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Due To The Inclusion Of Additives

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MECHANICAL PROPERTY ENHANCEMENT OF RECYCLED HIGH DENSITY POLYETHYLENE AND WOOD FIBER COMPOSITES DUE TO THE INCLUSION OF ADDITIVES

By

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ABSTRACT

MECHANICAL PROPERTY ENHANCEMENT OF RECYCLED HIGH DENSITY POLYETHYLENE/WOOD FIBER COMPOSITES DUE TO THE INCLUSION OF ADDITIVES

By

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Promotion of interfacial adhesion and fiber dispersion were sought through the inclusion of additives in high density polyethylene (HDPE) and wood fiber composites so as to enhance mechanical properties. Five additives were used to modify the recycled HDPE/wood fiber composite. Specimens were tested for tensile properties, impact strength, water sorption and creep. Specimens were also analyzed using scanning electron microscopy (SEM). Two of the five additives, low density polyethylene and stearic acid, were determined ineffective for enhancing properties. Chlorinated polyethylene had little effect, either positive or negative, on the composite's properties. Maleic anhydride modified polypropylene displayed potential for improving adhesion between the recycled polyethylene and wood fibers, based on improvements in tensile strength and modulus and SEM results. Ionomer modified polyethylene also displayed some positive results.

to my parents, for all the years of encouragement

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I. INTRODUCTION

INTRODUCTION

The use of plastics packaging is expected to escalate as society becomes more and more convenience and time oriented (Melosi, 1981). Plastics are lightweight, shatterproof, and cost effective and are rapidly replacing other packaging materials as gains are made in plastics technology. Plastic's expanding share of the municipal waste stream, its nonbiodegradable characteristics and the growing shortage of landfill space poses an eminent problem as plastic use increases. Plastic's share of the municipal waste is at 7.2% and is expected to increase to 9.8% by the year 2000 (Leaversuch, 1987). These figures are based on weight. The magnitude of the problem becomes even more significant when weight is converted to volume. Plastics packaging waste once converted to volume is figured to account for 31.4% of the materials in the municipal waste stream and is projected to be at 37.7% by the year 2000 ("Analyst: Solid Waste Becomes Crisis, 1988). Approximately 25% of the total packaging market is plastic. Plastics have such desirable properties that their use is expected to grow to 50% by the year 2000. It is evident that the use of plastics in the packaging market has become so prominent that banning is not plausible. Yet, in order to continue enjoying plastic's many advantages, its

disadvantages must also be dealt with. In 1988, approximately 2000 bills were introduced directed at the municipal waste problem (Serie, Mattheis, 1988). Packaging container legislation accounted for an estimated 300 bills with approximately 70% aimed directly at, or concerned with plastic packaging (Serie & Mattheis,1988). Packaging legislation includes taxes on litter stream type waste items, deposit laws, labeling so that plastics can be easily identified and separated to enhance recycling, regulatory review of packages and packaging materials, and prohibitions (Wright, 1987). The banning of plastic has been directed mainly at Polyvinyl chloride (PVC) because of the chlorine it releases when combusted, at plastics containing lead and cadmium because the metals form toxic ash when combusted, and at foamed polystyrene because it is not recyclable and emits chlorofluorocarbons during processing (Wright, 1987).

It is felt that a combination of recycling, landfilling and incineration would be the most effective way of dealing with plastic waste (Schneidman, 1987). According to the Enviromental Protection Agency, landfill numbers have dropped 50% in 1986 as compared to 1979. Present landfill space is reaching capacity and it is thus becoming more and more expensive. Incineration is a method for recovering energy from solid waste. Plastics, because they are petroleum based, are a significant contributor to the amount of recovered energy.

Problems have arisen concerning plastics incineration, however, in that some individuals feel it is a dangerous pollutant because of the toxins that various plastics emit. Thus, there is a debate over plastics place in incineration. Methods for incineration are also very expensive to set up and operate. Pyrolysis, a method in which solid waste is converted into gaseous, liquid or solid fuels by heating organic waste in an atmosphere of low oxygen so that combustion does not occur but chemical decomposition does, is another way to recover energy from solid waste. This method of energy retrieval has not been proven reliable, is far too expensive to be feasible, is considered to be the least advanced of the energy recovery technologies, and is therefore not considered as an effective alternative for relieving the plastic waste problem (Melosi, 1981). Although recycling may be the one method that provides the highest recovery value for plastic, the practice of plastics recycling is almost nonexistent. Currently, just over 1% of all plastic packaging is recycled, according to Wayne Pearson, executive director of the Plastics Recycling Foundation (Schneidman, 1987). Plastic waste is a valuable resource that has been back-shelved due to problems with collection, identification and markets. Growing concern over plastic consumption is likely to force the recycling dilemma on industry and the governemt, thus it is important to study the use of recycled plastics and their properties before social and legal action heightens. The future of plastics packaging may

rest on the ability to find methods and markets for recycled plastic.

Polyethylene terephthalate (PET) bottles are at present one of the few polymers actively sought and recycled. About four times as much tonnage is generated by high density polyethylene (HDPE), made into dairy bottles and various other containers, than that of PET ("Milk Bottles Reembodied", 1987). HDPE use for dairy bottles alone is equal to the entire PET bottle market ("Milk Bottles Reembodied, 1987). HDPE is easily identifiable and readily recyclable, due to the new washing systems that have been developed. Markets for the recycled HDPE are being investigated. The polymer is limited in its use for structural applications, due to its low stiffness and high creep properties. It is hoped that this particular drawback can be overcome by reinforcing the polymer with a stiff and strong filler. Reinforcing the polymer with a filler can increase its marketability by decreasing cost, obtaining special properties and improving load bearing capabilities. Wood fiber has been recognized as a possible filler because of its low cost, stiff and strong fibers, ease of processability and its availability. Unfortunately, cellulose fibers are not compatible with HDPE. The wood fibers are hydrophylic and polar while the polymer is hydrophobic and nonpolar. There is a lack of adhesion between the phases resulting in poor mechanical properties. When two dry substances are pressed

together in the absence of a bond, little effort is needed to pull them apart. Interfacial forces acting to adhere the two phases together will increase the composite's strength. If fibers are "wetted-out", ie, each fiber is totally enclosed by the matrix, and better dispersion of the fibers is achieved, improved mechanical properties will result. Prior work done in the area of short fiber reinforced thermoplastics has shown that cellulose fibers have not resulted in any significant degree of reinforcement, despite their stiffness and strength properties (Klason et al., 1984). The reason for this is thought to be the result of fiber damage occurring during compounding and processing and a lack of adhesion between the phases (Klason et al., 1984). The fiber stiffness and strength can be taken advantage of, if adhesion between the phases can offset some of the strength lost due to fiber damage.

The primary objectives of this investigation were to: (i)study the fiber-matrix interface of a recycled HDPE and wood fiber composite; and (ii) develop a method to achieve good fiber dispersion and adhesion between the phases so as to obtain a strong composite, and a viable recycled material.

II. EXPERIMENTAL

MATERIALS

The materials used to make the composites for this study consist of the following.

A. High Density Polyethylene dairy bottles were collected, cleaned using water, and the labels and caps removed before granulating into resin using a Lowline Granulator Model 68-913 from Polymer Machinery Corp. The resin supply used for this study was approximately 20% recycled unused HDPE and 80% recycled used HDPE. The dairy bottles were collected from several different dairies. Virgin and recycled HDPE resin samples were characterized using differential scanning calorimetry to determine changes in crystallinity and melt temperature. Virgin HDPE "Fortiflex A60-70-119" from Soltex Polymer Co. was used for purging during the extrusion process and the DSC test.

B. Aspen hardwood fibers obtained from Canfor Canadian Forest Products, were used as a reinforcing filler. Fiber bundles are formed by mixing wood chips and shavings with steam under pressure and refined using electric motors and refiner plates (rotating disks). A high yeild is acheived with very little damage occurring to change the lignin or hemicellulose. Aspen wood fiber cost is approximately $0.10/lb including freight cost. Cellulose is a hydrophilic glucan polymer. Most

hardwood species contain four types of cells; vessel segments, fibers, and transverse and axial parenchyma. The fibers perform the support role. Fibers are thick-walled, elongated cells with closed pointed ends. Fibers range in length from .7mm to 3mm.(Goldstein, 1977). The large amount of hydroxyl groups that occur throughout the structure can attract and hold water molecules by hydrogen bonding. Before the fibers are incorporated into the composite they are removed from their container and allowed to air dry for two to three days.

C. Five additives were studied for their effect on the recycled HDPE/wood fiber composite. They are listed in Table 1 followed by a description of each.

Table 1
Additives Used

1. Chlorinated Polyethylene (CPE 4213, 40% chlorine, DOW)
   Cost = $0.89/lb/truckload.

2. Ionomer Modified Polyethylene (Surlyn 1605, Du Pont)
   Cost = $1.27/lb/truckload.

3. Low Density Polyethylene (LDPE, DOW)
   Cost = $0.58-$0.64/lb/truckload or $0.53-$0.58/lb/railcar.

4. Maleic Anhydride Modified Polypropylene (Hercoprime, Himont)
   Cost = $12.00/lb.

5. Stearic Acid (Sigma)
   Cost = $1.12 - $1.84/gram (price varies with quantity purchased).

1. Chlorinated polyethylene (CPE) has excellent elongation and impact resistance, but poor creep resistance. CPE was selected for its polar nature which may aid in interfacial bonding when added to the composite. Maximum softness for CPE is obtained with 35-40% chlorine (Herman et al., 1981). The CPE used for testing with the recycled HDPE/wood fiber composite has a chlorine content of 40% by weight. CPE can cause minor eye and skin irritation due to the evolution of HCL at high temperatures. It can not be used to package fatty or oily foods.

2. Ionomer modified polyethylene is a thermoplastic material was also selected because of its polar nature. Ionomer modified polyethylene has ionic and polar bonds which may aid in interfacial bonding. Ionomers are transparent, tough, flexible, and have good abrasion resistance and excellent filler acceptance. It adheres to metals, nylon, other polyolefins and urethane finishes.

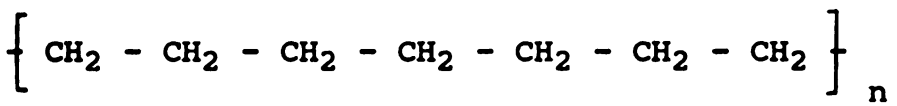
3. Low density polyethylene (LDPE) due to its many side branches has low crystallinity, is flexible and translucent, and has excellent impact resistance. Addition of LDPE to HDPE will result in decreasing percent crystallinity and viscosity during processing, thus decreasing brittleness of the final product.

4. Maleic anhydride modified polypropylene (MA.PP), a coupling agent, is the fourth additve listed. A coupling agent is one way to improve adhesion between the two phases. It acts as a link between the fiber and the matrix, thus the composite's strength will improve with bonding of the fiber-matrix. Covalently bonded materials form a structure that acts as one unit. Without the bond the two phases are only blended together and can be easily pulled apart.

5. Stearic acid is to be tested as a dispersant. It was selected for study based on the potential for preventing agglomeration of the filler particles. Evenly dispersed filler throughout the matrix will increase the mechanical properties of the composite. Agglomeration of the filler weakens the structure by causing points that will fail under stress. To maximize strength each fiber should be completely enclosed by the matrix (Folkes, 1982). Stearic acid is hoped to enhance the composite's morphology and strength.

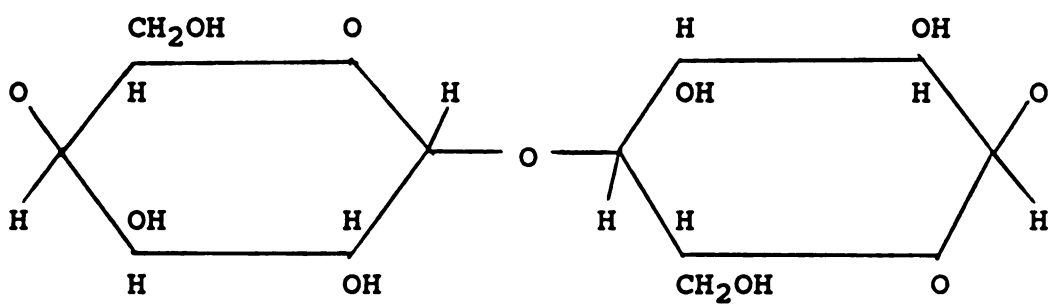
CHEMICAL COMPOSITION

A. High Density Polyethylene (HDPE)



- o 65-90% crystalline
- o 130-135^{0}C Tm
- o .94-.965g/cc density
- o -120^{0}C Tg
- o hydrophobic, nonpolar

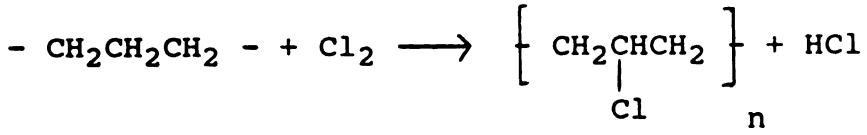
B. Aspen Hardwood Fibers



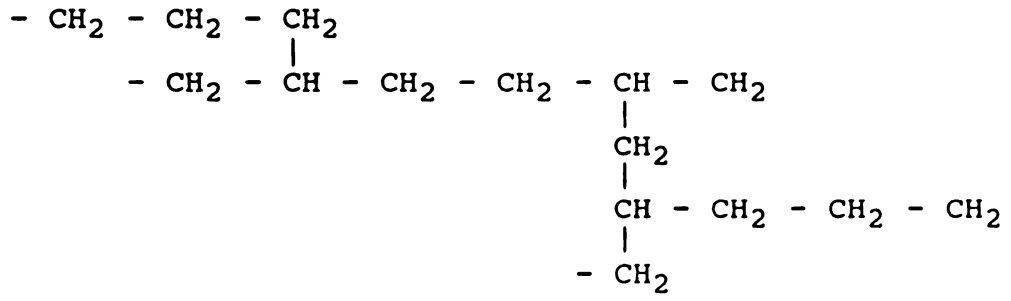
- o hydrophylic, polar
- o very crystalline
- o cell wall: cellulose (40-60%)
  lignin (20-30%)

C. Additives

1. Chlorinated Polyethylene (CPE)

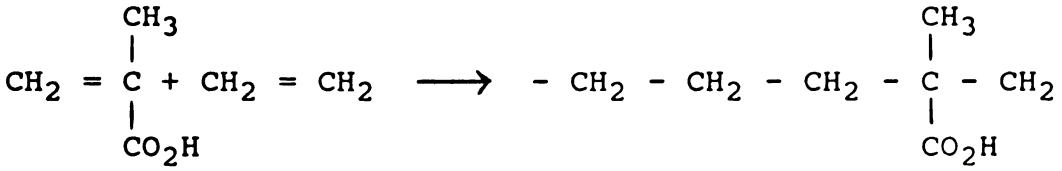


2. Low Density Polyethylene (LDPE)

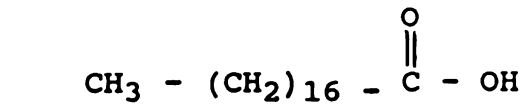


- o 40-60% crystallinity
- o 105-115^{0}C Tm
- o .916-.932g/cc density

3. Ionomer Modified Polyethylene

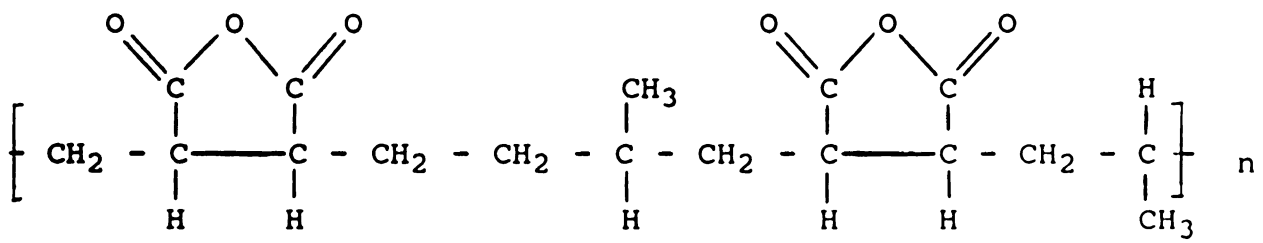


4. Stearic Acid



- 70°C Tm

5. Maleic Anhydride Modified Polypropylene (MA.PP)



METHODS

Material Preparation

The recycled HDPE is prepared as stated in the HDPE materials section. Each composite, with a few exceptions, is comprised of 30% wood fibers, 5% additive and 65% recycled HDPE by weight. (See appendix A for a detailed breakdown of the composite contents.) The recycled HDPE/wood fiber composites, with various additives, are produced utilizing a Baker Perkin, Model MPC/V-30 DE, 38 mm, 13:1 co-rotating twin screw extruder. The additives were mixed with the polymer prior to being added to the extruder's hopper. The mixing was done by thoroughly shaking the two in an enclosed container. The polymer was premelted in zone one and the wood fibers were hand fed into the extruder at zone 2. Adding fibers to pre-melted polymer is thought to be advantageous in reducing fiber damage and in gaining better dispersion. All three extruder zones and the die were preheated and maintained at a temperature of 150^{0}C. The compounder speed was set at 150 rpm's. Feed rate of the polymer can be varied with the desired percent wood fiber. For 30% wood fiber the rate was 4 (Feed rate setting is based on % of compounder speed rate).

The extruded composite rods are then converted into sheets using the Carver laboratory press compression molding machine, model M25 ton. The upper and lower platens are maintained at

150^{0}C. An initial ten minute warm up period is followed by ten minutes with the pressure held at 30,000 psi or more. The platens are then water cooled to room temperature for 15 minutes before the sheet is removed. Approximately three sheets can be made from 350 grams of material.

In order to evaluate the properties of the composites, the following ASTM standards were employed. The composites were initially screened to determine the effectiveness of the additive, using tensile and impact testing. If results were positive, further testing was conducted in the areas of water absorption, creep, and Scanning Electron Microscopy.

A. Tensile Property Determination

- o ASTM standard D638-77a Tensile Properties of Plastics.
- o Equipment: Instron, model 1114
  Tensilkut cutting machine

Dumbbell-shaped Type I specimens are cut from sheets such that they were .5 inches at the narrow section, using the Tensilkut cutting machine according to the ASTM standard. Specimens were tested on the Instron with a full scale load of 500 lbs, chart speed at 10 in/min., and crosshead speed equal to .5 in/min. The specimens were conditioned prior to testing at 23 +/- 2^{0}C and 50 +/- 5% RH for not less than 40 hours. Abrasive paper

is used to keep the specimen from slipping in the grips. Specimens that did not break in the narrow section were disregarded. Tensile strength, elongation at break and modulus of elasticity are calculated from the chart recorder results, using the following formulas.

$$\Delta L = \Delta X \frac{\text{crosshead speed (in/min)}}{\text{chart speed (in/min)}} \quad (1)$$

where: ΔL = change in gage length

ΔX = distance traveled on the chart

Gage length = length between grips

$$\text{For Modulus: Stress} = \frac{\text{force}}{\text{original minimum cross-sectional area}} \quad (2)$$

$$\text{Strain} = \frac{\text{change in length (stretch)}}{\text{original gage length}} \quad (3)$$

Tensile Strength = highest stress a material can carry

% Elongation at Break = strain at break x 100

B. Izod Impact Strength Determination

- o ASTM standard D256-81 Impact Resistance of Plastic and Electrical Insulating Materials.
- o Equipment: TMI 43-1 Izod Impact Tester

Specimen notcher

Test specimen are cut to the standard width of 0.5 inches (1.27 cm) and are 2 inches (5.08 cm) in length from compression molded plates. The samples are conditioned prior to testing for not less than 40 hours at 23 +/- 2^0C and 50 +/- 5%RH. A five pound pendulum is used for the test. According to the Izod impact test requirement, the specimen is notched. The notch allows for a brittle rather than a ductile fracture. Values are stated in inch-pound units.

C. Water Absorption

- ASTM standard D 570 Water Absorption of Plastics.
- Equipment: Instron, model 1114

Samples are tested for dimensional stability using the long term immersion method. Moisture gain over time is measured.

D. Creep Analysis

- ASTM standard D 2990-77 Tensile, Compressive, and Flexural Creep and Creep-Rupture of plastics.
- Equipment: clamps, fifty pound weights

Creep test provides information that will aid in predicting the

strength of a material subjected to long term loads. It also shows dimensional changes that are a result of a long term loads.

E. Scanning Electron Microscopy(SEM)

- o SEM manual
- o Equipment: SEM, model JEOL T-330

SEM aids in determining the presence of a bond and its effectiveness. The fracture surface of a specimen is studied. Alan Sliker, PhD., wood scientist, Michigan State Forestry Department, was consulted to evaluate SEM resutls.

F. Differential Scanning Calorimetry (DSC)

- o Du Pont DSC manual
- o Equipment: Du Pont 9900 DSC

The test is utilized to determine the melting temperature and degree of crystallinity of HDPE; virgin, used recycled, and unused recycled. Polymer crystallinity is an indication of strength. The more dense the polymer structure, the better the mechanical properties of the polymer. A sample size of 10mg is used for each test. The samples are ramped at 5^0C/min and a sweep of 120^0C (30^0C to 150^0C) is made, with each test taking a total of 24 minutes.

$$\% \text{ Crystallinity} = \frac{\Delta Hf}{\Delta H^*f} \times 100 \qquad (4)$$

where: ΔHf = heat of fusion of test sample

ΔH^*f = a known heat of fusion of a hypothetical 100% crystalline sample. (for PE ΔH^*f = 68.4 calories/gram)(Brennan, 1978).

III. LITERATURE REVIEW

COMPOSITE MATERIALS

Composites consist of one or more discontinuous phases enclosed in a continuous phase. The discontinuous phase is that which is harder and stronger, and thus provides the reinforcement. The continuous phase is called the matrix. The matrix keeps the fibers separated from one another, yet holds the fibers together while maintaining fiber orientation. It also protects the filler from the harmful effects of the environment and from abrasion. The matrix is a minor strengthening factor. The main purpose of the matrix is to transmit load to the fibers, which contribute the greater portion of the composite's strength. Therefore, crucial to the composite's ultimate properties is the fiber-matrix interface. Good adhesion between the phases is necessary for stress transfer to occur from the matrix to the stronger discontinuous phase. Poor adhesion will likely result in the interface being the point of failure. Composite materials are classified as particulate or fibrous, based on the discontinuous phase particle size and shape. The length (ℓ) and diameter (d), or the fiber-aspect ratio (ℓ/d) of a filler particle greatly influences the composite properties. Fibrous reinforcments have one long dimension, whereas particulate reinforcing fillers do not. The particulate reinforced composite will gain in stiffness but not in strength. Fibrous reinforcements improve stiffness, strength, and creep, all three of which are thermoplastic

physical properties in need of improvment for use in structural applications. There are two types of fibrous reinforced composite materials; continuous which have long fibers, and discontinuous which have short fibers. Interfacial adhesion between the phases is especially important for discontinuous fiber composites. Studies have shown that the presence of fiber ends within the body of the composite can cause crack initiations and thus lead to potential composite failure (Folkes, 1982). Interfacial strength will affect the generation of microcracks at the fiber ends caused when stress is applied. When a strong bond is present between the phases, the cracks will not be produced along the length of the fibers.

Prediction of Composite Properties

Theories have been developed for the prediction of tensile strength, tensile modulus and impact strength for fiber reinforced thermoplastics. Much work has been devoted to the prediction of tensile properties for composite materials. Strength and toughness are more difficult to predict. The rule of mixtures can be used to predict a composite's tensile modulus and tensile strength. For long fiber reinforced thermoplastics, the calculation is much simpler. It is assumed that all fibers are working at maximum efficiency and the

tensile force acting on the continuous reinforcement is shared between the matrix and all the fibers, with the ultimate tensile strain being reached in the fiber. It is also assumed that the bond between the fiber and the matrix is very good.

$$E_c = E_f \varnothing_f + E_m \varnothing_m \qquad (5)$$

$$\sigma_c = \sigma_f \varnothing_f + \sigma_m \varnothing_m \qquad (6)$$

Where: E = tensile modulus

σ = tensile strength

$\varnothing$ = volume fraction

subscripts c = composite

f = fiber

m = matrix (Clegg & Collyer, 1986)

The predicted values given by equations (5) and (6), tend to be higher than actual values. The equations are not totally valid, especially equation (6), since additional stresses are present, which are not considered in the rule of mixtures equations (Clegg & Collyer, 1986).

It is difficult to predict the properties of short fiber reinforced thermoplastics, as compared to long fiber reinforced

thermoplastics due to the fact that short fiber reinforcment generally has a three dimensional distribution of fiber orientations and a variety of fiber lengths that result from processing. The influence of fiber ends is to lower the elastic modulus and strength of short fiber reinforced composites (Agarwal & Broutman, 1980). When predicting the tensile modulus for short fiber reinforced composites, additional factors must be considered. Stiffness of short fiber reinforced thermoplastics depends on fiber length (and/or dispersion), volume fraction of fibers, the stress transfer efficiency of the interface and fiber orientation (Folkes, 1982). During processing, fiber damage may occur which often results in lower fiber aspect ratios. The term $n\ell$ can be added as the length correction factor such that equation (5) becomes,

$$E_c = n\ell E_f \varnothing_f + E_m \varnothing_m \tag{7}$$

The theory utilizing the length correction factor was developed by Cox (1952) where:

$$n\ell = \left[1 - \frac{\tanh(\beta\ell/2)}{\ell/2}\right] \tag{8}$$

where: ℓ = fiber length

$$\beta = \left[\frac{2G_m}{E_f A_f \ln(R/r)}\right]^{1/2} \tag{9}$$

where: G = shear modulus of the matrix

r = radius of the fiber

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

A_f = the cross-sectional area of all the fibers in the composite.

Equation (8) accounts for length variation. However, tensile modulus depends on the fiber aspect ratio (ℓ/d) and not just on fiber length. A number-average fiber length must be obtained to account for the ℓ/d variation.

Tensile strength is dependent on fiber length, volume fraction of fibers, the interfacial shear strength and fiber orientation (Clegg & Collyer, 1986). For short fibers, the average tensile stress on the composite will be given by:

$$\sigma_c = \sigma_m \phi_m + \bar{\sigma}_f \phi_f \qquad (10)$$

where: $\bar{\sigma}_f$ = average fiber stress = $\frac{1}{\ell}\int_0^{\ell} \sigma_f(x)\,dx$

If tensile stress builds up from the fiber ends in a non-linear way then

$$\sigma_f = \sigma_{f\infty}\left[1-\frac{(1-\beta)\ell_c}{\ell}\right] \quad \text{for } \ell > \ell_c \qquad (11)$$

where: σ_∞ = tensile stress in a continuous fiber in same matrix under the same loading conditions.

$\sigma_{f\infty}$ = average stress in the discontinuous fiber within a distance $\ell/2$ of either end.

ℓ_c = critical fiber length.

The fibers can be stressed to their tensile strengths when the fiber length is greater than the critical fiber length. If it is assumed that the fiber failure occurs when $\sigma_f = \sigma_{f\infty}$, then substituting in equation (10) gives

$$\sigma_c = \sigma_f\left[1-(1-\beta)\frac{\ell_c}{\ell}\right] + \sigma_m' \varnothing_m \qquad (12)$$

Comparison of equation (5) to equation (12) shows that discontinuous fibers provide less strength than continuous ones. If fibers are present in the matrix with lengths shorter than the critical fiber length, they will not be capable of supporting the load and failure will occur at the interface.

It is very difficult to predict the impact resistance of short fiber reinforced composites. Presently there are no models available on which to base predictions. If brittle fibers are added to a ductile matrix, the impact strength of the composite decreases rapidly as the fiber concentration increases (Clegg & Collyer, 1986). This is because the matrix is confined by the fibers and cannot deform to absorb the energy of impact. The work of fracture depends on the ability of a material to

transfer stress throughout its structure. Theories conflict as to whether adhesion has a positive effect on the impact strength of composite materials. One theory determined that impact strength cannot be used as an indication of adhesion between the phases because of other factors that effect impact resistance and speculated that a weak interface would be essential for absorbing the energy of impact (Clegg & Collyer, 1986). Another theory states that adhesion enhances impact strength by allowing stress to be transferred to the fibers so that the impact is spread over a larger area (Katz & Milewski, 1987).

Interfacial Strength

Each fiber-matrix system has an interface unique to it. The interface is dependent on the fiber's atomic arrangement and chemical properties and on the matrix's molecular makeup and chemical constitution. There are five main mechanisms that are often used to produce a bond between two substances (Hull, 1981). Adhesion can occur at the interface with the aid of one or more of the following mechanisms. The first is interdiffusion, in which a bond is formed by molecular entanglement. The strength of the bond is dependent on the degree of entanglement and the number of molecules involved. Electrostatic attraction between two surfaces can be utilized

to form a bond. The strength of the interface will depend on the charge density. A third method used to induce bonding is adsorption and wetting. Strong adhesion occurs only if the entire surface of the filler is completely wetted out. Another method, chemical bonding is done by forming a covalent bond between compatible chemical groups on the fiber surface and in the matrix. Interfacial strength will be dependent on the number and type of bonds formed. Failure at the interface will involve the breaking of bonds. The fifth method for bond forming is mechanical adhesion in which some bonding may occur purely by the mechanical interlocking of two surfaces.

There are three possible modes of composite failure. It is often difficult to determine where the failure has occurred. One failure type occurs at the interface with the separation of the two phases, which would be an adhesive failure. Separation of the fibers from the matrix is referred to as debonding. Failure can also be cohesive in which case either the fiber fractures or the matrix does. The type of failure is directly related to the bond strength. It is important to be able to measure the bond strength between the fibers and the matrix for evaluation of the composite for end usage. Unfortunately, satisfactory methods for measuring bond strength are not available due to the high degree of precision required for testing, and because of inherent problems with wood fiber specimen preparation. One of the better established tests is

discussed below.

Bond strength can be determined by performing tests with single fibers. The single fiber test can give data on shear strength of the interface bond. It has been determined that the relationship between compressive stress σ_c and shear stress τ_s is given by: (Hull, 1981)

$$\tau_s \approx 2.5\sigma_c \tag{13}$$

A value for the applied compressive stress, σ_c, at which debonding is first detected at the fiber ends can be obtained experimentally in order to determine the shear strength of the interface.

The tensile strength of the interface can also be determined utilizing the single fiber test. The following formula is used:

$$\sigma_\perp = \frac{\sigma_c(\nu_m - \nu_f)E_f}{(1+\nu_f-2\nu_f^2)E_m} \tag{14}$$

where: $\sigma_\perp$ = stress perpendicular to the fibers

σ_c = net section compressive stress (load divided by minimum area)

ν_m = Poisson's ratio of the matrix

ν_f = Poisson's ratio of the fiber

E = Young's modulus (Hull, 1981)

The tensile strength of the interface is obtained from σ_c at which debonding occurs.

The appearance of the fracture surface can sometimes be utilized as an indirect measure of the strength of the interface bond. There are generally changes in the appearance of the matrix fracture surface that correspond to the degree of adhesion (Hull, 1981).

The structure and properties of the fiber-matrix interface are a major factor in the mechanical and physical properties of composite materials. A composite with a weak interface will have a relatively low strength and stiffness but high impact strength, whereas a composite having a strong interface will have strength and stiffness but is very brittle (Clegg & Collyer, 1986). As stated earlier, a strong interface is crucial for the occurance of stress transfer from the matrix to the fibers. Load is transferred from the matrix to the fibers through the fiber ends and through the cylindrical surface of the fiber near the ends. ? For continuous fibers the fiber length is greater than the length over which the transfer of stress occurs and the effect of the fiber ends can be dismissed. This cannot be done for short fiber reinforced composites. The composite properties are directly related to fiber length. Stress transfer for discontinuous short fibers

is analyzed by considering the equilibrium of a small element of fiber such that

$$(\pi r^2)\sigma_f + (2\pi r dz)\tau = (\pi r^2)(\sigma_f + d\sigma_f)$$

which equals:

$$\frac{d\sigma_f}{dz} = \frac{2\tau}{r} \qquad (15)$$

(Agarwal & Broutman, 1980)

where: r = fiber radius

τ = shear stress on the cylindrical fiber-matrix interface.

dz = infintesimal fiber length.

Equation (15) indicates that for a fiber of uniform radius, the fiber stress increase rate is proportional to the shear stress at the interface. Thus fiber stress at cross-sectional distance z from the fiber end can be determined by integrating equation (15). (Agarwal & Broutman, 1980).

$$\sigma_f = \sigma_{f_o} + \frac{2}{r}\int_0^z \tau dz \qquad (16)$$

where: σ_{f_o} = stress on fiber ends.

Maximum fiber stress occurs at the midfiber length for short fiber (Agarwal & Broutman, 1980).

The minimum fiber length in which the maximum fiber stress can be achieved is defined as a load transfer or the critical fiber

length. It is over this fiber length that the load is transferred from matrix to fiber.

$$\frac{\ell_c}{d} = \frac{\sigma_{fu}}{2\tau_y} \qquad (17)$$

where: ℓ_c = critical fiber length

d = fiber diameter

σ_{fu} = maximum allowable fiber stress (or the fiber ultimate strength)

τ_y = matrix yield stress in shear

The critical length is sometimes referred to as the 'ineffective length' because over this length the fiber supports a stress less than the maximum fiber stress. Shear stress (τ) depends on processing conditions and interfacial adhesion. If adhesion between the phases is strong, then shorter fibers can be used to effectively reinforce the matrix (Katz & Milewski, 1987).

Review of Prior Research

Polymers reinforced with cellulose fibers have been researched by many to determine the effect of cellulose as a reinforcement. Following is a summary of some of the work completed in this area.

Sanschagrin, Sean and Kokta (1988) studied the encapsulation of cellulose fibers mixed with polystyrene at various concentrations. They compared the mechanical properties determined experimentally with theoretical predictions. It was concluded that the large differences occurring between experimental and calculated values are due to factors such as fiber orientation and fiber aspect ratio, which are not accounted for in the theoretical predictions. It was determined that mechanical properties improved with the reinforcement for oriented composites but a coupling agent was needed for property enhancement with an unoriented composite (Sanachagrin et al., 1988).

Mitchell, Vaughan and Willis (1976) studied laminates of paper and high density polyethylene versus glass-filled high density polyethylene for mechanical properties. They concluded that the cellulose filled laminate compared well with the glass filled laminate for mechanical properties yet, the full potential of a cellulose reinforced laminate would be realized

only if the cellulose fibers were distributed uniformly in the polyethylene, and if bonding were enhanced (Michell et al., 1976). They also concluded that water or humidity resistance of cellulose reinforced polyethylene laminates could be increased by acetylation or crosslinking with formaldehyde of the fibers, although some property loss still occurred (Michell et al., 1978).

Aspen wood fibers in the form of chemithermomechanical pulp(CTMP) utilized as a reinformcement in polyethylene was studied by Beshay, Kokta and Deneault (1986) to determine the effect on mechanical properties. The aspen fibers showed better mechanical properties than either mica or glass reinforced polyethylene, and the aspen fibers improved polyethylene's overall properties. Beshay (1986) also studied the effect of immersion in boiling water on the mechanical properties of a composite of linear low density polyethylene reinforced with CTMP. The mechanical properties did not change significantly but the fibers did improve polyethylene's properties. The CTMP filled composite displayed better properties than glass fiber or mica filled composites (Kokta et al., 1986).

Zadorecki and Flodin (1986) studied unsaturated polyesters reinforced with cellulose fibers. The cellulose fibers increased the tensile strength and modulus of the polyester.

When exposed to water however, properties were lowered due to the high amount of water uptake (Zadorecki & Flodin, 1986). It was determined that the adhesion between the phases was not strong during wet conditions. Formaldehyde and dimethylolmelamine were studied for their effect on the composite's properties when exposed to wet conditions. Water uptake was reduced and properties improved (Hua et al., 1987). Hua, Flodin and Ronnhult (1987) also studied mono- or dimethylolmelamine(DMM) resin treated cellulose for their effect on reducing water absorption. Wet strength of the cellulose-polyester composite improved considerably (Hua et al., 1987).

High density polyethylene filled with cellulose-based reinforcements was studied by Klason, Kubat and Stromvall (1984). These authors determined that the cellulose fibers did not produce any significant degree of reinforcement for the composite. Fiber damage occurring during compounding, poor fiber dispersion and poor adhesion between the phases were determined to be the reasons for the lack of property enhancement (Klason et al., 1984). A second study was conducted to determine if the above mentioned problems could be overcome with the inclusion of additives in the composite. Some of the additives that were chosen as dispersion aids did help in promoting better dispersion of the fibers. However, only one additive was found to induce adhesion namely, maleic anhydride modified polypropylene (Dalvag et al., 1985).

IV. RESULTS AND DISCUSSION

A. Differential Scanning Calorimetry (DSC)

1. Results:

The average percent crystallinity and melt temperature (Tm) of virgin high density polyethylene, as compared to recycled used and unused high density polyethylene, were determined not to be significantly different. (see appendix B for t-test results). Table 2 presents the data obtained from tests utilizing Differential Scanning Calorimetry. Averages were determined from two replications of each sample. As shown, there is only slight variation in the results obtained. The thermograms and accompaning DSC data of the representative samples are presented in Figure 1, A-F.

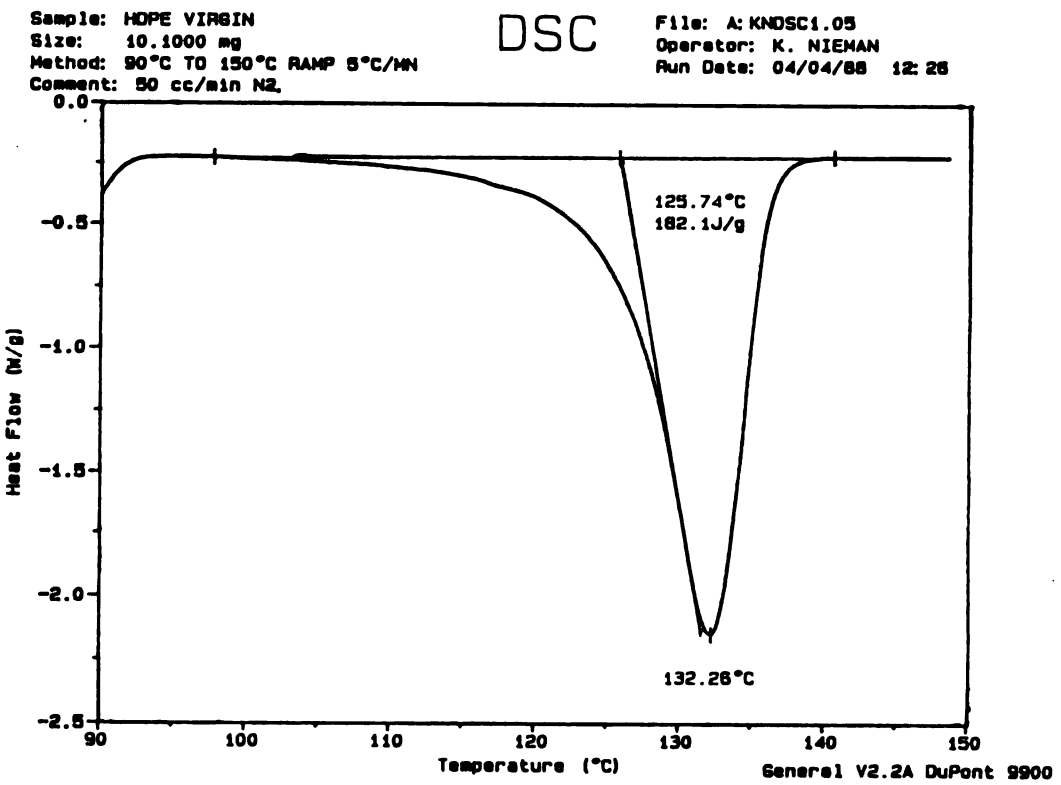
Table 2

Differential Scanning Calorimetry

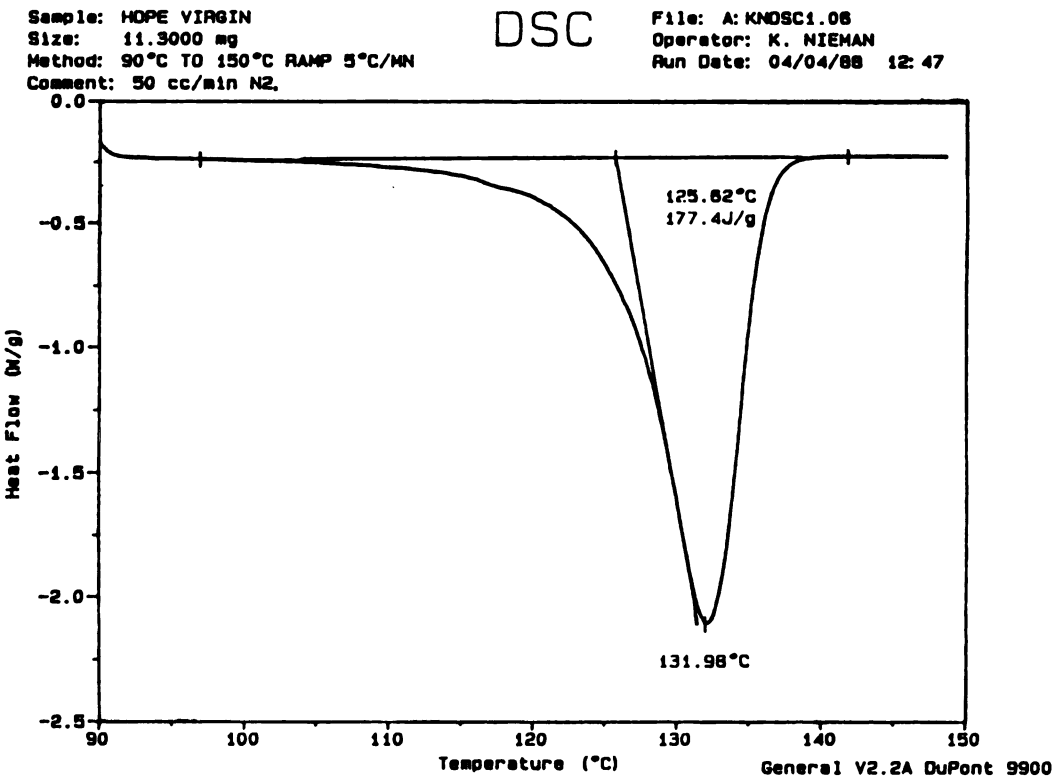
Material	% Crystallinity	Tm(^{0}C)
HDPE--Virgin		
Run 1	63.60	132.26
Run 2	61.97	131.98
Average	62.80	132.12
HDPE--Recycled, used		
Run 1	62.30	132.26
Run 2	62.53	132.06
Average	62.40	132.16
HDPE--Recycled, unused		
Run 1	63.79	132.18
Run 2	63.58	131.80
Average	63.70	131.99

DIFFERENTIAL SCANNING CALORIMETRY RESULTS
Figure 1

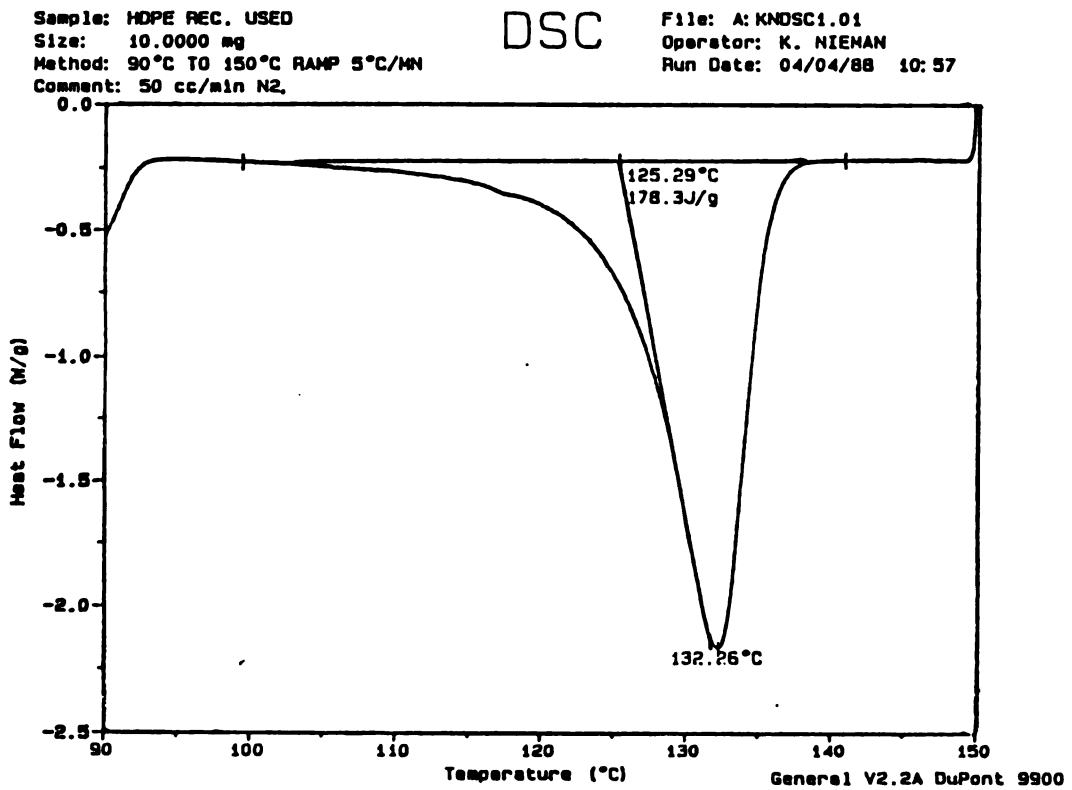
A.



B.



C.


Sample: HDPE REC. USED
Size: 10.0000 mg
Method: 90°C TO 150°C RAMP 5°C/MN
Comment: 50 cc/min N2.
DSC
File: A:KNDSC1.01
Operator: K. NIEMAN
Run Date: 04/04/88 10:57
125.29°C
178.3J/g
132.26°C
Heat Flow (W/g)
Temperature (°C)
General V2.2A DuPont 9900

D.

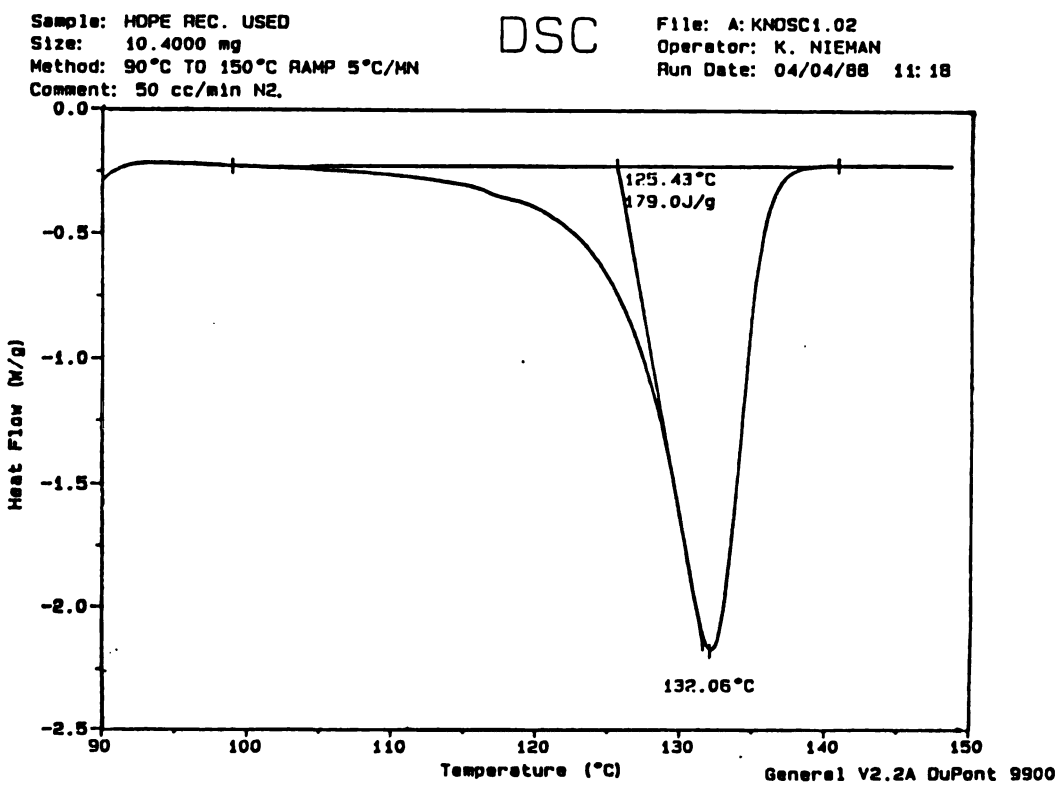
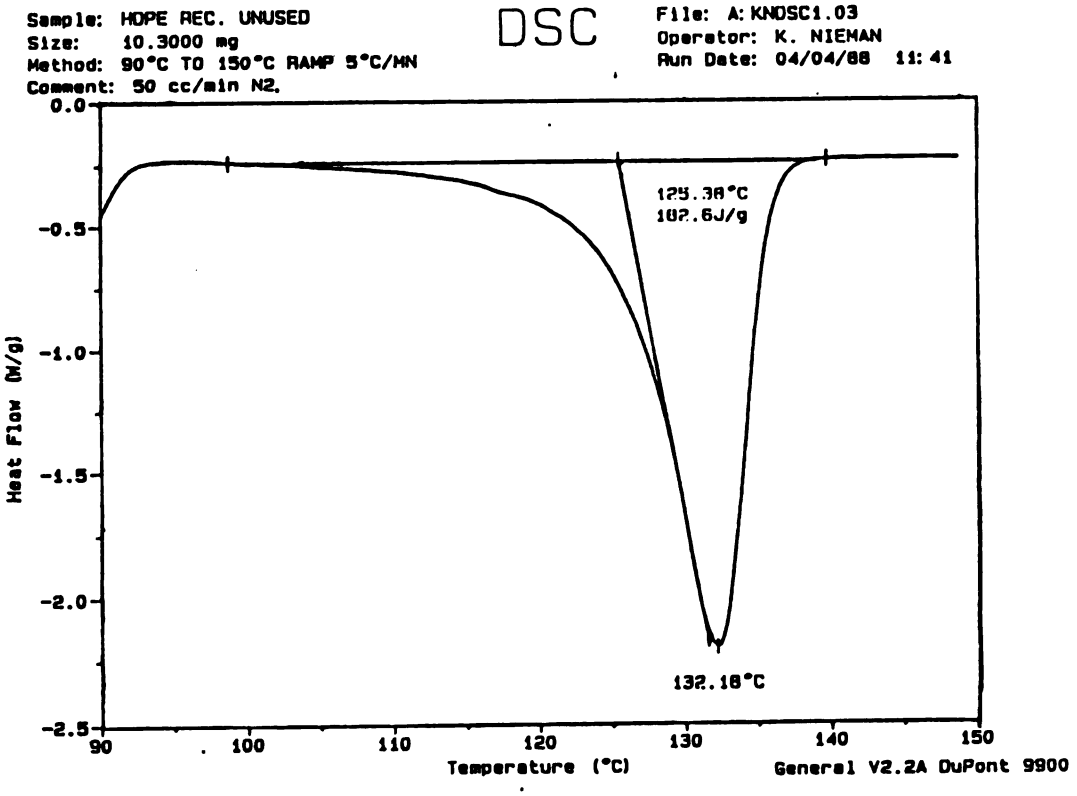
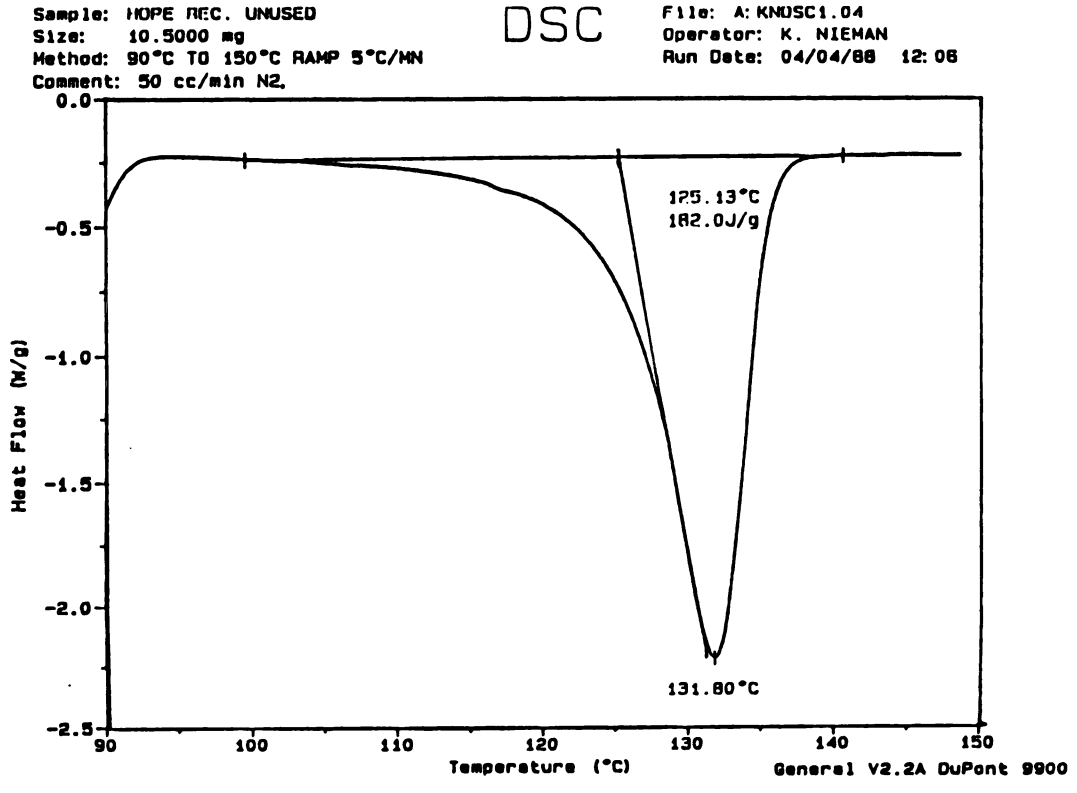

Sample: HDPE REC. USED
Size: 10.4000 mg
Method: 90°C TO 150°C RAMP 5°C/MN
Comment: 50 cc/min N2.
DSC
File: A:KNDSC1.02
Operator: K. NIEMAN
Run Date: 04/04/88 11:18
125.43°C
179.0J/g
132.06°C
Heat Flow (W/g)
Temperature (°C)
General V2.2A DuPont 9900

Figure 1 (cont.)

E.



F.



2. Discussion:

Polymer crystallinity is one indication of the polymer's strength. Comparison of the recycled resin with virgin resin can give an indication of changes that may have occurred as a result of recycling. A change in the melt temperature is an indication that changes in crystallinity and/or molecular weight distribution have occurred. Melt temperature is related to processibility and flow characteristics of resin. The Tm of the recycled resins are essentially the same as that of virgin HDPE. A breakdown in the polymer as a result of the recycling process would show itself in the polymer's structural regularity (Pattanakul, 1987). Polymer degradation, due to initial processing and forming, consumer use, exposure and reprocessing would be evident in a change in the resin's properties. Prior work done by Pattanakul (1987), also determined that there is little difference in melt flow index, tensile strength, elongation at yield and modulus of elasticity for recycled HDPE from milk bottles as compared to virgin HDPE.

B. Tensile Properties

1. Results:

Tensile strength results are tabulated in Table 3 and presented graphically in Figure 2. As shown, the addition of 30% wood fibers to recycled HDPE decreased tensile strength by approximately 20%. Significant differences were found for three of the seven specimens tested, namely; 5% maleic anhydride modified polypropylene, stearic acid, and 100% recycled HDPE when compared to the composite with no additive. (see t-test results in appendix B). As can be seen from Table 3 and Figure 2, incorporation of stearic acid resulted in significant lowering of the composite's tensile strength, thus having a negative effect on tensile strength. The composite containing 5% MA.PP had an average tensile strength almost equal to that of the recycled resin and surpassed that of the composite with no additive. The effect of MA.PP (5%) on tensile strength was determined to be significantly different than the composite with no additive, at an alpha level of .05. Composites with 2% MA.PP, chlorinated polyethylene and ionomer modified polyethylene also performed on the average better than the composite with no additive, but not at a statistically significant level.

Table 3

Tensile Strength
(psi)

Material	Mean	SD
No Additive	3914.48	378.27
Rec. HDPE (100%)	4977.62	187.75
CPE	4105.83	718.11
Ionomer	4121.72	445.95
LDPE	3555.94	690.57
MA.PP (2%)	4532.80	1003.91
MA.PP (5%)	4839.80	571.40
Stearic Acid	3134.88	555.61

Tensile modulus results are summarized in Table 4 and presented graphically in Figure 3. As shown, the inclusion of 30% wood fibers to the recycled HDPE resulted in an increase in the modulus of approximately 65%, as compared to the resin alone. Stearic acid and low density polyethylene's inclusion in the composite resulted in a decrease of modulus. The composite containing chlorinated polyethylene resulted in a modulus that was essentially equal to that of the composite with no additive. An increase in tensile modulus was also observed for composites containing MA.PP and ionomer modified polyethylene, as compared to the composite with no additive. Statistical analysis of the data indicated that the composite with no additive included, when compared to those with additives, is not significantly different at a .05 alpha level.

Table 4

Modulus of Elasticity
(psi)

Material	Mean	SD
No Additive	176509.30	45427.80
Rec. HDPE (100%)	111723.00	8669.82
CPE	178933.70	17348.00
Ionomer	212579.20	29186.20
LDPE	145606.90	42474.00
MA.PP (2%)	205640.50	29156.10
MA.PP (5%)	166571.40	32211.60
Stearic Acid	146164.50	26346.60

Elongation at break data is presented in Table 5 and is illustrated in Figure 4. As shown, the inclusion of 30% wood fiber in the recycled HDPE resulted in a substantial decrease in elongation of the composite, as compared to recycled HDPE resin with no fibers or additives. All composites containing additives exhibited higher percent elongation than the composite with no additive present. Statistical analysis indicates that the increase in elongation is significant for all composites with additives. (see appendix B for t-test results).

Table 5

Elongation at Break
(%)

Material	Mean	SD
No Additive	1.40	.37
Rec. HDPE(100%)	240.31	70.32
CPE	3.05	.66
Ionomer	3.10	.69
LDPE	3.75	.68
MA.PP (2%)	2.72	.93
MA.PP (5%)	3.75	.63
Stearic Acid	4.08	.71

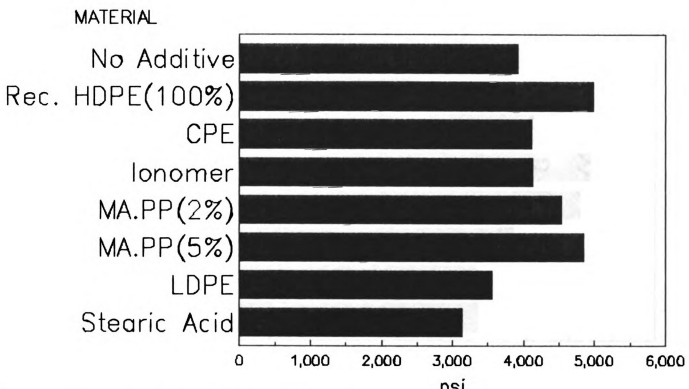
Specimens containing 5% MA.PP and 95% recycled HDPE were compared with specimens consisting of 100% recycled resin. No significant difference was found between the two for tensile strength or modulus. (See Table 6 and Appendix B).

Table 6

Recycled HDPE vs Recycled HDPE + MA.PP

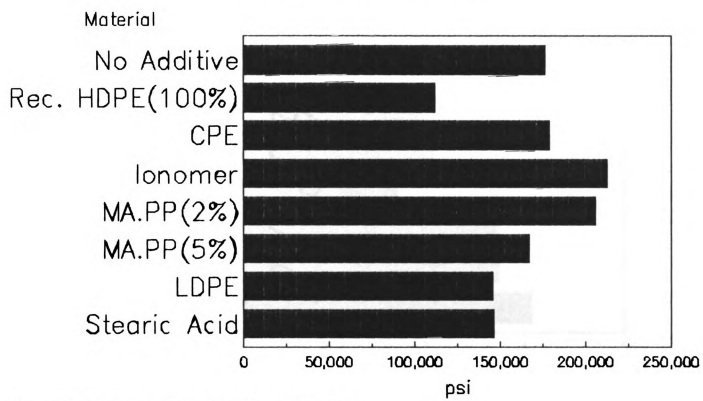
	Tensile Strength (psi)		Tensile Modulus (psi)	
Material	Mean	SD	Mean	SD
Rec. HDPE (100%)	4978.90	187.25	111723.00	8669.82
Rec. HDPE (95%) & MA.PP (5%)	4730.44	286.53	129720.40	26102.30

FIGURE 2
TENSILE STRENGTH



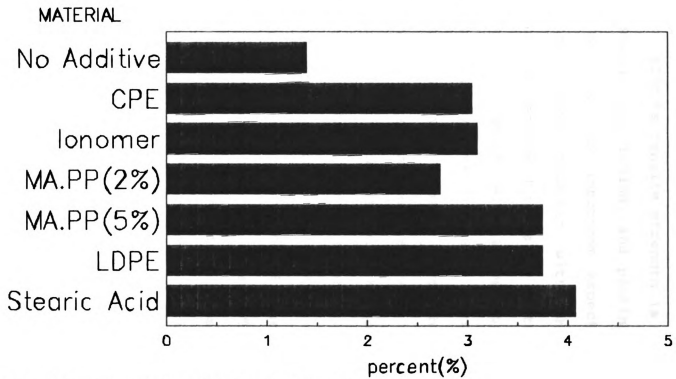
**all specimen contain 5% additive and 30% wood fiber unless otherwise stated.

FIGURE 3
MODULUS OF ELASTICITY



**all epecimen contain 5% additive and 30% wood fiber unless otherwise stated.

FIGURE 4
ELONGATION AT BREAK (%)



**all specimen contain 5% additive and 30% wood fiber unless otherwise stated.
**Recycled HDPE(100%) elongated 240% at break.

2. Discussion:

The tensile test is perhaps the most important test the composite material must undergo, due to the test's ability to portray the composite's overall mechanical strength and its indication of the way the composite will perform in other tests. How a filler affects tensile strength is dependent on the filler's size, shape, interfacing, and packing within the matrix (Folkes, 1980). A very important aspect of tensile strength is how the fibers interact with the matrix. Additives that induce homogeneous dispersion of the fibers or result in bonding between the phases will be apparent by an observed increase in tensile strength and modulus (Katz & Milewski, 1987). The results of tensile strength and modulus indicate MA.PP as having potential for improving the adhesion between the recycled HDPE and wood fibers. The composite with 5% MA.PP resulted in the highest tensile strength. Elongation at break for the composite containing 5% MA.PP is greater than expected. This could be the result of a third phase separation occurring from the inclusion of the additive. The composite containing 5% MA.PP displayed a higher tensile strength than the composite containing 2% MA.PP. However, a higher percent elongation at break was found for the 5% MA.PP composite than the 2% MA.PP composite. The conflicting tensile strength and modulus data may be a result of polypropylene's separation from polyethylene due to the two being dissimilar on a molecular level, which causes the composite to elongate more before break

with increasing percent MA.PP. The inclusion of ionomer modified polyethylene in the composite resulted in a 15% increase in modulus and a 6.6% increase in tensile strength. Because these results were positive, although not significant at a .05 alpha level, ionomer modified PE was chosen for further study. Chlorinated polyethylene, which displayed some positive results, was also selected for further study. The addition of MA.PP to recycled HDPE with no fibers had no significant effect on the resin, yet MA.PP does affect the composite. These results provide supportive evidence for the theory that MA.PP has the potential for improving the adhesion between the resin and fibers.

C. Impact Strength

1. Results:

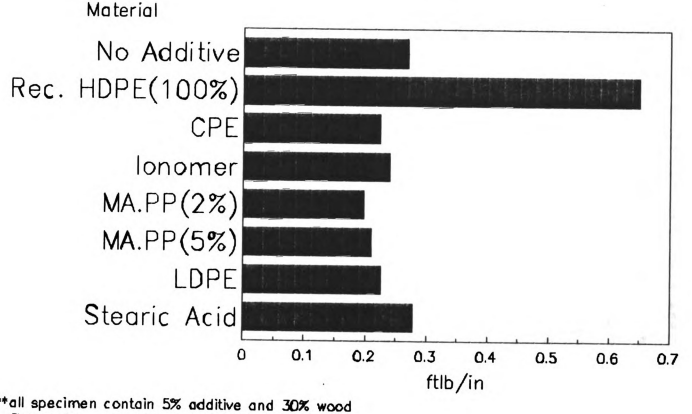
The addition of 30% wood fibers to recycled HDPE decreased impact strength by 59% as compared to recycled HDPE alone. Impact strength decreased for all the composites that contained additives, as compared to the composite with no additive. The only exception was the additive stearic acid, which exhibited an impact strength slightly higher than the no additive composite. (See Table 7 & Figure 5). MA.PP's (5% and 2%) inclusion in the composite decreased impact strength more than any of the other additives and were significantly different. Impact strength for 2% MA.PP was slightly lower than that of 5% MA.PP. (See Appendix B for t-test results).

Table 7

Izod Impact Strength
(ftlb/in)

Material	Mean	SD
No Additive	.269	.050
Rec. HDPE (100%)	.650	.063
CPE	.224	.044
Ionomer	.240	.018
LDPE	.226	.038
MA.PP (2%)	.197	.018
MA.PP (5%)	.210	.027
Stearic Acid	.277	.023

FIGURE 5
IZOD IMPACT STRENGTH



**all specimen contain 5% additive and 30% wood fiber unless otherwise stated.

2. Discussion:

The Izod impact test determines a specimen's resistance to breakage by flexural shock. The test measures a material's toughness, its deformation and breaking properties. Toughness is measured by the energy required to rupture a specimen. Fibers will improve impact strength if they have a higher ductility than the matrix, but most often fillers are rigid and make the composite brittle (Clegg & Collyer, 1986). Test results are also affected by temperature, impact velocity and stress distribution. The relationship between filler and matrix, and composite interfacial strength has not been established. However, one theory states that fiber-matrix adhesion will decrease impact strength, and that impact resistance is better for composites that have a weak interface that will act as an energy absorbing mechanism (Clegg & Collyer, 1986). MA.PP shows promising results for tensile strength and modulus which might be an indication that adhesion is occurring between the phases. If adhesion is occurring, then the data in this case indicates that adhesion decreases impact strength.

D. Water Sorption

1. Results:

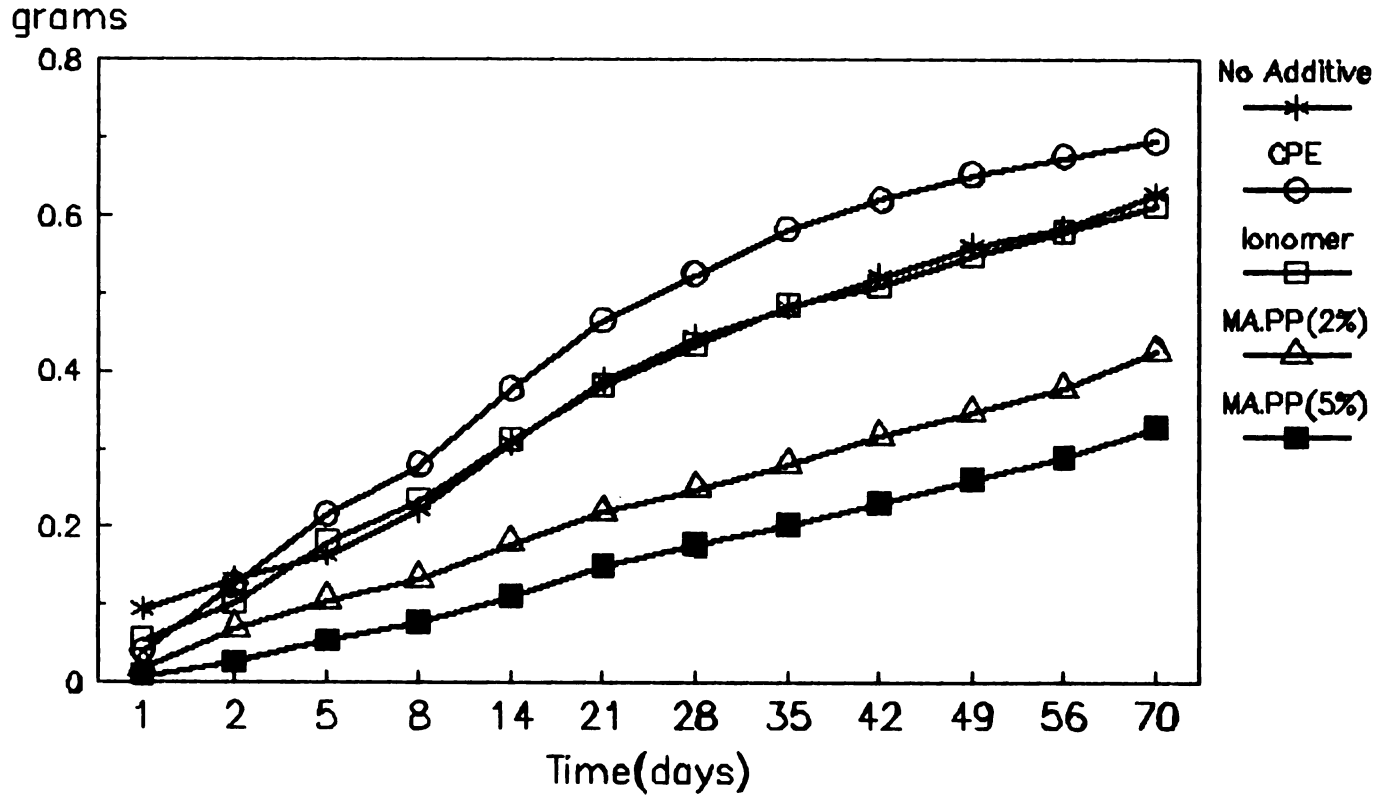
Chlorinated polyethylene's inclusion in the composite appears to promote water sorption in the composite material. Ionomer modified polyethylene did not affect water sorption in any appreciable manner. MA.PP decreased water sorption in the composite with increasing amount of additive. The composite that contained no additive sorbed 2.7% more water than 2% MA.PP and 4.1% more than 5% MA.PP (based on initial weight) after ten weeks immersed in water. Overall, the composite with no additive gained 8.1% its initial weight in water sorbed. Five percent and 2% MA.PP gained 4.0% and 5.4%, respectively, their original weight after ten weeks due to water sorption. (see Table 8 for percent moisture gain).

Table 8

Water Sorption
(10 weeks time)

Material	avg. initial weight(g)	avg. final weight(g)	% Gain
No Additive	7.78	8.4080	8.1
CPE	8.05	8.7469	8.7
Ionomer	7.87	8.4840	7.8
MA.PP (2%)	7.91	8.3360	5.4
MA.PP (5%)	8.28	8.6086	4.0

FIGURE 6
WATER ABSORPTION
(Avg. Moisture Gain)



**all specimen contain 5% additive and 30% wood fiber unless otherwise stated.

2. Discussion:

A plastic's moisture content is closely related to its mechanical properties, dimensional stability and appearance (ASTM D 570, 1987). Water acts as a plasticizer for many plastics, and tends to increase ductility and toughness, but reduces strength and modulus. Wood fibers are highly reactive with water, due to the large amount of hydroxyl groups present in the structure. Chemically treating the wood fibers to reduce their affinity for water can be done by replacing polar hydroxyl groups with less polar groups. A water resistant coating applied to the fibers can also help to reduce water sorption. Generally coatings that adhere to wood are also water sensitive (Goldstein, 1977). The hydrophylic nature of the fibers attracts water to the interface, thus resulting in loss of mechanical properties over time (Clegg & Collyer, 1986). A coupling agent could eliminate this problem. Adhesion between the phases will reduce the amount of water sorbed by the composite because the hydroxyl groups present on the wood fibers are bonded and thus, will not react with the water (Clegg & Collyer, 1986). MA.PP sorbed water, but at a slower rate than the composite with no additive. It appears that even if bonding is occurring with the addition of MA.PP to the composite, that a number of the hydroxyl groups are still free to sorb water molecules. Water sorption decreased with increasing MA.PP content, indicating that more bonding may be occurring with the higher percent MA.PP.

E. Creep Test

1. Results:

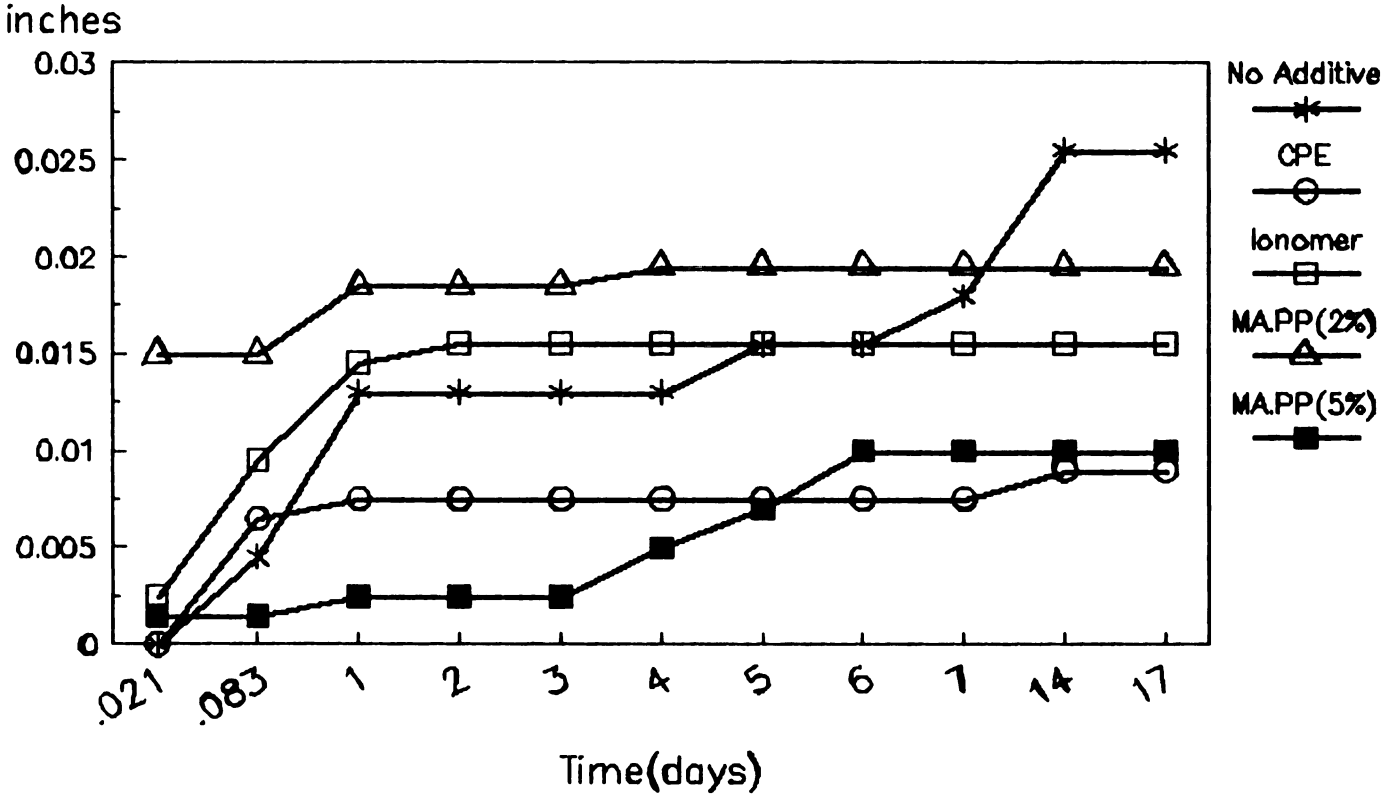
All of the composites exhibited creep, when subjected to the fifty pounds of load. Due to a time constraint only two specimens of each material were tested, thus results are suggestive rather than conclusive. Figure 7 displays the results of the creep test. As shown, the addition of additives to the composite appears to affect the composite's creep properties when compared to the composite with no additive. The additives were found to reduce the extent of creep in all of the composites in which additives were incorporated. (see Table 9).

Table 9

Creep Analysis

Material	% change (after 17 days)	
No Additive		
Run 1	.55	
Run 2	.73	Average = .64%
CPE		
Run 1	.34	
Run 2	.07	Average = .205%
Ionomer		
Run 1	.44	
Run 2	.24	Average = .34%
MA.PP (2%)		
Run 1	.22	
Run 2	.36	Average = .29%
MA.PP (5%)		
Run 1	.13	
Run 2	.30	Average = .215%

FIGURE 7
CREEP ANALYSIS



**all specimen contain 5% additive and 30% wood fiber unless otherwise stated.

2. Discussion:

The addition of fibers to the matrix reduces creep. The percent filler will also affect creep properties. A high content of filler in the composite will decrease the amount of free matrix available to creep (Katz & Milewski, 1987). The fiber-matrix interface also affects creep and the time a composite can endure a load without breaking. Adhesion of the fiber-matrix will allow the composite to act as one unit when subjected to a force. A composite with a strong interface will not pull apart as easily as one where there is no bonding of the fibers to the matrix. The composite with 5% MA.PP creeped less than the composite with no additive, thus adding to the evidence that there is adhesion occurring between the HDPE and wood fibers. But, CPE also displayed good creep results which does not correlate to CPE's mechanical test results. Further testing needs to be done to make an accurate interpretation. None of the specimens failed under the fifty pound load, although an ionomer modified polyethylene sample did have stress cracks present after three days of test.

G. Scanning Electron Microscopy (SEM)

1. Results:

Presented in Figure 8, A-J, are the scanning electron microscopy results for the HDPE and wood fiber composites. The fibers appear to be relatively whole in the photos of the various composites, and there is space between the fibers and the matrix for all the composites with the exception of MA.PP (5%).

Discussion:

A relatively smooth fracture surface will identify a good bond. A fracture surface showing a number of fibers protruding from the surface is an indication of fiber pull-out, and that stress is not transferring to the fibers. The SEM of the MA.PP composite with 5% additive suggested adhesion. There was difficulty in finding any fibers protruding from the MA.PP (5%) fracture surface. The fiber found in Figure 8-I, appears to have pulled apart and failed, and indicates a fiber failure rather than an adhesive failure. The space between the fibers and the matrix was slight, and the fibers did not pull-out but broke off at the surface. The MA.PP 2% composite SEM results varied from that of the MA.PP 5%, and did not show signs of adhesion. It is assumed that the material mix ratio for 2% MA.PP was not at an optimum. Better adhesion may also result with the 5% MA.PP if the fiber content is decreased.

SCANNING ELECTRON MICROSCOPY
Figure 8

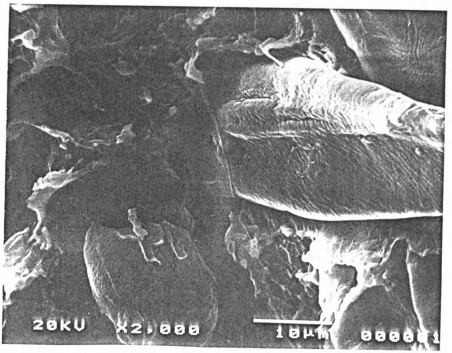


Fig. 8-A. Recycled HDPE (70%)/Wood Fiber (30%) composite. 2,000 magnification.

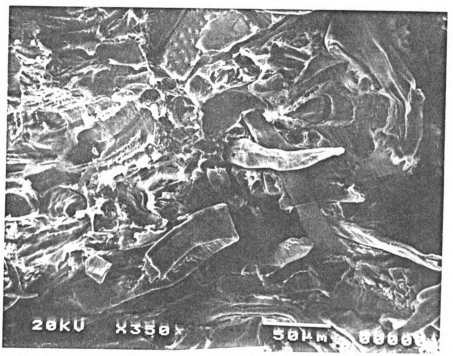


Fig. 8-B. Recycled HDPE (70%)/Wood Fiber (30%) composite. 350 magnification.

Figure 8 (cont.)

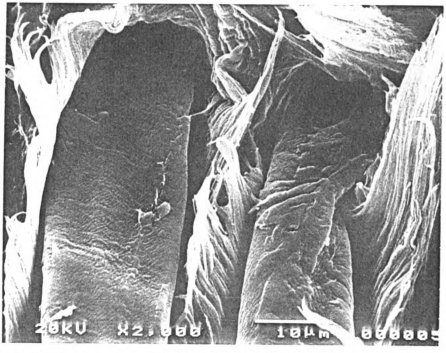


Fig. 8-C. Recycled HDPE (65%)/Wood Fiber (30%)/ Chlorinated PE (5%) composite. 2,000 magnification.

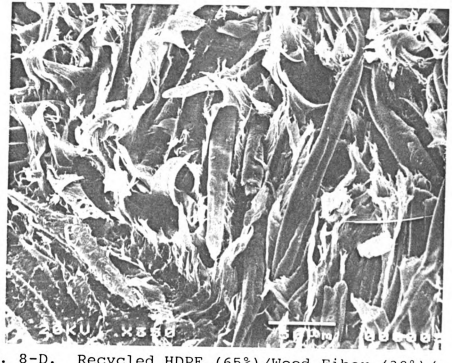


Fig. 8-D. Recycled HDPE (65%)/Wood Fiber (30%)/ Chlorinated PE (5%) composite. 350 magnification.

Figure 8 (cont.)

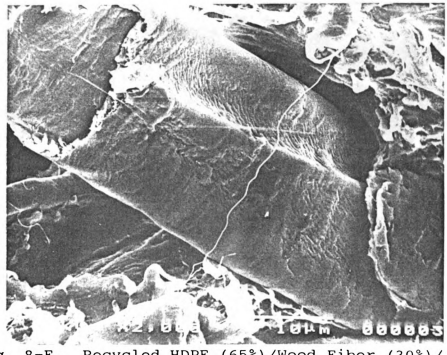


Fig. 8-E. Recycled HDPE (65%)/Wood Fiber (30%)/ Ionomer (5%) composite. 2,000 magnification.

Fig 8-F. Recycled HDPE (65%)/Wood Fiber (30%)/ Ionomer (5%) composite. 350 magnification.

Figure 8 (cont.)

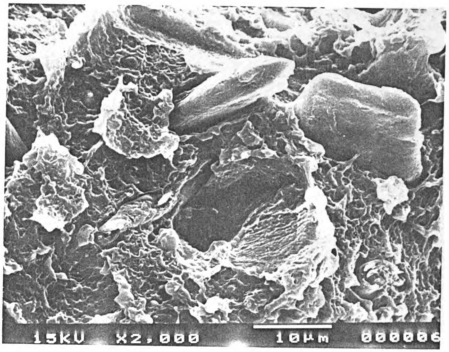


Fig. 8-G. Recycled HDPE (68%)/Wood Fiber (30%)/ MA.PP (2%) composite. 2,000 magnification.

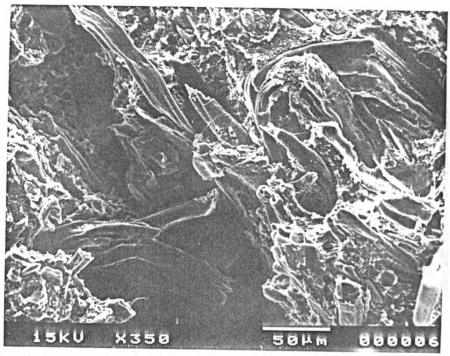


Fig. 8-H. Recycled HDPE (68%)/Wood Fiber (30%)/ MA.PP (2%) composite. 350 magnification.

Figure 8 (cont.)

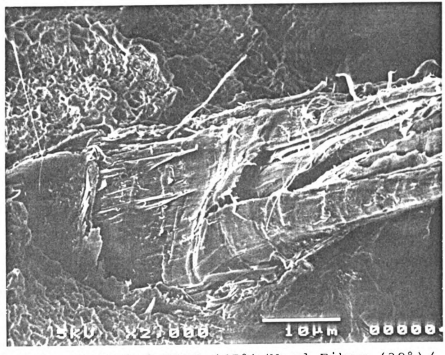


Fig. 8-I. Recycled HDPE (65%)/Wood Fiber (30%)/ MA.PP (5%) composite. 2,000 magnification.

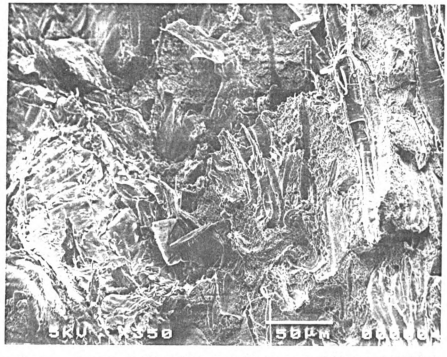


Fig. 8-J. Recycled HDPE (65%)/Wood Fiber (30%)/ MA.PP (5%) composite. 350 magnification.

V. SUMMARY

SUMMARY AND CONCLUSIONS

Maleic anhydride modified polypropylene showed potential for improving adhesion between the recycled high density polyethylene and wood fibers. MA.PP's addition to the composite resulted in an increase in tensile strength and modulus, and a decrease in impact strength. Sorption of water decreased with the inclusion of MA.PP, as did creep. Scanning electron microscopy results also indicated the occurrance of adhesion with 5% MA.PP.

Ionomer modified polyethylene showed some positive results but did not appear to be inducing adhesion. Inclusion of ionomer increased tensile strength and modulus, and had no appreciable effect on impact strength. Ionomer did not affect water sorption but did decrease creep. Signs of bonding could not be found from SEM results.

Chlorinated polyethylene gave some positive results but, like low density polyethylene and stearic acid, it did not enhance mechanical properties overall. Fiber pull-out and lack of adhesion were apparent on the SEM results.

The cost of Maleic Anhydride Modified Polypropylene, or any other additive, is an important consideration in the overall

cost of a product manufactured from a composite of recycled HDPE and wood fibers. MA.PP's inclusion in the composite resulted in improving mechanical properties more than the other additives, and is thus more likely to be considered for incorporation in the composite for end use. MA.PP has a cost of $12.00/ lb. It is the more expensive of the five additives analyzed (see Table 1). When using recycled materials to construct a product, it is important to keep the cost at a minimum, so the product can remain competitive with products utilizing other materials, recycled or virgin.

RECOMMENDATION FOR FUTURE WORK

A replication of the research conducted for this study is recommended in order to determine the legitimacy of the research findings. Determination of changes in mechanical properties after exposure to water would also be beneficial information. A more detailed creep test with a representive sample size in which specimen are subjected to a heavier load is also recommended for further research. Determination of the appropriate ratio of fiber to resin to additive so as to achieve optimal properties is perhaps the most important area that needs to be investigated.

VI. APPENDICES

APPENDIX A

MATERIAL DATA AND MANUFACTURERS

COMPOSITE CONTENTS

- Recycled HDPE from master batch.
- Wood Fibers--Aspen hardwood--from master batch.
- Additives:
  a. Chlorinated Polyethylene (CPE)--Dow Chemical Co.
  b. Maleic Anhydride Modified Polypropylene (MA.PP)--Himont Co., tradename is Hercoprime.
  c. Low Density Polyethylene (LDPE)--Dow Chemical Co.
  d. Stearic Acid--Sigma Chemical Co.
  e. Ionomer Modified Polypropylene--Du Pont, tradename is Surlyn.

Composite components: (percentage)

Composite	Additive	Wood Fiber	Rec. HDPE
CPE	4.90	30.30	64.80
Ionomer	5.00	32.00	63.00
MA.PP	1.95	27.50	70.55
MA.PP	4.82	28.28	66.90
MA.PP	5.00	0.00	95.00
LDPE	4.85	30.09	65.06
Stearic Acid	4.95	29.79	65.26
No Additive	0.00	30.00	70.00

Manufacturers of Materials

- Dow Chemical
  2020 Dow Center
  Midland, MI 48674
  (517) 636-1000

- Du Pont
  1007 Market St.
  Wilmington, DE 19898
  (302) 774-1000

- Himont USA, Inc.
  1313 N. Market St.
  Wilmington, DE 19894
  (302) 594-5500

- Soltex Polymer Company
  3333 Richmond Ave.
  Houston, TX 77098
  (713) 522-1781

- Canfor Canadian Forest Products
  Vancouver, British Columbia

Manufacturers of Equipment

- Baker Perkins, Inc.
  901 Durham Avenue
  S. Plainfield, NJ 07080
  (Mnfr extruders)

- Fred S. Carver, Inc.
  subsid. of Sterling Inc.
  W142 N9050 Fountain Blvd.
  Menomonee Falls, WI 53051
  (Mnfr lab press)

- Instron Corporation
  100 Royall St.
  Canton, MA 02021
  (Mnfr Instron)

- Polymer Machinery Corp.
  154 Woodlawn Road
  Berlin, CT 06037
  (Mnfr lowline granulator)

- Testing Machines, Inc.
  400 Bayview Ave.
  Amitycille, NY 11701
  (Mnfr impact tester)

APPENDIX B

DATA AND STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

Students t-test (two tailed) was conducted using Epistat. Composites containing additives were compared to the composite with no additive to determine significant difference at a 0.05 alpha level. The samples are independent. Calculations for the confidence limits on the difference between the means of the samples analyzed are also given.

DIFFERENTIAL SCANNING CALORIMETRY DATA
Analysis of High Density Polyethylene

Percent Crystalinity

Run	Material		
	Virgin	Recycled, Used	Recycled, Unused
1	63.60	62.30	63.79
2	61.97	62.53	63.58
NO.	2	2	2
MEAN	62.78500	62.41500	63.68500
MED	62.78500	62.41500	63.68500
SDEV	1.152655	0.160869	0.149870

Melt Temperature (Tm) (^{0}C)

Run	Material		
	Virgin	Recycled, Used	Recycled, Unused
1	132.26	132.26	132.18
2	131.98	132.06	131.80
NO	2	2	2
MEAN	132.120	132.160	131.990
MED	132.120	132.160	131.990
SDEV	0.197642	0.139754	0.272431

DSC T-TEST RESULTS

A. Samples Compared:

	Virgin(%Cryst)	Recycled, Used(%Cryst)
Means =	62.785	62.415
Variances =	1.328614	.0258789

t = .449439
df = 2
p = .6971257

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: .3699989 +/- t(2) * 1

B. Samples Compared:

	Virgin(%Cryst)	Recycled, Unused(%Cryst)
Means =	62.785	63.685
Variances =	1.328614	2.246093E-02

t = 1.094814
df = 2
p = .3878482

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: .9000015 +/- t(2) * 1

C. Samples Compared:

	Virgin(Tm)	Recycled, Used(Tm)
Means =	132.12	132.16
Variances =	3.906252E-02	1.953126E-02

t = .2263225
df = 2
p = .8419766

The MEANS of these 2 samples are NOT significantly different.
confidence limits calculation: 4.000855E-02 +/- t(2) * 1

D. Samples Compared:

	Virgin(Tm)	Recycled, Unused(Tm)
Means =	132.12	131.99
Variances =	3.906252E-02	7.421876E-02

t = .555859
df = 2
p = .6341908

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: .1299896 +/- t(2) * 1

TENSILE STRENGTH DATA

Run	Material				
	No-Add	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
1	3574	5043.5	5565.2	4487.2	4347.8
2	3904.3	3478.3	5165.2	4874.6	4347.8
3	4530.4	3391.3	4921.7	3947.8	4608.7
4	3565.2	4899.7	6730.4	4295.7	3739.1
5	3739.1	4121.7	3913	4991.3	3565.2
6	4173.9	3700.5	4434.8	5652.2	
7			4087	5426.1	
8			3652.2	5043.5	
9			3217.4		
10			3826.1		
11			4347.8		
NO	6	6	11	8	5
MEAN	3914.484	4105.834	4532.801	4839.800	4121.720
MED	3821.700	3911.100	4347.800	4932.950	4347.800
SDEV	378.270	718.109	1003.911	571.402	445.953

Tensile Strength Data Cont.

Run	Material		
	LDPE	St. Acid	Rec. HDPE(100%)
1	3405	3296.7	4782.6
2	3113.5	2838.8	5143.5
3	2838.8	2455.2	5217.4
4	3813.7	2838.8	4695.7
5	4608.7	3075.6	5095.7
6		4347.8	4912.7
7		3008.7	5095.7
8		3217.4	
9			
10			
11			
NO	5	8	7
MEAN	3555.940	3134.875	4977.615
MED	3405.000	3042.150	5043.500
SDEV	690.576	555.608	187.745

***all samples contain 5% additive and 30% wood fiber unless otherwise specified.

TENSILE STRENGTH t-TEST RESULTS

A. Samples Compared:

	No-Add	CPE
Means =	3914.484	4105.834
Variances =	143088.1	515670.5

t = .5774815
df = 10
p = .5763846

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 191.3501 +/- t(10) * 2.236068

B. Samples Compared:

	No-Add	MA.PP(2%)
Means =	3914.484	4532.801
Variances =	143088.1	1007837

t = 1.436207
df = 15
p = .171471

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 618.3169 +/- t(15) * 3.162278

C. Samples Compared:

	No-Add	MA.PP(5%)
Means =	3914.484	4839.8
Variances =	143088.1	326500.6

t = 3.426167
df = 12
p = 5.020976E-03

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 925.3164 +/- t(12) * 2.645751

D. Samples Compared:

	No-Add	Ionomer
Means =	3914.484	4121.72
Variances =	143088.1	198874

t = .8352729
df = 9
p = .4251815

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculations: 207.2363 +/- t(9) * 2

E. Samples Compared:

	No-Add	LDPE
Means =	3914.484	3555.94
Variances =	143088.1	476895.2

t = 1.096798
df = 9
p = .3012076

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 358.5435 +/- t(9) * 2

F. Samples Compared:

	No-Add	St. Acid
Means =	3914.484	3134.875
Variances =	143088.1	308701.7

t = 2.948515
df = 12
p = 1.217783E-02

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 779.6084 +/- t(12) * 2.645751

G. Samples Compared:

	No-Add	Rec. HDPE(100%)
Means =	3914.484	4977.615
Variances =	143088.1	35248

t = 6.582836
df = 11
p = 3.9587728E-05

The MEANS of these 2 samples are significantly different.

confidence limits calculations: 1063.131 +/- t(11) * 2.236068

TENSILE MODULUS DATA
(psi)

Run	Material				
	No-Add	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
1	116960	208697.1	243480	118031.1	173914.3
2	165380.4	173912	240312.7	153611.4	227665.5
3	215656	173912	194784	124222.9	227665.5
4	157536.2	157668.6	252170	183851.4	243480
5	243480	187292.3	197100	185778.8	190171
6	160042.9	172120	173914.3	188817.1	
7			176590.8	169565	
8			170749.1	208693.3	
9			208693.3		
10			216426.7		
11			187824		
NO	6	6	11	8	5
MEAN	176509.3	178933.7	205640.5	166571.4	212579.2
MED	162711.7	173912.0	197100.0	176708.2	227665.5
SDEV	45427.8	17348.0	29156.1	32211.6	29186.2

Tensile Modulus Data Cont.

Run	Material		
	LDPE	St. Acid	Rec. HDPE(100%)
1	117765.7	115122.9	115940
2	107450.7	117216	99377.1
3	122100	143370	117723.1
4	175746.7	131840	110146.7
5	204971.4	146981.8	104344
6		194785.5	109314.3
7		153040	125216
8		166960	
9			
10			
11			
NO	5	8	7
MEAN	145606.9	146164.5	111723.0
MED	122100.0	145175.9	110146.7
SDEV	42474.0	26346.6	8669.816

***all samples contain 5% additive and 30% wood fiber unless otherwise specified.

TENSILE MODULUS t-TEST RESULTS

A. Samples Compared:

	No-Add	CPE
Means =	176509.3	178933.7
Variances =	2.063725E+09	3.009576E+08

t = .1221201
df = 10
p = .9052231

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 2424.344 +/- t(10) * 2.236068

B. Samples Compared:

	No-Add	MA.PP(2%)
Means =	176509.3	205640.5
Variances =	2.063687E+09	8.500776E+08

t = 1.620503
df = 15
p = .1259516

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculations: 29131.13 +/- t(15) * 2.23607

C. Samples Compared:

	No-Add	MA.PP(5%)
Means =	176509.3	166571.4
Variances =	2.063687E+09	1.037587E+09

t = .4807461
df = 12
p = .6393428

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 9937.953 +/- t(12) * 2.236068

D. Samples Compared:

	No Add	Ionomer
Means =	176509.3	212579.2
Variances =	2.063687E+09	8.518331E+08

t = 1.525324
df = 9
p = .1615186

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 36069.88 +/- t(9) * 2.236068

E. Samples Compared:

	No Add	LDPE
Means =	176509.3	145606.9
Variances =	2.063725E+09	1.804041E+09

t = 1.156193
df = 9
p = .2773704

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 30902.42 +/- t(9) * 2.236068

F. Samples Compared:

	No Add	St. Acid
Means =	176509.3	146164.5
Variances =	2.063725E+09	6.941386E+08

t = 1.579911
df = 12
p = .1401119

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 30344.83 +/- t(12) * 2.236068

G. Samples Compared:

	No Add	Rec. HDPE(100%)
Means =	176509.3	111723
Variances =	2.063725E+09	7.516706E+07

t = 3.721657
df = 11
p = 3.371885E-03

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 64786.31 +/- t(11) * 2.236068

PERCENT ELONGATION DATA

Run	Material				
	No Add	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
1	1.7	3	2	4.5	3.5
2	1.6	3	1.38	4.375	2.25
3	1.7	2.4	2.38	4	3.13
4	1.5	4.25	2.82	3	4
5	1.1	2.5	4.63	2.875	2.63
6	.8	3.13	3.25	3.875	
7			3	4.125	
8			2.75	3.25	
9			1.75		
10			2.25		
11			3.75		
NO	6	6	11	8	5
MEAN	1.400000	3.046667	2.723637	3.750000	3.102000
MED	1.550000	3.000000	2.750000	3.937500	3.130000
SDEV	0.368783	0.659749	0.931153	0.626783	0.691787

Percent Elongation Data Cont.

Run	Material		
	LDPE	St. Acid	Rec. HDPE(100%)
1	4.5	4	308.75
2	4.25	4.125	142.5
3	3.25	2.75	246.25
4	2.875	3.625	263.75
5	3.875	4.5	
6		5.25	
7		4.125	
8		4.25	
9			
10			
11			
NO	5	8	4
MEAN	3.750000	4.078125	240.313
MED	3.875000	4.125000	255.000
SDEV	0.678924	0.713200	70.32200

***all samples contain 5% additive and 30% wood fiber unless otherwise stated.

PERCENT ELONGATION t-TEST RESULTS

A. Samples Compared:

	No Add	CPE
Means =	1.4	3.046667
Variances =	.1360005	.4352692

t= 5.336556
df = 10
p = 3.299713E-04

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 1.646667 +/- t(10) * 2.236068

B. Samples Compared:

	No Add	MA.PP(2%)
Means =	1.4	2.723637
Variances =	.1360005	.8670456

t = 3.30328
df = 15
p = 4.82626E-03

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 1.323637 +/- t(15) * 3.162278

C. Samples Compared:

	No Add	MA.PP(5%)
Means =	1.4	3.75
Variances =	.1360005	.3928572

t = 8.13894
df = 12
p = 3.099442E-06

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 2.350001 +/- t(12) * 2.645751

D. Samples Compared:

	No Add	Ionomer
Means =	1.4	3.102
Variances =	.1360005	.478569

t = 5.235242
df = 9
p = 5.381911E-04

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 1.702 +/- t(9) * 2

E. Samples Compared:

	No Add	LDPE
Means =	1.4	3.75
Variances =	.1360005	.4609375

t= 7.328751
df = 9
p = 4.421663E-05

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 2.350001 +/- t(9) * 2

F. Samples Compared:

	No Add	St. Acid
Means =	1.4	4.078125
Variances =	.1360005	.5086496

t = 8.341909
df = 12
p = 2.503395E-06

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 2.678126 +/- t(12) * 2.645751

G. Samples Compared:

	No Add	Rec. HDPE(100%)
Means =	1.4	240.3125
Variances =	.1360005	4945.184

t = 8.594624
df = 8
p = 2.598763E-05

The MEANS of these 2 samples are significantly different.

confidence limits calculation: 238.9125 +/- t(8) * 1.732051

MA.PP + HDPE

Tensile Strength

Run	Material	
	Rec. HDPE(100%)	Rec. HDPE + 5%MA.PP
1	4782.6	4347.8
2	5043.5	4817.4
3	5217.4	4521.7
4	4695.7	4695.7
5	5095.7	4782.6
6	4921.7	4991.3
7	5095.7	4469.6
8		5217.4
NO	7	8
MEAN	4978.900	4730.436
MED	5043.500	4739.150
SDEV	187.247	286.532

Tensile Modulus

Run	Material	
	Rec. HDPE(100%)	Rec. HDPE + 5%MA.PP
1	115940	112375.4
2	99377.1	113832.7
3	117723.1	187824
4	110146.7	113832.7
5	104344	118264
6	109314.3	147830
7	125216	123644.4
8		120160
NO	7	8
MEAN	111723.0	129720.4
MED	110146.7	119212.0
SDEV	8669.816	26102.3

Run	Izod Impact Material	
	Rec. HDPE(100%)	Rec. HDPE + MA.PP(5%)
1	.655	.445
2	.707	.292
3	.624	.275
4	.648	.363
5	.704	.305
6	.527	.423
7	.72	.322
8	.615	.282
No	8	8
MEAN	0.650000	0.338375
MED	0.651500	0.313500
SDEV	0.063386	0.065317

MA.PP + REC. HDPE t-TEST RESULTS

A. Samples Compared:

	Rec. HDPE (TS)	MA.PP + Rec. HDPE (TS)
Means =	4978.9	4730.436
Variances =	35061.33	82100.6

t = 1.953568
df = 13
p = 7.261483E-02

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 248.4639 +/- t(13) * 2.645751

B. Samples Compared:

	Rec. HDPE (TM)	MA.PP + Rec. HDPE (TM)
Means =	111723	129720.4
Variances =	7.516571E+07	6.813285E+08

t = 1.735326
df = 13
p = .1063097

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation: 17997.35 +/- y(13) * 2.645751

C. Samples Compared:

	Rec. HDPE(100%)(I)	Rec. HDPE + 5%MA.PP(I)
Means =	.65	.338375
Variances =	4.017796E-03	4.266245E-03

t = 9.684035
df = 14
p = < 10 (-6)

The MEANS of these 2 samples are significantly different.

confidence limits calculation: .311625 +/- t(14) * 2.645751

IZOD IMPACT DATA
(ftlb/in)

Run	Material				
	No Add	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
1	.246	.213	.174	.24	.243
2	.352	.31	.175	.22	.21
3	.199	.184	.194	.197	.256
4	.294	.22	.198	.24	.225
5	.318	.214	.206	.167	.256
6	.262	.205	.213	.205	.248
7	.23		.22	.184	
8	.251			.23	
NO	8	6	7	8	6
MEAN	0.269000	0.224333	0.197143	0.210375	0.239667
MED	0.256500	0.213500	0.198000	0.212500	0.245500
SDEV	0.049624	0.043803	0.017743	0.026774	0.018490

Izod Impact Data Cont.

Run	Material		
	LDPE	St. Acid	Rec. HDPE(100%)
1	.221	.318	.655
2	.166	.262	.707
3	.246	.256	.624
4	.196	.252	.648
5	.271	.275	.704
6	.194	.285	.527
7	.253	.29	.72
8	.262		.615
NO	8	7	8
MEAN	0.226125	0.276857	0.650000
MED	0.233500	0.275000	0.651500
SDEV	0.037794	0.023126	0.063386

***all samples contain 5% additive and 30% wood fiber unless otherwise stated.

IZOD IMPACT t-TEST RESULTS

A. Samples Compared:

	No Add	CPE
Means =	.269	.2243333
Variances =	2.462575E-03	1.918674E-03

t = 1.749076
df = 12
p = .1057843

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation:4.466667E-02 +/- t(12) * 2.6458

B. Samples Compared:

	No Add	MA.PP(2%)
Means =	.269	.1971429
Variances =	2.462575E-03	3.14802E-04

t= 3.619657
df = 13
p = 3.112641E-03

The MEANS of these 2 samples are significantly different.

confidence limits calculation:7.185714E-02 +/- t(13) * 2.6458

C. Samples Compared:

	No Add	MA.PP(5%)
Means =	.269	.210375
Variances =	2.462575E-03	7.168397E-04

t = 2.940719
df = 14
p = 1.074117E-02

The MEANS of these 2 samples are significantly different.

confidence limits calculation: .058625 +/- t(14) * 2.645751

D. Samples Compared:

	No Add	Ionomer
Means =	.269	.239667
Variances =	2.462583E-03	3.418746E-04

t = 1.366889
df = 12
p = .196722

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation:2.033334E-02 +/- t(12) * 2.6458

E. Samples Compared:

	No Add	LDPE
Means =	.269	.226125
Variances =	2.462575E-03	1.428408E-03

t = 1.944101
df = 14
p = 7.225883E-02

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation:4.287499E-02 +/- t(14) * 2.6458

F. Samples Compared:

	No Add	St. Acid
Means =	.269	.2768572
Variances =	2.462575E-03	5.348225E-04

t = .3827987
df = 13
p = .7080548

The MEANS of these 2 samples are NOT significantly different.

confidence limits calculation:7.857144E-03 +/- t(13) * 2.6458

G. Samples Compared:

	No Add	Rec. HDPE(100%)
Means =	.269	.65
Variances =	2.462575E-03	4.017796E-03

t = 13.38662
df = 14
p = < 10 (-6)

The MEANS of these 2 samples are significantly different.

confidence limits calculation: .381 +/- t(14) * 2.645751

WATER ABSORPTION DATA

(Average Moisture Gain in grams)

Time (days)	Material				
	No Additive	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
1	0.0950	0.0413	0.0200	0.0100	0.0570
2	0.1330	0.1273	0.0700	0.0270	0.1030
5	0.1650	0.2173	0.1070	0.0550	0.1820
7	0.2232	0.2798	0.1330	0.0790	0.2360
14	0.3094	0.3788	0.1800	0.1130	0.3120
21	0.3890	0.4663	0.2200	0.1510	0.3820
28	0.4448	0.5263	0.2500	0.1790	0.4350
35	0.4836	0.5838	0.2810	0.2046	0.4850
42	0.5230	0.6213	0.3170	0.2316	0.5120
49	0.5625	0.6538	0.3480	0.2636	0.5490
56	0.5860	0.6769	0.3790	0.2906	0.5800
70	0.6280	0.6969	0.4260	0.3286	0.6140

CREEP ANALYSIS DATA

(gain in inches)

Time(days)	Material				
	No Additive	CPE	MA.PP(2%)	MA.PP(5%)	Ionomer
.021	0.0000	0.0000	0.0150	0.0015	0.0025
.083	0.0045	0.0065	0.0150	0.0015	0.0095
1	0.0130	0.0075	0.0185	0.0025	0.0145
2	0.0130	0.0075	0.0185	0.0025	0.0155
3	0.0130	0.0075	0.0185	0.0025	0.0155
4	0.0130	0.0075	0.0195	0.0050	0.0155
5	0.0155	0.0075	0.0195	0.0070	0.0155
6	0.0155	0.0075	0.0195	0.0100	0.0155
7	0.0180	0.0075	0.0195	0.0100	0.0155
14	0.0255	0.0090	0.0195	0.0100	0.0155
17	0.0255	0.0090	0.0195	0.0100	0.0155

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