84	91.80
1/5	59.50	1.00	32.98	44.65	47.95	9872	186.3	29.95	91.80
Average.	56.41	0.98	36.58	42.23	45.13	9546.6	167.94	43.35	93.42

2/1	43.25	0.99	41.23	40.46	42.06	9988	198.1	30.12	89.87
2/2	55.45	0.98	37.56	40.68	43.29	9755	156.2	36.28	91.23
2/3	58.50	0.97	36.99	42.27	45.62	9100	178.0	55.49	93.21
2/4	58.98	0.99	35.49	43.53	47.61	9687	160.2	48.10	95.70
2/5	59.48	0.95	33.88	44.12	49.99	9846	151.3	47.53	97.42
Average.	55.13	0.98	37.03	42.21	45.71	9675.2	168.76	43.50	93.49

Average.	55.77	0.98	36.81	42.22	45.42	9610.9	168.35	43.43	93.46
S.D.	5.68	0.02	2.45	1.49	4.75	425.33	16.23	9.88	2.62

Table A-5 Testing properties of rubberwood-polymer composites D

Physical properties					Mechanical properties				
Sample/plece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	59.81	0.93	36.80	39.98	40.83	9711	174.8	52.38	100.10
1/2	55.34	0.93	35.03	40.11	42.22	9796	201.6	54.27	100.60
1/3	55.66	1.02	34.99	42.57	49.54	9560	176.5	36.87	94.20
1/4	56.14	1.03	30.51	43.35	54.35	9321	173.8	45.69	97.90
1/5	57.32	0.98	27.88	44.23	60.47	9972	168.0	50.78	96.60
Average.	56.85	0.98	33.04	42.05	49.48	9672	178.94	48.00	97.88

2/1	56.66	1.00	39.29	40.67	39.57	8800	159.6	52.68	99.15
2/2	56.12	0.99	38.12	41.54	43.35	9528	169.5	48.76	98.20
2/3	56.14	0.95	36.55	42.25	45.48	9789	170.3	40.21	98.10
2/4	57.12	1.02	30.56	43.28	50.11	9796	196.8	59.42	96.69
2/5	57.25	0.96	29.98	44.13	59.45	9850	171.3	50.18	97.30
Average.	56.66	0.98	34.90	42.37	47.59	9552.6	173.50	50.25	97.89

Average.	56.76	0.98	33.97	42.21	48.54	9612.3	176.22	49.13	97.89
S.D.	1.26	0.04	3.93	1.58	7.56	341.38	13.01	6.68	1.86



Table A-6 Testing properties of rubberwood-polymer composites E

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	21.49	0.72	81.44	17.65	21.29	7106	100.3	23.12	52.40
1/2	23.75	0.73	58.25	19.36	20.97	6082	88.6	19.10	67.80
1/3	23.15	0.70	63.24	18.29	24.54	6558	131.0	23.20	48.00
1/4	21.52	0.71	63.79	18.18	19.40	6759	105.1	14.36	66.40
1/5	23.95	0.69	54.51	19.54	25.70	5999	100.1	21.86	53.40
Average.	22.77	0.71	64.25	18.60	23.13	6500.8	105.2	20.33	57.60

2/1	23.12	0.73	61.11	18.34	24.17	6010	105.2	20.21	54.40
2/2	22.76	0.74	65.59	17.96	22.89	6623	99.8	19.45	62.40
2/3	20.89	0.70	85.25	17.85	23.38	6725	128.7	16.74	50.32
2/4	25.46	0.71	60.19	19.02	21.11	5997	101.1	21.10	69.96
2/5	27.11	0.68	55.23	20.00	26.45	7253	100.8	24.38	55.21
Average.	23.87	0.71	65.47	18.63	23.60	6521.6	107.12	20.38	58.46

Average.	23.32	0.71	64.86	18.62	22.99	6511.2	106.16	20.36	58.03
S.D.	1.90	0.02	10.4	0.80	2.28	469.99	13.34	3.09	7.90

Table A-7 Testing properties of rubberwood-MMA/AM composites F

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	30.34	0.73	52.60	27.46	14.00	7358	117.90	22.44	62.40
1/2	30.06	0.67	53.85	26.61	24.92	7214	111.40	20.81	66.00
1/3	29.23	0.75	55.05	25.23	21.50	7264	146.30	22.95	79.50
1/4	31.03	0.70	49.54	28.54	23.04	8621	133.00	25.58	68.10
1/5	32.70	0.76	46.73	28.90	25.78	8545	111.40	24.08	74.90
Average.	30.67	0.72	51.55	27.35	21.85	7800.40	124.00	23.17	70.18

2/1	29.08	0.75	54.16	26.34	22.05	8814	100.60	25.08	76.42
2/2	29.89	0.74	54.06	26.57	20.19	8563	128.30	24.79	70.29
2/3	32.18	0.77	49.99	28.79	19.20	7577	140.90	23.28	82.10
2/4	30.96	0.72	50.02	27.75	25.09	8010	142.80	20.70	64.66
2/5	30.15	0.78	53.33	27.48	24.48	7961	119.90	22.14	65.52
Average.	30.45	0.75	52.31	27.39	22.20	8185	126.50	23.20	71.80

Average.	30.56	0.74	51.93	27.37	22.03	7992.7	125.25	23.19	70.99
S.D.	1.18	0.03	2.70	1.19	3.57	615.09	15.42	1.71	6.82

Table A-8 Testing properties of rubberwood-MMA/AM composites G

Physical properties					Mechanical properties				
Sample/pece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	30.54	0.74	51.02	27.45	10.22	7512	118.60	17.95	66.60
1/2	29.61	0.75	55.60	26.57	12.38	7575	114.90	16.42	70.80
1/3	28.26	0.74	56.60	26.13	17.04	7719	126.60	15.38	69.00
1/4	27.10	0.72	58.31	24.91	19.03	8043	84.30	13.02	70.50
1/5	31.63	0.69	50.15	27.88	19.70	8331	156.30	16.00	66.40
Average.	29.43	0.73	54.34	26.59	15.67	7836	120.14	15.75	68.66

2/1	24.20	0.71	59.98	23.63	18.81	8547	161.00	15.98	68.86
2/2	30.19	0.73	53.12	28.14	13.35	8394	99.70	14.01	71.28
2/3	29.10	0.74	55.46	25.55	12.27	7949	120.00	15.76	70.11
2/4	28.11	0.72	57.21	25.46	21.08	8004	119.50	16.85	69.92
2/5	30.21	0.74	52.59	29.15	22.00	7683	120.60	17.10	70.01
Average.	28.36	0.73	55.67	26.39	17.50	8115.40	124.16	15.94	70.04

Average.	28.90	0.73	55.01	26.49	16.59	7975.70	122.15	15.85	69.35
S.D.	2.12	0.02	3.21	1.68	4.19	359.13	22.88	1.45	1.67

Table A-9 Testing properties of rubberwood-MMA/AM composites H

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	25.45	0.72	71.92	23.24	10.92	7330	116.60	15.64	60.00
1/2	29.95	0.73	54.11	25.55	15.30	8008	123.10	13.59	68.60
1/3	28.96	0.75	56.04	25.19	14.35	7380	126.40	14.85	74.80
1/4	25.82	0.74	59.86	24.28	13.50	7257	104.60	14.36	60.90
1/5	31.18	0.69	50.33	27.72	13.45	7569	119.90	14.50	71.60
Average.	28.27	0.73	58.45	25.20	13.50	7508.80	118.12	14.59	67.18

2/1	26.02	0.66	72.65	23.68	13.05	7800	118.60	15.90	69.58
2/2	20.12	0.77	55.69	26.27	14.42	7688	103.60	16.10	70.16
2/3	27.15	0.75	62.28	25.64	15.68	8101	125.80	14.89	69.95
2/4	26.98	0.74	65.45	24.51	14.62	7614	124.20	14.77	72.23
2/5	30.36	0.72	53.88	26.48	16.20	7393	117.40	18.15	59.46
Average.	27.73	0.73	61.99	25.32	14.79	7719.20	117.92	15.96	68.28

Average.	28.00	0.73	60.22	25.26	14.15	7614	118.02	15.28	67.73
S.D.	2.04	0.03	7.72	1.37	1.52	287.94	8.09	1.26	5.53

Table A-10 Testing properties of rubberwood-MMA/AM composites I

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Load/ing	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	25.74	0.73	61.29	24.13	12.32	7509	109.00	14.44	54.40
1/2	26.70	0.71	60.19	24.23	13.35	7435	124.80	16.93	70.00
1/3	25.69	0.73	63.67	23.37	15.51	7472	115.40	12.44	72.40
1/4	25.07	0.72	65.23	22.59	13.60	7847	105.40	13.08	66.60
1/5	28.05	0.72	57.02	25.00	13.50	7256	121.10	15.96	56.10
Average.	26.25	0.72	61.48	23.86	13.68	7565.75	115.14	14.57	65.85
2/1	25.72	0.71	62.37	23.45	12.98	7318	119.80	16.23	60.10
2/2	25.56	0.73	63.28	23.19	13.67	7795	121.70	14.55	62.42
2/3	24.99	0.74	64.43	22.98	14.20	7560	116.00	13.76	70.65
2/4	26.78	0.72	60.55	24.57	14.26	7468	123.80	14.08	69.88
2/5	27.29	0.70	60.14	25.52	15.04	7609	113.50	17.59	65.50
Average.	26.07	0.72	62.15	23.94	14.03	7550	118.96	15.24	65.71
Average.	26.16	0.72	61.82	23.90	13.85	7557.88	117.05	14.91	65.78
S.D.	1.00	0.01	2.47	0.94	0.94	186.92	6.40	1.70	6.33

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Table A-11 Testing properties of rubberwood-MMA/AM composites J

Physical properties					Mechanical properties				
Sample/pece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	23.78	0.71	71.88	20.19	10.32	7443	98.40	12.37	58.60
1/2	24.10	0.69	61.90	21.13	10.59	6922	120.10	14.74	57.60
1/3	26.02	0.75	54.03	23.37	15.78	8574	96.70	14.20	58.80
1/4	25.61	0.72	57.39	22.61	14.65	6521	105.20	14.67	54.60
1/5	25.57	0.73	60.62	22.54	12.40	7674	110.50	15.02	55.10
Average.	25.02	0.72	61.16	21.97	12.75	7426.80	106.18	14.20	57.00

2/1	24.03	0.66	69.38	20.79	11.52	7872	100.50	15.60	56.40
2/2	24.95	0.71	68.37	22.16	12.85	6791	101.60	15.44	60.00
2/3	27.01	0.72	55.52	24.65	16.68	8816	99.60	15.01	57.96
2/4	26.11	0.69	59.27	23.51	14.68	7013	119.40	14.59	59.94
2/5	25.24	0.70	61.59	22.74	13.18	7746	102.80	14.01	58.85
Average.	25.47	0.70	62.83	22.77	13.78	7647.60	104.78	14.93	58.63

Average.	25.25	0.71	62.00	22.37	13.27	7537.20	105.48	14.57	57.82
S.D.	1.04	0.02	6.05	1.36	2.15	755.45	8.44	0.92	1.88

Table A-12 Testing properties of rubberwood-MMA/AM composites K

Physical properties					Mechanical properties				
Sample/plece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	22.17	0.73	73.81	20.99	11.72	6302	112.50	14.06	56.40
1/2	26.26	0.70	59.19	21.68	12.60	7373	112.30	15.15	58.20
1/3	25.79	0.71	62.13	21.64	13.45	8099	95.40	13.40	55.10
1/4	25.73	0.71	62.40	21.05	12.99	7020	86.30	13.72	55.60
1/5	27.44	0.70	58.31	22.17	12.37	8166	110.60	11.89	50.30
Average.	25.48	0.71	63.17	21.51	12.63	7392	103.42	13.64	55.12

2/1	23.29	0.70	63.44	19.13	10.11	8261	102.60	12.26	52.64
2/2	25.63	0.72	60.59	22.76	12.55	7283	110.80	13.58	58.01
2/3	25.03	0.71	61.23	21.49	13.30	8016	100.00	14.11	56.42
2/4	24.52	0.72	62.14	20.65	13.17	7720	99.90	13.98	59.13
2/5	26.11	0.71	59.46	23.38	12.92	6994	113.60	15.01	57.84
Average.	24.92	0.71	61.37	21.48	15.46	7654.80	105.38	13.79	56.81

Average.	25.20	0.71	62.27	21.50	12.78	7523.4	104.40	13.72	55.97
S.D.	1.53	0.01	4.37	1.17	0.99	639.05	9.09	1.04	2.73

Table A-13 Testing properties of rubberwood-MMA/AM composites L

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	22.31	0.70	63.83	17.51	13.03	7201	117.9	11.20	52.80
1/2	22.20	0.68	66.00	16.98	12.41	5883	102.6	12.25	56.10
1/3	20.24	0.67	66.04	16.45	11.49	5411	81.5	13.86	58.20
1/4	23.11	0.69	62.59	17.99	12.35	7257	99.1	11.34	49.00
1/5	24.66	0.65	58.48	18.27	12.99	5813	92.0	13.10	51.80
Average.	22.50	0.68	63.39	17.44	12.45	6313	98.62	12.35	53.58

2/1	20.11	0.71	67.73	16.65	11.01	6020	100.2	13.88	52.03
2/2	20.23	0.72	67.10	16.84	13.28	7042	105.0	12.12	48.82
2/3	23.97	0.65	60.21	19.45	12.89	5998	99.8	10.05	57.64
2/4	22.01	0.66	63.56	18.39	12.45	5952	115.3	14.91	55.95
2/5	21.53	0.65	65.11	17.86	15.76	7228	90.8	10.28	54.08
Average.	21.57	0.68	64.74	17.84	11.94	6448	102.22	12.25	53.70

Average.	22.04	0.68	64.07	17.64	12.67	6380.5	100.42	12.30	53.64
S.D.	1.58	0.03	2.98	0.94	1.27	712.33	10.94	1.62	3.33

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Table A-14 Testing properties of rubberwood-MMA/2-EHA composites M

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	41.57	1.00	32.28	39.98	44.72	9396	130.1	53.41	64.80
1/2	50.42	0.96	30.73	42.89	38.08	7590	129.7	40.00	63.20
1/3	45.59	0.95	30.81	40.21	44.60	9551	130.2	51.83	61.80
1/4	43.40	0.94	32.05	40.09	43.35	9499	158.0	52.06	59.30
1/5	56.54	0.95	23.83	43.35	57.25	9161	138.3	50.00	66.00
Average.	47.50	0.96	29.94	41.30	45.60	9039.4	137.26	49.46	63.02

2/1	42.08	0.95	33.50	39.95	58.34	9250	140.2	51.10	65.12
2/2	51.64	0.96	29.97	42.49	44.26	9489	159.1	53.15	60.03
2/3	46.58	0.95	31.86	41.03	45.71	9660	133.5	51.90	62.71
2/4	43.15	1.00	33.29	40.68	38.19	7489	127.1	42.33	61.59
2/5	57.26	0.95	24.79	43.00	45.63	9388	133.0	53.65	64.44
Average.	48.14	0.96	30.68	41.43	46.43	9055.2	138.58	50.43	62.78

Average.	47.82	0.96	30.31	41.37	46.02	9047.3	137.92	49.95	62.90
S.D.	5.83	0.02	3.36	1.40	6.80	807.74	11.58	4.79	2.23

Table A-15 Testing properties of rubberwood-MMA/2-EHA composites N

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	59.48	0.93	22.08	49.35	46.76	7349	113.00	52.25	79.00
1/2	61.00	1.11	26.39	47.58	48.59	7187	111.60	54.67	93.10
1/3	60.35	0.92	28.33	46.65	46.24	7906	126.90	60.67	81.60
1/4	60.98	0.99	17.29	49.40	48.46	6942	86.80	53.73	65.10
1/5	60.38	0.98	14.45	54.22	47.74	6751	106.90	55.29	69.50
Average.	60.44	0.98	21.71	49.44	47.56	7227	109.04	55.32	77.60

2/1	60.22	0.97	23.19	49.97	46.59	6825	102.60	56.26	70.01
2/2	58.87	0.99	25.43	48.83	45.98	6897	92.50	54.08	74.26
2/3	58.26	0.98	29.21	45.51	48.10	7881	99.80	58.86	80.15
2/4	60.89	1.10	18.42	50.02	49.47	7276	113.50	55.54	82.28
2/5	59.58	0.95	15.56	51.21	47.85	7332	114.10	53.01	78.86
Average.	59.56	1.00	22.36	49.11	47.60	7242.2	104.50	55.55	77.11

Average.	60.00	0.99	22.04	49.28	47.58	7234.6	106.77	55.44	77.36
S.D.	0.93	0.06	5.35	2.44	1.14	407.76	11.71	2.61	8.02

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Table A-16 Testing properties of rubberwood-MMA/2-EHA composites O

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	48.28	0.97	30.27	44.79	50.35	8415	112.80	61.58	71.60
1/2	63.48	0.98	23.74	49.18	48.86	6487	124.80	50.00	70.80
1/3	61.47	0.97	24.57	47.22	47.94	7666	88.80	50.76	75.40
1/4	59.29	0.99	26.46	45.54	49.10	6908	113.10	59.02	59.80
1/5	70.00	1.00	22.17	50.27	50.03	7489	113.10	56.00	67.50
Average.	60.50	0.98	25.44	47.40	49.26	7393	110.52	55.47	69.02

2/1	47.35	0.99	31.12	44.85	49.64	7567	112.50	58.07	68.06
2/2	62.51	0.98	28.08	46.22	45.56	6829	113.10	59.52	60.18
2/3	62.57	0.98	25.49	47.71	44.28	7840	105.80	49.97	77.38
2/4	62.85	0.97	24.65	48.37	49.58	6525	120.60	53.26	71.72
2/5	71.06	1.00	23.24	49.18	51.54	8523	108.00	54.49	70.46
Average.	61.27	0.98	26.52	47.27	48.12	7456.8	112.00	55.06	69.56

Average.	60.89	0.98	25.98	47.34	48.69	7424.9	111.26	55.27	69.29
S.D.	7.80	0.01	2.99	1.94	2.22	726.68	9.60	4.23	5.73

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Table A-17 Testing properties of rubberwood-MMA/2-EHA composites P

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	53.91	1.01	25.32	44.57	41.63	8819	102.80	56.57	77.80
1/2	51.49	0.98	27.12	42.03	58.60	7640	114.00	50.25	58.80
1/3	46.60	0.99	30.03	41.42	39.91	7827	122.70	49.76	73.80
1/4	67.53	0.97	24.63	46.21	30.43	6039	119.50	56.57	67.20
1/5	76.21	0.96	24.13	49.00	60.70	7562	107.90	50.88	68.90
Average.	59.15	0.98	26.25	44.65	50.21	7577.4	113.38	52.81	69.30
2/1	53.82	1.02	25.72	46.89	40.82	7625	102.90	51.28	57.86
2/2	52.68	0.97	26.34	45.51	44.51	6141	111.50	55.49	76.35
2/3	47.58	0.99	31.24	42.32	59.48	7849	116.00	50.13	74.91
2/4	68.44	0.96	25.22	44.68	41.54	7750	123.20	49.98	59.09
2/5	75.32	0.98	24.46	46.27	61.64	8597	108.60	58.85	76.72
Average.	59.57	0.98	26.60	45.13	49.6	7592.4	112.44	53.15	68.99
Average.	59.36	0.98	26.43	44.89	49.91	7584.9	112.91	52.98	69.15
S.D.	11.34	0.02	2.41	2.40	11.11	893.36	7.48	3.48	8.02

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Table A-18 Testing properties of rubberwood-MMA/2-EHA composites Q

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	59.29	0.96	26.33	42.29	39.86	6482	106.20	54.74	71.30
1/2	54.00	0.97	27.27	41.68	44.06	7945	115.10	45.97	62.40
1/3	46.08	0.99	28.54	40.55	57.89	7527	144.10	53.33	72.80
1/4	61.93	0.98	26.28	43.37	56.27	8150	103.70	48.18	62.00
1/5	62.67	0.94	25.13	45.68	44.88	8268	118.00	56.85	63.20
Average.	56.79	0.97	26.71	42.71	48.59	7674.4	117.42	51.81	66.34

2/1	59.37	0.94	26.45	42.29	57.38	8356	117.20	57.72	62.28
2/2	53.85	0.99	27.24	41.64	44.35	8300	105.60	49.37	61.07
2/3	47.29	0.95	27.65	40.00	40.06	7638	140.80	52.28	73.09
2/4	63.04	0.97	25.24	43.53	56.94	8045	113.20	44.99	64.23
2/5	63.58	0.98	24.98	44.08	45.79	6594	111.90	55.16	70.59
Average.	57.43	0.97	26.31	42.31	48.90	7786.6	117.74	51.90	66.25

Average.	57.11	0.97	26.51	42.51	48.75	7730.50	117.58	51.86	66.3
S.D.	6.49	0.02	1.18	1.70	7.46	685.22	14.01	4.50	4.98

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Table A-19 Testing properties of rubberwood-MMA/2-EHA composites R

Sample/piece (unit)	Physical properties				Mechanical properties				
	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	60.70	1.00	34.01	38.71	47.14	7892	121.70	53.81	52.40
1/2	57.39	0.95	32.42	39.63	44.24	7750	106.90	51.87	56.40
1/3	59.26	0.97	24.55	42.15	44.07	8042	110.30	49.50	62.80
1/4	57.30	0.95	26.82	41.02	53.75	7700	119.00	47.17	62.60
1/5	55.62	0.94	31.83	40.68	54.57	7493	128.10	50.86	57.50
Average.	58.05	0.96	29.93	40.44	48.75	7775.4	117.20	50.64	58.34

2/1	61.08	0.95	33.88	39.32	42.29	7500	129.60	49.95	56.66
2/2	56.45	0.96	32.08	40.07	52.67	7659	121.20	50.28	63.18
2/3	57.18	0.97	25.42	41.13	48.22	8001	111.90	46.67	64.53
2/4	56.55	0.99	26.78	40.51	43.36	7687	108.50	50.91	58.51
2/5	59.65	0.93	31.61	40.26	55.48	7984	122.70	52.02	50.02
Average.	58.18	0.96	29.95	40.26	48.40	7766.2	118.78	49.97	58.58

Average.	58.12	0.96	29.94	40.35	48.75	7770.8	117.99	50.31	58.46
S.D.	1.90	0.02	3.63	0.99	5.11	200.6	8.12	2.16	4.85

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Table A-20 Testing properties of rubberwood-MMA/2-EHA composites S

Physical properties					Mechanical properties				
Sample/piece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	60.73	1.00	35.22	36.18	49.18	5514	108.30	49.29	64.80
1/2	58.93	0.95	35.65	35.52	46.98	8505	129.00	51.43	67.80
1/3	57.36	0.94	36.31	33.11	48.22	8340	123.00	50.21	60.40
1/4	56.06	0.96	32.11	36.50	47.85	8884	104.30	52.57	52.40
1/5	59.57	0.95	30.92	37.42	47.62	8737	134.30	52.37	53.20
Average.	58.53	0.96	34.04	35.75	47.97	7996	119.78	51.17	59.72
2/1	59.28	0.95	35.81	32.29	49.09	8814	121.50	52.57	52.15
2/2	62.56	0.97	32.25	36.84	50.89	8991	119.80	49.64	54.61
2/3	56.88	0.96	34.98	35.44	44.38	7776	116.70	51.35	61.17
2/4	53.01	0.98	35.79	33.70	47.94	7694	127.00	49.51	63.28
2/5	55.73	0.94	31.26	37.19	48.54	7003	121.20	52.35	65.72
Average.	57.49	0.96	34.02	35.09	48.17	8055.6	121.24	51.08	59.39
Average.	58.01	0.96	34.03	35.42	48.07	8025.8	120.51	51.13	59.56
S.D.	2.76	0.02	2.12	1.79	1.68	1087.88	9.06	1.35	5.98

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Table A-21 Testing properties of rubberwood-MMA/2-EHA composites T

Physical properties					Mechanical properties				
Sample/pece (unit)	Polymer Loading	Density (g/cm <sup>3</sup> )	Water absorption (%)	ASE (%)	Polymer Loading	MOE (MPa)	Flexure stress (MPa)	Polymer Loading	Compression (N/mm <sup>2</sup> )
1/1	60.07	0.95	39.01	29.47	51.58	7614	112.70	54.29	42.60
1/2	55.63	0.95	38.69	29.78	47.38	9189	141.20	52.41	54.70
1/3	56.36	0.93	38.27	29.84	49.94	9445	165.80	50.00	57.40
1/4	55.45	0.92	36.02	30.16	47.43	8282	125.70	49.43	51.05
1/5	56.30	0.94	35.26	31.12	48.25	8747	112.90	53.59	47.80
Average.	56.76	0.94	37.45	30.07	48.92	8655	131.66	51.94	50.71
2/1	59.15	0.95	40.05	28.18	50.68	8865	113.50	54.62	48.68
2/2	55.54	0.92	39.00	29.46	49.32	8338	129.30	51.52	52.06
2/3	57.27	0.93	38.42	30.32	46.40	9556	145.80	52.08	56.47
2/4	56.58	0.95	37.13	31.14	48.12	9213	139.00	53.37	55.38
2/5	54.46	0.94	36.35	31.55	47.37	7741	116.50	50.38	42.01
Average.	56.60	0.94	38.19	30.13	48.38	8743	128.82	52.39	50.92
Average.	56.68	0.94	37.82	30.10	48.65	8699	130.24	52.17	50.82
S.D.	1.73	0.01	1.55	1.00	1.67	685.11	17.65	1.82	5.49



## VITA

Miss Supuksorn Rungsri was born on April 8, 1977 in Bangkok. She received a Bachelor's Degree of Science in Chemistry from Chulalongkorn University in 1998. She has been a student of the Program of Petrochemistry and Polymer Science, Faculty of Science, Chulalongkorn University since 1999.



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