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COMPOSITE MATERIAL OF MIXED LOW DENSITY
POLYETHYLENE/POLYPROPYLENE AND WOOD FIBER

presented by

KOBDAJ VANICHVAROD

has been accepted towards fulfillment
of the requirements for

MASTER degree in PACKAGING



Major professor

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**COMPOSITE MATERIAL OF MIXED LOW DENSITY
POLYETHYLENE/POLYPROPYLENE AND WOOD FIBER**

By

Kobdaj Vanichvarod

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22

ABSTRACT

COMPOSITE MATERIAL OF MIXED LOW DENSITY POLYETHYLENE/POLYPROPYLENE AND WOOD FIBER

By

Kobdaj Vanichvarod

Mixing of post consumer plastics such as low density polyethylene (LDPE) and polypropylene (PP) has been applied for reducing the amount of plastic wastes in landfill. Poor mechanical properties may result with these mixed plastics. The addition of reinforcing fiber seems to improve the strength of the plastics.

In this study, the mechanical properties of LDPE/PP wood composite were investigated. Also, the effect of processing temperatures on the properties was studied. LDPE and PP were varied in six different ratios. Each variation was compounded with 40% of aspen wood fiber by wt. Each compound was processed at two different sets of temperatures: above the LDPE melting point (150 °C) and above the PP melting point (180 °C).

Overall, 0:100 LDPE:PP had the highest mechanical strength for both processing temperatures, while the best impact strength was achieved with 100:0 LDPE:PP and 0:100 LDPE:PP for the processing temperatures of 150 °C and 180 °C, respectively. In the case of blends, mechanical strength decreased with increasing ratios of LDPE. The best impact strength for 150 °C and for 180 °C were achieved with 80:20 and 20:80 LDPE:PP, respectively. In brief, the effect of processing temperature varied, depending on the ratio of LDPE and PP.

To My Dearest Parents

Dacha & Sumalee Vanichvarod

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CHAPTER 1

INTRODUCTION

Even if the amount of trash generated per person remains constant over the years, waste disposal can still be a problem. Changes in living style make the waste disposal problem become even more serious (Rodriguez, 1996). In the United States, population increased from 180 million in 1960 to 286 million in 2000, which was more than 59% (U.S. Census, 2000). During 1960 to 1999, municipal solid waste (MSW) generation increased at a faster rate, with the total waste per person becoming 72% greater (U.S. EPA, 1999).

MSW is composed of product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, batteries and other such items. During 1999, U.S. residents and businesses released 230 million tons of MSW, which is approximately 4.6 pounds of waste per person per day. Waste composition is shown in Figure 1.

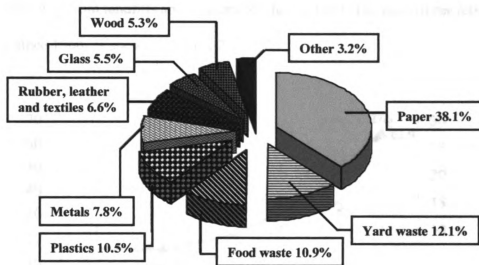


Figure 1. Total waste generation before recycling in 1999 (U.S. EPA, 2001a).

According to the United States Environmental Protection Agency (U.S. EPA), several techniques for management of MSW are recommended in order to avoid waste or divert materials from the waste stream. Some of these techniques are source reduction, recycling and composting (U.S. EPA, 2001a).

Source reduction is the design, manufacture, purchase, or use of materials (such as products and packaging) in order to decrease the amount or toxicity of trash generated. It reduces economic costs for disposal and handling due to avoided costs of recycling, municipal composting, landfilling, and combustion. It also preserves natural resources and reduces pollution (U.S. EPA, 2001b).

Recycling is the method by which many materials are collected and reused as raw materials in order to make new ones (U.S. EPA, 2001b). It diverts about 64 million tons

of materials away from landfills and incinerators during 1999. The rates of recycling have increased since 1960, as shown in Figure 2.

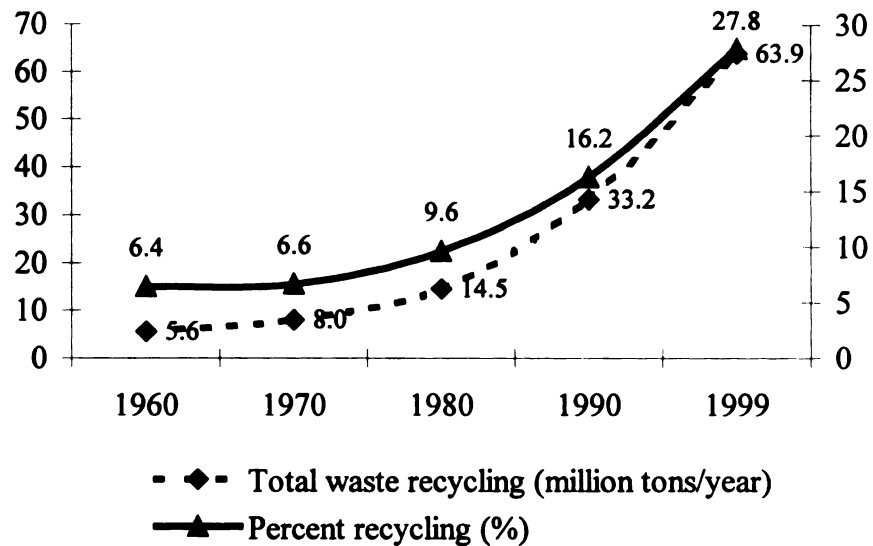


Figure 2. Waste recycling rate from 1960 to 1999 (U.S. EPA, 2001a).

The rates for several recycled materials in 1999 are presented in Figure 3. These materials may be obtained from curbside programs, drop off centers, buy-back programs and deposit systems.

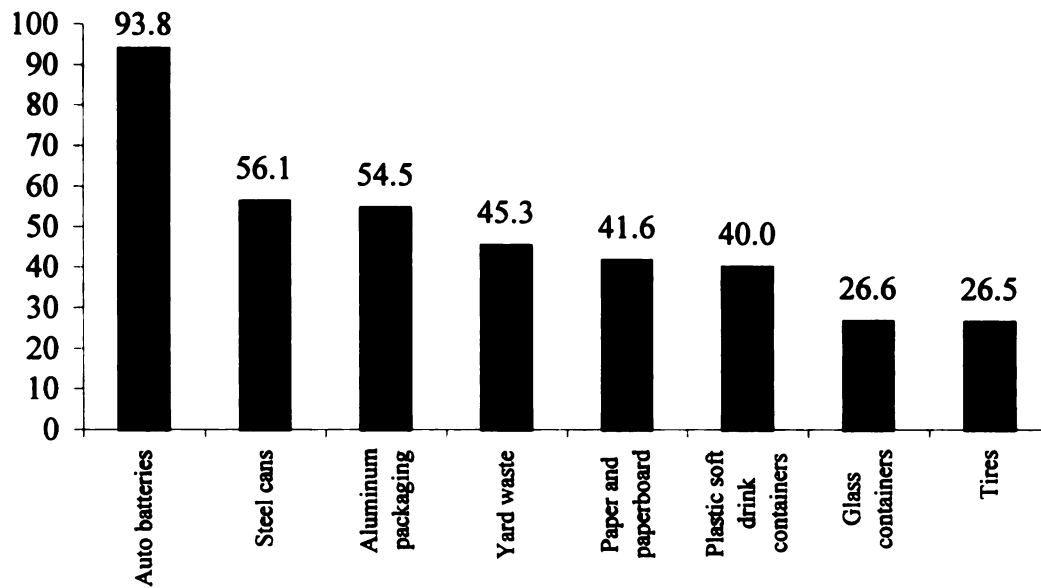


Figure 3. Recycling rates of selected materials during 1999 (U.S. EPA, 2001a).

Recycling has several benefits such as resource conservation, reduction of pollution, energy savings, and reduction of landfill space (U.S. EPA, 2001a). There are four main steps for recycling:

1. **Collecting:** The recyclable components are taken away from MSW.
2. **Separating:** The recyclable components are grouped by types of material before or after collection.
3. **Processing:** Those components are changed into reusable forms.
4. **Purchasing and using:** The reprocessed materials are sold into the market as new products (U.S. EPA, 2001b).

Composting is one form of recycling. It plays a key role in diverting organic wastes, such as food scraps and yard trimmings, with microorganisms (mainly bacteria and fungi)

producing a humus-like substance. Composting can be said to be nature's way of recycling organic wastes into new soil used in vegetable and flower gardens, landscaping, and many other applications (U.S. EPA, 2001a).

Beside the techniques above, waste combustion and landfilling are the other ways to manage waste. The combustion technique is the simplest method in which MSW is burned in an incinerator (Denison & Ruston, 1990). It reduces the bulk of waste and has the added benefit of energy recovery. However, some components may need to be removed from the waste stream because they can cause potentially harmful emissions, be difficult to burn, or cause problems in ash management (U.S. EPA, 2001b). A landfill is the place where the wastes are deposited on the land; moreover, it usually has a liner as a safeguard to ensure that components from the waste will not contaminate groundwater (U.S. EPA, 2001a).

In MSW, the plastic wastes have grown rapidly. They can be found in the form of durable and nondurable goods, as well as in the form of containers and packaging. Packaging is the largest category of plastics in MSW.

Durable products are, for instance, furniture, cases, appliances and other products, while nondurable products are trash bags, disposable diapers, cups, medical devices, household items, etc. Many types of resin are used to produce both durable and nondurable products. The plastics for household food containers, for example, are often produced from polystyrene in the form of foam or clear items. Trash bags, another example of

nondurable products, are usually made of high density polyethylene (HDPE) or low density polyethylene (LDPE).

For packaging, plastic resins are used to produce a variety of containers such as polyethylene terephthalate (PET) for soft drink bottles and HDPE for milk and water bottles. Beside these two resins, other resins such as LDPE and polypropylene (PP) can be used to make bags, sacks, wraps, lids, etc. Table 1 shows the amounts of various resins in packaging applications found in MSW.

Table 1. Total packaging resins in MSW during 1999 (U.S. EPA, 1999)

Type of resin*	Amount of resins (Thousand tons)	% by weight
PET	1,850	17
HDPE	4,180	37
PVC	480	4
LDPE/LLDPE	3,230	29
PP	1,110	10
PS	250	2
Other resins	70	1
Total	11,160	100

* PET = polyethylene terephthalate, HDPE = high density polyethylene, PVC = polyvinyl chloride, LDPE = low density polyethylene, LLDPE = linear low density polyethylene, PP = polypropylene, PS = polystyrene

To reduce these amounts of resins above, a widespread idea is that the products should be made biodegradable. However, this idea becomes less attractive, since some biodegradable materials accumulating in landfills need 10 to 20 years or more to be completely degraded. Another solution idea is that all plastic wastes should be collected and blended together. The drawback of this technique is that blending of immiscible plastics, such as PE and PP, will generally lead, even with virgin materials, to heterophase systems with mediocre properties (Dumoulin et al., 1987).

With recent advancements in the science and technology of composites, the use of wood fiber and plastic materials has gained strong momentum in process engineering and applications, such as in construction, building and automotive components (Sain et al, 2000). Wood and plastic composites production has grown rapidly because it combines the benefits of two materials. Some construction industries feel most comfortable working with wood, notwithstanding the gradual acceptance of vinyl sliding, window profiles, decking and fencing. The addition of plastic to wood makes the composite more resistant to rot, insects and warping. It also gives convenience for builders, and the combination can be ideal in many applications (Lauzon, 2000).

The use of cellulosic fibers as reinforcement filler offers several benefits, including low cost, ease of processing, low equipment abrasion, ease of surface modification, high strength to weight ratio, renewability, non-toxicity, recyclability, and improved properties and performance of composites. However, the problems of cellulosic fibers in thermoplastics are incompatibility with matrix resins, thermal instability above 200 °C,

low bulk density, hygroscopicity and difficulty of dispersion in ordinary plastic mixing equipment (Park & Balatinecz, 1997).

In this research, the mechanical properties of LDPE/PP and wood fiber composites were studied. Also, the effect of changing processing temperature from 150 °C to 180 °C was investigated. LDPE and PP resins, in virgin pellet form in order to control the variation, functioned as the matrix compound while the wood fiber was used as reinforcement filler. LDPE was selected due to it being found in large volume in MSW. PP was selected as an impurity in solid plastic wastes (Bernhardt, 1987; Laguna et al., 1987). The wood fiber was obtained from aspen, a hardwood. The benefits of wood fiber are the same as those of cellulosic fibers. The proportions of wood fiber and the matrix compound were maintained at 40% and 60%, respectively. The proportions of LDPE and PP were varied in 6 ratios, from 100% to 0% of each resin. Each proportion was processed at two different sets of temperatures: over the LDPE melting point (150 °C) and over the PP melting point (180 °C). The properties of each variation were evaluated in terms of mechanical strength and impact strength, and they were also compared with calculated values from the “rule of mixing”.

CHAPTER 2

LITERATURE REVIEW

Background of Composite Materials

The term composite can be defined in several ways depending upon the aspect of study (Schwartz, 1992). In general, composites are composed of two or more materials present as separate phases and combined to form the desired structure. Because of the combination of components, the composite will take advantage of certain properties from each component (Grayson, 1983).

The classifications of composites can also be divided in many ways depending on the concepts that need to be identified. The common identification of composites focuses on the structure, which are basic, micro and macro composite. (Hull 1981).

First, basic composites are composed of two or more different atoms or molecules. They may include compounds, alloys, polymers and ceramics. Second, microcomposites are combined with two or more different molecules or phases. By this definition, many materials considered to be homogenous could be classified as composites. Examples of this classification are steels, brasses and bronzes. Third, macrocomposites are composed of two or more structural forms of constituents, e.g., matrixes, and particles or fibers. With this classification, this discussion will emphasize macrocomposites.

Since the composite is considered as a combination of components, the components can be organic, inorganic or metallic (synthetic or natural structures), in the form of particles, rods, fibers, plates, foams, etc. Compared with homogenous materials, these additions provide more latitude in optimizing properties such as strength, density and cost (Grayson, 1983).

Fiber reinforced composites, called fibrous composites, are macro composites which use fibers to improve the mechanical strength. The fibers are characterized as having a lengthwise direction that is longer than the cross direction. With a small diameter, they tend to bend easily when pushed axially. Therefore, the fibers have to be supported in order to prevent individual fiber bending and buckling (Richardson, 1987; Agarwal & Broutman, 1990).

Matrix

The matrix is used as a structure to embed and adherently grip a reinforcing phase. The matrix serves to transfer stress from one fiber to another and to produce a fully dense structure (Grayson, 1983). Moreover, several functions can be performed by the matrix such as (1) to protect the reinforcements from environmental attack, which can result in a surface imperfections, (2) to act as a shelter to prevent cracks spreading from one fiber to another, (3) to keep the reinforcements in the desired orientation (Callister, 1994; Rojanarungtawee, 1998). Polymers have been used as a matrix since they successfully perform the roles above. Two types of polymers can be used: thermosetting and thermoplastic resins.

Thermosetting resins can be shaped only one time because they form irreversible covalent bonds, called cross linking, between the chains during processing, and will not melt and flow after that (Hernandez et al, 2000). They are generally convenient because they can be applied in fluid form, facilitating penetration and wetting in the unpolymerized state. Then, they can be turned to a solid form in proper conditions that are easily controlled by the operator. Since the condensation process is required for polymerization in order to form the shape, exothermicity, shrinkage and evolution of volatiles will be involved. Examples of these resins are epoxy, amide, and polyester (Grayson, 1983).

On the other hand, thermoplastic resins consist of linear or branched molecular chains. These chains are bonded together with secondary bonding forces or van der Waals forces (Broutman & Krock, 1967). The resins derive their strength and stiffness from the inherent properties of the monomer units and the very high molecular weight. This ensures that a high concentration of molecular entanglements, acting like cross-links, will be seen in amorphous thermoplastics, while a high degree of molecular order or alignment will be seen in crystalline materials (Hull, 1981).

In this experiment, two thermoplastic resins were used as the matrix phase. One was LDPE and the other was PP. LDPE is an addition polymer based on ethylene, with a branched structure. The density of LDPE is in the range of 0.91 to 0.925 g/cm³ (Ehrig, 1992). Since the amount of crystallinity is reduced by the branching of the polymer chain, LDPE has a low percent crystallinity, compared to other polyolefins such as HDPE. The

glass transition and melting temperatures are about -102°C and 105 to 115°C , respectively (Hernandez et al., 2000).

PP is an addition polymer based on propylene. The PP molecule has one methyl group attached to every other carbon atom, so this carbon is a chiral center. Because of the chiral center, PP can be classified into three forms. The isotactic form has all the methyl groups on one side of the main chain. The syndiotactic form has alternation of methyl groups on the main chain. The atactic form has methyl groups in random position (Rodriguez, 1996). The crystallinity of PP depends on the arrangement of the methyl groups. The first two forms can be crystallized, but the last one cannot. The properties of PP are also based on the formation. Isotactic PP has high stiffness, while atactic PP has a rubbery texture. The common form of PP in packaging is isotactic because it provides good flow properties at a wide range of flow rates (Hernandez et al., 2000). The glass transition and melting temperatures of isotactic PP are about -20°C and 175°C , respectively (Callister, 1994). The density of PP is about 0.9 g/cm^3 (Brydson, 1989).

Reinforcement

A reinforcement is used to improve the strength of a matrix, so it must be stronger and stiffer than the matrix, and must significantly modify the failure mechanism in an advantageous way (Grayson, 1983). The composite formed with the reinforcement will often be cheaper than the polymer matrix alone. The fibers alone are very brittle and their strength and stiffness cannot be increased. Once combined with a resin, the matrix

provides a protection for these fibers, and transfers the load from them. For this reason, an improvement in properties of fiber and matrix will be obtained over the matrix alone.

The strength of a composite depends on the geometry of the reinforcing filler. One or more fillers may be used in the form of particles or fibers. In the case of particulate filler, it has no length direction. Since the length of the filler limits the growth of cracks in a brittle matrix, a particulate filler does not improve the fracture strength of the matrix. However, there is an exception if a rubberlike substance is dispersed in a brittle matrix. Under these conditions, considerable toughening occurs, and this method is standard for improving the impact behavior of thermoplastics. High-impact polystyrene and ABS are common examples of this case (Clegg & Collyer, 1986).

The particles will share the load with the matrix, but to a lesser extent than fibers. Therefore, only stiffness is improved, while strength is not. The impact strength of the brittle matrix can be reduced with the addition of hard particles, which cause localized stress concentration within the matrix phase. Particulate filler is also used to improve high temperature performance, reduce friction, increase wear resistance, reduce shrinkage and improve mechanical properties. In most cases, the application of this filler is to reduce the cost of the material. Under these conditions, the filler is known as an additive, used to change the properties of the composite.

Fiber reinforcement improves stiffness, strength and creep resistance of the thermoplastic matrix. In general, the measurement of strength from experiments is much less than that

predicted from theory. This is because flaws in the form of cracks perpendicular to the applied load are present in the bulk material. Non-polymeric fibers have higher longitudinal strength since no flaws are present in the cross-section area (Clegg & Collyer, 1986).

Cellulose fibers are used as reinforcements for thermoplastics due to several advantages: (1) low cost, about 5 cents per pound, and renewable nature, (2) capable of working with thermoplastics such as PP, HDPE and PS, which soften at low temperatures and (3) biodegradable (Park & Balatinecz, 1997). The drawbacks of cellulose fibers are: (1) poor adhesion and (2) decomposition of lignocellulosics at high temperature (180 – 200 °C) (Sain & Kokta, 1994).

The important physical features of cellulose fiber are as follows: (1) The natural cellulose fiber is a long chain structure, which has a degree of polymerization of 10,000. (2) The molecule forms into a ribbon-like structure or a sequence of flat plates, linked together by oxygen bridges. (3) At the oxygen bridge, bending out of the plane of the ribbon and twisting are fairly easy, so that the molecule is quite flexible although much stiffer than a polyethylene chain. (4) Hydroxyl groups attach to other hydroxyl groups with hydrogen bonds. (5) The molecule has properties that depend on direction (Jenkins, 1972; Gauthier et al, 1998).

Although there are uncertainties about the exact form of the crystalline lattice, cellulose crystallizes readily. Natural cellulose fibers, such as cotton, flax and ramie, are highly

ordered; two-thirds of the fiber is crystalline and the rest is amorphous in a two-phase structure (Jenkins, 1972; Gauthier et al, 1998).

The wood cell is composed of cellulose, hemicellulose and lignin. Cellulose has a thermal softening temperature (T_g) range of 231 to 253 °C. The T_g 's of hemicellulose and lignin are in the range of 167 to 217 °C and 134 to 235 °C, respectively. Softwood fibers are 2.5 to 7.0 millimeters long and 15 to 65 micrometers in diameter, while hardwood fibers are 1.0 to 1.5 millimeters in length and 15 micrometers in diameter (Sun & Hawke, 1996).

Interfaces and Interphase

According to Schwartz (1992), when different constituents are intermixed or combined, there is always a contiguous region. It may simply be an interface, the surface forming the common boundary of the constituents. An interface is in some ways analogous to the grain boundaries in monolithic materials. For the composite, the interface is controlled in order to provide the desired properties from a given pair of materials. In some cases, the interface of a composite is weak, minimizing coupling of the reinforcement to the matrix. When the composite is deformed, cracks pass through the matrix until they reach a whisker. Since the interface between phases is weak, the separation of the matrix causes the whisker to pull out from the side of the advancing crack, rather than allowing the crack to pass through the whisker. The friction resulting from this pullout dissipates an amount of energy, which deflects the crack along the fiber. These phenomena result in substantial toughening of the composite, in some cases doubling fracture toughness

relative to the unreinforced composite. In some cases, however, the contiguous region is a distinct added phase, called an interphase. When such an interphase is present, there are two interfaces: between each surface on the interphase and its adjoining constituent, as shown in Figure 4.

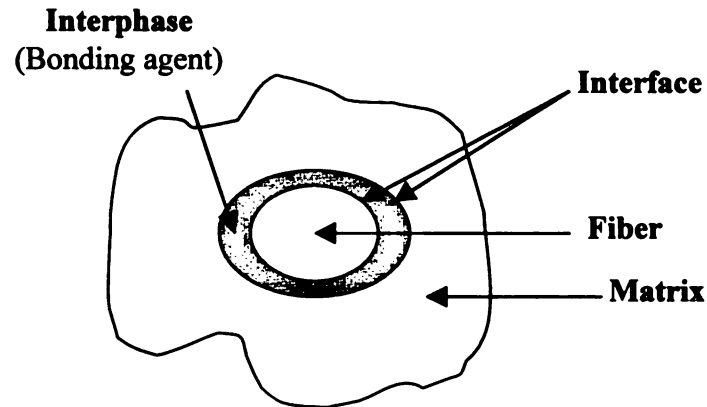


Figure 4. Makeup of interface between fiber and matrix.

The interphase of a composite is the region where loads are transmitted between the reinforcement and the matrix. The interaction between the reinforcement and the matrix varies from strong to weak, and can be controlled by using an appropriate coating on the fiber. In general, the composite is more rigid when it has strong interfacial bonds; although brittleness may result. On the other hand, a weak bond leads the composite to be tougher, but it tends to decrease stiffness. If the interfacial bond is weaker than the matrix, fracture and delamination will occur under loading conditions. Usually, a coupling agent is used to overcome the weak limits. The bond also affects the long term stability of the composite such as fatigue, environmental attack and resistance to hot-wet conditions (Schwartz, 1992).

Prediction of Properties

Successful prediction of mechanical properties of long fiber composites is difficult. The properties of short fiber reinforced composites are even more complicated to predict. This is due to the spectrum of fiber length and orientation, caused by processing to the final part. Besides, the amount of stress taken up by fibers will be affected by the fiber length (Clegg & Collyer, 1986).

For long fiber reinforcements, it is assumed that both the matrix and the fibers are elastic, and the Poisson's ratios are equal. All fibers are aligned in the direction of the tensile stress, as shown in Figure 5. The tensile strain of the composite, the matrix and the fibers are assumed equal throughout the material. The tensile force can be calculated by equation 1 (Clegg & Collyer, 1986):

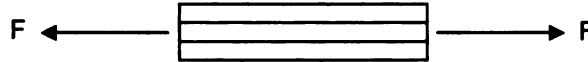


Figure 5. A tensile force acting on a thermoplastic composite, with long fibers aligned in the direction of tensile stress.

$$F_c = F_m + F_f \quad (1)$$

where F refers to tensile force.

The subscripts c, m and f refer to the composite, matrix and fibers, respectively.

In terms of stress, equation 1 can be expressed as equation 2:

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad (2)$$

where σ refers to the tensile stress.

A is the sum of the cross-sectional areas.

As mentioned above,

$$\epsilon_c = \epsilon_m = \epsilon_f = \epsilon$$

where ϵ refers to the tensile strain.

Therefore, equation 2 can be rewritten as equation 3:

$$E_c A_c = E_m A_m + E_f A_f \quad (3)$$

where E refers to the tensile modulus.

Instead of area, the volume may be used. The total volumes of the composite, matrix and fibers are expressed as follows (Clegg & Collyer, 1986):

$$v_c = l A_c$$

$$v_m = l A_m$$

$$v_f = l A_f$$

where l is the length of the composite sample.

Then

$$E_c v_c = E_m v_m + E_f v_f \quad (4)$$

If the volume fraction is substituted in equation 4, it can be expressed as equation 5:

$$E_c = E_m\phi_m + E_f\phi_f \quad (5)$$

where ϕ refers to the volume fraction.

Equation 5 represents the simple rule of mixtures, which gives values of the tensile modulus of the composite for long fiber composites closer to values from theoretical models than experimental values. If the value of the Poisson's ratios for the matrix and the fibers are not equal, about 1% error will be obtained from equation 5. For most thermoplastic matrices, Poisson's ratio is 0.4, approximately (Clegg & Collyer, 1986).

Compared to continuous fiber reinforcement, all short fibers do not work at maximum efficiency. It is assumed that the average strain in the fiber is not equal to that in the matrix. Due to its stiffness, the fibers limit the deformation of the surrounding matrix under an applied load. The load is transferred from the matrix to the fiber via the interfacial shear stress.

The shear stress will be maximum at the ends of the fiber but zero somewhere along the fiber, while the tensile stress will be higher at the center but zero at the end. If the fiber is long enough, the maximum tensile stress will reach the tensile stress in the matrix. $(L/D)_c$ refers to the critical aspect ratio, which is required to achieve this condition. In this ratio, L and D are the length and diameter of the fiber, respectively. In the case of L/D less than $(L/D)_c$, the tensile stress in the fiber will always be lower than that in the matrix. Thus, the transfer of load from the matrix to the fiber is poor, so maximum utilization of the fiber will not be achieved. In the case of L/D higher than $(L/D)_c$, the tensile stress at the

interface reaches a maximum over a greater proportion of the fiber length. Although the transfer of stress from the matrix to the fiber is efficient, the average tensile stress in the fiber is always less than that in the matrix. This results from the reduction of tensile stress at the ends of the fiber. Therefore, the efficiency of stress transfer will never reach 100% (Clegg & Collyer, 1986).

Equation 6 is used to accommodate the above change in reinforcement efficiency with fiber length. This is the fiber length correction factor and has a value of less than unity.

$$E_c = E_m \phi_m + \eta_L E_f \phi_f \quad (6)$$

η can be calculated from equation 7:

$$\eta = \frac{1 - \tanh(\beta L/2)}{(L/2)} \quad (7)$$

β can be calculated from equation 8:

$$\beta = \frac{(2\pi G_m)^{1/2}}{[E_f A_f \ln(R/r)]^{1/2}} \quad (8)$$

where G_m refers to the shear modulus of the matrix.

R is the mean separation of the fibers normal to their length.

r refers to the radius of the fiber.

It should be emphasized that E_c depends on L/D .

During processing, the fibers may be broken, leading to a lower L/D ratio than planned. Therefore, the amount of breakage of fiber is a concern. In order to model this variation in length, the number average fiber length must be obtained.

Uniaxially aligned composites have highly anisotropic behavior, with a considerable enhancement of tensile modulus in the direction of orientation. In this direction, the modulus is dominated by the matrix phase and may be estimated from equation 9:

$$1/E_c = \phi_f/E_f + \phi_m/E_m \quad (9)$$

The tensile strength of the short fiber composite can be modeled using equation 5. Then, equation 5 becomes equation 10 (Clegg & Collyer, 1986):

$$\sigma_{Tc} = \sigma_{Tm}\phi_m + \sigma_{Tf}\phi_f \quad (10)$$

where σ_T refers to the tensile strength .

In general, the ultimate tensile strain in the fiber is much less than that of the matrix. Also the tensile strength of the fiber is much more than that of the matrix. These can be expressed as $\sigma_{Tf}\phi_f \gg \sigma_{Tm}\phi_m$. σ_{Tf} and σ_{Tm} are the tensile strengths of the fiber and the matrix, respectively. There will be a stress in the matrix at which the ultimate tensile strain is reached in the fiber. Thus, the tensile strength of the composite can be estimated from equation 10 above.

If the fibers are not continuous, the average tensile stress in the composite will be expressed as equation 11:

$$\sigma_{Tc} = \sigma_m \phi_m + \bar{\sigma}_f \phi_f \quad (11)$$

where $\bar{\sigma}_f$ is the average fiber stress, which is given by equation 12:

$$\bar{\sigma}_f = 1/L \int_0^L \sigma_f(x) dx \quad (12)$$

If the tensile stress builds up from the fiber ends in a non-linear way, the tensile strength of fibers can be calculated by equation 13:

$$\bar{\sigma}_f = \sigma_{f\infty} [1 - (1 - \beta)L_c/L] \text{ for } L > L_c \quad (13)$$

where $\sigma_{f\infty}$ is the tensile stress in a continuous in the same matrix under the same loading condition.

L and L_c represent the length and the critical length of the fibers, respectively.

The fibers can be stressed to their tensile strengths when $L > L_c$. If it is assumed that the failure of the fiber occurs when $\bar{\sigma}_f = \sigma_{f\infty}$, by substituting equation 13 into equation 11, the tensile strength on the composite will be expressed as equation 14 (Clegg & Collyer, 1986).

$$\sigma_{Tc} = \sigma_{f\infty} [1 - (1 - \beta)L_c/L] \phi_f + \sigma_m \phi_m \quad (14)$$

Compared to equation 10, equation 14 shows that discontinuous fibers result in less strength in the composite than continuous fibers. However, 95% of the tensile strength of a continuous fiber reinforced composite can be reached when L/L_c is 10. In an injection molded product, normally 80% of the fibers are reduced to a length below L_c . Therefore,

the strength of the product is lower than the predicted strength for continuous fiber reinforcement.

The value of L_c represents the shortest fiber length that may be broken in a matrix. Below this length, there is insufficient tensile stress to break the fibers, so failure occurs at the fiber-matrix interface.

In general, L_c is greater than the predicted value because:

- (1) debonding of the fibers occurs at the ends where the shear stresses are large.
- (2) interaction between fibers constrains the motion of the matrix, leading to embrittlement.
- (3) the fracture process involves matrix fracture between bundles of fibers rather than individual fibers.

The tensile strength of short fiber reinforced thermoplastics decreases when the angle between the fiber axis and direction of loading increases. The tensile strength of the composite in a transverse direction is often less than that of the matrix material owing to the effects of the fibers (Clegg & Collyer, 1986).

Chtourou et al (1992) took a different approach to calculating the Young's modulus and the strength at yield of short fiber composites saying they can be estimated by equations 15 and 16:

$$E_c = k_{eff} E_f V_f + E_m V_m \quad (15)$$

$$\sigma_c = K_{eff} \sigma_f V_f + \sigma_m V_m \quad (16)$$

where V refers to volume fraction.

E is Young's modulus

k_{eff} and K_{eff} are the efficiency coefficients

The efficiency coefficients depend on microstructural parameters such as dispersion, orientation and adhesion. The effect of fiber length on K_{eff} from equation 16 can be expressed as equation 17:

$$K_{eff} = k_{eff} (1 - L_c/L) \quad (17)$$

In equation 17, k_{eff} is equal to 1/6 when fibers are oriented randomly in three dimensions. If the fibers are oriented randomly in the plane, k_{eff} is equal to 1/3. The k_{eff} is equal to 1/2 when the orientation of fibers is random at an angle of 90° from the plane (Chtourou & Ait-Kadi, 1992).

Mallick (1988) reported that the mechanisms of impact strength defined as the capability for absorbing or dissipating of energy, are affected by the following conditions:

- (1) Utilization of required energy in order to debond and pull out fibers from the matrix.
- (2) A weak interface between the matrix and fibers (Mallick, 1988; Chotipatoomwan, 1998).

Devi et al. (1997) reported that in the case of fiber reinforced thermoplastics, the greatest energy absorption during the pull-out process occurs when the length of the fibers is equal to the critical length (L_c). If the length of the fibers is less than L_c , the fibers tend to pull out from the matrix rather than be broken when the composite is fractured. The fracture energy will be a combination of the force to debond the fibers from the matrix and the force of friction between the fibers and the matrix. Equations 18 and 19 express the fracture energy (U) from pulling out the fiber.

$$U_1 = \frac{v\tau L^2}{12d} \quad \text{for } L < L_c \quad (18)$$

$$U_2 = \frac{v\tau L^3}{12d} \quad \text{for } L > L_c \quad (19)$$

where d refers to the fiber diameter.

τ is the interfacial friction stress.

v refers to the volume fraction of the fiber.

According to equation 18, it can be assumed that $U;L^2$ for $L < L_c$.

For $L = L_c$, the maximum energy can be estimated using equation 20:

$$U_{\max} = \frac{v\tau L^2}{12d} \quad (20)$$

From equation 18, the impact energy decreases as $U;L$. This decrease in the impact strength for the composites will occur when $L < L_c$. However, the impact strength of the composite is found to increase linearly with the weight fraction of the fiber (Devi et al, 1997; Chotipatoomwan, 1998).

Prior Research

Several studies have focused on the improvement of mechanical properties for fiber reinforced thermoplastic composites. Several types of resins have been used as the matrix, mixed with several types of fibers. Also, chemical treatments have been investigated in order to improve poor adhesion between the reinforcement fiber and the matrix.

Tormala et al. (1985) investigated the properties of composites of LDPE and plywood grindings. The composites were prepared by both injection and extrusion molding. The concentration of ground plywood was maintained at 30% by weight. The tensile modulus of the injection molded samples increased in the presence of the grindings (from 105 MPa to 230 MPa), while the tensile strength decreased about 20-30% due to poor adhesion between the resin and ground plywood. Also, the elongation of extruded samples was decreased in the presence of the ground plywood.

Chtourou et al. (1992) studied the reinforcement of recycled polyolefins with wood fiber. The recycled resins were composed of 95% polyethylene and 5% PP. The reinforcement was a chemithermomechanical pulp (CTMP), a mixture of 45% spruce, 45% fir and 10% poplar. Three different types of fiber/polymer mixtures were prepared by injection and compression molding under the same conditions. The tensile properties were presented as a function of the fiber concentration, fiber surface treatment with acetic anhydride and phenol-formaldehyde, and sample storage time in water. Non-treated fiber had better strength and toughness than treated fiber. Young's modulus increased by 150% when

30% of fibers by weight was added into the resins. In comparison of tensile properties, the highest values were obtained with 10% treated fiber. For water absorption, the treated fiber gave higher values than non-treated fiber.

Sain et al. (1994) investigated the improvement of mechanical and thermal properties of PP-wood fiber composites by modifying the composition with various interphase modifiers. The reinforcing fibers were chemithermomechanical pulp (CTMP), explosion pulp (EP) and sawdust (SD). The modifiers consisted of malated PP (MPP), itaconic anhydride-modified PP (ITPP), bismaleimide modified-PP (BPP) and bismaleimide modified-CTMP (BCTMP). The results showed that the mechanical and thermal properties were improved with the addition of modifiers, which developed interactions between the PP and wood fiber. The best properties were obtained with 40% wood fiber by weight in the composite in the presence of about 10% modifier by weight.

Chotipatoomwan (1998) studied the mechanical and physical properties of paper fiber and HDPE composites. There were two kinds of fiber fillers in this experiment: mixed and deinked paper fiber. The properties of the composites were studied by varying the fiber content at 0%, 10% 20%, 30% and 40% and using the same processing conditions for producing all composites. The addition of paper fiber into HDPE caused a reduction in tensile and impact strength, but an increase in tensile modulus. Water absorption increased with increasing paper fiber. In comparing the properties, mixed paper fiber composites gave better results than deinked paper fiber composites.

Rojanarungtawee (1998) investigated the effect of mixed resins in different proportions on the mechanical properties of plastic/wood fiber composites. The matrix phases were formed by HDPE and PP resins, which were varied from 0% to 100% by weight. The reinforcement was aspen wood fiber. The mixed resins and wood fibers were compounded at two different sets of processing temperatures, 180 °C and 150 °C. At a processing temperature of 180 °C, the greatest ultimate tensile strength and modulus of elasticity were obtained with 30:70 and 10:90 PP:HDPE, respectively. At a processing temperature of 150 °C, only 100% HDPE and 30:70 PP:HDPE were processable. Studying of effect of temperatures from 150 °C to 180 °C, 0:100 PP:HDPE statistically showed no significant difference at both temperature.

Ricciardi (1999) investigated the impact of additives on the physical and mechanical properties of HDPE and paper fiber composites. Three additives were used in this experiment: maleic anhydride modified HDPE (MAHDPE), low molecular weight PP (Proflow 1000) and LDPE with a high melt flow index. The study investigated the effects of MAHDPE at 3%, 6% and 10%. For the effects of Proflow 1000 and LDPE at 5% and 10%, the MAHDPE was maintained at 6%. The results showed that the additives had no significant effect on modulus of elasticity, elongation and Izod impact strength. MAHDPE tended to improve yield strength at 10% and tensile strength at 3%. MAHDPE also seemed to decrease debonding in water at every percentage.

Thepwiwatjit (2000) studied the mechanical properties of recycled HDPE bottles from household use and wood fiber composites. The reinforcement was aspen fiber. Five

different ratios were investigated: 100% HDPE/0% fiber, 90% HDPE/10% fiber, 80% HDPE/20% fiber, 70% HDPE/30% fiber and 60% HDPE/40% fiber. 60% virgin HDPE with 40% fiber was produced as a control. The processing conditions were 120 RPM screw speed and 150 °C. The addition of fiber did not improve the tensile properties of the composites, but decreased tensile strength, yield strength and elongation. The modulus and impact strength slightly increased. The water absorption test showed that the composites gained more weight as fiber content increased.

Wu et al. (2000) studied the effects of fiber surface pretreatment on the interfacial strength and mechanical properties of wood fiber/polypropylene (WF/PP) composite. Sawdust, used as a reinforcement, was treated with two modifiers: a vinyl-trimethoxy silane coupling agent and maleic anhydride (MA) grafted styrene-ethylene-butylene-styrene (SEBS) triblock copolymer. The highest tensile properties were obtained with the WF/PP composite containing fibers pretreated with an acid-silane solution. The Charpy impact strength of WF/PP pretreated with MA grafted SEBS was higher than that of the untreated WF/PP composite.

Recently, Uerkanarak (2001) investigated the effects of processing parameters on the mechanical properties of HDPE/wood fiber composites. The filler was aspen wood fiber. The HDPE and fibers were maintained at 60% and 40%, respectively. The processing parameters varied were feed port location (ports 1 to 3) and screw speed (80, 100 and 120 rpm). Feed port location 3 did not result in successful formation of the composite. The highest tensile strength, yield strength, modulus of elasticity and elongation were

obtained when the fibers were loaded into port 2, while the highest impact strength and water absorption were obtained at port 1. In the case of screw speed, the highest tensile properties were obtained at 100 rpm, while the best impact strength and highest water absorption were obtained at 80 and 120 rpm, respectively.

CHAPTER 3

MATERIALS

Polymer Matrix

The pellet form of medium anti-block resin low density polyethylene (LDPE) was provided by Dow Plastics Company under the trade name Dow Polyethylene 133A. The density and melt flow rate of this LDPE are 0.923 g/cc (ASTM D 792) and 0.22g/10 min (ASTM D 1238) respectively. This resin was selected because it could be used as a substitute for recycled material from grocery or merchandise bags in MSW. Virgin resin can be expected to provide about the same properties as recycled resin in this application (Yam et. al., 1988). The properties of Dow Polyethylene 133A are shown in Appendix A.

The pellet form of extrusion and injection-molding-grade polypropylene homopolymer (PP) was provided by Dow Plastics Company under the trade name INSPIRE H704-04. The density and melt flow rate of this PP are 0.9 g/cc (ASTM D 792) and 4g/10 min (ASTM D 1238) respectively. The PP was used in this experiment as representative of a common impurity in recycled polyolefins. This is because the polyolefins, which make up 60 to 80% of solid plastic wastes, can be separated from more dense polymers through techniques based on density differences, but LDPE cannot readily be separated from PP this way (Bernhardt, 1987; Laguna et al., 1987). The properties of Dow INSPIRE H704-04 are shown in Appendix A.

Reinforcement or filler

Aspen wood fibers were provided by Abitibi Corporation, Alpena, Michigan. They are hardwood fibers, which have average length of fiber of 1.22 millimeters. The fibers were produced by the thermal mechanical pulping (TMP) process. Wood chips are thermally softened under high vapor pressure steam, at approximately 120°C. Then, they are ground and defibrillated into fibers and fiber bundles. The fibers from TMP provide better dispersion in nonpolar hydrocarbon polymers because they still contain lignin and natural waxes (Sun & Hawke, 1996; Woodhams et al., 1984).

CHAPTER 4

METHODS

In the preparation of the matrix compound, the LDPE and PP pellets were fed into a stirring machine, which made the pellets well-mixed. The proportions of LDPE and PP were varied as shown in Table 2.

Table 2. Variation of LDPE and PP

% (w/w) LDPE	% (w/w) PP
0	100
20	80
40	60
60	40
80	20
100	0

Next, the well-mixed pellets were compounded with aspen wood fiber using a Baker Perkins Model ZSK 30, 30 mm, 26:1 co-rotating twin screw extruder (Werner & Pfleiderer Corporation, Ramsey, New Jersey). The proportion of wood fiber and matrix compound was maintained at 40% fiber and 60% polymer by weight. The calculation of this proportion is shown in Appendix B.

The extruder consists of three zones, which have different functions. These are the feeding section, compression zone and metering zone. First, the feed zone is located below the feed hopper and acts as a conveyor for feeding the polymers to the rest of the

barrel. Second, the compression zone makes the polymers into a melt. After the polymers are melted completely, they go through the metering zone and the exit die (Birley et al., 1992). In this experiment, the temperatures along the three components were divided into six zones. The temperatures of these zones were set in two different configurations as shown in Tables 3 and 4.

Table 3. The set of temperatures over the LDPE melting point

Zone	1	2	3	4	5	6
Temperature (°C)	150	150	150	150	150	150

Table 4. The set of temperatures over the PP melting point

Zone	1	2	3	4	5	6
Temperature (°C)	180	180	150	150	150	150

The temperatures of zones four to six were set to 150 °C because they ensure that while the polymer is completely melted, the wood fibers are not burned (Oladipo et al., 1999). The polymers were fed into the hopper, which was set at a speed of approximately 100 rpm and then passed through zone 1. The screw speed was also set at approximately 100 rpm. There are three feed ports on the extruder, shown in Figure 6. Port 2 was selected as the fiber feed location because it provides the best mechanical properties (Uerkanarak, 2001). There, the fiber was mixed with the melted polymers, to form the composite. Next, the composite stream exited through the die and was cut into pieces approximately 6 inches long.

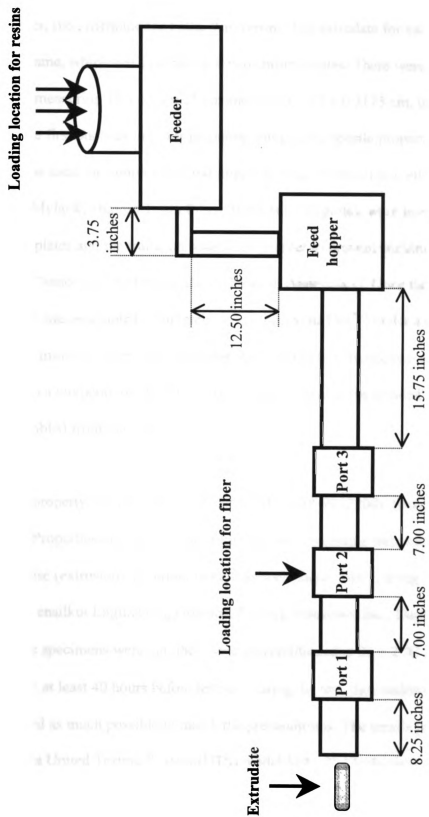


Figure 6 . Extruder diagram

The composite was molded into sheets using a Carver Laboratory Press, Model M (Fred S. Carver, Inc., Menomonee Falls, Wisconsin). The extrudate for each composite was put into a frame, which was laid between two chrome plates. There were two different frames, measuring 15 x 15 x 0.25 cm and 12.7 x 12.7 x 0.3175 cm, used in the molding step. The first one was used for preparing samples for tensile property testing, while the latter was used for samples for Izod impact testing. Sheets of polyethylene terephthalate (PET) (Mylar®, Dupont Teijin Films, Hopewell, Virginia), were inserted between the chrome plates and the frame on both sides in order to prevent stickiness. This method was called a “sandwich” technique and is shown in Appendix C. Once the plate-frame structure was assembled completely, it was heated at 150 °C under a pressure of 30,000 psi for 5 minutes. When the extrudates were completely melted into a sheet, the press was cooled to a temperature of 30°C using tap water. Finally, the molded sheet was disassembled from the frame.

Tensile property testing conformed to ASTM D 638-99 (2000), Standard Test Method for Tensile Properties of Plastics. The composite test specimens were cut along the lengthwise (extrusion) direction into a dumbbell shape, type I, using Tensilkut, Model 10-13 (Tensilkut Engineering Division, Sieburg Industries, Inc., Danbury, Connecticut). After the specimens were cut, they were preconditioned at 23 ± 2 °C and $50 \pm 5\%$ relative humidity at least 40 hours before testing. During the test, the conditions of the test were controlled as much possible to match the preconditions. The tensile property testing was done by a United Testing System (UTS) model SFM-20 Mechanical Test System. This machine worked with laser extensometer no. EXT 62LOE and laser power source model

no. EXT-62-LHMO (United Calibration Corp. 5802 Engineer Dr. Huntington Beach, Ca), to detect the distance of extension of the specimen. Before testing, the thickness and the width of specimens were measured along their narrow sections, using a digital vernier caliper Digimatic (Mitutoyo Corporation, Japan). The UTS machine was set, according to the ASTM 638-99 type I condition, as follows:

Load cell	= 1000 lb
Speed of testing	= 0.2 in./min
Extension gage length	= 2 ± 0.01 inches
Distance between grips	= 4.5 ± 0.2 inches

The data for tensile strength and modulus of elasticity were recorded and calculated automatically. The force (lb)/extension (in) curves were plotted on a Graphtec XY Plotter, type MP 3200 (Japan).

Izod impact testing conformed to ASTM D 256-97 (2000), Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics. The composite test specimens were cut along the lengthwise (extrusion) direction into pieces 12.7 x 64 x 3.18 mm and notched with an angle of $22 \frac{1}{2}^{\circ} \pm \frac{1}{2}^{\circ}$ to a depth of 2.5 mm, according to Test Method A. The notching was done by a TMI notching cutter (Testing Machine Inc., Amityville, New York). These specimens were preconditioned at $23 \pm 2^{\circ}\text{C}$ and $50 \pm 5\%$ relative humidity at least 40 hours before testing. When the test was performed, the test condition was set as much as possible to match the preconditioning. The Izod impact testing was performed using a TMI 43-I Izod impact tester (Testing Machines Inc., Amityville, New York) with a 5-lb pendulum. The specimens were positioned as a

vertical cantilever beam and were broken by a single swing of the pendulum. Both type of failure and impact resistance values were recorded. Four possible types of failures are defined and shown in Figure 7 as follows:

- C Complete Break - A break where the specimen separates into two or more pieces.
- H Hinge Break - An incomplete break that cannot support itself above the horizontal when the other part is held vertically (less than 90° included angle)
- P Partial Break - An incomplete break that does not meet the definition for a hinge break but has fractured at least 90% of the distance between the vertex of the notch and the opposite side.
- NB Non-Break - an incomplete break where the fracture extends less than 90% of the distance between the vertex of the notch and the opposite side.

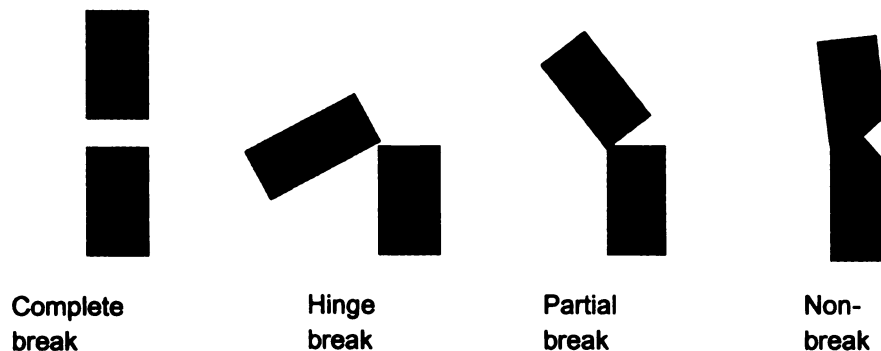


Figure 7. Four types of failures

Finally, both tensile property testing and Izod impact testing data were compared to values from the rule of mixtures, shown in Equation 21:

$$P_C = W_{LDPE} P_{LDPE} + W_{PP} P_{PP} \quad (21)$$

where P refers to the property value.

W represents the weight fraction.

The subscripts of C , $LDPE$ and PP refer to the composite, low density polyethylene and polypropylene, respectively.

The data were evaluated using statistical analysis from SPSS software, using the Least Significant Difference Method (LSD) test and Duncan's Multiple Range Test (DMRT) at the 99% significance level.

CHAPTER 5

RESULTS

Processing Above the LDPE Melting Point (150 °C)

1. Tensile Strength

The results of tensile strength measurements are presented in Table 5 and Figure 8. For comparison, calculated values from the “rule of mixing” are shown in Table 6 and also presented graphically in Figure 8. Tensile strength decreased as the amount of LDPE increased.

The highest tensile strength was obtained with 100% PP, and the lowest tensile strength with 100% LDPE. Statistical analysis at the 99% confidence level showed significant differences between all samples except pure LDPE and 80:20 LDPE:PP.

Table 5. Average tensile strength (psi) at processing temperature of 150 °C

Ratio of LDPE:PP	Tensile Strength ¹
0:100	3,763.10 ± 71.31 a ²
20:80	3,017.57 ± 97.72 b
40:60	2,564.38 ± 65.71 c
60:40	2,011.38 ± 43.17 d
80:20	1,517.46 ± 42.06 e
100:0	1,350.73 ± 69.44 e

¹Tensile Strength (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 6. Calculated tensile strength (psi) from “rule of mixing” at processing temperature of 150 °C

Ratio of LDPE:PP	Calculated Tensile Strength
0:100	3,763.10
20:80	3,280.63
40:60	2,798.15
60:40	2,315.68
80:20	1,833.20
100:0	1,350.73

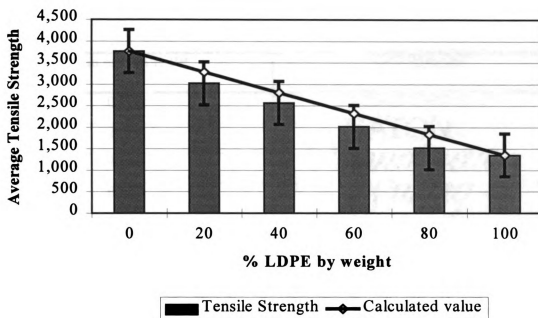


Figure 8. Comparison between average and calculated values of tensile strength (psi) at processing temperature of 150 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

2. Yield Strength

The results for yield strength are presented in Table 7 and Figure 9. Yield strength also tended to follow the “rule of mixing”. Calculated values are shown in Table 8 and also presented graphically in Figure 9. The yield strength decreased as the amount of PP was decreased.

Statistical analysis at the 99% confidence level again showed significant difference between all samples except pure LDPE and 80:20 LDPE:PP.

Table 7. Average yield strength (psi) at processing temperature of 150 °C

Ratio of LDPE:PP	Yield Strength ¹
0:100	3,756.91 ± 157.42 a ²
20:80	3,017.48 ± 218.01 b
40:60	2,563.51 ± 147.23 c
60:40	2,010.22 ± 96.33 d
80:20	1,510.22 ± 110.88 e
100:0	1,348.97 ± 156.68 e

¹Yield Strength (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 8. Calculated yield strength (psi) from “rule of mixing” at processing temperature of 150 °C

Ratio of LDPE:PP	Calculated Yield Strength
0:100	3756.91
20:80	3275.32
40:60	2793.73
60:40	2312.15
80:20	1830.56
100:0	1348.97

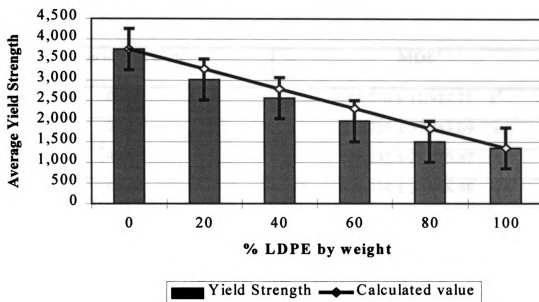


Figure 9. Comparison between average and calculated values of yield strength (psi) at processing temperature of 150 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

3. Modulus of Elasticity (MOE)

The results of MOE are shown in Table 9 and Figure 10. These results tended to differ from those calculated from the “rule of mixing,” which are presented in Table 10 and graphed in Figure 10. Thus, the results of MOE did not follow the “rule of mixing”.

The highest MOE values were found at 0:100, 20:80, 40:60 and 60:40 LDPE:PP, which were significantly higher, at the 99% confidence interval, than 80:20 and 100:0 LDPE:PP. The differences within these two groups were not statistically significant.

Table 9. Average MOE (psi) at processing temperature of 150 °C

Table 9. Average MOE (psi) at processing temperature of 150 °C

Ratio of LDPE:PP	MOE ¹
0:100	243,210 ± 51,927.77 a ²
20:80	274,725 ± 57,243.69 a
40:60	208,232 ± 21,620.67 a
60:40	206,438 ± 24,888.48 a
80:20	128,924 ± 18,104.69 b
100:0	109,632 ± 11,922.92 b

¹MOE (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 10. Calculated MOE (psi) from “rule of mixing” at processing temperature of 150 °C

Ratio of LDPE:PP	Calculated MOE
0:100	243,210
20:80	216,494
40:60	189,779
60:40	163,063
80:20	136,348
100:0	109,632

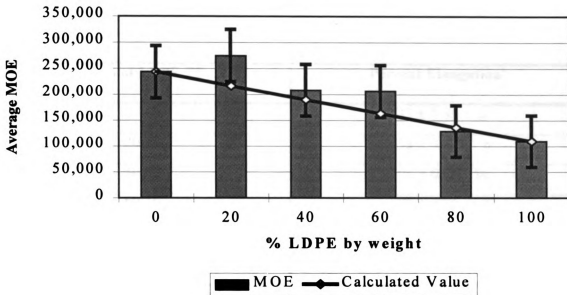


Figure 10. Comparison between average and calculated values of MOE (psi) at processing temperature of 150 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

4. Percent Elongation

The results for percent elongation are presented in Table 11 and Figure 11. Again, these results tended to differ from those calculated from the “rule of mixing,” which are presented in Table 12 and presented graphically in Figure 11.

The highest value of percent elongation was obtained with 100% PP and the lowest with 60:40 LDPE:PP. Statistical analysis at the 99% confidence level showed significant differences between the higher value and all others. The 20:80 and 60:40 blends also differed. However, the differences in percent elongation at 40:60, 80:20 and 100:0 LDPE:PP were not statistically significant.

Table 11. Average percent elongation (%) at processing temperature of 150 °C

Ratio of LDPE:PP	Percent Elongation ¹
0:100	5.35 ± 0.56 a ²
20:80	3.33 ± 0.78 b
40:60	3.02 ± 0.49 bc
60:40	2.01 ± 0.20 c
80:20	2.47 ± 0.60 bc
100:0	2.51 ± 0.47 bc

¹Percent Elongation (%) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 12. Calculated percent elongation (%) from “rule of mixing” at processing temperature of 150 °C

Ratio of LDPE:PP	Calculated Percent Elongation
0:100	5.35
20:80	4.78
40:60	4.21
60:40	3.65
80:20	3.08
100:0	2.51

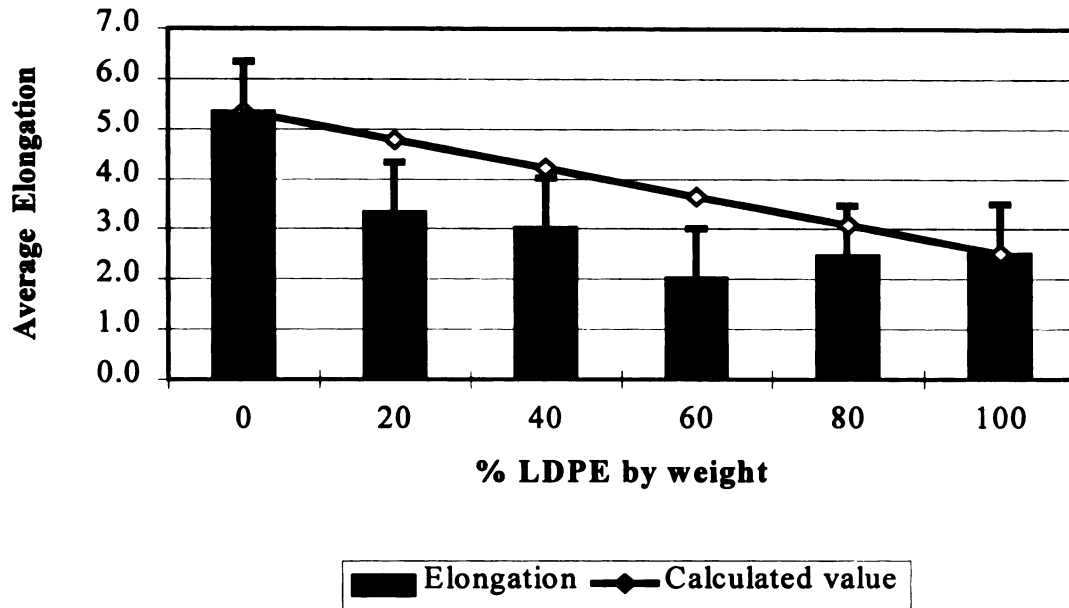


Figure 11. Comparison between average and calculated values of elongation (%) at processing temperature of 150 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

5. Izod Impact Strength

Table 13 and Figure 12 present the results for Izod impact strength. For comparison, calculated values from the “rule of mixing” are shown in Table 14 and Figure 12. Izod impact strength increased as the amount of LDPE increased. Then, it tended to follow the “rule of mixing.”

The highest Izod impact strength was obtained with 100% LDPE. Statistical analysis at the 99% confidence interval showed significant differences between all samples except two groups: the group of pure PP and 80:20 LDPE:PP, and the group of 60:40 and 80:20 LDPE:PP.

There were also differences in type of failure. All of the specimens with 100% PP, 20:80, 40:60 and 60:40 LDPE:PP were completely broken after impact by the hammer, while those specimens with 80:20 LDPE:PP and 100% LDPE gave different results. For the 80:20 variation, the failure was a mix of hinge and complete breaks. The type of failure from pure LDPE was a mix of hinge and partial break.

Table 13. Average Izod impact strength (ft-lb/in) and type of failure at processing temperature of 150 °C

Ration of LDPE:PP	Izod Impact Strength ¹	Type of Failure
0:100	0.630 ± 0.235 d ²	Complete
20:80	0.949 ± 0.576 d	Complete
40:60	1.302 ± 0.252 c	Complete
60:40	1.925 ± 0.190 b	Complete
80:20	2.076 ± 0.184 b	Complete and Hinge
100:0	2.559 ± 0.388 a	Hinge and Partial

¹ Izod Impact Strength (ft-lb/in) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 14. Calculated Izod impact strength (ft-lb/in) from “rule of mixing” at processing temperature of 150 °C

Ratio of LDPE:PP	Calculated Izod Impact Strength
0:100	0.630
20:80	1.016
40:60	1.402
60:40	1.787
80:20	2.173
100:0	2.559

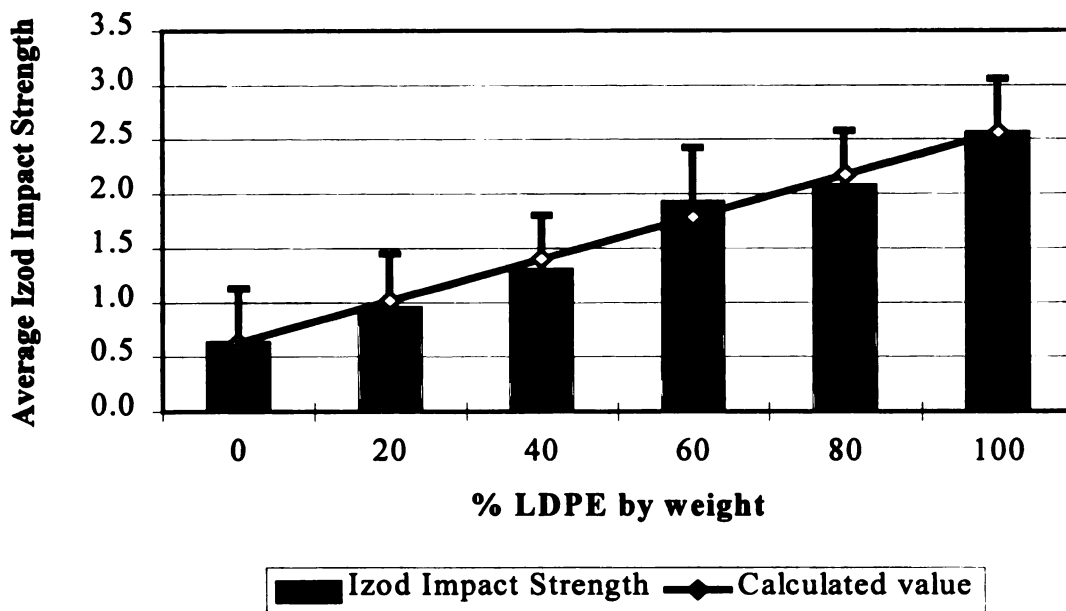


Figure 12. Comparison between average and calculated values of Izod impact strength (ft-lb/in) at processing temperature of 150 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

Processing Above the PP the Melting Point (180 °C)

1. Tensile Strength

The results of tensile strength measurements are presented in Table 15 and Figure 13. For comparison, calculated values from the “rule of mixing” are shown in Table 16 and also presented graphically in Figure 13. Tensile strength decreased as the amount of LDPE increased. Then, it tended to follow the “rule of mixing”.

The highest tensile strength was obtained with 100% PP, and the lowest tensile strength with 100% LDPE. Statistical analysis at the 99% confidence level showed significant differences between all samples except 60:40 and 80:20 LDPE:PP.

Table 15. Average tensile strength (psi) at processing temperature of 180 °C

Ratio of LDPE:PP	Tensile Strength ¹
0:100	3,382.12 ± 206.72 a ²
20:80	3,025.78 ± 246.37 b
40:60	2,673.01 ± 137.17 c
60:40	2,145.80 ± 91.02 d
80:20	1,893.03 ± 89.95 d
100:0	1,393.74 ± 161.18 e

¹Tensile Strength (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 16. Calculated tensile strength (psi) from “rule of mixing” at processing temperature of 180 °C

Ratio of LDPE:PP	Calculated Tensile Strength
0:100	3,382.12
20:80	2,984.44
40:60	2,586.77
60:40	2,189.09
80:20	1,791.42
100:0	1,393.74

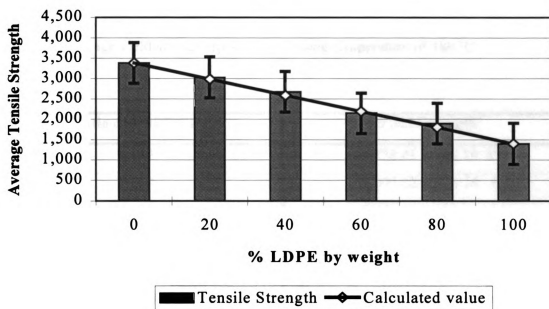


Figure 13. Comparison between average and calculated values of tensile strength (psi) at processing temperature of 180 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

2. Yield Strength

The results for yield strength are presented in Table 17 and Figure 14. Yield strength also tended to follow the “rule of mixing”. Calculated values are shown in Table 18 and presented graphically in Figure 14. The yield strength decreased as the amount of PP decreased.

The highest yield strength was obtained with 100% PP. Statistical analysis at the 99% confidence interval showed significant differences between all samples except two groups: the group of pure PP and 80:20 LDPE:PP, and the group of 60:40 and 80:20 LDPE:PP.

Table 17. Average yield strength (psi) at processing temperature of 180 °C

Ratio of LDPE:PP	Yield Strength ¹
0:100	3,378.41 ± 208.16 a ²
20:80	3,005.62 ± 334.74 b
40:60	2,670.74 ± 137.33 b
60:40	2,134.66 ± 101.55 c
80:20	1,892.80 ± 90.06 c
100:0	1,392.60 ± 161.14 d

¹Yield Strength (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 18. Calculated yield strength (psi) from “rule of mixing” at processing temperature of 180 °C

Ratio of LDPE:PP	Calculated Yield Strength
0:100	3378.41
20:80	2981.25
40:60	2584.09
60:40	2186.92
80:20	1789.76
100:0	1392.60

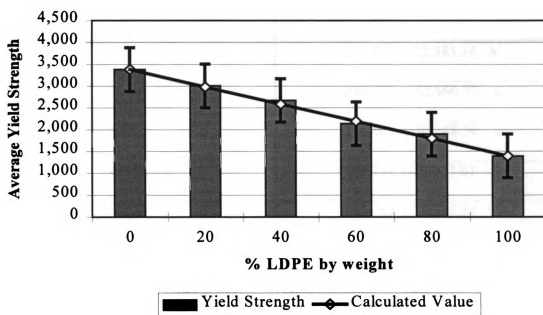


Figure 14. Comparison between average and calculated values of yield strength (psi) at processing temperature of 180 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

3. Modulus of Elasticity

The results of MOE are shown in Table 19 and Figure 15. Again, these results tended to follow the “rule of mixing.” Table 20 and Figure 15 present these calculated values. The MOE decreased as the amount of LDPE increased.

The highest MOE values were found at 0:100, 20:80 and 40:60 LDPE:PP, which were significantly different, at the 99% confidence interval, from 80:20 and 100:0 LDPE:PP.

Table 19. Average MOE (psi) at processing temperature of 180 °C

Ratio of LDPE:PP	MOE ¹
0:100	261,252 ± 72,383.16 a ²
20:80	246,143 ± 42,566.01 a
40:60	231,061 ± 30,348.36 a
60:40	197,231 ± 19,133.61 ab
80:20	155,988 ± 21,747.54 bc
100:0	101,857 ± 21,948.84 c

¹MOE (psi) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 20. Calculated MOE (psi) from “rule of mixing” at processing temperature of 180 °C

Ratio of LDPE:PP	Calculated MOE
0:100	261,252
20:80	229,373
40:60	197,494
60:40	165,615
80:20	133,736
100:0	101,857

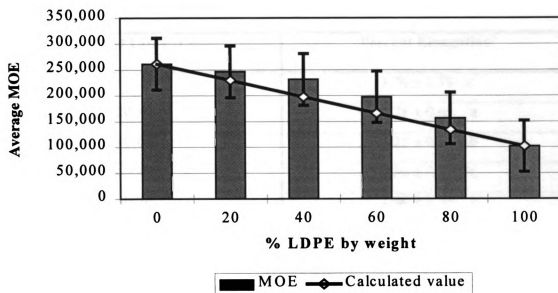


Figure 15. Comparison between average and calculated values of MOE (psi) at processing temperature of 180 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

4. Percent Elongation

The results for percent elongation are presented in Table 21 and Figure 15. These results tended to differ from those calculated from the “rule of mixing,” which are presented in Table 22 and presented graphically in Figure 15.

Elongation at 100% PP and 20:80 LDPE:PP was significantly higher than at 60:40 and 80:20 LDPE:PP. 80:20 had the lowest percent elongation, significantly different from all other samples except for 60:40 LDPE:PP.

Table 21. Average of percent elongation (%) at processing temperature of 180 °C

Ratio of LDPE:PP	Percent Elongation ¹
0:100	3.76 ± 0.38 a ²
20:80	3.28 ± 0.61 a
40:60	3.22 ± 0.53 ab
60:40	2.36 ± 0.33 bc
80:20	1.96 ± 0.36 c
100:0	2.92 ± 0.43 ab

¹Percent Elongation (%) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 22. Calculated percent elongation (%) from “rule of mixing” at processing temperature of 180 °C

Ratio of LDPE:PP	Calculated Percent Elongation
0:100	3.76
20:80	3.59
40:60	3.42
60:40	3.26
80:20	3.09
100:0	2.92

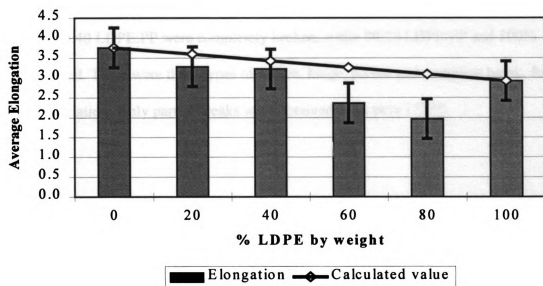


Figure 16. Comparison between average and calculated values of elongation (%) at processing temperature of 180 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

5. Izod Impact Strength

The results of Izod impact strength are shown in Table 23 and Figure 16. These results tended to differ from those calculated from the “rule of mixing,” which are presented in Table 24 and graphed in Figure 16.

The highest Izod impact strength was obtained with 100% PP. Statistical analysis at the 99% confidence level showed significant differences between 100% PP and all other samples except 20:80 LDPE:PP. The group of 40:60, 60:40 and 80:20 LDPE:PP had significantly lower impact strength than the other samples.

There were also differences in type of failure. All of the specimens with 100% PP, 20:80, 40:60 and 60:40 LDPE:PP were completely broken, while 80:20 LDPE:PP and 100% LDPE differed. There were three types of failure, hinge, partial and complete break, for the 80:20 variation. Only partial breaks were obtained from pure LDPE.

Table 23. Average of Izod impact strength (ft-lb/in) and type of failure at processing temperature of 180 °C

Ratio of LDPE:PP	Izod Impact Strength ¹	Type of Failure
0:100	1.935 ± 0.316 a ²	Complete
20:80	1.867 ± 0.316 ab	Complete
40:60	1.104 ± 0.443 c	Complete
60:40	1.212 ± 0.370 c	Complete
80:20	1.108 ± 0.165 c	Complete, Partial and Hinge
100:0	1.555 ± 0.368 b	Hinge and Partial

¹ Izod Impact Strength (ft-lb/in) = Mean ± Standard Deviation (SD).

²Different letters within the column show highly significant differences by Duncan's Multiple Range Test (DMRT) at 99% significance level.

Table 24. Calculated Izod Impact Strength (ft-lb/in) from “rule of mixing” at processing temperature of 180 °C

Ratio of LDPE:PP	Calculated Izod Impact Strength
0:100	1.935
20:80	1.859
40:60	1.783
60:40	1.707
80:20	1.631
100:0	1.555

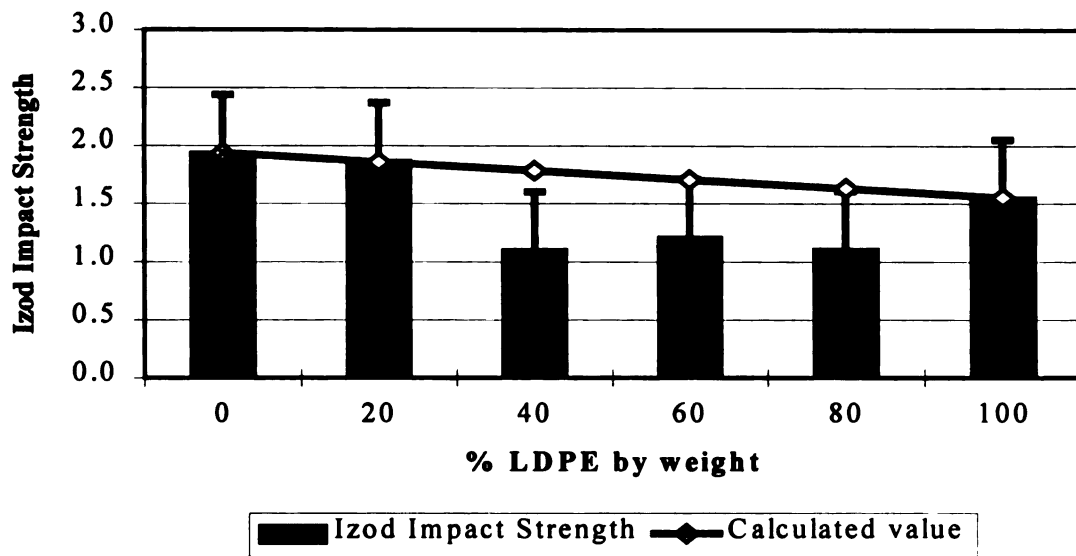


Figure 17. Comparison between average and calculated values of Izod impact strength (ft-lb/in) at processing temperature of 180 °C, for composites with 40% wood fiber and 60% matrix of PP/LDPE

The Effect of Temperature

The effect of temperature was studied by a comparison of each of the mechanical properties for the same resin ratio between those two temperatures. With statistical analysis at the 99% confidence interval, the results for tensile strength and yield strength for the two ratios of 100% PP and 80:20 LDPE:PP showed a significant difference between the two temperatures while the rest did not show significant difference between these temperatures.

For modulus of elasticity, statistical analysis at the 99% confidence interval showed the ratios of 40:60 and 80:20 LDPE:PP had significant differences between the two temperatures while the remaining ratios did not show significant differences.

For percent elongation, there were five ratios that showed significant difference between the two temperatures; only the ratio of 20:80 LDPE:PP did not show a significant difference.

For Izod impact resistance, statistical analysis at the 99% confidence interval showed that all of the ratios had a significant difference between the temperatures.

The raw data for all mechanical properties are shown in Appendix D and the statistical analyses are reported in Appendix E.

CHAPTER 6

DISCUSSION

Processing Above the LDPE Melting Point (150 °C)

The mechanical behavior of composites can be investigated by measuring tensile properties. In this study, all test specimens were cut only in the lengthwise (extrusion) direction, since these are less variable than those from the crosswise direction (Rojanarungtawee, 1998). The tensile measurements used were tensile strength, yield strength, modulus of elasticity and % elongation at yield. These results are useful for qualitative characterization and development (Chotipatoomwan, 1998).

In general, the addition of fibrous fillers is used to improve mechanical properties of composites; however, a lack of adhesion between the hydrophobic polymer and hydrophilic fiber may cause poor strength properties. Sain et al. (1993) studied the effects of the composition of composites on their mechanical properties. Their results showed that the presence of cellulosic fiber, e.g. aspen, in the PP composites caused a reduction of tensile strength. Herrera-Franco and Aguilar-Vega (1997) also confirmed that the addition of fiber reduced the tensile strength because the high viscosity of the matrix during composite fabrication may hinder proper dispersal of fiber.

The highest tensile strength was obtained with 100% PP. The tensile strength of the composite is less than that of 100% PP without fiber. This is due to the reason above. The

tensile strength of the composite tended to decrease with addition of LDPE. Comparison with strength calculated from the “rule of mixing” confirmed that tensile strength reasonably followed the “rule of mixing.”

The addition of LDPE tends to decrease the tensile strength of the composite because it affects the crystallinity of the composite. The crystallinity is one of the factors that affects the tensile strength. As it is increased, the tensile strength will be increased. Basically, LDPE has a more branched structure. Most PP in packaging is isotactic, which is highly crystalline. The presence of branches in the backbone chain limits the formation of crystallinity by introducing irregularities in the structure. Therefore, LDPE is less crystalline than PP. The addition of LDPE resulted in the amorphous region of the composite being increased while the crystalline region was decreased. Then, the tensile strength also decreased.

The results for yield strength, MOE and elongation also changed for the same reason as the tensile strength. The highest values for both yield strength and elongation were obtained with 100% PP, while the highest MOE was obtained in the group of 0:100, 20:80, 40:60 and 60:40 LDPE:PP. Statistical analysis did not show significant differences within these groups. This is because MOE is affected by various factors such as filler geometry, particle size dispersion, and filler concentration. In addition, fiber orientation and spherulite size of the polymer components also affect the modulus (Bigg, 1987).

The last mechanical property in this experiment was Izod impact resistance. This test method is used to determine the resistance to breakage by flexural shock of plastics and composites, as indicated by the energy extracted from a standardized pendulum-type hammer, mounted in a standard machine, in breaking standard specimens with one pendulum swing. The notch on the specimen concentrates the stress in order to minimize the deformation and direct the fracture to the part of the specimen behind the notch (Chotipatoomwan, 1998).

In general, the inclusion of fillers in plastic matrices makes the composite more brittle. However, the fracture behavior is mostly determined by the properties of the polymer matrices. Most of the energy used for material fracture is required for straining and fracturing of the matrices (Berlin et al, 1986). For brittle matrices, the introduction of a disperse filler raises the surface energy of the material fracture, and can improve the impact strength of the composites. The filler decreases the surface energy in case of non-brittle matrices because of the reduction of the volume fraction in the plastic zone. Then, the impact strength decrease with the addition of fillers (Chotipatoomwan, 1998).

According to the Izod impact resistance data, the highest value was obtained with 100% LDPE. This can result from the lesser amount of crystallinity. Again, crystallinity plays an important role for impact resistance. Since the addition of LDPE, which is less crystalline than PP, increases the amorphous region of the composite, the impact resistance will be increased.

Processing Above the PP Melting Point (180 °C)

As previously described, the results of tensile strength, yield strength, MOE and elongation also depend on the same factors. The highest values are obtained with 100% PP except for MOE and elongation.

The highest MOE was found at three variations, which are 100% PP, 20:80 and 40:60 LDPE:PP, for the same reason as in processing at 150 °C. Statistical analysis at the 99% confidence level showed no significant difference within this group. For elongation, there were two highest values, obtained with 100% PP and 20:80 LDP:PP. The reason for the elongation results might be inconsistent fiber distribution during processing.

Examining the “rule of mixing, ” only elongation differed, while tensile strength, yield strength and MOE tended to follow the rule. Again, inconsistent fiber distribution might occur during processing.

For Izod impact resistance, the highest value was obtained with 100% PP. The results also differ from the “rule of mixing. ” In fact, the value of Izod impact resistance should increase with the presence of amorphous regions. Poor adhesion between the matrix and the wood fiber might occur during processing, causing dissipation of the maximum energy resulted from mechanical friction during the pullout process and debonding of the fiber (Lawrence, 1974).

The Effect of Temperature

A summary of the effect of processing temperatures on variations and mechanical properties is presented in Table 25.

Table 25. The effect of temperature on variations and mechanical properties

Mechanical properties	Variation LDPE:PP					
	0:100	20:80	40:60	60:40	80:20	100:0
Tensile Strength	-	0	0	0	+	0
Yield Strength	-	0	0	0	+	0
MOE	0	0	+	0	+	0
Percent elongation	-	0	+	+	-	+
Izod impact resistance	+	+	+	-	-	-

Note: Different symbols represent significant differences between processing temperature of 150 °C and 180 °C by Duncan's Multiple Range Test (DMRT) at the 99% confidence level. Where + refers to properties at 180 °C significantly higher than at 150 °C, - refers to properties at 150 °C significantly higher than at 180 °C and 0 refers to no significant difference between properties at 150 °C and 180 °C.

From Table 25, the effect of processing temperature can be described in 6 cases. First, the results from 0:100 LDPE:PP showed that increasing the temperature from 150 °C to 180 °C affected tensile strength, yield strength, percent elongation and Izod impact resistance.

The first three properties tended to decrease with increasing temperature, while the latter tended to increase. On the other hand, MOE was not affected by increasing temperature.

Second, the effect of processing temperature on 20:80 LDPE:PP revealed that increasing temperature had no effect on tensile strength, yield strength, MOE and percent elongation, whereas Izod impact resistance improved with increasing temperature.

Third, increasing the processing temperature showed no effect on tensile strength and yield strength obtained with 40:60 LDPE:PP, while it tended to increase MOE, percent elongation and Izod impact resistance

In the case of 60:40 LDPE:PP, increasing the processing temperature from 150 °C to 180 °C did not affect tensile strength, yield strength, and MOE. On the other hand, percent elongation and Izod impact resistance were affected by increasing temperature; elongation tended to increase, but the impact resistance decreased.

Next, all mechanical properties of 80:20 LDPE:PP were affected by increasing temperature. Tensile strength, yield strength and MOE tended to increase, while percent elongation and Izod impact resistance decreased.

For the last variation of 100:0 LDPE:PP, its tensile strength, yield strength and MOE were not affected by increasing the processing temperature from 150 °C to 180 °C. In

contrast, percent elongation increased and Izod impact resistances decreased when the processing temperature increased.

Increasing the temperature also affected the color of the extrudate. The color of extrudate from the processing temperature of 180 °C tended to be slightly darker than that from 150 °C. This could be due to thermal degradation of the fiber at high temperature (Sain & Kokta, 1994).

Rojanarungtae (1998) processed composites of mixed HDPE and PP with wood fiber. The PP was Pro-Fax 7823, Himont, USA, which had 0.5 g/min melt flow rate and 0.897 g/cm³ density. It was found that only 70:30 HDPE:PP and 100:0 HDPE:PP was processable. Since the melting point of PP was around 175 to 185 °C, the compounding temperature at 150 °C was too low for PP to melt during processing. Therefore, it was surprising that the PP in this research melted sufficiently to form a composite at 150 °C. This might result from the effect of molecular structure on melt viscosity of the PP (Birley et al, 1992). Polymer chains are highly coiled in the equilibrium state and there is a high degree of both inter- and intra-chain entanglement. When resins are forced to move by the extruder, the chains tend to become aligned and disentangled. There will also be some slippage of the chains over each other (Birley et al, 1992). Thus, the viscosity decreases as shear increases. However, this should be investigated further.

CHAPTER 7

CONCLUSIONS

In the study of mechanical properties of LDPE/PP and wood composites, the values of tensile strength, yield strength, MOE and elongation were measured, as well as impact resistance. The variation of 0:100 LDPE:PP for both processing temperature seemed to provide the highest mechanical strength, while the impact strength tended to differ. The highest Izod impact strength of 150 °C was obtained with 100:0 LDPE:PP, but the highest value of 180 °C was gained with 0:100 LDPE:PP.

In the cases of tensile strength and yield strength, decreasing the crystalline fraction, which resulted from the presence of LDPE in the PP matrix, led to decrease these two properties. However, lack of crystallinity in the PP matrix could not be used to explain the results for MOE and elongation because they did not vary gradually. Geometry, size and concentration of the fiber filler might cause changes in MOE and elongation (Bigg, 1987). The explanation of the impact strength differs for the two temperatures. For processing at 150 °C, the increase in the impact strength might be the same reason as for tensile strength and yield strength, but the value from 180 °C might be due to increased mechanical friction during the pullout process and debonding of fibers (Lawrence, 1974).

The effect of the processing temperature on mechanical properties of the blends varied with blend composition.

RECOMMENDATIONS FOR FUTURE RESEARCH

Interference with mechanical properties of polymer-wood composites might occur due to poor compatibility between the polar hydrophilic wood fiber and the non-polar hydrophobic polymer matrix, indicating weak interfacial adhesion and poor dispersion of wood fiber in the matrix due to strong fiber-fiber interactions resulting from hydrogen bonding.

A recommendation for future research is to investigate the addition of chemical modification as a coupling agent, such as maleic anhydride modified HDPE (MAHDPE), bismaleic modified-PP (BPP), etc, in order to modify compatibility between the matrix and the fibers.

Also, the physical characteristics of the composite such as fiber orientation and nucleation size of blends should be investigated in order to provide more explanation of for the effects on mechanical properties.

Instead of compression molding, injection molding might be used to prepare the specimens in order to provide more precision in experimental data.

APPENDIX A

Table 26. Properties of Dow Polyethylene 133A

Physical Properties		Test method	Value ⁽¹⁾ English (SI)
<u>Resin Properties</u>			
Melt Index, g/10 min		ASTM D 1238	0.22
Density, g/cc		ASTM D 792	0.9230
DSC Melting point, °F (°C)		Dow Method	232 (111)
VICAT Softing Point, °F (°C)		ASTD D 1525	203 (95)
<u>Film Properties, 2.0 mil (51 µm)</u>			
Puncture Resistance, ft-lb _f /in ³ (J/cm ³)		Dow Method	44 (4)
Dart Impact (Method A), g		ASTM D1709	253
Elmendorf Tear, g	MD	ASTMD 1922	302
	CD		197
Tensile Yield, psi (MPa)	MD	ASTM D 882	1933 (13)
	CD		1688 (12)
Ultimate Tensile, psi (MPa)	MD	ASTM D 882	3604 (25)
	CD		3824 (26)
Ultimate Elongation, %	MD	ASTM D 882	328
	CD		620
Toughness, ft-lb _f /in ³ (J/cm ³)	MD	ASTM D 882	1627 (135)
	CD		2249 (186)
Gloss, 45°		ASTM D 2457	46
Haze, %		ASTM D 1003	14

⁽¹⁾Typical value, not to be construed as specification (Dow Plastics Chemical, Midland, MI).

Table 27. Properties of Dow Inspire H704-04

Physical Properties	Test method	Value⁽¹⁾ English (SI)
Melt Index, g/10 min	ASTM D 1238	4.0
Density, g/cc	ASTM D 792	0.9
Tensile Strength at yield, psi (MPa)	ASTM D 638	5000 (34.5)
Elongation at yield, %	ASTM D 638	12
Flexural Modulus	ASTMD 790A	250,000 (1725)
Deflection Temperature Under Load Unannealed, °F (°C)	ASTM D 648	207 (97)
Notched Izod, ft-lb/in ³ (J/cm ³)	ASTM D 256A	0.8 (42.5)

⁽¹⁾Typical value, not to be construed as specification (Dow Plastics Chemical, Midland, MI).

APPENDIX B

Calculation for the proportion of wood fiber and matrix compound

In order to attain a proportion of wood fiber and matrix compound of 40:60, w/w, it is necessary to calculate the polymer feed rate and fiber feed rate to know how much fiber must be fed into the extruder port (Rojanarungtawee, 1998). The calculations were as follows:

1. Polymer feed rate

- 1.1 Feed the well-mixed pellets through the extruder hopper with screw speed at 100 rpm.
- 1.2 Once the extrudate exits the die, start cutting the extrudate every one minute until five samples of extrudate are cut.
- 1.3 Wait until the extrudates cool and weigh each extrudate.
- 1.4 Calculate the polymer feed rate from

$$\text{Polymer feed rate (g/min)} = \frac{\text{Total extrudate weight (g)}}{5 \text{ (min)}}$$

2. Fiber feed rate

- 2.1 Calculate the fiber feed rate from

$$\text{Fiber feed rate (g/min)} = \text{Polymer feed rate} \times (40/60)$$

- 2.2 Calculate the amount of fiber to be fed into the port per minute from

$$\text{Amount of fiber (g)} = \frac{\text{Fiber feed rate (g/min)}}{1 \text{ min}}$$

APPENDIX C

Compression molding process: “sandwich technique”

This process is called a sandwich because the extrudate is placed between two chrome plates before applying pressure. The processing steps are shown as follows:

1. Set temperature on top and bottom of mold plate to 150 °C.
2. Assemble the extrudate, frame, Mylar sheets and chrome plates as shown in Figure 17.
3. Once the temperature of mold plates reaches 150 °C, place the assembly on the bottom mold plate.
4. Turn off the hydraulic chamber valve by turning clockwise and increase the pressure to 30,000 psi by moving the handle. Avoid wrinkles by pressing the assembly softly
5. Hold for 5 minutes. If pressure drops, apply more pressure.
6. To cool down the temperature, turn the temperature setting to 30 °C and turn on the cooling system (tap water).
7. After the temperature reaches 30 °C, withdraw the assembly from the mold and remove all components with care.
8. For clean up, set the temperature to 200 °C. Place the chrome plates on the mold plate and wait for 5 minutes. Then, remove all resins with a scraper.

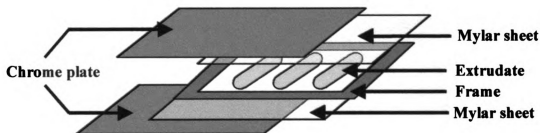


Figure 18. “Sandwich technique” diagram

APPENDIX D

Table 28. Results of tensile strength (psi) at processing temperature of 150 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	3,579.62	3,704.80	3,953.17	3,905.58	3,672.35	3,763.10	159.47
20:80	3,203.63	2,834.02	2,755.17	3,247.70	3,047.33	3,017.57	218.52
40:60	2,747.34	2,619.26	2,541.24	2,571.65	2,342.40	2,564.38	146.93
60:40	2,012.95	1,901.00	1,942.53	2,052.48	2,147.94	2,011.38	96.52
80:20	1,430.55	1,469.15	1,468.08	1,664.61	1,554.90	1,517.46	94.05
100:0	1,577.94	1,213.28	1,308.43	1,434.26	1,219.72	1,350.73	155.28

Table 29. Results of yield strength (psi) at processing temperature of 150 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	3,571.41	3,702.23	3,949.10	3,889.62	3,672.21	3,756.91	157.42
20:80	3,203.63	2,835.30	2,755.17	3,246.90	3,046.42	3,017.48	218.01
40:60	2,747.17	2,618.67	2,538.46	2,571.65	2,341.60	2,563.51	147.23
60:40	2,012.27	1,898.97	1,942.53	2,051.20	2,146.14	2,010.22	96.33
80:20	1,430.39	1,589.54	1,460.31	1,663.39	1,407.46	1,510.22	110.88
100:0	1,577.35	1,211.35	1,307.48	1,434.26	1,214.41	1,348.97	156.68

Table 30. Results of modulus of elasticity (psi) at processing temperature of 150 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	259,462	158,918	299,264	259,273	239,136	243,210	51,927.77
20:80	332,961	209,561	288,135	220,157	332,810	274,725	57,243.69
40:60	229,628	217,054	175,006	199,112	220,359	208,232	21,620.67
60:40	200,780	181,660	197,835	203,646	248,271	206,438	24,888.48
80:20	100,910	139,283	120,473	140,120	143,832	128,924	18,104.69
100:0	110,432	104,007	104,075	129,849	99,797	109,632	11,922.92

Table 31. Results of percent elongation at processing temperature of 150 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	6.25	4.72	5.26	5.33	5.21	5.35	0.56
20:80	2.78	3.78	2.64	4.49	2.98	3.33	0.78
40:60	3.4	2.26	3.19	3.43	2.83	3.02	0.49
60:40	2.27	2.06	1.86	2.09	1.77	2.01	0.20
80:20	2.63	1.70	3.14	2.88	2.00	2.47	0.60
100:0	2.18	3.32	2.40	2.19	2.48	2.51	0.47

Table 32. Results of Izod impact strength (ft-lb/in) and type of failure at processing temperature of 150 °C

Replication	Variation LDPE:PP											
	0:100		20:80		40:60		60:40		80:20		100:0	
	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure
1	1.033	C	0.540	C	1.014	C	2.288	C	1.968	H	2.489	H
2	0.542	C	0.426	C	1.304	C	2.078	C	1.994	H	2.321	H
3	0.538	C	0.250	C	1.354	C	1.922	C	2.034	H	2.056	H
4	0.893	C	0.538	C	1.438	C	1.857	C	1.660	H	3.203	P
5	0.518	C	2.689	C	1.201	C	2.089	C	2.179	H	1.832	P
6	0.588	C	1.111	C	1.282	C	2.140	C	2.123	H	1.936	P
7	0.216	C	0.965	C	1.246	C	1.893	C	1.875	H	2.773	P
8	0.729	C	0.417	C	1.449	C	1.959	C	2.278	H	2.757	P
9	0.716	C	0.972	C	0.936	C	1.786	C	2.094	H	2.768	P
10	0.923	C	0.802	C	1.066	C	1.835	C	2.172	C	2.525	P
11	0.529	C	0.951	C	0.965	C	1.863	C	2.295	C	2.902	P
12	0.323	C	1.121	C	1.380	C	1.524	C	2.136	C	2.911	P
13	0.353	C	1.002	C	1.474	C	1.670	C	2.335	C	2.677	P
14	0.860	C	1.174	C	1.511	C	2.031	C	1.844	C	2.432	P
15	0.686	C	1.272	C	1.907	C	1.943	C	2.158	C	2.807	P
Mean	0.630		0.949		1.302		1.925		2.076		2.559	
SD	0.235		0.576		0.252		0.190		0.184		0.388	

Note: C = Complete break; H = Hinge break; and P = Partial break.

Table 33. Results of tensile strength (psi) at processing temperature of 180 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	3,218.89	3,390.15	3,715.41	3,200.11	3,386.06	3,382.12	206.72
20:80	2,964.24	3,142.92	2,726.13	2,917.90	3,377.71	3,025.78	246.37
40:60	2,506.23	2,663.90	2,740.70	2,862.99	2,591.24	2,673.01	137.17
60:40	2,131.33	2,278.19	2,087.60	2,187.47	2,044.42	2,145.80	91.02
80:20	1,861.05	1,901.40	1,783.05	1,888.24	2,031.42	1,893.03	89.95
100:0	1,348.26	1,298.79	1,678.37	1,294.97	1,348.30	1,393.74	161.18

Table 34. Results of yield strength (psi) at processing temperature of 180 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	3,208.87	3,389.93	3,713.89	3,199.81	3,379.56	3,378.41	208.16
20:80	ND	ND	2,725.94	2,914.40	3,376.51	3,005.62	334.74
40:60	2,504.79	2,656.26	2,739.99	2,861.81	2,590.85	2,670.74	137.33
60:40	2,130.97	2,277.28	2,086.71	ND	2,043.66	2,134.66	101.55
80:20	1,860.83	1,901.08	1,782.64	1,888.08	2,031.35	1,892.80	90.06
100:0	1,347.38	1,296.59	1,677.07	1,294.38	1,347.56	1,392.60	161.14

Note: ND = Not Detected

Table 35. Results of modulus of elasticity (psi) at processing temperature of 180 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	277,349	300,233	137,245	269,020	322,412	261,252	72,383.16
20:80	237,610	253,850	212,300	211,665	315,289	246,143	42,566.01
40:60	182,539	264,432	245,676	230,256	232,400	231,061	30,348.36
60:40	218,078	208,886	180,810	204,923	173,459	197,231	19,133.61
80:20	158,328	176,654	127,284	176,431	141,242	155,988	21,747.54
100:0	91,962	85,344	139,363	102,949	89,670	101,857	21,948.84

Table 36. Results of percent elongation at processing temperature of 180 °C

Ratio LDPE:PP	Replication					Mean	SD
	1	2	3	4	5		
0:100	3.58	4.07	4.13	3.20	3.82	3.76	0.38
20:80	ND	ND	3.48	3.77	2.59	3.28	0.61
40:60	3.70	3.34	2.89	2.47	3.68	3.22	0.53
60:40	1.93	2.36	2.43	ND	2.73	2.36	0.33
80:20	1.57	2.10	2.41	1.62	2.09	1.96	0.36
100:0	3.16	3.52	2.47	2.56	2.91	2.92	0.43

Table 37. Results of Izod impact strength (ft-lb/in) and type of failure at processing temperature of 180 °C

Replication	Variation LDPE:PP											
	0:100		20:80		40:60		60:40		80:20		100:0	
	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure	Impact Strength	Type of failure
1	1.471	C	1.843	C	0.937	C	1.608	C	0.847	C	1.408	P
2	2.311	C	1.73	C	0.319	C	1.138	C	1.275	C	1.449	P
3	2.196	C	1.873	C	0.622	C	1.248	C	0.966	C	1.608	P
4	1.369	C	2.395	C	0.891	C	0.900	C	0.966	C	1.596	P
5	1.928	C	1.427	C	0.827	C	2.094	C	1.154	C	0.988	P
6	2.380	C	1.560	C	1.054	C	1.857	C	1.327	C	1.814	P
7	1.901	C	1.818	C	1.571	C	1.097	C	1.192	C	1.318	P
8	1.681	C	2.378	C	1.110	C	1.009	C	1.135	C	1.365	P
9	1.790	C	2.041	C	0.979	C	0.929	C	1.126	C	1.584	P
10	1.740	C	2.468	C	1.275	C	0.930	C	1.071	C	2.221	P
11	1.973	C	1.643	C	0.922	C	1.238	C	1.012	H	2.218	P
12	2.273	C	1.699	C	1.375	C	1.312	C	1.427	H	1.471	P
13	1.644	C	1.707	C	0.893	C	1.012	C	1.145	H	1.968	P
14	2.128	C	1.754	C	2.110	C	0.951	C	0.840	H	1.145	P
15	2.238	C	1.666	C	1.670	C	0.851	C	1.135	P	1.173	P
Mean	1.935		1.867		1.104		1.212		1.108		1.555	
SD	0.316		0.316		0.443		0.370		0.165		0.368	

Note: C = Complete break; H = Hinge break; and P = Partial break.

APPENDIX E

Table 38. One-way Analysis of Variance of tensile strength at processing temperature of 150 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	21461102.8	5	4292220.57	187.920	.000
Within Group	548176.185	24	22840.674		
Total	22009279.0	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: tensile strength at processing temperature of 150 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01				
		e	d	c	b	a
100:0	5	1350.7260	2011.3800	2564.3780	3017.5700	3763.1040
80:20	5	1517.4580				
60:40	5					
40:60	5					
20:80	5					
0:100	5					
Sig.		.094	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Table 39. One-way Analysis of Variance of yield strength at processing temperature of 150 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	21456764.2	5	4291352.85	183.769	.000
Within Group	560444.945	24	23351.873		
Total	22017209.2	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: yield strength at processing temperature of 150 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01				
		e	d	c	b	a
100:0	5	1348.9700	2010.2220	2563.5100	3017.4840	3756.9140
80:20	5	1510.2180				
60:40	5					
40:60	5					
20:80	5					
0:100	5					
Sig.		.108	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Table 40. One-way Analysis of Variance of MOE at processing temperature of 150 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	7.805E+10	5	1.561E+10	17.964	.000
Within Group	2.086E+10	24	869017305		
Total	9.891E+10	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: MOE at processing temperature of 150 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01	
		b	a
100:0	5	109632.00	
80:20	5	128923.60	
60:40	5		206438.40
40:60	5		208231.80
20:80	5		234724.80
0:100	5		243210.60
Sig.		.311	.082

Means for groups in homogeneous subsets are displayed.

Table 41. One-way Analysis of Variance of percent elongation at processing temperature of 150 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	34.274	5	6.855	21.668	.000
Within Group	7.592	24	.316		
Total	41.867	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: percent elongation at processing temperature of 150 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01		
		c	b	a
60:40	5	2.1100		
80:20	5	2.4700	2.4700	
100:0	5	2.5140	2.5140	
40:60	5	3.0220	3.0220	
20:80	5		3.3340	
0:100	5			5.3540
Sig.		.026	.034	1.000

Means for groups in homogeneous subsets are displayed.

Table 42. One-way Analysis of Variance of Izod impact resistance at processing temperature of 150 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	39.899	5	7.980	69.804	.000
Within Group	9.603	84	.114		
Total	49.502	89			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: Izod impact resistance at processing temperature of 150 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01			
		d	c	b	a
60:40	15	.62980	1.30180	1.85853	2.55927
80:20	15	.94862			
100:0	15				
40:60	15				
20:80	15			2.07633	
0:100	15				
Sig.		.012	1.000	.081	1.000

Means for groups in homogeneous subsets are displayed.

Table 43. One-way Analysis of Variance of tensile strength at processing temperature of 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	13813767.6	5	2762753.51	100.707	.000
Within Group	658404.641	24	27433.527		
Total	14472172.2	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: tensile strength at processing temperature of 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01				
		e	d	c	b	a
100:0	5	1393.7380				
80:20	5		1893.0320			
60:40	5		2145.8020			
40:60	5			2673.0120		
20:80	5				3025.7800	
0:100	5					3382.1240
Sig.		1.000	.024	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Table 44. One-way Analysis of Variance of at yield strength processing temperature of 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	12883390.9	5	2576678.18	84.534	.000
Within Group	640099.152	21	30480.912		
Total	13523490.0	26			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: yield strength at processing temperature of 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01			
		d	c	b	a
100:0	5	1392.5960			
80:20	5		1892.7940		
60:40	4		2134.6550		
40:60	5			2670.7400	
20:80	3			3005.6167	
0:100	5				3378.4120
Sig.		1.000	.054	.010	1.000

Means for groups in homogeneous subsets are displayed.

Table 45. One-way Analysis of Variance of MOE at processing temperature of 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	9.208E+10	5	1.842E+10	11.890	.000
Within Group	3.717E+10	24	1.549E+9		
Total	1.292E+11	29			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: MOE at processing temperature of 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01		
		c	b	a
100:0	5	101858.80		
80:20	5	155987.80	155987.80	
60:40	5		197231.20	197231.20
40:60	5			231060.60
20:80	5			246142.80
0:100	5			261251.80
Sig.		.040	.111	.025

Means for groups in homogeneous subsets are displayed.

Table 46. One-way Analysis of Variance of percent elongation at processing temperature of 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	10.223	5	2.045	10.603	.000
Within Group	4.050	21	.193		
Total	14.272	26			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: percent elongation at processing temperature of 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01		
		c	b	a
80:20	5	1.9580		
60:40	4	2.3625	2.3625	
100:0	5		2.9240	2.9240
40:60	5		3.2160	3.2160
20:80	3			3.2800
0:100	5			3.7600
Sig.		.189	.012	.016

Means for groups in homogeneous subsets are displayed.

Table 47. One-way Analysis of Variance of Izod impact resistance at processing temperature of 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	10.689	5	2.138	18.446	.000
Within Group	9.736	84	.116		
Total	20.425	89			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: Izod impact resistance at processing temperature of 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01		
		c	b	a
40:60	15	1.10367		
80:20	15	1.10787		
60:40	15	1.21160		
100:0	15		1.55507	
20:80	15		1.86680	1.86680
0:100	15			1.93487
Sig.		.418	.014	.585

Means for groups in homogeneous subsets are displayed.

Table 48. One-way Analysis of Variance of tensile strength at processing temperature of 150 and 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	35309640.0	11	3209967.27	127.698	.000
Within Group	1206580.83	48	25137.101		
Total	36516220.8	59			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: tensile strength at processing temperature of 150 and 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01					
		f	e	d	c	b	a
100:0 @ 150°C	5	1350.72					
100:0 @ 180°C	5	1393.73					
80:20 @ 150°C	5	1517.45					
80:20 @ 180°C	5		1893.03				
60:40 @ 150°C	5		2011.38				
60:40 @ 180°C	5		2145.80				
40:60 @ 150°C	5			2564.38			
40:60 @ 180°C	5			2673.01			
20:80 @ 150°C	5				3017.57		
20:80 @ 180°C	5				3025.78		
0:100 @ 180°C	5					3382.12	
0:100 @ 150°C	5						3763.10
Sig.		.122	.020	.284	.935	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Table 49. One-way Analysis of Variance of yield strength at processing temperature of 150 and 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	34341854.4	11	3121986.76	117.021	.000
Within Group	1200544.10	45	26678.758		
Total	35542398.5	56			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: yield strength at processing temperature of 150 and 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01					
		f	e	d	c	b	a
100:0 @ 150°C	5	1348.97					
100:0 @ 180°C	5	1392.60					
80:20 @ 150°C	5	1510.22					
80:20 @ 180°C	5		1892.79				
60:40 @ 150°C	5		2010.22				
60:40 @ 180°C	4		2134.66				
40:60 @ 150°C	5			2563.51			
40:60 @ 180°C	5			2670.74			
20:80 @ 180°C	3				3005.62		
20:80 @ 150°C	5				3017.48		
0:100 @ 180°C	5					3378.41	
0:100 @ 150°C	5						3756.91
Sig.		.162	.037	.322	.912	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Table 50. One-way Analysis of Variance of MOE at processing temperature of 150 and 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	1.717E+11	11	1.561 E+10	12.915	.000
Within Group	5.803 E+10	48	1.209 E+09		
Total	2.298 E+11	59			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: MOE at processing temperature of 150 and 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01		
		c	b	a
100:0 @ 180°C	5	101858.80		
100:0 @ 150°C	5	109632.00		
80:20 @ 150°C	5	128923.60		
80:20 @ 180°C	5	155987.80	155987.80	
60:40 @ 180°C	5		197231.20	197231.20
60:40 @ 150°C	5		206438.40	206438.40
40:60 @ 150°C	5		208231.80	208231.80
40:60 @ 180°C	5			231060.60
20:80 @ 150°C	5			234724.80
0:100 @ 150°C	5			243210.60
20:80 @ 180°C	5			246141.80
0:100 @ 180°C	5			261251.80
Sig.		.027	.033	.014

Means for groups in homogeneous subsets are displayed.

Table 51. One-way Analysis of Variance of percent elongation at processing temperature of 150 and 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	45.208	11	4.110	15.886	.000
Within Group	11.642	45	.259		
Total	56.850	56			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: percent elongation at processing temperature of 150 and 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01				
		e	d	c	b	a
80:20 @ 180°C	5	1.9580				
60:40 @ 150°C	5	2.1100	2.1100			
60:40 @ 180°C	4	2.3625	2.3625	2.3625		
80:20 @ 150°C	5	2.4700	2.4700	2.4700		
100:0 @ 150°C	5	2.5140	2.5140	2.5140		
100:0 @ 180°C	5	2.9240	2.9240	2.9240	2.9240	
40:60 @ 150°C	5		3.0220	3.0220	3.0220	
40:60 @ 180°C	5			3.2160	3.2160	
20:80 @ 180°C	5			3.2800	3.2800	
20:80 @ 150°C	5			3.3340	3.3340	
0:100 @ 180°C	5				3.7600	
0:100 @ 150°C	5					5.3540
Sig.		.012	.018	.014	.031	1.000

Means for groups in homogeneous subsets are displayed.

Table 52. One-way Analysis of Variance of Izod impact resistance at processing temperature of 150 and 180 °C

Analysis of variance

	Sum of square	df	Mean Square	F	Sig.
Between Groups	51.030	11	4.639	40.302	.000
Within Group	19.338	168	.115		
Total	70.369	179			

Post Hoc Tests

Multiple Comparisons and Homogeneous Subsets

Dependent Variable: Izod impact resistance at processing temperature of 150 and 180 °C

Duncan

Variation LDPE:PP	N	Subset for alpha = .01						
		g	f	e	d	c	b	a
0:100 @ 150°C	15	0.6298						
20:80 @ 150°C	15	0.9486	0.9486					
40:60 @ 180°C	15		1.1037	1.1037				
80:20 @ 180°C	15		1.1079	1.1079				
60:40 @ 180°C	15		1.2116	1.2116				
40:60 @ 150°C	15			1.3018	1.3018			
100:0 @ 180°C	15				1.5551	1.5551		
60:40 @ 150°C	15					1.8585	1.8585	
20:80 @ 180°C	15					1.8668	1.8668	
0:100 @ 180°C	15						1.9349	
80:20 @ 150°C	15						2.0763	
100:0 @ 150°C	15							2.5593
Sig.		.010	.051	.147	.041	.016	.109	1.000

Means for groups in homogeneous subsets are displayed.

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