

THESIS





# LIBRARY Michigan State University

This is to certify that the

thesis entitled

Composite of Wood Fiber and Recycled

HDPE Bottles from Household Use

presented by

Nualrahong Thepwiwatjit

has been accepted towards fulfillment of the requirements for

M.S. degree in Packaging

Suran

Major professor

Date Jan . 11, 2000

MSU is an Affirmative Action/Equal Opportunity Institution

**O**-7639

## PLACE IN RETURN BOX to remove this checkout from your record. TO AVOID FINES return on or before date due. MAY BE RECALLED with earlier due date if requested.

,

DATE DUE	DATE DUE	DATE DUE
0205 MAY 162006	1 0009	
	10V UI 2000 5001 9 8	

11/00 c/CIRC/DateDue.p65-p.14

\_\_\_\_\_

# COMPOSITE OF WOOD FIBER AND RECYCLED HDPE BOTTLES FROM HOUSEHOLD USE

By

Nualrahong Thepwiwatjit

.

## A THESIS

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

### MASTER OF SCIENCE

School of Packaging

#### ABSTRACT

# COMPOSITE OF WOOD FIBER AND RECYCLED HDPE BOTTLES FROM HOUSEHOLD USE

By

Nualrahong Thepwiwatjit

The main concern in recycling is market opportunities for the reclaimed materials. The use of recycled plastic as a composite in some structural materials could be an attractive outlet. Lately, the use of the natural fiber reinforced thermoplastics has been rising. This study investigated composites of aspen wood fiber reinforced high density polyethylene from used household bottles. The effects of various fiber contents on the mechanical properties of the composites, including tensile properties, impact strength, and water absorption, were evaluated.

It was found that an increase of wood fiber content did not improve the tensile properties of the composites. With an increase in the fiber concentration, the tensile strength, yield strength and % elongation decreased, while the modulus and impact strength slightly increased. The fiber fraction in the composites had a very large effect on water absorption. The more the fiber content, the higher was the gain in weight. At the end, most properties were worse in the recycled HDPE matrix composite than in the virgin HDPE matrix composite. To my family

#### ACKNOWLEDGEMENTS

I would like to express my gratitude to my major professor, Susan Selke, PhD. (School of Packaging, Michigan State University), and my committee members, Jack Jiacin, PhD. (School of Packaging, Michigan State University) and Indrek Wichman, PhD. (Department of Mechanical Engineering, Michigan State University) for their guidance and assistance.

I would like to thank Kelby Thayer for his instruction in use of Instron, and Rujida Leepipattananwit for her instruction in use of several machines and a lot of useful information. I also would like to thank many friends for their help and support.

# **TABLE OF CONTENTS**

List of Table	es	vii
List of Figu	res	viii
Chapter 1	Introduction	1
Chapter 2	Literature Review	
	2.1 Background in MSW	7
	2.2 Garbage Disposal Techniques	
	2.2.1 Landfilling	8
	2.2.2 Incineration	9
	2.2.3 Recycling	10
	2.3 Background in Composite Materials	
	2.3.1 Matrix	12
	2.3.2 Reinforcement	14
	2.3.3 Interface	15
	2.3.4 Prediction of Properties	16
	2.3.5 Natural Reinforced Thermoplastics	20
	2.4 Prior Research	21
Chapter 3	Experimental Design	
	3.1 Materials	26
	3.2 Methods	27
Chapter 4	Results and Discussion	
	4.1 Tensile Strength	31
	4.2 Yield Strength	34
	4.3 Percent Elongation	36
	4.4 Modulus of Elasticity	38
	4.5 Izod Impact Strength	40
	4.6 Water Absorption	42

	4.7 Discussion			
	4.7.1	Tensile properties	44	
	4.7.2	Impact Strength	46	
	4.7.3	Water Absorption	47	
Chapter 5	Conclusions and Recommendations			
	5.1 Conclusions		48	
	5.2 Recommendation	ns	49	
Appendix A			50	
Appendix B			56	
References			69	

## **LIST OF TABLES**

Table 1. Plastic Packaging by Resin Type	3
Table 2. Several Methods to Manage Materials in MSW	7
Table 3. Energy Value Generated from Different Material in the WTE Facilities	10
Table 4. Sample Treatments	28
Table 5. Tensile Strength	32
Table 6. Yield Strength	34
Table 7. Percent Elongation	36
Table 8. Modulus of Elasticity	38
Table 9. Izod Impact Strength	40
Table 10. Percent Increase in Weight due to the Water Absorption	42
Table 11. Comparison of Mechanical Properties of Virgin HDPE	
and Recycled HDPE Resin	45
Table 12. Exact Composition (% by Weight) of Each Treatment	
from the Experiment	51
Table 13. Izod Impact Strength Data	52
Table 14. Tensile Strength Data	53
Table 15. Yield Strength Data	53
Table 16. Modulus of Elasticity Data	54
Table 17. Elongation Data	54
Table 18. Water Absorption Data	55

# LIST OF FIGURES

Figure 1.	Tensile Strength	33
Figure 2.	Yield Strength	35
Figure 3.	Elongation	37
Figure 4.	Modulus of Elasticity	39
Figure 5.	Izod Impact Strength	41
Figure 6.	Water Absorption	43

#### Chapter 1

#### **INTRODUCTION**

The booming of recycling has just occurred during the past fifteen years when the garbage problem was considered a crisis. At that time, several techniques were used for waste disposal, such as landfilling and incineration. Typically, most of the garbage was dumped on a landfill site. But with the rapidly increasing amounts of solid waste, it seemed that the landfill capacity might not be enough to carry the entire load [1]. As for incineration, which helps in volume reduction of waste materials by burning them, there was also concern about the problems of noise and gaseous emissions [2].

In 1989, the U.S. Environmental Protection Agency (EPA) published a model to manage solid wastes according to the hierarchy of waste treatments expressed in "The Solid Waste Dilemma-An Agenda for Action" [3].

The first step is source reduction or waste prevention, which is to avoid the generation of unnecessary waste in the first place before it becomes garbage. For example, using a washable or reusable cup instead of a single-use plastic cup can eliminate one item of trash.

Recycle comes as the second step. This technique is to recover materials from either industrial scrap or post consumer waste and reuse them to make new products instead of using the virgin ones. The composting of organic wastes such as food and yard trimmings is also included in this step as a natural recycling process.

The next approach is incineration with energy recovery. The benefit of incineration is substantial volume reduction as well as energy recovery. The waste-to-

energy facility is designed to extract energy from discarded mixed refuse by burning it, and uses the heat to generate energy, either steam or electricity.

Landfilling is the last step in the hierarchy. Simply, the wastes are removed from the dwelling area and dumped onto a landfill site. EPA considered it to be the last choice because after all other solutions are employed, there are still the rest (about 20% of municipal waste [4]) that has nowhere to go except to the landfill.

Since then, under the influence of "green earth" and "environmentally friendly" mottoes, people turned to paying more attention and taking more action in recycling activities.

Of all the garbage, packaging is of high concern because it is widely used and has a short lifetime [5], and thus continually flows into the waste stream. Approximately 33 percent by weight of the municipal solid waste stream is packaging [6]. Among them, paper packaging is the largest amount (percent by weight), followed by glass, plastics, steel, wood, and aluminum respectively [7].

Generally, the share of plastics in the municipal waste stream in terms of weight is much less than in terms of volume, due to the result of compacting and density [8]. As the result, plastic garbage has more impact on the landfill capacity than other materials.

Compared to other resources, plastic packaging is favored due to its better characteristics of light weight with superior strength properties, easier manufacturing and finishing, safety after damage (plastics do not injure), and low costs [8]. Consequently, the use of plastic in packaging applications has been expanding greatly, as well as its waste after it is used. This makes the idea about making a biodegradable product seem to be interesting. However, this solution becomes less charming when people realize that it

also takes a long time in a landfill (around 10-20 years) to be thoroughly decomposed [9]. Therefore, plastics are being recycled increasingly because it not only reduces wastes, but also saves energy used in production of new plastic items from its original resources [5].

Recycling of plastics involves several steps including materials collection, transportation, and separation (together with sorting and cleaning), before reprocessing into useable products [5]. Notably, the main point of reprocessing is not just to produce a useable product but it needs to be marketable as well.

A potential market for recycling is to replace virgin resin; therefore, it needs to be high quality and cost competitive with its counterparts. With a little help in promotion of mechanical properties with proper additives, post-consumer resins can be made suitable for reuse in their original applications.

In the meantime, cost competition is quite a problem. As the price for virgin resin fluctuates, the price for recycled plastics is fixed due to their stable processing costs. Accordingly, there is a need to find new markets for recovered post-consumer plastics, such as by replacing other materials, i.e. wood and metals, in some applications.

Although several kinds of plastic resin are available in the market, there are six resins that account for almost all of the plastics used in packaging (Table 1).

LDPE	33%
HDPE	31%
PS	11%
PP	9%
PET	7%
PVC	5%
Others	4%

Table 1. Plastic packaging by resin type [10]

Low density polyethylene (LDPE) is the number one in the total amount used. This type of resin is mostly found in the forms of grocery bags, garbage bags, milk pouches, bread wrap, plastic sandwich bags, and stretch film [11]. Technically, LDPE bags can be recycled back into plastic bags, but mostly consumers tend to throw away them after use.

The second one is high density polyethylene (HDPE). HDPE is commonly used for milk, juice and water containers (unpigmented HDPE bottles) as well as household chemical containers (pigmented HDPE bottles) [10]. These rigid containers are easier to separate and collect, thus make them become one of the top recycled materials. The rate of recycling has increased from 252 million pounds in 1991 [12] to 734 million pounds in 1998 [13].

Since the natural, unpigmented HDPE has a value about one third higher than pigmented HDPE [14], it needs to find a value-added outlet for those products. Examples can be some structural implements. However, there is a limitation of using polyethylene as a structural material in that it has low stiffness and high creep, which can be overcome by making a composite material with reinforcement. Therefore, this study will use the returned HDPE bottles from household uses such as detergent bottles, oil and beverage bottles as the main material in the experiment.

Lately, for reinforcing thermoplastics, there has been rising interest in natural reinforcements in the composites, due to a concern about the ultimate disposability and environmental impact of the waste residues generated by the traditional reinforcing materials such as glass fibers, talc, and mica [15]. It was found that the properties of

wood fiber reinforced polypropylene composites were similar to those in glass fiber reinforced polypropylene composites [16].

These natural organic fillers such as wood fibers and paper fibers are slowly taking the place of the dominant reinforcements in the market as a result of their low cost, low density, acceptable specific strength properties, renewable nature, comparative ease of processability, enhanced energy recovery, and biodegradability [9, 17, 18]. However, they have a disadvantage in that they cannot withstand high temperatures. The fibers will degrade at approximately 200°C, which limits the range of plastic materials they may be combined with [9]. Besides, due to the different natures of the matrix and the reinforcements in a natural reinforced material, the poor compatibility has been shown to lead to several drawbacks such as poor interfacial adhesion, poor fiber dispersion, poor water resistance, and surface defects (unaesthetic) [17].

In this study, the matrix material in the composite was the granulated HDPE bottles from household uses and Aspen wood fibers were used as the reinforcement. The fact that wood fibers are polar and hydrophilic, while HDPE is nonpolar and hydrophobic, may cause such problems as those mentioned above. Most prior research concentrated on improving the adhesion between the fibers and matrix. Since these bottles from household uses mostly contained chemical agents, they typically are copolymer HDPE to prevent the stress-cracking phenomenon. They may therefore combine better with the wood fibers than the 100% HDPE bottles. Therefore, this study will look into the characteristics of the Aspen wood fiber/ recycled HDPE bottle composites without any influence from additives.

The primary objective of this study is to investigate the recycling potential of the returned HDPE bottles from household uses as a composite material with Aspen wood fibers. Then the effect of varying amounts of wood fibers on mechanical performance such as tensile strength and impact strength, as well as the effect of water absorption, will be examined.

There is an interesting point of this experiment in that these recycled bottles will be cleaned and then ground to be used as the matrix material without removal of the labels. It is anticipated that the glue and paper from the labels may slightly influence the mechanical performance of the samples. However, it is assumed that the results of these studies would provide a fundamental understanding of recycling of HDPE bottles from household uses. As well as, it may save time and cost of the label removing process before recycling.

#### Chapter 2

#### LITERATURE REVIEW

#### 2.1 Background in MSW

MSW or municipal solid waste can be defined as the waste generated by homes and businesses, as opposed to industrial and agricultural waste [19]. It became a crisis over the past ten years when single-use or throwaway items were booming for a convenient life-style. The idea of "use it once and throw it away" became popular among Americans and thus promoted the increase of garbage [10].

The problems in management of the generation and disposal of MSW had oppressed many parts of the industrial world. In 1989, the European Community generated about 110 million tons of MSW. The total of Japan's industrial and municipal waste was approximately 330 million tons. The United States was the worst, where the public generated about 180 million tons of MSW in 1989 [1].

As stated before, there are several means to handle the municipal solid waste problem. Table 2 shows that each material in MSW can generally be managed in at least two ways.

			Energy	Prepared	
Material	Recycling	Composting	Recovery	Fuel	Landfill
Paper and					
paperboard	X	X	X	X	X
Plastics	X		X	X	X
Glass	X				X
Metals	X				X
Textiles	X		X	X	X
Rubber	X		X	X	X
Wood	X	X	X	X	X
Yard trimmings		X	X		X
and food wastes					

Table 2. Several methods to manage materials in MSW [20]

#### 2.2 Garbage Disposal Techniques

#### 2.2.1 Landfilling

Typically, the easiest and oldest way to get rid of this garbage was to dump it on a landfill site. But with the trend of higher and higher amounts of solid waste, it seemed that the landfill capacity might not be enough. The problem became a crisis when many landfills in operation at that time were forced to close because their standards could not meet the rigid regulations by government on ground-water contamination [21]. At the same time, some landfills were filled up and only a few replacement sites could be opened since new site selection needed time for selection and processing to meet those stricter standards. Moreover, the decision was difficult because everybody gave away garbage but no one wanted to live near it [10, 21]. This problem was one factor leading to the development of other choices for garbage disposal, such as composting and recycling.

At this moment, the lack of landfill space is not a problem anymore. Although the number of landfill sites is less than before, the total capacity is higher because the size of the new landfills is bigger. Moreover, the rate of waste generation has decreased since 1994, thanks to the growth in recycling and composting programs. The MSW going to landfill has declined from 83 percent of all MSW in 1986 to 55.4 percent in 1996 [22].

Nowadays, landfills have evolved into special types, for example, composting sites that more suitable for degradable materials, hazardous waste sites where toxic chemicals can be isolated and kept securely, and sanitary landfills which are specifically designed to avoid leachate problems [4].

#### 2.2.2 Incineration

Incineration (also waste combustion and energy recovery facility) was another way to solve this problem. The main purpose of garbage combustion is to reduce its volume. It can reduce up to 65 - 70 percent of the original waste volume, while the rest still goes to the landfill [21]. This not only saves more space in the landfill, which increases its useful life, but also decreases the problems of odor and sanitation in the landfill [7]. As a by-product, the heat from the burning process can be used to generate steam or electrical energy. This modern waste-to-energy (WTE) facility needs special combustion chambers and can reduce the volume of MSW before going to landfill by as much as 90 percent [23]. The benefit from selling this energy may be able to cover the high investments in the incineration units (from costs of processing and emission control systems, which are expensive) that sometimes exceed the costs of landfill operation. With this WTE facility, incineration becomes more attractive. However, its disadvantages that may make it lose some favor are the problems of noise and gaseous emissions [2]. Although it can be controlled by existing technologies, the disposal of the solid residues from the combustion is still an issue (incinerator ash containing a high concentration of hazardous heavy metals and the fineness of the materials can pollute the surrounding areas) [21].

Plastics in incineration may provide a better benefit. Since plastics are obtained from petroleum, they give more energy than other materials in MSW when they burn. Compared to common fuels, plastics packaging generates about double the energy of Wyoming coal and almost the same energy as fuel oil (Table 3).

Material	BTU/Pound
Plastics	
Polyethylene	19,900
Polypropylene	19,850
Polystyrene	17,800
Rubber	10,900
Newspaper	8,000
Leather	7,200
Corrugated Boxes (paper)	7,000
Textiles	6,900
Wood	6,700
Average for MSW	4,500 - 4,800
Yard waste	3,000
Food waste	2,600
Heat content of common fuels	
Fuel oil	20,900
Wyoming coal	9,600

Table 3. Energy value generated from different material in the WTE facilities [23]

Unfortunately, the feed for the incinerator comes in the form of mixed materials. The energy from MSW therefore is lowered to only about one-third of that from the plastics alone. However, with their high stored energy, they can help the burning process occur more completely and leave less ash [23].

### 2.2.3 Recycling

As seen in Table 2, except for landfilling, recycling is the only way that can deal with almost every type of material in MSW. Since there is usually a benefit in energy reduction for production of new items, recycling seems to be a favored alternative.

Recycling, as defined by Layzon and Wood is "the recovery of materials and products that have completed their useful service life, and their conversion into material for further use, or a new end product" [24]. Recycling can be classified into four categories of techniques: primary, secondary, tertiary and quaternary [1].

- Primary recycling is the transformation of recovered material into the same or similar items to those of virgin material with equivalent performance characteristics. For example, glass bottles can be recycled into new glass bottles, and aluminum cans can be reprocessed into new aluminum cans.
- Secondary recycling is to utilize recycled material to produce new products that demand less stringent specifications than the original, such as plastic toys or trash cans from recycled plastic packaging.
- 3. Tertiary recycling is the process of producing chemicals and fuel from scrap or waste materials. For example, pyrolysis, which is basically a thermal decomposition, will break down large complex molecules into smaller forms of liquid or gas that can subsequently be used as fuel.
- 4. Quaternary recycling is the recovery of energy from waste materials by incineration.

In practice, there are three main requirements for recycling systems. The first one is consistent and reliable sources of recyclable materials. Collection and separation are also included in this step. Second, some methods are needed for processing the recovered materials into usable products. The last one is market opportunities for the reprocessed materials [7].

#### 2.3 Background in Composite Materials

Composites are one kind of structural materials. They are generally used because of their better desired properties which could not be obtained by either of the constituent materials acting alone. A composite is formed when two or more materials are combined as a macroscopic structural unit. A common example of a composite is the strawreinforced clay bricks that had been used since ancient times. However, the first reason for that was presumed to be based on the need to prevent cracking of the clay during drying, rather than on structural reinforcement. Later, several structural composites such as steel-reinforced concrete, polymer reinforced with glass fibers and many other materials were developed [25].

Three basic components in a fiber-reinforced composite are polymer matrices, reinforcements and interfaces. Composite structural elements are now used in a variety of components for automotive, aerospace, marine, and architectural structures, in addition to consumer products such as skis, golf clubs, and tennis rackets [26].

#### 2.3.1 Matrix

The matrix is the material that holds the reinforcement together. Usually, it has lower strength than the reinforcement. The main functions of the matrix are (i) to provide the fiber protection from exposure to the environment as well as protect against fiber abrasion, (ii) to transfer and distribute stress load onto the fiber, and (iii) to separate and keep fibers in the desired location and orientation. In many cases, the matrix contributes some desired properties such as ductility, toughness, or electrical insulation. Additionally, it causes the fibers to act as an aggregation in resisting deformation or failure under load,

along with limiting the maximum temperature to which the composite can be exposed. Several materials can be used as the matrix layer in composites, such as polymers, metals, and ceramics, depending on the specific requirements [25, 27].

In general, polymeric matrices or plastic materials are in the highest commercial use, primarily because of the ease of processing with these materials. Plastics can be simply divided into two groups: thermoplastics and thermosets.

In a thermoplastic polymer, the molecules are held together with secondary bonds (intermolecular forces) such as van der Waals and hydrogen bonds. At elevated temperatures and pressure, these bonds can be temporarily broken, and allow the molecules to move or flow into new positions. After cooling down, the bonds are restored and result in a new solid shape. Therefore, a thermoplastic polymer can be heat softened, melted, and reshaped as many times as desired.

Thermoplastic polymers in composites have high impact strength and higher resistance to failure, which provide a better withstanding of matrix microcracking in composite laminates. However, compared to thermoset matrices, thermoplastic polymers have developed slowly due to their high melt or solution viscosity, causing difficulty in incorporation of continuous fibers into the matrix [26].

In a thermoset polymer, the molecules are chemically joined together by crosslinks, forming a rigid, three-dimensional network structure. Once these cross-links are formed during the polymerization reaction, subsequent heating (if high enough) will not melt these plastics but damage them. So they cannot be reformed by softening and remolding under the application of heat and pressure. Thermoset polymers in composites generally provide thermal stability, chemical resistance, good adhesion, and relative ease of fabrication. They also show less creep and stress relaxation than thermoplastic polymers. However, they have some disadvantages, for example, limited storage life (before the final shape is molded) at room temperature, long fabrication time in the mold, and low strains to failure causing low impact strength [26].

## 2.3.2 Reinforcement

Reinforcing fibers in the composite materials are the main load-carrying members. They provide high strength and modulus as well as resistance to bending and breaking under the applied stress. There are three types of fibrous reinforced composites, namely particulate, continuous and discontinuous fibers [28].

Particulate composites are made of different sizes and shapes of particles randomly dispersed in the matrix. Due to the random distribution of particles, these composites can be considered as quasi-homogeneous on a scale larger than the particle size. Particulate composites may contain either nonmetallic or metallic particles in a nonmetallic or metallic matrix. Examples of this type are concrete and glass reinforced with mica flakes.

Continuous fiber composites are reinforced by long continuous fibers and are the most efficient for stiffness and strength. They also have greater strength and modulus in the fiber axis direction and generally lack physical strength in the transverse direction. The continuous fibers can be all parallel, can be oriented at right angles to each other, or can be oriented along several directions.

Discontinuous composites consist of short fibers or whiskers in the reinforcing phase. These short fibers can be either all oriented along one direction or randomly oriented. In a discontinuous fiber composite, the stress along the fiber is not uniform. The length ( $\ell$ ) to diameter (d) ratio of the fiber, commonly called the aspect ratio ( $\ell$ /d), determines the level of strength that the composite will reach. If the fiber is shorter than the critical length, the composite will fail at a low strength level [27, 28]. The principal fibers in commercial use are various types of glass and carbon [26].

#### 2.3.3 Interface

An interface between the fiber and matrix is a bonding at the interface due to adhesion between the matrix and the fiber. It is a key to determining the potential properties of the composite, since the stresses loading on the composites are transferred from the matrix into the fiber across the interface.

As a result, a strong interfacial bond between the fiber and matrix is needed. So the matrix must be capable of developing a mechanical or chemical bond with the fiber. Normally, fibers are coated with a coupling agent that will form a bond between the fiber and the matrix and provide improvement in the interface conditions [27]. Moreover, the fiber and matrix materials should also be chemically compatible, so that undesirable reactions do not take place at the interfaces [25].

Other components that may also be found in a composite material are coupling agents, coatings, and fillers. Coupling agents and coatings, as mentioned before, are applied on the fibers to improve their wetting with the matrix, thus promoting bonding

across the fiber/matrix interface. Fillers are added in some polymeric matrices mainly to lessen cost and improve the composite's dimensional stability [26].

#### **2.3.4 Prediction of Properties**

There are many factors that influence the properties of composites, such as fiber type, length of fiber, aspect ratio (length to diameter ratio), fiber alignment, fiber volume, interface, component matrix, processing procedures and environmental effects.

Several methods have been developed for the prediction of properties such as tensile strength and tensile modulus for fiber reinforced thermoplastics. However, the strength and toughness are more difficult to predict. For long fiber reinforced composites, the calculation is much more simple, owing to an assumption that all fibers are working at the highest efficiency and the load acting on the continuous reinforced material is shared between the matrix and all fibers, with the maximum tensile strain being reached in the fibers. It is also assumed that the bond between the fiber and the matrix is very good. Thus, tensile modulus and tensile strength can be predicted as shown in equations 1 and 2 respectively [29].

$$E_{c} = E_{f} \varnothing_{f} + E_{m} \varnothing_{m}$$
(1)

$$\sigma_{\rm c} = \sigma_{\rm f} \mathcal{O}_{\rm f} + \sigma_{\rm m} \mathcal{O}_{\rm m} \tag{2}$$

Where: E = tensile modulus

 $\sigma$  = tensile strength

$$\emptyset$$
 = volume fraction

and subscripts c = composite f = fiber m = matrix

However, these predicted values are likely to be higher than actual values because of the present of additional stresses, which are not considered in the assumption mentioned above.

As compared to long fiber reinforcement, the properties of short fiber reinforced thermoplastics are more difficult to predict, since the short fiber reinforcements generally distribute in a three-dimensional orientation in the matrix, and there is diversity in the length of the fibers. Tensile forces are transferred from the matrix to the fibers through the fiber ends and through the cylindrical surfaces of the fiber near the ends. For continuous fibers, the fiber length is greater than the length over which the stress transfer occurs; thus the effect of the fiber ends can be discarded. This cannot be done for short fiber reinforced composites.

When predicting the tensile modulus for short fiber reinforced composites, the length correction factor must be considered. Therefore, the tensile modulus of the composite can be calculated through equation 3.

$$E_{c} = \eta \ell E_{f} \mathscr{O}_{f} + E_{m} \mathscr{O}_{m}$$
(3)

Where:

(4)

$$\eta_{\ell} = \left[\frac{1 - \tanh(\beta \ell / 2)}{(\ell / 2)}\right]$$

 $\ell$  = fiber length

$$\beta = \left[\frac{2\pi G_m}{E_f A_f \ln(R/r)}\right]^{1/2}$$
(5)

Where: G = shear modulus of the matrix
r = radius of the fiber
R = mean separation of the fibers normal to their length
A<sub>f</sub> = the cross-sectional area of all the fibers in the composite

Moreover, the tensile modulus also depends on the fiber aspect ratio ( $\ell$ /d). A

number-average fiber length should be taken into account.

For tensile strength prediction for short fiber reinforcement, equation 6 can be utilized with an additional factor of average tensile stress on the composite.

$$\sigma_{\rm c} = \sigma_{\rm m} \varnothing_{\rm m} + \sigma_{\rm f} \varnothing_{\rm f} \tag{6}$$

Where:  $\sigma_f$  = average fiber stress

$$=\frac{1}{\ell}\int \sigma_f(x)dx$$

If tensile stress is built up from the fiber ends in a non-linear way, then the tensile strength of the fiber can be calculated by:

$$\sigma_{f} = \sigma_{fc} \left[ 1 - (1 - \beta) \frac{\ell_{c}}{\ell} \right]$$
  
for  $\ell = \ell_{c}$  (7)

Where:  $\sigma_f$  = tensile stress in a continuous fiber in same matrix

under the same loading conditions

 $\sigma_{f^{\text{sc}}}$  = average stress in the discontinuous fiber within a

distance  $\ell/2$  of either end.

 $\ell_{\rm c}$  = critical fiber length

When the fiber length is greater than the critical fiber length, it is assumed that the fiber failure occurs when  $\sigma_f = \sigma_{f\alpha}$ . Substituting equation 7 in equation 6 gives equation 8 as

$$\sigma_{c} = \sigma_{f} \left[ 1 - (1 - \beta) \frac{\ell_{c}}{\ell} \right] + \sigma_{m} \phi_{m}$$
(8)

Comparing equation 2 to equation 8, it can be seen that discontinuous fibers result in less stress than continuous fibers. If the length of fibers in the matrix is shorter than the critical fiber length, the fibers will not be efficient in supporting the load, thus the failure will take place at the interface.

It is very difficult to predict the impact strength resistance of short fiber reinforced composites. If brittle fibers are added to a ductile matrix, the impact strength of the composite will decrease as the fiber content increases. This is because the matrix is bound by the fibers and cannot deform to absorb the impact load. The failure depends on the ability of a material to transfer stress through its structure. However, the improvement in adhesion enhances impact strength by allowing stress to be transferred to the fibers so that the impact is spread over a larger area [30]. In addition, the stiffness of short fiber reinforced thermoplastics depends on fiber length and/or dispersion, volume fraction of fibers, the stress transfer efficiency of the interface and fiber orientation [31].

#### **2.3.5 Natural Reinforced Thermoplastics**

Recently, wood fiber reinforced polymer composites have received substantial attention both in the literature and in industry. This is because wood fibers are strong, light-weight, non abrasive, non hazardous, cheap and plentiful as well as renewable. As reinforcing agents, wood fibers can alleviate the increase in cost and potential shortage of plastics and provide desired properties to satisfy the high demand for inexpensive highperformance building materials [17]. Since wood fibers are a kind of short fibers, they are classified as discontinuous fibers. Addition of short fiber reinforcement to thermoplastic materials can be used to enhance physical properties and performance characteristics.

Wood fiber composites can be made by extrusion, compression, or injection molding to form a variety of products that can be used in packaging, paper products, building materials, automobile parts, etc. [32].

The different in polarities of the fiber and the matrix result in poor bonding between these two phases. The poor bonding becomes more of a problem when the polymer matrix shrinks due to changes in temperature and thus leaves gaps between the two components. Another problem in the incorporation of fibers into the thermoplastic matrix is the interfiber hydrogen bonding of the fibers which tends to hold them together, leading to poor dispersion of the reinforcements in the composites [17]. Technically, the enhancement of interfacial adhesion can be achieved by one of the following methods: fiber modification, interface-active additives, and matrix modification [16].

#### 2.4 Prior Research

Several researchers have studied the properties of composites of polymer matrices with reinforcements from natural resources like cellulose fibers, wood fibers, and paper fibers. Some of those works are summarized as follows. As mentioned before, the different nature of the polymer matrix and the fiber reinforcement causes a disadvantage in the properties of the composite. Thus, research was also conducted to investigate the effect of additives as well as the effect of fiber treatments on improving the adhesion between the fibers and matrix.

Mitchell, Vaughan and Willis studied the mechanical properties of paper and high density polyethylene compared to those of glass-filled high density polyethylene. It was concluded that the cellulose-filled laminate compared well with the glass-filled laminate in mechanical properties. However, it would be better if the cellulose fibers were distributed uniformly in the matrix, and if bonding were enhanced. Further, acetylation or crosslinking of the fibers with formaldehyde could enhance the water resistance of the cellulose-reinforced polyethylene [33].

A study of HDPE and cellulose-based filler composites by Klason, Kubat and Stromvall found that the cellulose fibers did not show any significant support in the composite. The reasons might be fiber damage during compounding, poor fiber dispersion and poor adhesion between the two phases [34]. Then, to solve the above problem, Dalvag, Klason and Stronvall conducted research with adding additives to the composite. They found that several additives helped in promoting the dispersion of fibers but only maleic anhydride modified polypropylene (MAPP) promoted the adhesion of the composite [35].

Kokta, Deneault and Beshay studied the mechanical properties of aspen wood fibers in the form of chemithermomechanical pulp (CTMP) reinforced polyethylene. Compared to mica and glass reinforcements, the aspen fibers showed better mechanical properties, including polyethylene's overall properties [36].

Zadorecki and Flodin found that the cellulose fibers increased the tensile strength and modulus of unsaturated polyesters reinforced with cellulose fibers. But properties were lowered when exposed to water because the adhesion between the phases was not strong during wet conditions [37].

Yam et al investigated the mechanical properties of composites of Aspen fiber (a hardwood), and spruce fiber (a softwood) with recycled HDPE from post-consumer milk bottles. It was found that the tensile strength and elastic modulus of composites made from recycled HDPE were about the same as those of composites made from virgin HDPE. No significant difference in mechanical properties between the hardwood composites and the softwood composites was found [38].

Gogoi investigated the effects of fiber pre-treatment, screw configuration of a twin-screw extruder, and compounding temperature on the mechanical properties of composites. Granulated HDPE milk bottles were used as the polymer matrix, while aspen wood fiber was used as the filler. The results showed that tensile strength decreased with an increase in fiber content. The effect of fiber pre-treatment in term of tensile and flexural yield strength showed that acetylated and untreated aspen fibers were better than heat treated. The mechanical properties of the composite are sensitive to screw configuration and temperature [32].

Kalyankar tested the effect of ethylene vinyl acetate copolymer incorporated in a composite of Spruce fibers and regrind post consumer milk bottles. The results showed improvement in impact strength but not in tensile strength [39].

Nieman studied the mechanical properties of recycled HDPE and wood fiber composites. Five additives were used, low density polyethylene (LDPE), stearic acid, chlorinated polyethylene, maleic anhydride modified polypropylene (MAPP) and ionomer modified polyethylene. From tensile strength and modulus, only maleic anhydride modified polypropylene showed potential for improving adhesion between the polymer matrix and wood fibers. Ionomer modified polyethylene also displayed some positive results, while the others were determined ineffective for enhancing properties [31].

Later, Maria D. Keal conducted research on the effect of dual additive systems on the mechanical properties of composites of wood fibers and recycled HDPE milk containers. The additive systems were two of the stearic acid, maleic anhydride modified polypropylene and ionomer modified polyethylene; thus three combinations were used. The use of additives did improve tensile properties and creep but decreased impact strength. Only the stearic acid/ionomer additive system did not reduce impact strength. Compared to the effect of single additive, none of the dual additive systems provided significantly better improvement [40].

JoAnna Childress studied composites of 40% Aspen fibers in a recycled HDPE matrix with the inclusion of additives. Four additives were investigated in this study (ionomer modified polyethylene (Surlyn), maleic anhydride modified polypropylene (MAPP) and two low molecular weight polypropylenes (Proflow 1000 and Proflow

3000). The inclusion of MAPP in the composite improved its mechanical properties overall. Surlyn offered some positive effects but not at statistically significant levels, whereas both Proflows decreased the mechanical properties of the composites [41].

Chtourou et al studied composites of recycled mixed polyolefins (95% PE and 5% PP) and a mixture of 45% spruce, 45% fir and 10% poplar produced by chemicothermomechanical pulp (CTMP). The composites were made by injection molding and compression molding. The results showed that the greater amount of fibers, the higher the Young's modulus and the strength at yield. At 30% by weight of fibers, Young's modulus increased 150%. By fiber surface modification with acetic anhydride and phenol formaldehyde, 10% treated fiber composites displayed an improvement in tensile strength as well as lower water sorption than 10 % non-treated fiber composites [9].

Raj et al studied mechanical properties of organic fibers from blending peanut hulls and pecan shells in reinforced polyethylene composites. Variations in compression molding temperature and fiber concentration, and the effect of polyisocyanate as a coupling agent were studied. They investigated several mechanical properties including tensile strength, elongation, fracture energy, modulus, and impact strength. It was found that the tensile strength decreased as the fiber content increased in the untreated fiber composites because of the poor bonding between fiber and polymer. Polyisocyanate was found to improve tensile strength, but it had no effect on the modulus of the composites. Both untreated and treated composites had low impact strength. They summarized that composite matrix modification would be necessary to maintain or improve impact strength [42].

A comparison between two mixing methods, melt-mixing and solution-mixing, of short pineapple leaf fiber (PALF) reinforced low density polyethylene was made by George et al. It was found that solution-mixed composites provided better tensile properties than melt-mixed composites. The effect of fiber content was also evaluated. As the fiber content increased, the mechanical properties increased while the elongation at break decreased. Longitudinally oriented composites expressed better properties than randomly and transversely oriented composites. Compared to other cellulose-fiber reinforced low density polyethylene, it was indicated that PALF showed superior performance [18].

PALF reinforced polyester composites were investigate by Devi, Bhagawam, and Thomas. Again, the effect of fiber content was evaluated, as well as fiber length and fiber surface modification. As fiber content increased, tensile strength, Young's modulus, elongation at break and impact strength also increased. The optimum fiber length in this study was at 30 mm [43].

Oksman and Clemons (1998) evaluated the mechanical properties of wood fiberpolypropylene composites. Since polypropylene has poor impact strength especially at low temperatures, three impact modifiers (two different ethylene/propylene/diene terpolymers (EPPM) and maleated styrene-ethylene/butylene-styrene triblock copolymers (SEBS-MA)) were investigated. All three agents were found to improve impact strength of the composites. Addition of maleic anhydride modified polypropylene (MAPP) as a compatibilizer was also studied. MAPP alone did not effect the impact strength of the composite but it showed a positive effect when used together with those three elastomers [44].
#### Chapter 3

#### **EXPERIMENTAL DESIGN**

#### 3.1 Materials

The matrix material used in this study was high density polyethylene (HDPE) from post-consumer containers of several kinds of household supplies such as detergent bottles, oil, and beverage bottles which were provided by Granger Recycling Center. All non-food bottles were labeled with "made of 25% or more post-consumer resin". All caps were removed and, without removal of the labels, the bottles were cleaned with warm water and cut into small pieces (about a quarter to one-eighth of the bottle) and then airdried. Next, they were ground into granulates by using the granulator machine (B.T.P. Granulator Double Angle Cut, Polymer Machinery, Granulator Div., Berlin, Connecticut). The resins were conditioned at  $23 \pm 2$  °C and  $50 \pm 5$  %RH for about 40 hours before being used as the matrix material in the combining process.

High density polyethylene polymer has a melting point around 130 - 135°C and a glass transition temperature of -120 °C. The density of HDPE is around 0.94-0.96 g/cc. It is a highly crystalline structure (between 65-90% crystallinity) which promotes high tensile strength, better stiffness, and good moisture barrier properties. It is a hydrophobic and nonpolar thermoplastic.

Aspen hardwood fibers were employed as the reinforcing filler in this study. Aspen is in the genus *Populus* and divided into Bigtooth aspen, *Populus grandidentata*, and Quaking aspen, *Populus tremuloides*. Hardwoods are different from softwoods in that hardwoods have a vessel element while softwoods do not [45]. Generally, most

hardwoods are composed of four types of cells, namely: fibers, vessel segments, axial parenchyma, and transverse parenchyma. Fibers are polar and hydrophillic. The cell walls contain approximately 40-60% cellulose and 20-30% lignin.

Aspen hardwood fibers in this experiment were in the form of thermomechanical pulp (TMP). In this mechanical pulping process, wood chips were fed into refiner at about 120 °C, which ground and defibrillated the chips into fibers. There is only a minimum amount of damage to the lignin or hemicellulose during this pulping process, so the wood fibers retain nearly all of their lignin and natural waxes, which can help in better dispersion of wood fiber into the nonpolar hydrocarbon polymer matrix [46].

The fibers were also conditioned for at least 40 hours at  $23 \pm 2$  °C and  $50 \pm 5$  %RH prior to the testing.

### 3.2 Methods

#### 1. Test specimen preparation

The composite materials were made by combining the resins and wood fibers using a Baker Perkins Model ZSK-30, 30mm, 26:1 co-rotating twin-screw extruder (Werner & Pfleiderer Corporation, Ramsey, New Jersey).

The extruder consists of three parts, feed zone, compression zone and metering zone. The feed zone, which is attached below the feed hopper, functions as a channel for the resins to get into the barrel. The resins start melting in the compression zone and then flow to exit through the die at the metering zone. The compounding speed of the extruder was set at 120 rpm and the temperature of all 6 processing zones was set at 150°C. Water was used as a coolant to keep a consistent temperature throughout the process. Six treatments, as shown in Table 4, were performed.

	Ground bottle	Fiber
Treatments	(% by weight)	(% by weight)
1	100	0
2	90	10
3	80	20
4	70	30
5	60	40
6	60% virgin HDPE resin	40

#### Table 4. Sample treatments

\* Exact compositions (% by weight) from the experiments are shown in Appendix A

HDPE resins were fed into the extruder at zone 1 and allowed to run through the extruder at least 15 minutes before combining the fibers to minimize contamination with the cleaning resin which may be retained in the machine. Then the wood fibers were fed into the last zone to prevent fiber damage from high temperatures in the process. The extrudate exited from the die and was cut into approximately 4-inch long pieces.

The extruded materials were compressed into sheets using a compression molding machine (Carver Laboratory Press, Model M, Fred S. Carver Inc., Menomonee Falls, Wisconsin). About three pieces of the extrudate were put between a frame, which was topped and bottomed with Mylar sheets and two chrome plates. (Mylar sheets made from polyethylene terephthalate (PET) help in preventing the melted material from sticking to the plates.) There were two sizes of frames, 15x15x0.25 cm for the tensile property test samples, and 12.7x12.7x0.3175 cm for the impact test and water absorption test samples.

The "sandwich" configuration was heated up to 150 ° and held under a pressure of 30,000 psi for approximately 10 minutes. Then, the sample was cooled down with cooling water to room temperature. The molded sheet was kept at  $23 \pm 2$  °C and  $50 \pm 5$ 

%RH for at least 40 hours to obtain a uniform distribution of internal stress before cutting. The sheets were cut into the desired shape for each test, such as a dumbbell shape for tensile testing and a rectangular shape (0.5x2.5x0.125 in) for Izod impact testing, and water absorption testing.

#### 2. Tensile testing

ASTM D638-91, Tensile Standard Test Method for Tensile Properties of Plastics, was followed. The specimens were cut into a dumbbell shape (type I) using a Tensilkut, Model 10-13 (Tensilkut Engineering Division, Sieburg Industries, Inc., Danbury, Connecticut).

Using an Instron testing machine, Model SFM-20 (United Calibration Corp., Huntington Beach, California) with a load cell capacity of 1000 lbs, the results of tensile strength, % elongation, modulus of elasticity and yield strength were calculated using the incorporated computer program. The results were then analyzed using the SPSS program for One Way ANOVA and Least Significant Difference (LSD). The comparisons between compositions were analyzed by the LSD method at the 95% confidence level.

## 3. Izod impact strength testing

By following ASTM D256-92, Standard Test Methods for Impact Resistance of Plastics and Electrical Insulating Materials, Izod impact strength was determined. The specimens were cut in the dimensions of  $0.5 \times 2.5 \times 0.125$  in and notched by a TMI notching cutter. (The angle of the notch was  $22.5^{\circ} \pm 0.5^{\circ}$  and the depth of the notch was 0.1 inch)

At least ten specimens were tested using a TMI 43-I IZOD impact tester with a 5lb pendulum. They were held as a vertical cantilever beam and broken with a single swing of the pendulum. When the sample failed, the type of failure was classified following the ASTM standard.

The statistical analysis and the comparison between compositions were analyzed by the same method as described above.

## 4. Water absorption testing

ASTM D570-81 was followed with some adaptation. Composite material samples were cut into 0.5x2.5x0.125 in dimension, and the edges were smoothened with sand paper to prevent absorption from the uneven surface. The specimens were conditioned at  $23 \pm 2$  °C and  $50 \pm 5$  %RH no less than 48 hours prior to the testing. The samples were immersed in water at room temperature and allowed to reach equilibrium in about 2 months. The change in weight was monitored and used to calculate the % water absorption. Before weighing, the samples were wiped of surface water with filter paper.

Percent water absorbed was calculated when equilibrium was reached by the formula:

% water absorption = <u>gain in weight (g)</u> x 100 original wt. (g)

#### Chapter 4

#### **RESULTS AND DISCUSSION**

The mechanical properties of the composite samples were evaluated by the test methods described in the previous chapter. At least five specimens of each treatment were tested for tensile properties and water absorption. Twelve specimens of each composition were tested for Izod impact strength.

#### 4.1 Tensile Strength

Table 5 presents the tensile strength results for various fiber amounts in the Aspen wood fiber reinforced recycled HDPE composites. It was found that the tensile strength of the composites had a tendency to decrease as the fiber content increased (Figure 1). The one-way analysis of variance method (ANOVA - see Appendix B for Statistical Analysis results) confirmed that there was a significant difference in the tensile strength between the treatments. However, the result by the least significant difference method (LSD) at the 95% confidence level showed no significant difference between 10%, 20% and 30% fiber content, and no significant difference between 30% and 40% fiber content. This might be affected by the wide range of the tensile strength values of the 20%, 30% and 40% samples (see exact data in Table 12 in the Appendix A).

In comparing matrices of recycled HDPE and of virgin resin at 40% wood fiber, it was found that the tensile strength of the composite of virgin HDPE was higher than that of the recycled one.

Table 5. Tensile Strength (lbs/in<sup>2</sup>)

Conditions	Average	SD
0% fiber (100% ground	3528.5714	49.7187
recycled bottle)		
10% fiber + 90% ground	2926.1429	77.9090
recycled bottle		
20% fiber + 80% ground	2872.8333	238.6901
recycled bottle		
30% fiber + 70% ground	2673.6667	251.9727
recycled bottle		
40% fiber + 60% ground	2377.1667	343.6780
recycled bottle		
40% fiber + 60% virgin	3332.8333	460.3540
HDPE resin		



Figure 1. Tensile Strength

40%\* = 40% wood fiber + 60% virgin HDPE resin

#### 4.2 Yield Strength

The yield strength results of the test samples are shown in Table 6 and Figure 2. Similar to the results for tensile strength, the yield strength of the composites tended to decrease as the fiber content increased.

The ANOVA result, again, showed there was a significant difference in the yield strength between treatments. The LSD results indicated no significant difference between 10% and 20% fiber content, and between 30% and 40 % fiber content. However, the group of 10% and 20% had a significant difference in yield strength from the group of 30% and 40%.

Table 6. Yield Strength (lbs/in<sup>2</sup>)

Conditions	Average	SD
0% fiber (100% ground recycled bottle)	3174.6986	203.2025
10% fiber + 90% ground recycled bottle	2605.5971	301.5207
20% fiber + 80% ground recycled bottle	2385.7667	579.8986
30% fiber + 70% ground recycled bottle	1842.5500	510.9522
40% fiber + 60% ground recycled bottle	1770.0757	309.7499
40% fiber + 60% virgin HDPE resin	2391.0650	315.0880

Furthermore, the difference in yield strength was significant for the different polymer matrices. The 40% wood fiber composite with the recycled HDPE matrix had much lower yield strength than the 40% wood fiber composite with the virgin HDPE matrix.

The exact data for yield strength testing and the statistical analysis results can be seen in Appendices A and B respectively.

Figure 2. Yield Strength



40%\* = 40% wood fiber + 60% virgin HDPE resin

#### 4.3 Percent Elongation

The test results for percent elongation of wood fiber reinforced recycled HDPE composite systems are presented in Table 7 and Figure 3.

By ASTM standards based on the shape of the stress-strain curve, the % elongation of 100% recycled HDPE was defined as the % elongation at yield while that of the rest was defined as the % elongation at break. It was obviously that the elongation was strongly dependent on the fiber content. It decreased tremendously with addition of reinforcement even at only the 10% level.

#### Table 7. Percent Elongation

Conditions	Average	SD
0% fiber (100% ground	43.0400 <sup>1</sup>	17.9953
recycled bottle)		
10% fiber + 90% ground	$4.8800^2$	1.3025
recycled bottle		
20% fiber + 80% ground	5.0043 <sup>2</sup>	1.6680
recycled bottle	· .	
30% fiber + 70% ground	2.2786 <sup>2</sup>	0.9684
recycled bottle	_	
40% fiber + 60% ground	1.9043 <sup>2</sup>	0.7266
recycled bottle		
40% fiber + 60% virgin	1.3433 <sup>2</sup>	0.4852
HDPE resin		
1 - 0/ alongstion	-4	

1 = % elongation at yield

2 = % elongation at break

According to the LSD statistical testing, there was no significant difference between the conditions for the various fiber contents in the recycled matrix. However, Figure 3 shows a slight trend of declination as the fiber amount increased. In addition, no significant difference was found between the recycled and virgin HDPE matrix.



Figure 3. Elongation

40%\* = 40% wood fiber + 60% virgin HDPE resin

#### 4.4 Modulus of Elasticity

Table 8 and Figure 4 demonstrate the results for modulus of elasticity for thewood fiber reinforced HDPE composite systems.

Unlike tensile strength, yield strength and % elongation, the modulus of elasticity in the test specimens tended to increase with an increase in the fiber fraction. Statistical analysis at the 95% confidence level by the LSD method confirmed that the modulus was affected by the incorporation of wood fiber.

On the other hand, the different polymer matrices had no effect on the modulus of the composite (no significant difference was found by the LSD method).

Conditions	Average	SD
0% fiber (100% ground	91.5714	37.5449
recycled bottle)		
10% fiber + 90% ground	211.5714	28.3482
recycled bottle		
20% fiber + 80% ground	183.1667	61.4242
recycled bottle		
30% fiber + 70% ground	281.2857	91.2080
recycled bottle		
40% fiber + 60% ground	290.4286	79.8850
recycled bottle		
40% fiber + 60% virgin	393.1667	98.4630
HDPE resin		

 Table 8. Modulus of Elasticity (KPsi)





40%\* = 40% wood fiber + 60% virgin HDPE resin

## 4.5 Izod Impact Strength

The results of Izod impact strength testing are tabulated in Table 9. Figure 5 shows a trend of slight increase in impact strength with an increase in amount of incorporated fiber. However, no significant difference was found at the 95% confidence level by the LSD method except for the pair of 10% and 30%. Moreover, the impact strength was reduced at 40% fiber content.

At 40% wood fiber, the impact strength of the virgin matrix system was much lower than that of the recycled matrix system.

Conditions	Type of failure	Izod impact strength (ft-lb/in)			
		Average	SD		
0% fiber (100% ground recycled bottle)	Partial	0.8888	0.0698		
10% fiber + 90% ground recycled bottle	Partial	1.1149	0.1051		
20% fiber + 80% ground recycled bottle	Partial	1.2318	0.0715		
30% fiber + 70% ground recycled bottle	Partial and Complete	1.2786	0.2052		
40% fiber + 60% ground recycled bottle	Partial, Hinge, and Complete	1.2225	0.2347		
40% fiber + 60% virgin HDPE resin	Hinge and complete	0.8991	0.1414		

 Table 9. Izod impact strength





40%\* = 40% wood fiber + 60% virgin HDPE resin

#### 4.6 Water Absorption

Table 10 shows the percent water absorption in term of % increase in weight for each condition. The effect of fiber content in the composite materials is illustrated in Figure 6.

As the percent fibers increased, the gain in weight due to the water absorption increased. Results from ANOVA (see Appendix B) showed that there was a significant difference in these five conditions, which means the amount of fiber incorporated has an effect on water absorption. The LSD method at the 95% confidence level confirmed that there were significant differences between the 10%, 20% and 30% fiber content, but no difference between 30% and 40%. (Details of the data for water absorption testing and the statistical analysis are shown in Appendices A and B.) There was also a significant difference in % water uptake between recycled and virgin polymer matrices.

Conditions	Average	SD
0% fiber (100% ground	0.0891	0.0082
recycled bottle)		
10% fiber + 90% ground	1.5705	0.2598
recycled bottle		
20% fiber + 80% ground	3.4039	0.7856
recycled bottle		
30% fiber + 70% ground	9.3568	2.7460
recycled bottle		
40% fiber + 60% ground	9.5649	1.6313
recycled bottle		
40% fiber + 60% virgin	7.2532	1.5822
HDPE resin		

Table 10. Percent increase in weight due to the water absorption.





40%\* = 40% wood fiber + 60% virgin HDPE resin

#### 4.7 Discussion

There are many factors that influence the properties of composites, such as fiber type, length of fiber, aspect ratio (length to diameter ratio), fiber alignment, interface, matrix resin morphology, processing procedures and environmental effects.

#### 4.7.1 Tensile properties

Basically, the purpose of using fiber reinforcement is to improve the strength of the polymer matrix [30]. However, weak adhesion between the polymer and filler can cause difficulty in development of a composite property.

Since the wood fiber and the polymer matrix of the composite samples had a difference in polarity, the interface of the composite was poor. Therefore, the tensile strength and yield strength in this experiment were decreased with increasing fiber content.

The wide range of tensile properties in the composition, which can be seen in the high standard deviations, may result from poor fiber dispersion. The high viscosity of the matrix during the composite fabrication and the polarity of the fiber, which tend to hold the fibers together, may cause poor distribution of fibers. Instead of spreading out evenly in the polymer, the fibers were more likely to crowd randomly in the matrix, leading to lack of uniformity of the composite systems. Thus, the more the fiber fraction, the higher was the variation.

In most cases, no significant difference was found between the 10% and 20% wood fiber samples, as well as between the 30% and 40% wood fiber samples. It could be that somewhere between 20% and 30% is a critical point that affects the difference in the

properties, or it could be simply that the large standard deviations obscure the smaller differences.

In comparing the recycled HDPE to the virgin resin at the same fiber content, except for the % elongation, most tensile properties of the composite with virgin HDPE matrix were superior to those of the composite with recycled HDPE. This was probably because the virgin HDPE itself had higher tensile properties than the recycled HDPE from household used bottles (Table 11).

It was also found that percent decrease of tensile strength, yield strength, and % elongation in recycled HDPE matrix is higher than those in virgin HDPE matrix. This might show that the recycled HDPE matrix in the composite provided worse properties than the virgin HDPE matrix in the composite. However, it is very difficult to make an exact comparison since the collected bottles, by their nature, are a complex mixture of blow molding grades of HDPE.

Table 11. Comparison of mechanical properties of virgin HDPE and recycled HDPE resins.

Mechanical	V	/irgin HDPE	3	Recycled HDPE			
properties	0%	40%	%	0% fiber	40%	%	
	fiber*	fiber	change		fiber	change	
Tensile Strength (Psi)	3882	3332.83	-14.15	3258.57	2377.17	-27.05	
Yield Strength (Psi)	3850.11	2391.07	-37.90	3174.7	1770.08	-44.24	
Modulus (KPsi)	110	393.17	257.43	91.57	290.43	217.17	
% Elongation	26.96	1.3433	-95.02	43.04	1.9043	-95.58	
Impact Strength	1.73	0.8991	-48.03	0.8888	1.2225	37.55	
(π-1b/1n)							

\* Source from previous experiment by Chotipatoomwan (1998) [47].

#### 4.7.2 Impact strength

The trend towards increasing impact strength with a higher fiber content was not the result which was expected from a ductile matrix such as HDPE. The addition of wood fiber is generally found to reduce the impact strength of such composites [29].

However, the fracture behavior of the composites can be mainly determined by the properties of the polymer matrix, because most of the energy required to break the materials is used for straining and fracturing of the polymer matrix [48].

For brittle matrices, an incorporation of the dispersed fillers increases the surface energy of material fracture, which means that the filler can improve the impact strength of the composites. In contrast, the filler reduces the surface energy in the non-brittle matrices because of the decrease of the volume portion of matrix in the plastic zone. As a result, the impact strength decreases with the addition of filler [47].

The matrix of the composite samples in this experiment is of the non-brittle type. Therefore, how the addition of fiber can increase the impact strength of the composite was not clear. A possible reason could be that the filler might absorb the extra energy required to pull fibers out of the matrix during crack propagation. During the impact strength testing, the type of failure of most test samples was evaluated as partial and hinge break, rather than the complete break type. The upper and lower parts of the notch of the samples were observed to be held together by groups of fiber in the composite materials. This may contribute to an increase in impact strength of the samples.

Another possible reason may be related to the fact that there is a correlation between the work of fracture and the impact strength for ductile polymer. It was assumed

that a decrease of adhesion between matrix and filler might cause an increase in the relative elongation at rupture and thus increase certain impact strength.

#### 4.6.3 Water absorption

Owing to their hydrophillic characteristics, wood fibers tend to absorb water. However, the polymer matrix that covers these fibers should play some role in preventing direct contact between the water and the fibers, so the absorption should happen only with the water that permeates through the plastic layer.

In this study, the samples were cut and edges were smoothed with sandpaper before immersion into water. However, this did not protect the fibers at the cut edges from exposure to the water. Therefore most of the water uptake was assumed to be from absorption by the fibers at the edge.

It can be seen that the effect of water absorption in the composite is strongly dependent on the fiber fraction. A tremendous increase in % water absorption occurred at 30% fiber.

Many polymeric matrix composites are able to absorb moisture from the surrounding environment. Not only would the weight of the composite be increased, dimensional changes and some properties might be affected as well. If this will result in a defect in an application, the composite surface must be defended from water diffusion by proper paints or coatings.

#### Chapter 5

## **CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1 Conclusions**

An increase of wood fiber content did not improve the tensile properties of the composite made of Aspen wood fiber and recycled HDPE used household bottles. One reason for that might be the poor bonding between the two main components in the materials. Overall, the amount of wood fibers incorporated in the composite systems had an effect on their properties.

The tensile strength, yield strength and % elongation decreased with an increase in the fiber concentration. On the other hand, the modulus and impact strength tended to improve with increase in the fiber content.

The % water uptake also increases with an increase in % fiber content. Finally, most properties were worse in the recycled HDPE matrix composite than in the virgin HDPE matrix composite, but this may be due to differences in the HDPE resins themselves, rather than to the effect of recycling.

### 5.2 Recommendations for future research

In this experiment, an improvement in tensile properties of the composite failed to result, due to the poor bonding between the matrix and the reinforcement. Therefore, the effect of coupling agents to improve the adhesion between the wood fiber reinforcement and the recycled HDPE used household bottles should be investigated.

Another issue is fiber treatment to develop a better distribution of fiber in the matrix. This method may be a factor for improving the mechanical properties of this composite system.

**APPENDIX A** 

.

Treatment	HDPE rate (g/min)	Fiber rate (g/min)	% HDPE	% wood fiber
1	29.82	-	100	0
2	26.08	3.12	89.32	10.68
3	24.97	5.98	80.68	19.32
4	14.50	6.46	69.18	30.82
5	10.67	6.68	61.50	38.50
6	9.92	6.51	60.38	39.62
	(virgin resin)		(virgin resin)	

Table 12. Exact composition (% by weight) of each treatment from the experiment.

ber + 60%	n HDPE	csin	Izod	Strength	(ft-lb/in)	0.823	0.785	0.937	0.861	0.779	0.779	0.996	0.922	0.730	0.914	1.025	1.238	0.8991	0.1414
40% fi	virgi	I	type	of	failure	c	c	c	c	c	J	c	Н	ပ	c	υ	c		1
ber + 60%	I recycled	oute	Izod	Strength	(ft-lb/in)	1.240	0.704	3.784*	1.146	1.446	0.996	1.146	1.360	1.472	1.360	1.238	1.339	1.2225	0.2227
40% fil	ground	ō	type	of	failure	Η	J	Р	Р	Р	c	c	Η	c	Ρ	Ρ	Ρ		100
ber + 70%	I recycled	ourie	Izod	Strength	(ft-lb/in)	1.126	1.382	1.382	1.193	1.183	1.333	1.659	1.360	1.434	1.099	6.781*	0.914	1.2786	0.2012
30% fil	ground	5	type	of	failure	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	С	С	С		
ber + 80%	l recycled	oure	Izod	Strength	(ft-lb/in)	1.240	1.278	1.193	1.344	1.268	1.117	4.503*	1.183	1.258	1.248	1.136	1.285	1.2318	0.0679
20% fil	ground		type	of	failure	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ		
ber + 90%	I recycled	OULIC	Izod	Strength	(ft-lb/in)	1.088	1.126	0.937	1.126	1.278	1.042	1.268	1.155	1.183	1.071	1.146	0.959	1.1149	0.1051
10% fi	ground		type	of	failure	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ		
fiber	% ground	can nonine)	Izod	Strength	(ft-lb/in)	0.823	0.899	0.974	0.816	0.816	0.929	0.967	0.816	0.847	0.884	0.877	1.017	0.8888	0.0698
%0	(100%	Iccycle	type	of	failure	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ	Ρ		
	Comolo	ardinec				1	2	3	4	5	9	7	80	6	10	11	12	average	SD

Table 13. Izod Impact Strength Data (ft-lb/in)

\* These numbers are discarded because they are very different from others.

	0% fiber	10% fiber +	20% fiber +	30% fiber +	40% fiber +	40% fiber +
Sample	(100% ground recycled bottle)	90% ground recycled bottle	80% ground recycled bottle	70% ground recycled bottle	60% ground recycled bottle	60% virgin HDPE resin
1	3346	2861	3045	2949	2834	3629
2	3184	3018	3179	2495	n/a	2849
3	3261	3018	2909	2434	2464	3498
4	3242	2812	n/a	2415	2118	2765
5	3251	2963	2485	2826	2714	n/a
6	3238	2900	2780	2923	2048	3301
7	3288	2911	2839	n/a	2085	3955
Average	3258.5714	2926.1429	2872.8333	2673.6667	2377.1667	3332.8333
SD	49.7187	77.9090	238.6901	251.9727	343.6780	460.3540
Maximum	3346	3018	3179	2949	2834	3629
Minimum	3184	2812	2485	2415	2048	2765

Table 14. Tensile Strength Data (lbs/in<sup>2</sup>)

Table 15. Yield Strength Data (lbs/in<sup>2</sup>)

	0% fiber	10% fiber +	20% fiber +	30% fiber +	40% fiber +	40% fiber +
Sample	(100% ground	90% ground	80% ground	70% ground	60% ground	60% virgin
Sample	recycled bottle)	recycled bottle	recycled bottle	recycled bottle	recycled bottle	HDPE resin
1	3344.34	2835.57	2891.28	2182.92	2062.02	2312.35
2	3182.78	2372.75	2381.44	n/a	1666.83	2130.96
3	3247.37	2961.82	2847.77	1731.92	1762.56	2490.4
4	3236.49	2746.05	n/a	1565.21	1544.55	1981.01
5	3248.22	2352.12	1622.09	2712.82	1832.87	n/a
6	3236.81	2800.58	1734.06	1383.31	2221.69	2605.88
7	2726.88	2170.29	2837.96	1479.12	1300.01	2825.79
Average	3174.6986	2605.5971	2385.7667	1842.5500	1770.0757	2391.0650
SD	203.2025	301.5207	579.8986	510.9522	309.7499	312.0880
Maximum	3344.34	2961.82	2891.28	2712.82	2221.69	2825.79
Minimum	2726.88	2170.29	1622.09	1383.31	1300.01	1981.01

	0% fiber	10% fiber +	20% fiber +	30% fiber +	40% fiber +	40% fiber +
Sample	(100% ground	90% ground	80% ground	70% ground	60% ground	60% virgin
	recycled bottle)	recyclea bottle	recycled bottle	recycled bottle	recycled bottle	HDPE resin
1	82	202	226	290	454	578
2	68	193	111	243	209	356
3	103	241	239	454	324	301
4	50	225	n/a	267	259	399
5	156	230	202	159	248	n/a
6	121	230	221	237	277	327
7	61	160	100	319	262	398
Average	91.57	211.57	183.17	281.29	290.43	393.17
SD	37.5449	28.3482	61.4212	91.2080	79.8850	98.4630
Maximum	156	241	239	454	454	578
Minimum	50	160	100	159	209	301

Table 17. Elongation Data (%)

	0% fiber	10% fiber +	20% fiber +	30% fiber +	40% fiber +	40% fiber +
Sample	recycled bottle)	recycled bottle	recycled bottle	recycled bottle	recycled bottle	HDPE resin
1	40.15	5.12	7.97	2.28	1.89	0.96
2	21.09	3.74	4.03	1.60	0.77	0.86
3	28.16	5.83	4.93	1.07	1.50	1.47
4	63.95	6.98	5.86	2.44	2.00	1.10
5	32.60	3.78	2.58	4.19	2.99	n/a
6	69.01	5.29	4.46	2.12	2.57	2.18
7	46.32	3.42	5.20	2.25	1.61	1.49
Average	43.0400	4.8800	5.0043	2.2786	1.9043	1.3433
SD	17.9953	1.3025	1.6680	0.9684	0.7266	0.4852
Maximum	69.01	6.98	7.97	4.19	2.99	2.18
Minimum	21.09	3.42	2.58	1.07	0.77	0.86

	0% fiber	10% fiber +	20% fiber +	30% fiber +	40% fiber +	40% fiber +
Sample	(100% ground recycled bottle)	90% ground recycled bottle	80% ground recycled bottle	70% ground recycled bottle	60% ground recycled bottle	60% virgin HDPE resin
1	0.0879	1.2577	3.2945	5.4515	10.6477	8.4229
2	0.1046	1.4987	3.4151	6.5410	8.5238	9.6172
3	0.0852	1.9548	3.1166	9.9285	8.6182	8.5555
4	0.0958	1.2676	3.9327	10.1722	7.3558	5.7433
5	0.0822	1.5427	4.7845	13.8606	10.6187	5.6356
6	0.0827	1.7955	2.2805	10.2418	9.0621	6.3248
7	0.0854	1.6764	3.0036	9.3020	12.1282	6.4729
Average	0.0891	1.5705	3.4039	9.3568	9.5649	7.2532
SD	0.0082	0.2598	0.7856	2.7460	1.6313	1.5822

Table 18. Water Absorption Data (%)

**APPENDIX B** 

# **One-Way Analysis of Variance (ANOVA)**

## **TENSILE STRENGTH**

	Sum of	df	Mean	F	Sig.
	Squares		Square		
Between Groups	3970272.44	5	794054.49	11.0296	0.0000
Within Groups	2303768.40	32	71992.76		
Total	6274040.84	37			

.

## **Post Hoc Tests**

## Multiple Comparisons

# Dependent Variable: TENSILE STRENGTH LSD

(I)	(J) Fiber	Mean			95% Confide	ence Interval
Fiber	Content	Difference	Std. Error	Sig.	Lower	Upper
Content		(I-J)			Bound	Bound
0%	10%	332.4286*	143.4202	0.0270	40.2911	624.5660
	20%	385.7381*	149.2765	0.0145	81.6718	689.8044
	30%	584.9048*	149.2765	0.0004	280.8385	888.9710
	40%	881.4048*	149.2765	0.0000	577.3385	1185.4710
	40%*	-74.2619	149.2765	0.6223	-378.3282	229.8044
10%	0%	-332.4286*	143.4202	0.0270	-624.5660	-40.2911
	20%	53.3095	149.2765	0.7233	-250.7568	357.3758
	30%	252.4762	149.2765	0.1005	-51.5901	556.5425
	40%	548.9762*	149.2765	0.0009	244.9099	853.0425
	40%*	-406.6905*	149.2765	0.0104	-710.7568	-102.6242
20%	0%	-385.7381*	149.2765	0.0145	-689.8044	-81.6718
	10%	-53.3095	149.2765	0.7233	-357.3758	250.7568
	30%	199.1667	154.9115	0.2078	-116.3778	514.7112
	40%	495.6667*	154.9115	0.0031	180.1222	811.2112
	40%*	-460.0000*	154.9115	0.0056	-775.5445	-144.4555
30%	0%	-584.9048*	149.2765	0.0004	-888.9710	-280.8385
	10%	-252.4762	149.2765	0.1005	-556.5425	51.5901
	20%	-199.1667	154.9115	0.2078	-514.7112	116.3778
	40%	296.5000	154.9115	0.0646	-19.0445	612.0445
	40%*	-659.1667*	154.9115	0.0002	-974.7112	-343.6222
40%	0%	-881.4048*	149.2765	0.0000	-1185.4710	-577.3385
	10%	-548.9762*	149.2765	0.0009	-853.0425	-244.9099
	20%	-495.6667*	154.9115	0.0031	-811.2112	-180.1222
	30%	-296.5000	154.9115	0.0646	-612.0445	19.0445
	40%*	-955.6667*	154.9115	0.0000	-1271.2112	-640.1222
40%*	0%	74.2619	149.2765	0.6223	-229.8044	378.3282
	10%	406.6905*	149.2765	0.0104	102.6242	710.7568
	20%	460.0000*	154.9115	0.0056	144.4555	775.5445
	30%	659.1667*	154.9115	0.0002	343.6222	974.7112
	40%	955.6667*	154.9115	0.0000	640.1222	1271.2112

\* The mean difference is significant at the 0.05 level

# **One-Way Analysis of Variance (ANOVA)**

# YIELD STRENGTH

	Sum of	df	Mean	F	Sig.
	Squares		Square		
Between Groups	9113564.99	5	1822713.00	12.4207	0.0000
Within Groups	4842673.02	33	146747.67		
Total	13956238.01	38			

# Post Hoc Tests

## Multiple Comparisons

# Dependent Variable: YIELD STRENGTH LSD

(I)	(J)	Mean			95% Confide	ence Interval
Fiber	Fiber	Difference	Std. Error	Sig.	Lower	Upper
Content	Content	(I-J)			Bound	Bound
0%	10%	569.1014*	204.7630	0.0089	152.5079	985.6950
	20%	788.9319*	213.1241	0.0008	355.3276	1222.5362
	30%	1332.1486*	213.1241	0.0000	898.5443	1765.7529
	40%	1404.6229*	204.7630	0.0000	988.0293	1821.2164
	40%*	783.6336*	213.1241	0.0008	350.0293	1217.2379
10%	0%	-569.1014*	204.7630	0.0089	-985.6950	-152.5079
	20%	219.8305	213.1241	0.3098	-213.7738	653.4348
	30%	763.0471*	213.1241	0.0011	329.4428	1196.6515
	40%	835.5214*	204.7630	0.0003	418.9279	1252.1150
	40%*	214.5321	213.1241	0.3214	-219.0722	648.1365
20%	0%	-788.9319*	213.1241	0.0008	-1222.5362	-355.3276
	10%	-219.8305	213.1241	0.3098	-653.4348	213.7738
	30%	543.2167*	221.1694	0.0195	93.2442	993.1891
	40%	615.6910*	213.1241	0.0068	182.0866	1049.2953
	40%*	-5.2983	221.1694	0.9810	-455.2708	444.6741
30%	0%	-1332.1486*	213.1241	0.0000	-1765.7529	-898.5443
	10%	-763.0471*	213.1241	0.0011	-1196.6515	-329.4428
	20%	-543.2167*	221.1694	0.0195	-993.1891	-93.2442
	40%	72.4743	213.1241	0.7360	-361.1300	506.0786
	40%*	-548.5150*	221.1694	0.0184	<b>-998.4875</b>	-98.5425
40%	0%	-1404.6229*	204.7630	0.0000	-1821.2164	-988.0293
	10%	-835.5214*	204.7630	0.0003	-1252.1150	-418.9279
	20%	-615.6910*	213.1241	0.0068	-1049.2953	-182.0866
	30%	-72.4743	213.1241	0.7360	-506.0786	361.1300
	40%*	-620.9893*	213.1241	0.0064	-1054.5936	-187.3850
40%*	0%	-783.6336*	213.1241	0.0008	-1217.2379	-350.0293
	10%	-214.5321	213.1241	0.3214	-648.1365	219.0722
	20%	5.2983	221.1694	0.9810	-444.6741	455.2708
	30%	548.5150*	221.1694	0.0184	98.5425	998.4875
	40%	620.9893*	213.1241	0.0064	187.3850	1054.5936

\* The mean difference is significant at the 0.05 level

# **One-Way Analysis of Variance (ANOVA)**

# PERCENT ELONGATION

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9325.33	5	1865.07	32.9711	0.0000
Within Groups	1979.84	35	56.57		
Total	11305.17	40			
## Multiple Comparisons

## Dependent Variable: PERCENT ELONGATION LSD

(I)	(J) Fiber	Mean			95% Confide	ence Interval
Fiber	Content	Difference	Std. Error	Sig.	Lower	Upper
Content		(I-J)			Bound	Bound
0%	10%	38.1600*	4.0202	0.0000	29.9986	46.3214
	20%	38.0357*	4.0202	0.0000	29.8743	46.1971
	30%	40.7614*	4.0202	0.0000	32.6000	48.9228
	40%	41.1357*	4.0202	0.0000	32.9743	49.2971
	40%*	41.6967*	4.1843	0.0000	33.2020	50.1913
10%	0%	-38.1600*	4.0202	0.0000	-46.3214	-29.9986
	20%	-0.1243	4.0202	0.9755	-8.2857	8.0371
	30%	2.6014	4.0202	0.5218	-5.5600	10.7628
	40%	2.9757	4.0202	0.4641	-5.1857	11.1371
	40%*	3.5367	4.1843	0.4037	-4.9580	12.0313
20%	0%	-38.0357*	4.0202	0.0000	-46.1971	-29.8743
	10%	0.1243	4.0202	0.9755	-8.0371	8.2857
	30%	2.7257	4.0202	0.5022	-5.4357	10.8871
	40%	3.1000	4.0202	0.4458	-5.0614	11.2614
	40%*	3.6610	4.1843	0.3876	-4.8337	12.1556
30%	0%	-40.7614*	4.0202	0.0000	-48.9228	-32.6000
	10%	-2.6014	4.0202	0.5218	-10.7628	5.5600
	20%	-2.7257	4.0202	0.5022	-10.8871	5.4357
	40%	0.3743	4.0202	0.9264	-7.7871	8.5357
	40%*	0.9352	4.1843	0.8244	-7.5594	9.4299
40%	0%	-41.1357*	4.0202	0.0000	-49.2971	-32.9743
	10%	-2.9757	4.0202	0.4641	-11.1371	5.1857
	20%	-3.1000	4.0202	0.4458	-11.2614	5.0614
	30%	-0.3743	4.0202	0.9264	-8.5357	7.7871
	40%*	0.5610	4.1843	0.8941	-7.9337	9.0556
40%*	0%	-41.6967*	4.1843	0.0000	-50.1913	-33.2020
	10%	-3.5367	4.1843	0.4037	-12.0313	4.9580
	20%	-3.6610	4.1843	0.3876	-12.1556	4.8337
	30%	-0.9352	4.1843	0.8244	-9.4299	7.5594
	40%	-0.5610	4.1843	0.8941	-9.0556	7.9337

#### **One-Way Analysis of Variance (ANOVA)**

## MODULUS

	Sum of	df	Mean	F	Sig.
	Squares		Square		
Between Groups	349739.66	5	69947.93	14.0873	0.0000
Within Groups	168820.24	34	4965.30		
Total	518559.90	39			

#### Multiple Comparisons

## Dependent Variable: MODULUS LSD

(I)	(J) Fiber	Mean			95% Confid	ence Interval
Fiber	Content	Difference	Std. Error	Sig.	Lower	Upper
Content		(I-J)			Bound	Bound
0%	10%	-120.0000*	37.6651	0.0031	-196.5446	-43.4554
	20%	-91.5952*	39.2030	0.0255	-171.2654	-11.9251
	30%	-189.7143*	37.6651	0.0000	-266.2589	-113.1697
	40%	-198.8571*	37.6651	0.0000	-275.4018	-122.3125
	40%*	-301.5952*	39.2030	0.0000	-381.2654	-221.9251
10%	0%	120.0000*	37.6651	0.0031	43.4554	196.5446
	20%	28.4048	39.2030	0.4737	-51.2654	108.0749
	30%	-69.7143	37.6651	0.0729	-146.2589	6.8303
	40%	-78.8571*	37.6651	0.0438	-155.4018	-2.3125
	40%*	-181.5952*	39.2030	0.0001	-261.2654	-101.9251
20%	0%	91.5952*	39.2030	0.0255	11.9251	171.2654
	10%	-28.4048	39.2030	0.4737	-108.0749	51.2654
	30%	-98.1190*	39.2030	0.0173	-177.7892	-18.4489
	40%	-107.2619*	39.2030	0.0098	-186.9321	-27.5917
	40%*	-210.0000*	40.6829	0.0000	-292.6777	-127.3223
30%	0%	189.7143*	37.6651	0.0000	113.1697	266.2589
	10%	69.7143	37.6651	0.0729	-6.8303	146.2589
	20%	98.1190*	39.2030	0.0173	18.4489	177.7892
	40%	-9.1429	37.6651	0.8097	-85.6875	67.4018
	40%*	-111.8810*	39.2030	0.0073	-191.5511	-32.2108
40%	0%	198.8571*	37.6651	0.0000	122.3125	275.4018
	10%	78.8571*	37.6651	0.0438	2.3125	155.4018
	20%	107.2619*	39.2030	0.0098	27.5917	186.9321
	30%	9.1429	37.6651	0.8097	-67.4018	85.6875
	40%*	-102.7381*	39.2030	0.0130	-182.4083	-23.0679
40%*	0%	301.5952*	39.2030	0.0000	221.9251	381.2654
	10%	181.5952*	39.2030	0.0001	101.9251	261.2654
	20%	210.0000*	40.6829	0.0000	127.3223	292.6777
	30%	111.8810*	39.2030	0.0073	32.2108	191.5511
	40%	102.7381*	39.2030	0.0130	23.0679	182.4083

## **One-Way Analysis of Variance (ANOVA)**

#### IMPACT STRENGTH

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.7297	5	0.3459	16.2409	0.0000
Within Groups	1.3419	63	0.0213		
Total	3.0716	68			

.

## Multiple Comparisons

## Dependent Variable: IMPACT STRENGTH LSD

		· · · · · · · · · · · · · · · · · · ·				
(I)	(J) Fiber	Mean			95% Confide	ence Interval
Fiber	Content	Difference	Std. Error	Sig.	Lower	Upper
Content		(I-J)			Bound	Bound
0%	10%	-0.2262*	0.0596	0.0003	-0.3452	-0.1071
	20%	-0.3431*	0.0609	0.0000	-0.4648	-0.2213
	30%	-0.3899*	0.0609	0.0000	-0.5116	-0.2681
	40%	-0.3337*	0.0609	0.0000	-0.4554	-0.2120
	40%*	-0.0103	0.0596	0.8629	-0.1294	0.1087
10%	0%	0.2262*	0.0596	0.0003	0.1071	0.3452
	20%	-0.1169	0.0609	0.0595	-0.2386	0.0048
	30%	-0.1637*	0.0609	0.0092	-0.2855	-0.0420
	40%	-0.1075	0.0609	0.0824	-0.2293	0.0142
	40%*	0.2158*	0.0596	0.0006	0.0968	0.3349
20%	0%	0.3431*	0.0609	0.0000	0.2213	0.4648
	10%	0.1169	0.0609	0.0595	-0.0048	0.2386
	30%	-0.0468	0.0622	0.4547	-0.1712	0.0775
	40%	0.0094	0.0622	0.8809	-0.1150	0.1337
	40%*	0.3327*	0.0609	0.0000	0.2110	0.4545
30%	0%	0.3899*	0.0609	0.0000	0.2681	0.5116
	10%	0.1637*	0.0609	0.0092	0.0420	0.2855
	20%	0.0468	0.0622	0.4547	-0.0775	0.1712
	40%	0.0562	0.0622	0.3701	-0.0682	0.1805
	40%*	0.3796*	0.0609	0.0000	0.2578	0.5013
40%	0%	0.3337*	0.0609	0.0000	0.2120	0.4554
	10%	0.1075	0.0609	0.0824	-0.0142	0.2293
	20%	-0.0094	0.0622	0.8809	-0.1337	0.1150
	30%	-0.0562	0.0622	0.3701	-0.1805	0.0682
	40%*	0.3234*	0.0609	0.0000	0.2016	0.4451
40%*	0%	0.0103	0.0596	0.8629	-0.1087	0.1294
	10%	-0.2158*	0.0596	0.0006	-0.3349	-0.0968
	20%	-0.3327*	0.0609	0.0000	-0.4545	-0.2110
	30%	-0.3796*	0.0609	0.0000	-0.5013	-0.2578
	40%	-0.3234*	0.0609	0.0000	-0.4451	-0.2016

## One-Way Analysis of Variance (ANOVA)

### % CHANGE IN WEIGHT

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	581.4926	5	116.2985	52.1147	0.0000
Within Groups	80.3372	36	2.2316		
Total	661.8297	41			

## Multiple Comparisons

# Dependent Variable: % CHANGE IN WEIGHT LSD

(I)	(J) Fiber	Mean			95% Confid	ence Interval
Fiber	Content	Difference	Std. Error	Sig.	Lower	Upper
Content		(I-J)			Bound	Bound
0%	10%	-1.4809	0.7985	0.0718	-3.1004	0.1385
	20%	-3.3148*	0.7985	0.0002	-4.9342	-1.6954
	30%	-9.2677*	0.7985	0.0000	-10.8871	-7.6483
	40%	-9.4758*	0.7985	0.0000	-11.0952	-7.8564
	40%*	-7.1641*	0.7985	0.0000	-8.7835	-5.5446
10%	0%	1.4809	0.7985	0.0718	-0.1385	3.1004
	20%	-1.8339*	0.7985	0.0276	-3.4533	-0.2144
	30%	-7.7867*	0.7985	0.0000	-9.4062	-6.1673
	40%	-7.9949*	0.7985	0.0000	-9.6143	-6.3754
	40%*	-5.6831*	0.7985	0.0000	-7.3025	-4.0637
20%	0%	3.3148*	0.7985	0.0002	1.6954	4.9342
	10%	1.8339*	0.7985	0.0276	0.2144	3.4533
	30%	-5.9529*	0.7985	0.0000	-7.5723	-4.3334
	40%	-6.1610*	0.7985	0.0000	-7.7804	-4.5416
	40%*	-3.8492*	0.7985	0.0000	-5.4687	-2.2298
30%	0%	9.2677*	0.7985	0.0000	7.6483	10.8871
	10%	7.7867*	0.7985	0.0000	6.1673	9.4062
	20%	5.9529*	0.7985	0.0000	4.3334	7.5723
	40%	-0.2081	0.7985	0.7958	-1.8276	1.4113
	40%*	2.1036*	0.7985	0.0123	0.4842	3.7231
40%	0%	9.4758*	0.7985	0.0000	7.8564	11.0952
	10%	7.9949*	0.7985	0.0000	6.3754	9.6143
	20%	6.1610*	0.7985	0.0000	4.5416	7.7804
	30%	0.2081	0.7985	0.7958	-1.4113	1.8276
	40%*	2.3118*	0.7985	0.0064	0.6923	3.9312
40%*	0%	7.1641*	0.7985	0.0000	5.5446	8.7835
	10%	5.6831*	0.7985	0.0000	4.0637	7.3025
	20%	3.8492*	0.7985	0.0000	2.2298	5.4687
	30%	-2.1036*	0.7985	0.0123	-3.7231	-0.4842
	40%	-2.3118*	0.7985	0.0064	-3.9312	-0.6923

#### REFERENCES

- 1. Ehrig, R.J. (ed), <u>Plastics Recycling Products and Processes</u>, Hanser Publishers, New York, 289 pp. (1992).
- Mangialardi, T., L. Piga, G. Schena, and P. Sirini, "Characteristics of MSW incinerator ash for use in concrete", <u>Environmental Engineering Science</u>, Vol. 15, No. 4, pp. 291-297, (1998).
- 3. U.S.EPA. 1990. U.S. Environmental Protection Agency. <u>Report to Congress: Solid</u> <u>Waste Disposal in the United States</u>. EPA/530-SW-88-011B. Washington, DC.
- 4. Mustafa, N. (ed), <u>Plastics Waste Management: Disposal, Recycling, and Reuse</u>, Marcel Dekker, Inc., New York, 413 pp. (1993).
- 5. Bisio, L.A., and M. Xanthos (ed), <u>How to Manage Plastics Waste: Technology and</u> <u>Market Opportunities</u>, Hanser Publishers, New York, 253 pp. (1995).
- 6. Plastics Resource Staff. Waste Reduction. [Online] Available http://www.plasticsresource.com/resour...cs\_in\_perspective/waste\_reduction.html, November 11, 1999
- 7. Selke, S., <u>Packaging and the Environment: Alternatives, Trends and Solutions</u>, Technomic Publishing Company, Inc., Pennsylvania, 179 pp. (1990).
- Bongaerts, C.J., and D. Castiglione, <u>Technological Innovation in the Plastic Industry</u> and its Influence on the Environmental Problems of Plastic Waste, ECSC-EEC-EAEC, Brussels – Luxembourg, 74 pp. (1992).
- Chtourou, H., B. Riedl, and A. Ait-Kadi, "Reinforcement of Recycled Polyolefins with Wood Fibers", <u>Journal of Reinforced Plastics and Composites</u>, Vol.11, pp. 372-394 (1992).
- 10. Kimbell D., <u>Recycling in America: a Reference Handbook</u>, ABC-CLIO Inc., California, 254 pp. (1992).
- Plastics Resource Staff. Plastics. [Online] Available http://www.plasticsresource.com/resour...cs\_in\_perspective/plastics.html, November 11, 1999.
- 12. Modern Plastics Staff, "Recycling Statistics", <u>Modern Plastics Encyclopedia</u>, Vol. 69, No. 13, pp. 44-49, (1992).

- Plastics Resource Staff. Pounds of Plastic Bottles Recycled Increased 7 Percent During 1998: Reached All-Time High of 1.45 Billion Pounds. [Online] Available http://www.plasticsresource.com/readin...\_releases/99/99june23\_bottle\_rate.html, November 11, 1999
- Smith, S.S., "Opaque Milk Jugs Contain Recycling Issues", <u>Plastics News</u>, Vol. 10, No. 13, p. 21, (1998).
- Narayan, R., and R.P. Neu, "Composite System of Lignocellulosics with Hydrophobic Materials", <u>Materials Research Society Symposia Proceedings</u>, Vol. 195, pp. 55-63, (1990).
- Krishnan, M., and R. Narayan, "Compatibilization of Biomass Fibers with Hydrophobic Materials", <u>Materials Research Society Symposia Proceedings</u>, Vol. 266, pp. 93-104, (1992).
- 17. Karnani, R., "Kenaf-Reinforced Polypropylene Composites", M.S. Thesis, Michigan State University, 1996.
- George, J., S.S. Bhagawen, N. Prahakaran, and S. Thomas, "Short Pineapple-Leaf-Fiber-Reinforced Low-Density Polyethylene Composites", <u>Journal of Applied</u> <u>Polymer Science</u>, Vol. 57, pp. 843-854 (1995).
- 19. Stilwell, J.E., C.R. Canty, P.W. Kopt, and A.M. Montrone, <u>Packaging for the</u> <u>Environment: A Partnership for Progress</u>, Amacom, New York, 262 pp. (1991).
- 20. The Role of Recycling in Integrated Solid Waste Management to the Year 2000, Keep America Beautiful, Stamford, Connecticut (1994).
- 21. Denison, R.A. and J. Ruston (ed), <u>Recycling and Incineration : Evaluating the</u> <u>Choices</u>, Island Press, Washington, D.C., 322 pp. (1990).
- 22. Plastics Resource Staff. Information on Disposal. [Online] Available http://www.plasticsresource.com/dispos...ackgrounder/disposal\_backgrounder. html, November 11, 1999
- 23. Plastics Resource Staff. Waste-to-Energy. [Online] Available http://www.plasticsresource.com/resour...cs\_in\_perspective/waste-to-energy.html, November 11, 1999.
- Lauzon C. and G. Wood (ed), <u>Environmentally Responsible Packaging A Guide to</u> <u>Development, Selection and Design</u>, Pira International, Leatherhead, Surrey, UK, 136 pp. (1995).
- 25. Gibson, R.F., <u>Principles of Composite Material Mechanics</u>, McGraw-Hill, Inc., New York, 425 pp. (1994).

- 26. Mallick, P.K., <u>Fiber-Reinforced Composites: Materials, Manufacturing, and Design</u>, Marcel Dekker, Inc., New York, 469 pp. (1988).
- 27. Simpson, R.J., "Composite Materials from Recycled Multi-Layer Polypropylene Bottles and Wood Fibers", M.S. Thesis, Michigan State University, 1991.
- 28. Daniel, M., and O. Ishai, <u>Engineering Mechanics of Composite Materials</u>, Oxford University Press, 395 pp. (1994).
- 29. Clegg, D.W., and A.A. Collyer (ed), <u>Mechanical Properties of Reinforced</u> <u>Thermoplastics</u>, Elsevier Applied Science Publishers, New York, 326 pp. (1986).
- 30. Katz, S.H., and J.V. Milewski (ed), <u>Handbook of Fillers for Plastics</u>, Van Nostrand Reinhold Co., New York, 467 pp. (1987).
- 31. Nieman, K.A., "Mechanical Property Enhancement of Recycled HDPE and Wood Fiber Composites Due to the Inclusion of Additives", M.S. Thesis, Michigan State University, 1989.
- 32. Gogoi, B.K., "Processing-Morphology-Property Relationships for Compounding Wood Fibers with Recycled HDPE Using a Twin-Screw Extruder", M.S. Thesis, Michigan State University, 1989.
- Michell, A.J., J.E. Vaughan and D. Willis, "Wood Fiber—Synthetic Polymer Composites" I. Laminates of Paper and Polyethylene" <u>Journal of Polymer Science</u>: <u>Symposium</u>, No. 55, pp. 143-154, (1976).
- 34. Klason, C., J. Kubat, and H.E. Stronvall, "Efficiency of Cellulose Filler in Common Thermoplastics Part I: Filling Without Processing Aids or Coupling Agents", <u>International Journal of Polymeric Materials</u>, Vol. 10, pp. 159-187, (1984).
- 35. Dalavag, H., C. Klason, and H.E. Stronvall, "The Efficiency of Cellulose Filler in Common Thermoplastics Part II: Filling With Processing Aids or Coupling Agents", <u>International Journal of Polymeric Materials</u>, Vol. 11, pp. 9-38, (1985).
- 36. Kokta, B., C. Deneault, and A.D. Beshay, "Use of Grafted Aspen Fibers in Thermoplastic Composites: IV Effects of Extreme Conditions on Mechanical Properties", <u>Polymer Composites</u>, Vol.7, pp. 337-348, (1986).
- 37. Zadorecki, P. and P. Flodin, "Properties of Cellulose-Polyester Composites", Polymer <u>Composites</u>, Vol. 7, pp. 170-175, (1986).
- 38. Yam, K., V. Kalyankar, S. Selke, and C. Lai, "Mechanical Properties of Wood Fiber/Recycled HDPE Composites" <u>Society of Plastics Engineers Technical</u> <u>Conference ANTEC'88</u>, pp. 1809-1811, (1988).

- 39. Kalyankar, V., "Mechanical Characteristics of Composites Made from Recycled HDPE Obtained from Milk Bottles", M.S. Thesis, Michigan State University, 1989.
- 40. Keal, M.D., "The Effect of Dual Additives Systems on the Mechanical Properties of Aspen Fiber/Recycled HDPE Composites", M.S. Thesis, Michigan State University, 1990.
- 41. Childress, J.D., "Wood Fiber/High Density Polyethylene Composites: Ability of Additives to Enhance Mechanical Properties", M.S. Thesis, Michigan State University, 1991.
- Raj, R.G., B.V. Kokta, and J.D. Niziio, "Studies on Mechanical Properties of Polyethylene-Organic Fiber Composites. I. Nut Shell Flour", <u>Journal of Applied</u> <u>Polymer Science</u>, Vol. 45, pp. 91-101, (1992).
- 43. Devi, L.U., S.S. Bhagawam, and S. Thomas, "Mechanical Properties of Pineapple Leaf Fiber-Reinforced Polyester Composites", <u>Journal of Applied Polymer Science</u>, Vol. 64, pp. 1379-1348, (1997).
- 44. Oksman, K., and C. Clemons, "Mechanical Properties and Morphology of Impact Modified Polypropylene-Wood Flour Composites", Journal of Applied Polymer Science, Vol. 67, pp. 1503-1513, (1998).
- 45. Rojanarungtawee, S., "Composite of wood fiber and mixed recycled thermoplastics", M.S. Thesis, Michigan State University, 1998.
- 46. Woodhams, R.T., G. Thomas and D.K. Rodgers, "Wood Fibers as Reinforcing Fillers for Polyolefins", <u>Polymer Engineering and Science</u>, Vol. 24, pp. 1166-1171, (1984).
- 47. Chotipatoomwan, T., "Processing and Mechanical Property Testing of Paper Fiber and HDPE Composites", M.S. Thesis, Michigan State University, 1998.
- 48. Berlin, A.A., S.A. Volfson, N.S. Enikolopian, and S.S. Negmatov (ed), <u>Principles of</u> <u>Polymer Composites</u>, Springer-Verlag, New York, 124 pp. (1986).