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COMPOSITE MATERIALS FROM RECYCLED MULTI-LAYER POLYPROPYLENE BOTTLES AND WOOD FIBERS

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Major professor

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## COMPOSITE MATERIALS FROM RECYCLED MULTI-LAYER POLYPROPYLENE BOTTLES AND WOOD FIBERS

By

Rodney James Simpson

A THESIS

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

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#### ABSTRACT

## COMPOSITE MATERIALS FROM RECYCLED MULTI-LAYER POLYPROPYLENE BOTTLES AND WOOD FIBERS

By

Rodney James Simpson

The feasibility of using recycled multi-layer polypropylene (PP) bottles in combination with untreated hardwood aspen fiber (thermomechanical pulp or TMP) was tested by evaluating the mechanical properties of the reclaimed polymer and virgin PP composites. Up to fifty weight-percent of wood fiber was incorporated into the matrix. Specimens were tested in both length and cross direction for Izod impact strength, tensile properties and flexural modulus. Specimens were subject to water absorption and also to creep testing in ambient and extreme environmental conditions. Orientation of the wood fiber resulted in significantly higher mechanical properties for both polymer-wood fiber composites, at each fiber concentration. The PP Reclaim-wood fiber composite was superior to the virgin PP composite, possibly due to multilayer materials permitting an increase in adhesion at the interface. The multi-layer material also displayed better dimensional stability under extreme environmental conditions.

to my wife, for her support and inspiration

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#### INTRODUCTION

Our throwaway society that has emerged during the late twentieth century produces so much pollution and waste that it is slowly strangling itself. The historically cheap and simple solution of burying trash in a sanitary landfill is no longer workable. Opposition to landfills, often referred to as the not-in-my-backyard or Nimby syndrome, is slowing the opening of new sites (Nulty, 1990). In addition, a third of the 6,500 municipal landfills in the U.S. are expected to reach capacity by the mid-1990s (Fahey, 1990). Along with the opposition to new landfill sites, stricter government-mandated environmental standards and controls have accelerated the cost of landfill operation. Tipping fees, the price of dumping municipal solid waste in landfills, rose 30% in 1988 to a national average of \$27 per ton (Nulty, 1990). One solution, as practiced by a Florida landfill, is to mine the landfill for materials to recycle which creates additional space for garbage and reduces the cost of operation (Fahey, 1990). With the annual production of refuse in the U.S. to increase to 193 million tons by the end of the century, Cook (1990) suggests only four ways to deal with solid waste: "Bury it, burn it, recycle it - or don't make as much in the first place."

Incineration, a "resource recovery" method popular in the

1970s, creates as many problems as it solves. Incinerators produce an ash with such a high ratio of toxic metals to harmless substances that it often legally qualifies as a hazardous waste, and they toxify the atmosphere with traces of heavy metals and dioxins (Luoma, 1990). Yet, with all these problems, incinerator operators say that pollution controls such as high-temperature furnaces, scrubbers and bag houses The problem becomes virtually eliminate harmful emissions. economic: construction costs run as high as \$500 million, and even though public utilities are required by law to purchase the power, the energy produced is not cost-competitive (Beck et al., 1989). Incineration has blinded the public to the opportunities that waste reduction and recycling offer.

Waste reduction is the most desirable environmental alternative for waste disposal in the hierarchy of waste management options (Resource Integration Systems Ltd., 1987). A reduction in the quantity of material used per unit of product has been used effectively to reduce waste in the past (e.g., light weight glass beverage bottles), although for economic rather than solid waste considerations. The method with the greatest potential for waste reduction, according to Selke (1990), is to persuade people to moderate their needs and desires, thus creating a direct reduction of material goods. This, however, is unlikely because our society in the United States places a greater emphasis on convenience.

Recycling has long been viewed as part of the solution to the problem of solid waste management (Spang, 1990). An industry spokesperson from Du Pont concurs that a greater emphasis should be placed on recycling, as the real solution to the solid waste problem (Chemical Marketing Reporter, May 1990). The U.S. Environmental Protection Agency (EPA) estimated that 13% or 23.5 million tons of the country's municipal solid waste (MSW) in 1988 was recovered (not necessarily recycled) (Recycling Times, July 1990). Recovered materials are those that are separated from the waste stream and are categorized as recycled, only if markets exist. The recovery of materials is expected to reach between 20% and 28% of MSW generated in 1995 (Recycling Times, July 1990). In addition, Brown et al. (1990) predict that in the year 2030, waste reduction and recycling industries will have largely replaced the garbage collection and disposal companies of today. In contrast, a new national average recycling goal of 40% by 1996 is being considered by the U.S. Environmental Protection Agency (EPA), heavily stressing market development for secondary materials and ensured supply of recovered materials to reach this goal (Recycling Times, August 1990a). Roughly eight million into recyclable American homes now sort refuse and nonrecyclable piles for curbside collection, with recycled material expected to double by 1992 (Nulty, 1990). Revenues in the post-consumer business rose to about \$6 billion in 1989 compared to \$4.8 billion in 1988. Revenue is expected to grow

between 25% and 30% annually over the next five years (Nulty, 1990).

The recyclable material of choice these days is plastic. Throughout 1990 industry's giants aggressively promoted plastics recycling and made capital investments to bring reprocessing capacity on line throughout the country (Recycling Times, December 1990). Leidner (1981) describes the action of recycling plastics from both post consumer and industrial waste as secondary recycling. Redefined by Selke (1990), secondary recycling is the manufacture of new products from recycled materials which possess less stringent specifications than the original.

According to the U.S. Environmental Protection Agency, the recycling rate for plastic is around 1% vs. 20% for paper, 27% for aluminum beverage cans, and 7% for glass (Thayer, 1989). In 1988, the volume of discarded plastics in the MSW stream was 19.9%, although, by weight, plastics represented only 9.2%. Of the 14.3 million tons of plastics discarded, 1.1% was recovered (Recycling Times, July 1990). The largest single source of plastic waste in 1985 was packaging, representing 40-weight percent (4,921,000 metric tons) of resin use (Resource Integration Systems Ltd, 1987). Plastic packaging is highly visible as a waste management problem due to its overall volume percent and short life span. Also, it

is predicted that 50% of the total packaging material will be plastic by the year 2000, up from approximately 25% in 1985 (Resource Integrated Systems Ltd, 1987). Currently, the recycled plastic packaging is the polyethylene most terephthalate (PET) beverage container. More than 175 million pounds of PET was recovered and recycled in 1988. The second most recovered plastic packaging was high-density polyethylene (HDPE), the plastic used to make one-gallon milk and water jugs (American Metal Market, September 1990). Recovered highdensity polyethylene bottles were purchased at an average of 9 to 14 cents a pound in 1988 (American Metal Market, April 1990). Current buying prices for baled plastic containers are about 5 cents a pound, while baled PET consisting of only clear materials is worth 9 cents a pound (American Metal Market, September 1990).

The market share of plastic food containers has increased quite rapidly in recent years and is projected to grow at over 10% per year for the next 10 years. The fastest growing segments of plastic packaging for food will be coextruded, high barrier, multi-layer bottles, jars, and cans, and thermoplastic dual-ovenable trays (Lindsay, 1988). Multilayer, high barrier products have come under attack in environmental circles recently because of alleged recycling problems. Yet, multi-layer packaging, in itself, is a form of source reduction. To match the properties achieved with a

multi-layer material, single plastic packages may need up to four times the amount of material (Thayer, 1990). One polyolefin which is being used extensively in multi-layer plastic packaging is polypropylene.

After three decades in commercial production, polypropylene (PP) has a world market growth rate of about 10 percent (Potter, 1990). Yet, Kaushick (1990) pegs U.S. growth at a Polypropylene has captured some of the 5.7 percent rate. demand for high-density polyethylene or polystyrene because of its pricing (Kaushick, 1990). In 1987, 12.6 billion pounds of plastics were used for packaging in the U.S.; roughly 10 percent (1.3 billion pounds) were of the PP resin type (Selke, The price for virgin PP homopolymer in 1990 was at 40 1990). to 41 cents a pound in October, up from 35 cents in March (Chemical Marketing Reporter, October 1990a). Although PP is in its infant stage as a recycled medium, Du Pont and American National Can have developed a program to collect, sort, and market recycled PP, as well as PVC, PS, and LDPE bottles. They plan to develop markets for their output and intend to pioneer automated sorting technology to separate the different plastics (Chemical Marketing Reporter, October 1990b).

Addition of recycled material from multi-layer barrier juice, ketchup bottles, and retort containers improved some mechanical properties of polypropylene (PP) homopolymers,

primarily in the areas of tensile strength, elongation, flexural modulus, and impact strength (Plastics World, 1990). In addition, a study which was conducted by the Plastic Bottle Institute (PBI) concluded that multi-layer bottle reclaim can be used in a mixed monolayer polypropylene stream (Plastics World, 1990). Since the mechanical properties of recycled multi-layer polypropylene containers have demonstrated some improvement over homopolymers, this study will focus on the use of ketchup bottles as a low-cost matrix with wood fibers to form a composite.

Composite materials, as defined, are composed of a reinforcing structure, surrounded by a matrix (Richardson, 1987). Creating a PP/wood fiber composite material provides a way to extract some value from recycled, multi-layer plastic, while acquiring the stiffness properties of the wood fibers. The wood fibers chosen to be used as the reinforcement are aspen hardwood fibers in the form of thermomechanical pulp (TMP). When used as a reinforcement in composite materials, wood pulp fibers possess strength and modulus properties which compare favorably with glass fibers when one considers the density of the fibers (Woodhams et al., 1984). Wood fibers also have a number of advantages such as lower cost, light weight, and resistance to damage during processing (Raj et al, 1988).

A strong interface between the reinforcement and the matrix is

extremely important to develop composites with improved physical and mechanical properties. Unfortunately, good bonding between the wood fibers and polypropylene is difficult because wood fibers are hydrophilic and polar while polypropylene is hydrophobic and nonpolar. Moreover, fibers have a high degree of intermolecular hydrogen bonding and during the mixing of fibers and thermoplastics the fibers tend to agglomerate, unless fibers are wetted to reduce fiber-tofiber bonding (Kokta et al., 1990). Yet, wood fibers produced from mechanical pulping still retain most of their lignin and natural waxes, materials which can aid fiber dispersion in nonpolar hydrocarbon polymers (Woodhams et al., 1984).

In 1985, reinforced thermoplastics represented a 15% share of the composite market. Nylon and polypropylene were the most commonly used resins representing 50% of total production (Vu-Khanh, 1987). The PP/wood fiber composite has potential for high volume processing into a myriad of products because of the inherent ease of processing and the increase in stiffness and creep resistance. Bigg and Preston (1989) examined the potential for solid-state stamped parts from thermoplastic matrix sheet composites. Recycled aseptic packaging containers (juice boxes) made primarily of softwood fibers and polyethylene, are currently being processed into recycled products, eg., plastic lumber (Recycling Times, August 1990b). Additionally, the composite has the potential to replace material such as wood and concrete for products such as mailbox posts, picnic tables, speed bumps, highway markers, parking stops, fences, park benches, etc.

The primary objectives of this study were: (i) to investigate the use of a recycled multi-layer polypropylene container (ketchup bottle) as the matrix with wood fiber to form a composite; (ii) to determine the effect fiber content and fiber orientation has on the mechanical properties of the composite structure; (iii) to examine the effect barrier materials in the PP reclaim have on the dimensional stability of the composite structure under extreme environmental conditions; (iv) to develop a secondary use for discarded multi-layer packaging made from predominately polypropylene resin; and (v) to compare actual mechanical properties with theoretical mechanical properties, where appropriate.

## LITERATURE REVIEW

## COMPOSITE MATERIALS

A composite is formed when two or more materials are combined, with the intent of accomplishing better results than can be obtained by a single, homogeneous material. Composites are separated into two basic forms: (i) composite materials and (ii) composite structures. Composite materials are composed of a reinforcing structure surrounded by a continuous matrix, where as composite structures display a discontinuous matrix. The matrix usually has a lower strength than the reinforcement and is the material that holds the reinforcement together. Composite materials can be classified as either fibrous or particulate, depending on the geometry of the reinforcement. There are three basic components in a fiber-reinforced composite: matrix, fiber, and the fiber-matrix interface (Katz and Milewski, 1978).

The main functions of the matrix are to transfer and apportion stresses onto the fiber, and to maintain desired orientation and separation of the fibers. The matrix also provides protection against fiber exposure to environmental conditions as well as fiber abrasion. The matrix will additionally cause the fibers to act as an aggregation in resisting deformation

or failure under load, along with limiting the maximum temperature to which the composite can be exposed.

The fiber gives the composite high tensile strength and modulus, and provides resistance to bending and breaking under the applied load or stress.

The fiber-matrix interface determines the potential properties of the composite. The stresses acting on the matrix are transmitted to the fiber across the interface. Bonding at the interface is due to adhesion between the matrix and the fiber. Fibers are often coated with a coupling agent which forms a bond between the fiber and the matrix providing improvement in interfacial conditions.

There are two types of fibrous reinforced composites: discontinuous. Continuous-filament continuous and (unidirectional) composites have greater strength and modulus in the fiber axis direction and generally lack physical strength in the transverse direction. In a discontinuous fiber composite, the stress along the fiber is not uniform. The length (1) to diameter (d) ratio of the fiber, or aspect ratio (1/d) determines the level of strength the composite will achieve. If the fiber is shorter than the critical length, the composite will fail at a low strength level. Therefore, it is important that the properties of a composite be predictable from a knowledge of the component matrix, fiber, fiber volume, and fiber orientation.

#### PREDICTION OF PROPERTIES

The mechanical properties of a composite are related to the properties and distribution of its components, and their chemical and physical interactions. Many analytical models and failure theories have been used in the analysis of the mechanical properties of different types of composites.

The modulus is the bulk property of a composite that depends primarily on the geometry, modulus, particle size distribution and concentration of the filler (Bigg, 1987). The Rule of Mixtures as specified by Jindal (1986) can be used to estimate the strength of a composite, by:

$$\sigma_{\rm c} = \sigma_{\rm f} V_{\rm f} + \sigma_{\rm m} V_{\rm m} \tag{1}$$

where:  $\sigma_c$  = Ultimate strength of the composite  $\sigma_f$ ,  $\sigma_m$  = Ultimate strength of the fibers, matrix  $V_f$ ,  $V_m$  = Volume fraction of the fibers, matrix (Jindal, 1986)

This equation assumes a continuous-unidirectional composite with stress direction parallel to the fibers and perfect bonding of all fibers to the matrix (Katz and Milewski, 1978). Yet, the stress is not uniform along the fiber for a discontinuous fiber composite. The properties of a discontinuous (short) fiber composite are a function of the fiber length and fiber ends (Agarwal and Broutman, 1980). A fiber can be defined as any material that has a high ratio of length to cross sectional area, with the minimum ranging from 10:1 to 100:1, a maximum cross sectional area of 7.85 x  $10^{-5}$  in.<sup>2</sup> and a maximum transverse dimension of 0.010 in. (Katz and Milewski, 1978). In comparison, Richardson (1977) defined a short-fiber composite as having a fiber length-to-diameter ratio between 10 and 1000. The mechanism of stress transfer can allow interpretation of the performance of a discontinuous fiber composite. The distribution of stress along the length of a fiber can be explained by examining the force equilibrium of an infinitesimal length, dz, of a short-fiber composite:

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

$$\frac{d\sigma_f}{dz} = \frac{2\tau}{r}$$

where:  $\sigma_f$  = the fiber stress in the axial direction  $\tau$  = shear stress on the cylindrical interface r = the fiber radius dz = element of length in axial direction

(Agarwal and Broutman, 1980)

This indicates that the rate of increase of fiber stress is proportional to the shear stress at the interface, provided the fiber is of uniform radius. The equation (2) can be integrated to obtain the fiber stress on a cross section a distance z away from the fiber end:

$$\sigma_{\rm f} = \sigma_{\rm f0} + \frac{2}{\rm r} \int_0^2 \tau \, dz$$
 (3)

where:  $\sigma_{f0}$  = the stress on the fiber end

(Agarwal and Broutman, 1980)

At equal strain, the average stress will be lower in a short fiber than in a continuous composite fiber, because the ends of short fibers are not loaded to the same level as the center (Richardson, 1977). When the fiber has an aspect ratio (length-to-diameter ratio) that equals or exceeds the critical aspect ratio, the stress in the center will be equivalent to that of a continuous length fiber (Katz and Milewski, 1978). The critical aspect ratio  $(1/d)_c$  can be expressed as:

$$\left(\frac{1}{d}\right)_{c} = \frac{S_{f}}{2Y}$$
(4)

where: 1, d = the length and diameter of the fiber  $(1/d)_c$  = the critical aspect ratio  $S_f$  = the tensile stress of the fiber

> Y = the yield strength of the matrix in shear or the fiber-matrix interfacial shear strength, whichever is the lowest (Katz and Milewski, 1978)

The critical aspect ratio would result in fiber fracture at its midpoint. The stressed fiber will de-bond from the matrix and the composite will fail at a low level of strength when the fiber is shorter than the critical length (Katz and Milewski, 1978). Fiber length is an important parameter in the determination of stress to be transferred from the matrix to the fiber. This may be expressed as:

$$L_f = DST_f$$
(5)

where: 
$$L_f = critical fiber length$$

- D = diameter of the fiber
- S = strength of the matrix bond to fiber
   (approx. equal to shear strength of matrix)
  T<sub>f</sub> = tensile strength of fiber

(Richardson, 1987)

As the angle between the fiber axis and loading direction increases, the strength of an aligned short-fiber composite decreases. For a discontinuous fiber composite, Katz and Milewski (1978) provide an estimate for tensile strength using the rule of mixtures expressed as:

$$S_{c} = V_{f} S_{f} \left( 1 - \frac{1_{c}}{21} \right) + V_{m} S_{m}$$
(6)

where:  $S_c$  = tensile strength of the composite  $V_f$  = volume fraction of the fiber  $V_m$  = volume fraction of the matrix  $S_f$  = tensile strength of the fiber  $S_m$  = tensile strength of the matrix  $l_c$  = critical length of the fiber 1 = length of the fiber (Katz and Milewski, 1978)

When applying the rule of mixtures to plastic matrix filled composites, the  $V_f$  must be greater than 10% and less than 70%. A fiber volume fraction lower than 10% will yield a strength similar to that of the matrix and anything higher than 70% will show a decrease in properties (Katz and Milewski, 1978).

The interfacial strength between the matrix and the filler is difficult to determine. Many bonding mechanisms are possible between a polymer and filler; these include ionic, covalent, electrostatic, and van der Waals (Bigg, 1987). Hull (1981) describes five main mechanisms for adhesion at the interface (either in isolation or in combination) to produce the bond, (1) adsorption and wetting, (2) interdiffusion, (3) electrostatic attraction, (4) chemical bonding, and (5) mechanical adhesion. When two solids are brought together, the surface roughness at the micro level prevents the surfaces from coming into contact except at isolated points. For effective wetting of a fiber surface the liquid resin must cover every part of the surface to displace all the air. Yet, this bonding mechanism is usually not achieved because of the contamination of the fiber surface, entrapped air at the solid surface, and because of displacements at the surface due to shrinkage stresses during the cure process.

Interdiffusion (also referred to as autohesion in relation to adhesives), as a bonding mechanism, is achieved by molecular entanglements of two polymer surfaces promoted by the presence of plasticizing agents and solvents. Interdiffusion is accomplished by pre-coating the fibers with polymer prior to mixing with the matrix.

Ionic bonding or acid-base interactions are forces of attraction which allow surfaces with dissimilar charges (+,-) to bond. This electrostatic attraction plays a more important role as a coupling agent and is not likely to contribute extensively to the bond strength of the fibermatrix composite.

Coupling agents, which are applied to fiber surfaces prior to mixing of composites, allow for chemical bonding to form

between themselves and chemical groups in the matrix. Interface failure then must involve breaking of the bond(s), adding to the strength of the composite.

Mechanical bonding occurs by the interlocking of two surfaces mechanically. Unless a large number of re-entrant angles appear on the fiber surface, a high strength in tension is unlikely. Roughness of the fiber surface may provide strength in shear by supplying a large surface area for increased chemical bonding with the use of surface wetting.

The need to understand the role of the fiber/matrix interface has led to the introduction of additional experimental techniques particularly designed to measure the interfacial shear strength. A fiber pull-out test will allow for the direct measurement of the interfacial shear strength of a fiber/polymer composite (Mader and Freitag, 1990). The interfacial shear strength can be obtained by the equation:

$$\tau_{\rm d} = \frac{F_{\rm d}}{2\pi r_{\rm f} L} \tag{7}$$

where:  $\tau_d$  = interfacial shear strength of the composite  $F_d$  = the debonding load  $r_f$  = the fiber radius L = the embedded length (Mader and Freitag, 1990) The shear-lag analysis is restricted to the case of an elastic fiber and a plastic interface yielding at constant stress.

Compression of fibrous materials will cause fibers to align perpendicular to the orifice of a mold resulting in a random orientation. Randomly oriented short-fiber composites are produced to obtain composites that are isotropic in a plane (Agarwal and Broutman, 1980). Prediction of properties of randomly oriented short-fiber composites is complex. Zadorecki et al. (1986) demonstrated how Tsai and Pagano's equation derived from orthotropic elastic theory can be used to predict the modulus of composites containing fibers that are randomly oriented in a plane:

$$E_{random} = \frac{3}{8}E_{L} + \frac{5}{8}E_{T}$$
 (8)

where:  $E_L$  = longitudinal modulus of the composite  $E_T$  = transverse modulus of the composite

(Zadorecki et al., 1986)

Both moduli must be of an aligned short-fiber composite having the same fiber aspect ratio and fiber volume fractions as the composite under consideration (Zadorecki et al., 1986).

Randomly oriented short-fiber composites are quasiisotropic, that is, having similar mechanical properties in all directions. Therefore, a laminate analysis procedure is utilized to predict the strength of randomly oriented shortfiber composites (Agarwal and Broutman, 1980).

There are no theoretical developments capable of predicting the impact strength enhancement of composites (Bigg et al, 1988). Although impact strength is an important property, factors such as microscale morphological changes in the polymer, caused by the filler, affect the strength of fiber composites (Bigg, 1987). In addition, fiber orientation, fiber aspect ratio, and interfacial adhesion, affect the impact strength of fiber composites (Bigg et al., 1988).

The packing fraction of a filler has a functional influence on the mechanical properties of a composite. Large volumes are occupied by poorly packing fillers, contributing to a reduction in continuity of the matrix in a composite. The packing of random, rigid fibers is extremely poor. Discontinuous short fibers do not pack as well as continuous fibers and their reinforcing efficiencies are only 50-70% of continuous fibers. Packing fractions will remain lower for discontinuous fibers unless the fibers are perfectly parallel and butted end to end (Parratt, 1972). The material packing of rigid fibers depends on their aspect ratio. For threedimensional random fibers, volume concentration is proportional to  $(L/d)^{-2}$ , compared with random fibers in a plane where packing is proportional to  $(L/d)^{-1}$ . The packing of parallel fibers is independent of the aspect ratio (Parratt, 1972).

Since the matrix absorbs the shock of impact, fillers having high packing fractions will tend to decrease impact strength much less at the same filler volume (Katz and Milewski, 1978). Packing fraction is also a determining factor in creep and stress relaxation. Relative packing fraction determines the proportion of free matrix. Therefore, maximum creep resistance can be expected at the maximum packing fraction,  $P_f$ . Creep for composites can be estimated from relative modulus data:

$$\epsilon(t) = \epsilon_1(t) \frac{E_1}{E}$$
 (9)

where:  $\epsilon$  = the creep elongation at any time (t)  $\epsilon_1$  = the corresponding creep of the matrix E = the elastic modulus of the composite  $E_1$  = the elastic modulus of the matrix

(Katz and Milewski, 1978)

Calculations are valid only up to a point when the filler begins to debond from the matrix. At this point, catastrophic failure most likely will occur.

### PRIOR RESEARCH

Wood fiber as a reinforcement for thermoplastic composites is attracting an increasing amount of attention in research laboratories, primarily with the inclusion of dispersants and coupling agents.

Hardwood pulp, in the form of highly bleached cellulose, was added to polypropylene at several concentrations by Bataille, They studied the effects of Ricard and Sapieha (1989). surface pre-treatment of cellulosic fibers and the processing time temperature the cellulose-containing and on polypropylene. Little adhesion was found at high elongation levels between the untreated fibers and polypropylene. Interfacial adhesion improved significantly with the treatment of fibers with coupling agents. Noted was the improvement of adhesion and dispersion of fibers in the matrix with the presence of maleic anhydride modified polypropylene.

Woodhams, Thomas and Rodgers (1984) compared stiffness characteristics of talc, glass, and softwood pulp fiber-filled polyolefins. Softwood pulp fibers in the form of Kraft (bleached and unbleached), mechanical and chemical-mechanical pulps, waste pulps, and reclaimed newspapers were dispersed into high density polyethylene (HDPE) and isotactic polypropylene (PP). Carboxylic dispersion agents were added to aid dispersion. They concluded that the addition of

carboxylic waxes aids dispersion and permits inclusion of 40 to 50 weight-percent wood fibers. Flexural strengths of 70 MPa and flexural moduli of 5 to 6 GPa were obtained for both isotactic PP and HDPE when filled with 40 to 50 weight-percent wood fibers.

Rai. Kokta. Maldas and Daneault (1988) studied the reinforcement of thermoplastics with wood fibers. Aspen chemithermomechanical pulp (CTMP) was dispersed in linear low density (LLDPE) and high density (HDPE) polyethylenes using four different isocyanates as bonding agents. The tensile properties of aspen fiber composites compared favorably with glass and mica fiber reinforced composites. The isocvanate provided significant improvement in mechanical properties (i.e., stress and modulus) for both HDPE and LLDPE composites.

Cellulose in the form of highly bleached hardwood pulp, used as a filler in linear low density polyethylene (LLDPE) and high density polyethylene (HDPE), was examined by Bataille, Allard, Cousin and Sapieha (1990) to determine the mechanical properties. Benzoyl peroxide (BPO) was applied to the cellulose fibers both prior to ("MS" method) and during processing ("DM" method). No significant effect of the various treatments was gained except for the benzoyl peroxide treated composite using method DM. Higher yield strengths were indicated for LLDPE than HDPE, probably due to easier interaction between the polymer chain and other constituents.

Kokta. Maldas, Daneault and Beland (1990) studied the mechanical properties of treated hardwood aspen (chemithermomechanical pulp (CTMP) and sawdust) incorporated into poly(vinyl chloride). The fibers were latex coated or grafted with vinyl monomers, in addition to treatment with coupling agents (e,g., maleic anhydride, obietic acid, and linoleic acid) and various additive dispersants (e.g., stearic acid or anhydrides). Generally, the mechanical properties improved, compared to untreated composites. Grafting of the fibers was most effective. Coupling agents performed better than dispersants, of which linoleic acid was most promising.

Maldas and Kokta (1990) studied the potential of the recycling of polystyrene-hardwood aspen fiber (CTMP) composites. They evaluated the dimensional stability and mechanical properties of the recycled composites and the original polymer. The influence of a coupling agent and various treatments on the properties of the polystyrene-hardwood fiber composite were also studied. They concluded that treated wood-fiber-filled thermoplastic composites offer excellent mechanical properties and dimensional stability under extreme conditions (e.g., exposure to boiling water). Moreover, in comparison to the original composites, the mechanical properties and dimensional stability of the recycled composites did not change
significantly even after exposure to extreme conditions.

Henequen fibers as a reinforcing element with waste polyethylene (PE) were formed into a panel and examined by Ramirez and Solis (1984) to determine the physical and mechanical properties for comparison with properties of commercial panels. The waste PE was recovered from waste films from packing. River sand in the form of feldspar and quartz was added to the matrix to increase environmental resistance (e.g., ultraviolet (UV) light). Ramirez and Solis concluded that the composite material had good mechanical and physical properties and an increase in environmental resistance by about 1000% with the incorporation of sand. In addition, the fibers did not degrade in the molding process, sustaining their inherent mechanical properties.

Zadorecki and Michell (1989) examined the future use of cellulose wood fibers as reinforcements in synthetic organic polymers to form composites. Wood cellulose proposed as reinforcement was in the form of wood fibers, cellulose fibers, microfibrillar, and microcrystalline cellulose. Zadorecki and Michell concluded that more sophisticated processing will be required bringing together the separation of fibers and the formation of the polymers, if full potential of the reinforcement is to be achieved. Furthermore, in the commodity field it is expected that cellulose fiberthermoplastics with coupling agents will be introduced commercially, to compete with mineral filled polymers.

Composites prepared by Hua, Zadorecki and Flodin (1987) involved combining unsaturated polyester and surface treated cellulose as a reinforcing material. Formaldehyde and dimethylolmelamine (DMM) were used as surface treatments for cellulose fibers in the form of bleached kraft paper. The experimental design utilized five treatments. Tensile strength and the elongation of the cellulose fibers were determined in dry and wet conditions along with the tensile strength and modulus of the cellulose-polyester composites. DMM was found to be an effective surface modifying agent for cellulose fibers. An improvement by more than 50% was achieved in the wet strength of the composite, along with a reduction of water uptake (46 to 52 percent) by the composite.

Lightsey, Short and Sinha (1977) tested pulp mill residue as a filler for low density polyethylene (LDPE) and polystyrene (PS) to form composites using a Brabender Rhomex extruder. Kraft pulp mills in Georgia, Florida, and Louisiana supplied the wood pulp residue, the major species being southern yellow pine (loblolly and slash pine). They concluded that the tensile strength and modulus of the composites containing wood residue are only slightly greater than composites filled with wood flour. Bonding between the polystyrene matrix and the filler was weak.

The effect of alkali treatment on the surface adhesion of sisal fibers to polyester resin was examined by Navin and Rohatgi (1986). Retted sisal fibers from Bhopal, India were soaked in an aqueous solution of NaOH (5 wt%) for various time periods. Alkali treatment significantly increased wettability of the surface of sisal fibers with polyester resin. In addition, Navin and Rohatgi found that alkali treatment of sisal fibers for 90 hours resulted in adhesion with polyester and an increase in tensile strength.

Aspen hardwood fibers in the form of TMP, used as a filler in high density polyethylene (HDPE), was examined by Gogoi (1989) to determine the mechanical properties. Gogoi also studied the effect of fiber pretreatment, screw configuration, and compounding temperature on the mechanical properties of the composite. Gogoi found that the screw configuration which has the longest mixing time imparts the best overall strength, although it produces maximum damage to the fibers. Gogoi also concluded better adhesion to acetylated and untreated fibers than to heat-treated fibers at 30 percent fiber concentration.

Keal (1990) studied the effect of combining two additives with high density polyethylene (HDPE) and 30 weight-percent aspen wood fibers. The additives studied were stearic acid, a

dispersing agent; ionomer modified polypropylene; and maleic anhydride modified polypropylene, both to increase interfacial bonding. No significant improvement was gained by the combination of additives as compared to the use of one additive, except for modulus of elasticity. In addition, Keal concluded that the use of additives improved properties, except impact strength.

## EXPERIMENTAL

## <u>Materials</u>

## **Thermoplastics**

The material used for the matrix was primarily a polypropylene random copolymer (Fortilene<sup>®</sup>4104) in the form of regrind from multi-layer squeezable ketchup bottles. Regrind was chosen as a representation of post consumer waste. The regrind was in granulated form, made from containers recycled in the closed loop manufacturing operation. The container has four primary layers bound with two adhesive layers to ensure product quality. The layers consist of polypropylene, ethylene vinyl alcohol, adhesive, and regrind (PP/tie/EVOH/tie/regrind/PP).

Polypropylene random copolymers are a type of polypropylene in which the basic structure of the polymer chain has been changed by the incorporation of a different monomer molecule, in this case, an ethylene comonomer is used. The physical properties of the PP are changed providing an improvement in optical properties, improved impact resistance, increased flexibility, and a decreased melting point (Walsh, 1990). Yet, the same chemical resistance, water barrier properties, and organoleptic properties as PP homopolymers are preserved.

Random copolymer PP typically contains between 99 to 93 wt.-% of propylene molecules and 1 to 7 wt.-% of ethylene molecules (Walsh, 1990). Ethylene/propylene random copolymers are produced in the same reactors used to produce homopolymer PP by the simultaneous polymerization of propylene and ethylene molecules.

Random copolymers are usually more flexible than homopolymer PP with flexural modulus values (secant at 1% strain) ranging from 70,000 to 150,000 psi, compared to 150,000 to 200,000 psi for homopolymers. Table 1 provides a summary of mechanical properties of the Fortilene<sup>®</sup>PP used in this experiment.

#### Table 1. Properties of Fortilene PP (Solvay, 1990).

Density (g/cc)	0.898
Melt Flow Index <sup>1</sup> (g/10 min)	1.7
Tensile Strength at Break (psi)	3900
Elongation at Break (%)	550
Tensile Modulus <sup>2</sup> (psi)	97,000
Flexural Modulus <sup>2</sup> (psi)	130,000
Notched Izod Impact Strength (ft-lbf/in)	0.8

<sup>1</sup> 230°C/2160 g <sup>2</sup> Secant at 1% strain

Ethylene Vinyl Alcohol (EVOH) is a semi-crystalline polymer formed by hydrolyzed copolymers of vinyl acetate and ethylenes. The resulting EVOH copolymer is an atactic polymer with the following molecular structure (Fig. 1).

## Fig. 1. Molecular structure of EVOH (Foster, 1987).

EVOH is hydrophilic and will absorb moisture due to the presence of hydroxyl groups (-OH) in the molecular structure. Moisture absorbed material becomes plasticized and hydrogen bonding is reduced, thereby increasing chain mobility in the amorphous regions. The EVOH used in the multi-layer ketchup bottle is Grade EP-F 101 (EVAL<sup>®</sup>Solarnol DC, EVALCA) with a density of 1.19 g/cc and a melting point of 181°C (Foster, 1987). EVOH has high mechanical strength, elasticity, surface hardness, good abrasion resistance, and excellent weatherability.

Specialty designed adhesive resins (tie resins) are used due to the poor adhesion between the EVOH and PP resins. The trade name of the adhesive used in the production of the multi-layer ketchup bottle is Admer<sup>®</sup> (Mitsui Monoply MT38) manufactured by Mitsui Petrochemical Industries, Ltd.

EVOH resin contained in the ketchup bottle is recovered and reused as a layer of regrind due to economic reasons. The percent of regrind used varies depending on the amount of trim

and scrap produced. The coextruded ketchup bottle contains almost 95 weight-percent PP with the remainder of the structure containing EVOH and adhesive (Table 2).

Table 2. Ketchup bottle multi-layer structure (weight %).Resin MaterialWeight Percent

Random Copolymer PP (Fortilene <sup>®</sup> 4101, Solvay)	94.50
EVOH (EVAL Solarnol DC, EVALCA)	3.75
Adhesive (Admer <sup>®</sup> , Mitsui Monoply MT38)	1.75

## <u>Filler</u>

Hardwood aspen (Populus Tremuloides, Michx), in the form of thermomechanical pulp (TMP) was supplied by Lionite Hardboard, Phillips, Wisconsin. The hardwood fiber was produced using the pressurized refiner process. In this process, wood chips are softened by a digester at about 100 p.s.i. of steam pressure for 3 to 5 minutes, to help equalize chip moisture content. The wood chips are then ground into fiber using a In the refiner, the chips are forced Bauer 418 refiner. between two oppositely rotating grinding blades. Exiting the blades, the wood pulp is then blown continuously through a Heil flash tube dryer (40 in. diam. x 150 ft.) at an entrance temperature of 475°F. In the dryer, the fiber is suspended for ~ 20 seconds and exits at temperature of 175°F, with a moisture content of ~ 7%. The pulp yield is about 95% with insignificant modification and removal of the lignin. The

majority of the fibers are separated with slight damage (i.e., exposure of secondary wall surface).

Wood is a composite material containing three major polymers: 1) cellulose, 2) hemicellulose, and 3) lignin, which serve as the skeletal, matrix, and encrusting substances, respectively (Schniewind, 1989).

Cellulose is a polydisperse linear syndiotactic organic polymer with the basic monomeric unit D-glucose (Fig. 2). D-glucose links through a glycosidic bond in the beta configuration between carbon 1 and carbon 4 of adjacent units forming long-chain 1,4-B-glucans. Each monomeric unit within the cellulose chain has three hydroxyl groups, specifically two secondary and one primary hydroxyl group (Schniewind, 1989). The cellulose fiber is made up of 55-75% crystalline and 25-45% amorphous regions. In the amorphous regions, the hydroxyl groups are highly accessible and readily reactive in all chemical reactions. The crystalline regions are not readily accessible to reactant molecules, and it is the crystalline nature of cellulose that provides strength and stiffness. Cellulose is a hydrophilic polymer (it absorbs water readily and swells), although swelling is limited to the amorphous regions of the fiber.



Fig. 2. Chain formulas of cellulose and xylan (Browning, 1963).

The hemicellulose is linear polysaccharides that are displayed continuously with cellulose and lignin in plant cell walls. Xylan is the predominant hemicellulose in hardwood comprising of 20-30% of the wood substance. Hardwood xylans consist of a main chain with random side chains along the backbone (Fig. The main chain is made up of 1,4-linked B-D-xylopyranose 2). residues, some transporting a single terminal 4-O-mythyl- $\alpha$ -Dglucuronic acid unit attached to C-2 (Schniewind, 1989). Additionally, an average of seven acetyl groups per ten xylose units are attached to either C-2 or C-3. Hardwood xylans are amorphous in their natural state. In addition to xylan, hardwoods also contain less than 5% of a glucomannan, composed B-D-glucopyranose and B-D-mannopyranose 1,4-linked of residues (Schniewind, 1989).

The third important component of the cell wall is lignin. Wood lignins are predominantly aromatic and almost totally insoluble in solvents, not hydrolyzable to monomeric units, and devoid of the highly regular structure so characteristic of other natural polymers (Browning, 1963). Lignin is composed of phenylpropane units that encrust the intercellular space of the cell wall. Most hardwoods contain 22-28% of lignin. Hardwoods have a quiacylsyringyl lignin with one or two methoxyl groups (Schniewind, 1989). Of the total amount of lignin present, 20-25% occurs mainly in the intercellular region and primary wall, while the cell wall contains 75-80%. Lignin concentration varies from 50-100% in the middle lamella-primary wall to 20-25% in the secondary wall (Schniewind, 1989). Lignin is completely amorphous and softens at temperatures of 165-175°C under normal conditions (Bodig and Jayne, 1982). Browning (1963) lists the components of Trembling aspen (Populus tremuloides) in percent of extractive-free wood (Table 3).

Table 3. Composition of Trembling aspen (percent of extractive-free wood (Browning, 1963).

Species	Glucan	Hannan	Galactan	Xylan	Arabinan	Uronic anhydride	Acetyl	Lignin	Ash	
Trembling aspen (Populus tremuloides)	57.3	2.3	0.8	16.0	0.4	3.3	3.4	16.3	0.2	

The structure of a cellulose fiber consists of (1) a primary wall (~0.1 $\mu$  thick) containing mostly noncellulosic substances (i.e., waxes and pectin), (2) a secondary wall (~4 $\mu$  thick) which contains almost all the cellulose present in the fiber along with a considerable amount of lignin, and (3) the lumen, which is the hallow center of the fiber cell (Browning, 1963). Three distinct layers (S<sub>1</sub>, S<sub>2</sub>, S<sub>3</sub>) are almost always present in the secondary wall with the S<sub>2</sub> layer being the most extensive of the three (Bodig and Jayne, 1982).

Hardwoods are composed of fibers which are threadlike cells accompanied by larger-diameter vessels and short parenchyma cells (rays). The fibers provide mechanical support while the vessels are the main channel of fluid transportation, and the parenchyma cells are for food storage (Bodig and Jayne, 1982). In aspen hardwood, like other hardwoods, fibers and vessels are the most abundant type. Browning (1963) provides the cell type proportions and fiber dimensions of Quaking aspen (Populus tremuloides Michx) (Table 4).

	Portion of Ce	lle nercent		-	ons	
	Vessels	Fibers	Rays	Vessel length Avg., mm	Fiber length Avg., mm	Fiber diameter range #
Quaking aspen	33.8	55.1	11.1	0.67	1.04	10 - 27

# Table 4. Cell type proportions and fiber dimensions (Browning, 1963).

(Populus tremuloides Nichx)

# <u>Methods</u>

#### Composition

This experiment is comprised of eight treatments in terms of material composition, two of which were pure polymer material (100%). Aspen wood fiber was incorporated into the remaining six matrix materials at concentration levels of 30, 40, and 50 percent by weight. The exact wood fiber-matrix content is presented in Table 5. (See Table 17, Appendix A for actual material used by weight.) The wood fibers were air-dried in ambient conditions (23°C, 50% RH) until reaching moisture equilibrium.

Treatments	Composite	Wood Fiber (%)	Matrix (%)
	30% Fiber Level		
1	- Virgin PP	30.80	69.20
2	- PP Reclaim	24.66	75.34
	40% Fiber Level		
3	- Virgin PP	40.41	59.59
4	- PP Reclaim	38.66	61.34
	50% Fiber Level		
5	- Virgin PP	52.44	47.56
6	- PP Reclaim	51.44	48.56
. 7	100% Virgin PP		100.00
8	100% PP Reclaim		100.00

Table 5. Actual composite contents by weight-percent.

Note: For actual material used by weight refer to Appendix A.

The virgin PP resin was made into plates approximately 0.0625 in. thick and granulated with a BTP Granulator Model 68 SPL (Polymer Machinery, Berlin, CT) to achieve an equal density and friction as the PP Regrind. Like densities were important to produce similar fiber to polymer ratios, since feed rates could not be altered sufficiently to allow for the dissimilar frictions.

#### Compounding

A Baker-Perkins Model MPC/V-30 DE, 38mm, 13:1 intermeshing self-wiping corotating twin-screw extruder (Baker-Perkins, Saginaw, MI) was used to mix the polymer and wood fibers. The temperature of the feeder, transition, and metering zones of the extruder was 185°C. The compounder speed was 100 rpm. The polymer feed rate and subsequent average load percent varied for each of the fiber concentrations. The polymer was added at the feeder zone while the wood fibers were added at an open port in the transition zone. The extruded material was allowed to cool to room temperature and then was compression molded into plates approximately 0.125 in thick using a Carver Model M 25 Ton laboratory press (Fred S. Carver, Inc., Menomonee Falls, MI). Plates were made using three lengths of material. The mold was heated at 185°C platen temperature for 15 min under pressure (30,000 psi), and then cooled down under pressure to a temperature of ~50°C by circulating cold water for about 10 min in the press.

Specimens for tensile, impact, flexural modulus, creep, and water adsorption were made according to ASTM standards (ASTM, 1988).

#### <u>Specimens</u>

Molded plates were cut into tensile and creep specimens (Type I dumbbell shape with a ~2 in. gauge length) using a Tensilkut Model 10-13 specimen cutter (Tensilkut Engineering, Danbury, Creep specimens were cut parallel to the direction of CT). the extrudate (lengthwise). Flexural modulus samples were cut into 6.0 in. x 0.5 in. x 0.125 in. bars using a band saw. Impact specimens were cut into 2.5 in. x 0.5 in. x 0.125 in. bars and notched using a TMI Notching Cutter Model TMI 2205 Tensile Machines, Inc., Amityville, NY). The specimens for tensile, impact, and flexural modulus were made in both lengthwise and crosswise direction to the extrudate to study the effects. Specimens used for the water absorption test were cut by a circular drill bit. Vernier callipers were used for measurements of composite specimen dimensions.

#### <u>Conditioning</u>

The specimens were conditioned at standard laboratory atmosphere (23°C, 50% RH) for 40 h using Procedure A of ASTM D618-61: Conditioning Plastics and Electrical Insulating Materials for Testing (ASTM, 1988), prior to testing. Air circulation was provided on all sides of each specimen.

## Testing

Tensile strength, tensile modulus, and elongation at break were measured using an Instron Tester Model 4201 (Instron, Canton, MA), following ASTM D 638-87b: Tensile Properties of Plastics (ASTM, 1988) at ambient conditions (23°C, 50% RH). The rate of elongation was 2 in/min., gauge length was 3.5 in, and full scale load was 500 lbs. Sandpaper was lodged between specimen and grips to deter slippage. The average of five measurements was used to report mechanical properties.

Flexural modulus was tested using Method I, Procedure A of ASTM D790-86: Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials (ASTM, 1988) on a electromechanical test frame fitted with a 20 lb. load cell (United Testing System, UTS). Crosshead speed was 1.00 in/min, support span length was 4.0 in, and a 16:1 spanto-depth ratio was used. The average of five measurements was used to report the tangent modulus of elasticity.

Impact strength was tested using Method A (Izod Type) of ASTM D256-87: Impact Resistance of Plastics and Electrical Insulating Materials (ASTM, 1988). Fracture energies were determined using a TMI 43-1 Izod Impact Tester (Testing Machines, Inc., Amityville, NY) with a 5 ft-lb. pendulum load. The average of eight measurements was used to report Izod impact strength.

Water sorption was determined using a 2-h boiling water procedure of ASTM D570-81: Water Absorption of Plastics (ASTM, 1988). Moisture gain was reported as an average of three measurements.

For creep extension ASTM D 2990-77: Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics (ASTM, 1988) was used. Weights (50-1b) were attached to the bottom of the end grips. Measurements were made at set time intervals up to 500 hours. Creep extension was measured by grip separation and was tested in ambient (23°C, 37% RH) and extreme (37°C, 92% RH) conditions. Extension was reported as an average of two samples and is suggestive rather than conclusive.

MSTAT statistical program (version 5.0, Michigan State University, 1988) was used to perform statistical analyses for tensile strength, elongation at break, tensile modulus, flexural modulus, and Izod impact strength. The following statistical analyses were performed:

- A two-way analysis of variance to specify any statistically significant variable effects.
- A one-way analysis of variance and orthagonal contrasts to determine if the compared variables are statistically significant.

#### RESULTS

A two-way analysis of variance was performed for the tensile test, Izod impact test, and flexural modulus to determine any significance between the means, at an alpha level of .05. Also, a one-way analysis of variance with accompanying orthagonal comparisons was performed to determine any significance between variable means (Table 37, Appendix C). The results from these statistics can be found in Appendix C.

## Tensile Test

Tensile strength results are located in Table 6. The fiber content for each matrix material was tested parallel (lengthwise) and perpendicular (crosswise) to the extrudate, providing a total of 12 variables. In addition, the matrix materials were tested parallel to the extrudate. Each variable had five replications for a total of 70 samples. Tensile strength data are located in Table 19 of Appendix B. The samples in the lengthwise direction for each matrix and fiber content, exhibited significantly higher tensile strength compared to the crosswise fiber direction of the extrudate.

Results for percent elongation are located in Table 7. Data for percent elongation are located in Appendix B, Table 20.

Var.		Fiber		
No.	Material	Direction	Mean	SD
1.	30% Wood fiber-PP	lengthwise	3100.8	307.9
2.	30% Wood fiber-PP Reclaim	lengthwise	3469.5	332.2
3.	30% Wood fiber-PP	crosswise	2059.1	77.7
4.	30% Wood fiber-PP Reclaim	crosswise	2522.8	187.5
5.	40% Wood fiber-PP	lengthwise	2848.7	628.7
6.	40% Wood fiber-PP Reclaim	lengthwise	2835.6	684.6
7.	40% Wood fiber-PP	crosswise	1803.2	187.5
8.	40% Wood fiber-PP Reclaim	crosswise	1619.4	58.0
9.	50% Wood fiber-PP	lengthwise	2259.8	225.1
10.	50% Wood fiber-PP Reclaim	lengthwise	2375.9	453.6
11.	50% Wood fiber-PP	crosswise	1355.7	105.3
12.	50% Wood fiber-PP Reclaim	crosswise	1238.7	190.4
13.	100% PP		2619.2	173.3
14.	100% PP Reclaim		2397.7	102.6

Table 6: Tensile strength at break  $(lb/in^2)$ .

Table 7: Percent elongation at break (%).

Var.	Vatarial	Fiber	Meen	
NO.	Material	Direction	Mean	80
1.	30% Wood fiber-PP	lengthwise	7.39	0.87
2.	30% Wood fiber-PP Reclaim	m lengthwise	11.44	1.11
3.	30% Wood fiber-PP	crosswise	5.36	0.38
4.	30% Wood fiber-PP Reclaim	m crosswise	7.61	1.23
5.	40% Wood fiber-PP	lengthwise	7.39	0.82
6.	40% Wood fiber-PP Reclaim	m lengthwise	5.88	0.82
7.	40% Wood fiber-PP	crosswise	4.14	0.82
8.	40% Wood fiber-PP Reclaim	m crosswise	3.52	0.31
9.	50% Wood fiber-PP	lengthwise	3.78	0.61
10.	50% Wood fiber-PP Reclaim	m lengthwise	3.93	0.96
11.	50% Wood fiber-PP	crosswise	2.76	0.56
12.	50% Wood fiber-PP Reclaim	m crosswise	2.34	0.25
13.	100% PP		689.40	269.50
14.	100% PP Reclaim		214.60	43.29

Samples with low fiber content exhibited longer percent elongation at break. Overall, samples in the lengthwise fiber direction showed significantly higher elongation when compared to the crosswise direction, for both matrices.

Young's modulus of elasticity for each of the variables are located in Table 8. Tensile modulus of elasticity data are located in Table 21 of Appendix B. An increase in fiber content increased the modulus in both directions. Overall, the samples in the lengthwise fiber direction displayed significantly higher tensile modulus when compared to the crosswise direction of the extrudate. Also, tensile modulus was significantly higher for each fiber content of the PP-wood fiber composite in both directions, compared to the PP Reclaim-wood fiber composite.

Table of tound 2 modulus of gradetorel (this is )	Table	8:	Young's	modulus	of	elasticity	$(lb/in^2)$ .
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Var.					Fiber		
No.	Ma	teria	L		Direction	Mean	SD
1.	30%	Wood	fiber-PP		lengthwise	98054	3088
2.	30%	Wood	fiber-PP	Reclaim	lengthwise	63186	4513
3.	30%	Wood	fiber-PP		crosswise	85284	4114
4.	30%	Wood	fiber-PP	Reclaim	crosswise	59495	5998
5.	40%	Wood	fiber-PP		lengthwise	101226	2514
6.	40%	Wood	fiber-PP	Reclaim	lengthwise	77269	7993
7.	40%	Wood	fiber-PP		crosswise	93732	11525
8.	40%	Wood	fiber-PP	Reclaim	crosswise	63583	7822
9.	50%	Wood	fiber-PP		lengthwise	119044	16053
10.	50%	Wood	fiber-PP	Reclaim	lengthwise	84300	8438
11.	50%	Wood	fiber-PP		crosswise	110116	6463
12.	50%	Wood	fiber-PP	Reclaim	crosswise	72884	6130
13.	100	t PP				48842	6044
14.	1009	t PP I	Reclaim			51608	2432

## Flexural Test

Flexural modulus results are shown in Table 9. Five replications of the tangent modulus in bending were calculated to find the variable mean, for a total of 70 samples. Data from the flexural modulus test are located in Table 22 of Appendix B. The samples in the lengthwise direction showed significantly higher flexural modulus compared to the crosswise direction of the extrudate. Additionally, flexural modulus was significantly higher in the lengthwise direction for the PP Reclaim-wood fiber composite at 40% and 50% fiber content, when compared to PP-wood fiber composite.

Table 9: Flexural modulus  $(ft/in^2)$ .

Var.	· · · · · · · · · · · · · · · · · · ·	Fiber	<u> </u>	
No.	Material	Direction	Mean	SD
1.	30% Wood fiber-PP	lengthwise	381566	70145
2.	30% Wood fiber-PP Recla	im lengthwise	302778	18038
3.	30% Wood fiber-PP	crosswise	249337	26751
4.	30% Wood fiber-PP Recla	im crosswise	283459	17988
5.	40% Wood fiber-PP	lengthwise	349872	40062
6.	40% Wood fiber-PP Recla	im lengthwise	449102	48934
7.	40% Wood fiber-PP	crosswise	334162	43930
8.	40% Wood fiber-PP Recla	im crosswise	319691	30121
9.	50% Wood fiber-PP	lengthwise	409282	24709
10.	50% Wood fiber-PP Recla	im lengthwise	459342	58922
11.	50% Wood fiber-PP	crosswise	341608	29396
12.	50% Wood fiber-PP Recla	im crosswise	358206	9043
13.	100% PP		326106	23180
14.	100% PP Reclaim		195648	18566

## Impact Test

Eight replications of the Izod impact testing were calculated to find the variable mean for a total of 112 samples. Izod impact testing results are located in Table 10. Data from the Izod impact test are located in Appendix B, Table 23. Overall, the samples in the lengthwise direction displayed significantly higher impact strength compared to the crosswise direction of the extrudate, excluding the 30% wood fiber-PP Reclaim composite. In addition, impact strength was significantly higher in the lengthwise direction of the 30% wood fiber-PP composite compared to the 30% wood fiber-PP Reclaim composite in the lengthwise direction.

Var.					Fiber	<u></u>	
No.	Ma	teria	1		Direction	Mean	SD
1.	308	Wood	fiber-PP		lengthwise	1.005	0.13
2.	30%	Wood	fiber-PP	Reclaim	lengthwise	0.788	0.11
3.	30%	Wood	fiber-PP		crosswise	0.748	0.08
4.	30%	Wood	fiber-PP	Reclaim	crosswise	0.799	0.08
5.	40%	Wood	fiber-PP		lengthwise	1.049	0.11
6.	40%	Wood	fiber-PP	Reclaim	lengthwise	1.145	0.07
7.	40%	Wood	fiber-PP		crosswise	0.831	0.18
8.	40%	Wood	fiber-PP	Reclaim	crosswise	0.870	0.07
9.	50%	Wood	fiber-PP		lengthwise	1.007	0.10
10.	50%	Wood	fiber-PP	Reclaim	lengthwise	1.043	0.04
11.	50%	Wood	fiber-PP		crosswise	0.930	0.28
12.	50%	Wood	fiber-PP	Reclaim	crosswise	0.964	0.07
13.	100	t PP				0.525	0.12
14.	1009	% PP I	Reclaim			0.641	0.12

Table 10: Izod impact strength (ft.lb/in).

#### Creep Test

Two replications were averaged for each variable in the parallel (lengthwise) direction of the extrudate, for each of the environmental conditions, for a total of 32 samples. Creep extension was reported as an average of two samples. Results after 500 hours are located in Table 11. Creep extension data for both ambient and extreme conditions are located in Table 24 and Table 25 of Appendix B, respectively. Creep extension results are displayed graphically for each environmental condition (Figures 3 and 4).

Matrix and Co	r ondition	No Fiber	Increase 30% Fiber	in Length 40% Fiber	(in) 50% Fiber
Ambien	at				
Pl	P	0.056	0.024	0.027	0.026
PI	P Reclaim	0.041	0.018	0.014	0.018
Extre	ne				
PI	P	0.126	0.094	0.181	
PI	P Reclaim	0.121	0.106	0.076	0.076

Table 11. Effect of fiber content on creep extension (500 h).

NOTE: 50% wood-PP samples failed in extreme cond. after 20 h.

Creep extension did not level off after 500 h for any one of the variables.

Creep Extension - Ambient Conditions.







Creep Extension - Extreme Conditions.





#### Water Absorption

Water sorption results for 8 variables are located in Table 12. Weight gain data from three replications were averaged for each variable, for a total of 24 samples. Data from the test are located in Appendix B, Table 26. Water sorption increased linearly with an increase in wood fiber content.

Table 12. Water absorption test (%).

Var. No.	Composite Material	Mean	SD
1.	30% Wood Fiber-PP	1.65	0.05
2.	30% Wood Fiber-PPR	1.41	0.07
3.	40% Wood Fiber-PP	2.79	0.25
4.	40% Wood Fiber-PPR	2.36	0.15
5.	50% Wood Fiber-PP	3.76	0.18
6.	50% Wood Fiber-PPR	3.88	0.78
7.	100% PP	0.10	0.01
8.	100% PPR	0.24	0.01

ASTM D570 - 81, 2-hr Boiling Water Immersion Test was used.

## **Results Summary**

Overall, both PP-wood fiber composites tested parallel (lengthwise) to the extrudate displayed significantly higher mechanical test results compared to the samples tested perpendicular (crosswise) to the extrudate. The virgin PPwood fiber composite showed significantly higher results in both percent elongation at break and tensile modulus. The PP Reclaim-wood fiber composite displayed a significantly higher Izod impact strength and flexural modulus. Creep extension was more pronounced in the virgin PP-wood fiber composite, particularly in extreme environmental conditions. Water absorption increased with an increase in fiber content.

## Linear Regression

A linear regression was performed for each mechanical test to obtain the slope of the line (excluding creep and water absorption). This could be used to predict a resulting property value, given an appropriate wood fiber concentration (i.e., less than 50% wood fiber). The mechanical tests demonstrating a good line fit (i.e., an R value ~1.0) are located in Table 13, with the corresponding equations located in Appendix A, Table 18.

#### Table 13. Linear Regression.

Mechanical Test	R Value	
Izod Impact Strength - PP Crosswise	0.998	
Izod Impact Strength - PPR Crosswise	0.997	
Tensile Strength - PP Crosswise	0.967	
Tensile Modulus - PP Crosswise	0.998	
Tensile Modulus - PPR Crosswise	0.954	
Tensile Modulus - PP Lengthwise	0.979	
Tensile Modulus - PPR Lengthwise	0.976	
Flexural Modulus - PPR Crosswise	0.995	
Flexural Modulus - PPR Lengthwise	0.941	

NOTE: Equations for the slope of each line above can be found in Appendix A, Table 18.

#### DISCUSSION

#### Tensile Strength

Tensile strength as a function of wood fiber content and fiber orientation is shown in Figure 5. The tensile strength of both composite structures increased at 30% fiber content. Tensile strength for the PP Reclaim-wood fiber composite is comparable in value to a composite comprised of 30% CTMP and PP with addition of PP-maleated propylene wax (3% by weight of polymer) as a coupling agent (Raj et al., 1989). Although strength decreased steadily after 30% fiber content with the increase in filler concentrations for both composite structures in both directions, the EVOH and adhesive contained in the PP Reclaim may be contributing as coupling agents.

Although the tensile strength of a composite is strongly dependent on the degree of adhesion between the fibers and the matrix, it is difficult to predict. Bigg (1987) described an upper and lower bound response to tensile strength and empirical formulas associated with each bound for predicting the tensile strength of the composite. The lower bound response assumes weak or no adhesion between the polymer and filler, while the upper bound response assumes strong adhesion between the two materials. The formulas (not shown) can be

Tensile Strength at Break.



TENSILE STRENGTH AS A FUNCTION OF WOOD FIBER CONTENT AND **ORIENTATION.** FIGURE 5.

used to predict tensile strengths for composites made with fillers which provide partial or limited reinforcement (i.e., spherical particles, metallic fillers, talc, and mica flakes). In comparison, fibers are able to support stresses transferred from the polymer and quantitative information from simple experiments can be obtained.

## Percent Elongation

Percent elongation at break as a function of wood fiber content and orientation is presented graphically in Figure 6. Elongation values for the PP Reclaim-wood fiber composite in both lengthwise and crosswise direction were much higher at 30% fiber content than for the PP-wood fiber composite. In comparing the 30% wood fiber-PP Reclaim composite in the lengthwise direction with that of a composite produced from 30% CTMP and PP (Raj et al., 1989), the PP Reclaim composite exhibits a 300% higher elongation value. This high elongation value is not the outcome one would expect from a ductile matrix such as PP. In addition, as fiber content increased, both composite structures show decreased elongation values.

Since elongation is one dimension of volume, Katz and Milewski (1978) describe elongation as a cube root of volume, accordingly:

$$\epsilon_{\rm c} = \epsilon_{\rm m} \left[ 1 - \left( \frac{V_{\rm f}}{P_{\rm f}} \right)^{1/3} \right]$$
(10)

where 
$$\epsilon_c$$
 = Elongation of the composite  
 $\epsilon_m$  = Elongation of the matrix  
 $P_f$  = Maximum volumetric packing filler fraction  
 $V_f$  = Fraction filler volume  
(Katz and Milewski, 1978)

This formula does not consider several factors such as Poisson's ratio of the matrix, Einstein's coefficient of the filler, adhesion of the matrix to the filler, and possibly, <u>Tg</u> of the matrix (Katz and Milewski, 1978).

Since the composites tested exhibit large concentrations of wood fiber, the fibers are less capable of moving with the matrix, and accordingly, the matrix is not free to stretch around them. Additionally, very weak interfacial bonding causes almost immediate separation of the matrix from the fiber (Katz and Milewski, 1978).







# Tensile Modulus

Young's modulus as a function of fiber concentration and orientation appears in Figure 7. Tensile modulus increased with an increase in fiber concentration except for the PP-wood fiber composite in the crosswise direction at 50% fiber content. Tensile modulus results are much lower than values found by Raj et al. (1989), at wood fiber concentrations of 30% and 40%. Their CTMP-PP composites exhibited tensile moduli over 200,000 psi for both wood fiber concentrations.

Changes in composite stiffness, as measured by tensile modulus, are more dependent upon fiber length than fibermatrix adhesion (Crosby and Drye, 1986). Short-fibers, like the hardwood aspen fibers used in this study, have a relatively small fiber aspect ratio (1/d).

#### Table 14. Physical and mechanical properties of aspen fiber.

Young's Modulus	Avg. Fiber Length	Avg. Fiber Diameter
3.654 10 <sup>6</sup> psi	1.04 mm	0.010 - 0.027 mm

Note: Length and diameter can be found in Table 4. of the Materials section (Browning, 1968) and Young's modulus is an engineering elastic constant for undegraded microfibrillar cellulose (Schniewind, 1989).

Data from Table 14 may be used to calculate the theoretical modulus values of the resulting composite structures for any volume of fiber using the empirical equation for composites Young's Modulus of Elasticity.




containing fibers randomly oriented in a plane:

where

where

where

$$E_{random} = \frac{3}{8} E_{L} + \frac{5}{8} E_{T}$$
(11)  

$$E_{L} = E_{m} \frac{1 + \left(2 \frac{1}{d}\right) \eta_{L} V_{f}}{1 - \eta_{L} V_{f}}$$

$$E_{T} = E_{m} \frac{1 + 2 \eta_{T} V_{f}}{1 - \eta_{T} V_{f}}$$

$$\eta_{L} = \frac{\left(\frac{E_{t}}{E_{m}}\right) - 1}{\left(\frac{E_{t}}{E_{m}}\right) + \left(2 \frac{1}{d}\right)}$$

$$\eta_{T} = \frac{\left(\frac{E_{f}}{E_{m}}\right) - 1}{\left(\frac{E_{f}}{E_{m}}\right) + 2}$$

$$E_{f} = Modulus \text{ of the fiber}$$

$$E_{m} = Modulus \text{ of the matrix material}$$

$$V_{f} = Volume \text{ fraction of fiber}$$

$$\frac{1}{d} = \text{Length and diameter of the fiber}$$

$$(Agarwal and Broutman, 1980)$$

Calculating  $E_{R}$  using the aforementioned empirical formulas results in the following tensile moduli (Table 15).

Com	posite Structure	Theoretical Value (PSI e+03)
30%	PP	330 - 411
30%	PP Reclaim	340 - 419
408	PP	451 - 552
40%	PP Reclaim	463 <del>-</del> 562
50%	PP	592 <del>-</del> 708
50%	PP Reclaim	607 - 720

Table 15. Theoretical tensile moduli for the tested composite structures.

Although the theoretical tensile moduli represent composites containing randomly oriented fibers, the resulting values are more in-line with those obtained by Woodhams et al. (1984) and Raj et al. (1989). The percentage difference in flexural and tensile moduli is not usually as large as the difference in strength values, although a true correlation between flexural properties and other mechanical properties has never been established (Katz and Milewski, 1978).

#### Flexural Modulus

The flexural modulus for the PP Reclaim-wood fiber composite increased with increasing fiber content and the PP-wood fiber composite showed varying results (Figure 8). During the application of load, one face of the sample is under compression and the other face is in tension, and the failure of fiber-reinforced composites normally occurs on the tension side (Katz and Milewski, 1978). Tangent Modulus of Elasticity.





The highest flexural modulus values were achieved in the PP Reclaim-wood fiber composite (lengthwise) at both 40% and 50% fiber content, compared to the PP-wood fiber composite at the same fiber content and orientation.

In comparing the resulting flexural modulus of 40% wood fiber-PP Reclaim (lengthwise) with that of 40% hardwood-PP studied by Woodhams et al. (1984), the PP Reclaim composite is 28% lower. This was probably due to their use of unmodified PP and/or wax processing aids in the experiment.

Flexural strength was not calculated although flexural moduli values may be an indication of the outcome. If so, it can be argued that an increase in flexural strength for the PP-Reclaim composite, in comparison to the PP composite, would be due to the sub components (EVOH and adhesive) acting as coupling agents. Parratt (1972) states that coupling agents have three main effects in resin composites:

1. Longer retention of strength under wet conditions,

- 2. Increased flexural strength,
- 3. Increased tensile strength (much rarer).

In addition, it could be argued that these effects may be due to a more complete penetration of the fibers when wetted by the resin in the presence of a coupling agent (Parratt, 1972).

#### Impact Strength

Izod Impact strength (notched) generally increased with an increase in the fiber concentration for both composites (Figure 9). The higher impact strength value may be attributed to fiber bonding at the interface. The observance of lower impact strength values with addition of fibers described by Raj et al. (1989) and by Woodhams et al. (1984) is a contrasting behavior, and can be attributed to the lack of adhesion at the interface. Fillers having high packing fractions will tend to reduce impact strength much less at the same filler volume (Katz and Milewski, 1978).

Impact strength, fundamentally speaking, is proportional to the area beneath the stress-strain curve at high testing speeds (Katz and Milewski, 1978). Although, impact strengths are not fundamental properties like other measures of toughness. Richardson (1977) states that impact strengths are critically dependent on specimen dimensions and the geometry of the matrix, providing that the sharper the notch the lower the impact strength.

Impact strength is an important mechanical property, yet it is difficult to predict in a filled polymer. Hence, there are no theoretical models capable of predicting the impact strength improvement of composites (Bigg et al., 1988).

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### Creep Extension

Extreme environmental conditions severely affected creep extension in both composite structures in comparison to ambient conditions (Figure 10). The PP-wood fiber composite exhibited poor dimensional stability at 50% content and broke after 20 h in extreme conditions. At 40% wood fiber content, the PP-wood fiber composite extended 140% longer than the PP Reclaim-wood fiber composite in the extreme conditions. These results suggest that the structural materials used in the PP Reclaim provide longer retention of strength under wet conditions, acting as a coupling agent as previously stated.

Several factors such as temperature, moisture, and stress level affect the viscoelastic properties of a composite (Mohan and Adams, 1985). Fillers increase the relative viscosity of thermoplastics and reduce creep over a period of time for an applied stress.

Creep can be estimated from modulus data using the formula:

$$\epsilon(t) = \epsilon_1(t) \frac{E_1}{E}$$
 (12)

where 
$$\epsilon$$
 = Creep elongation at any time (t)  
 $\epsilon_1$  = Creep of the matrix  
E = Modulus of the composite  
 $E_1$  = Modulus of the matrix  
(Katz and Milewski, 1978)

Creep Extension after 500 h.



EFFECT OF FIBER CONCENTRATION ON CREEP EXTENSION (500 H). FIGURE 10.

The predicted values (Table 16) come extremely close to the actual data in the PP-wood fiber composite in ambient conditions as well as the PP Reclaim-wood fiber composite in extreme conditions. Yet, the remaining predicted values are not as accurate (Figure 11). Use of this formula to predict creep extension of a composite is not as reliable as testing.

Table 16. Effect of fiber content on creep extension (500 h): Actual vs. predicted.

		Increase in Length (in)							
Matrix and	No	3	08	4	408		50%		
Condition	Fiber	Actual	Pred.	Actual	Pred.	Actual	Pred.		
Ambient (23°C, 3	7% RH)								
PP	0.056	0.024	0.028	0.027	0.027	0.026	0.023		
PP Reclaim	0.041	0.018	0.033	0.014	0.027	0.018	0.025		
Extreme (37°C, 9	4% RH)								
PP	0.126	0.094	0.063	0.181	0.061		0.052		
PP Reclaim	0.121	0.106	0.099	0.076	0.081	0.076	0.074		

NOTE: The 50% wood fiber-PP composite samples failed after 20 h.

Ethylene vinyl alcohol copolymer (EVOH), one of the structural materials in the PP Reclaim, is extremely affected by water. EVOH, above relative humidities of 80%, is plasticized to the point where its glass-transition temperature drops below room temperature and water absorption and water vapor diffusion both rise abruptly (Wachtel et al., 1985). The plasticization of the EVOH reduces hydrogen bonding, allowing segmental motion of the chains which may promote an increase in







interfacial adhesion with an increase in reaction with the hydroxyl groups (-OH) found on the cellulosic fibers. An important aspect of fatigue is that local failures in the matrix and at the weak interface can ruin the integrity of the composite even though the fibers remain unchanged (Agarwal and Broutman, 1980).

#### Water Absorption

Samples of the composites were immersed in boiling water and Figure 12 shows the water uptake that occurred during a 2-hour period. Water sorption was estimated using the formula:

$$W = \frac{W_w - W_o}{W_o} \times 100\%$$
(13)

Water uptake increased with an increase in fiber content, which is what could be expected from the hydrophilic nature of cellulose fibers (Zadorecki and Flodin, 1986).

### Discussion Summary

Wood fiber incorporated into both composites provide an improvement in tensile strength and stiffness, while the matrix provides environmental protection (e.g., moisture). Yet, the PP Reclaim-wood fiber composite has been proven to be more useful in structural applications that will be exposed to extreme environmental conditions (i.e., temperature and RH). Water Absorption (%).





WATER SORPTION (%) AS A FUNCTION OF WOOD FIBER CONTENT. FIGURE 12.

#### CONCLUSION

The PP Reclaim-wood fiber composite exhibited improved mechanical properties compared to the PP-wood fiber composite. Increase in content of wood fibers improved mechanical properties for both composites, except for tensile strength and percent elongation at break which decreased after 30% fiber content. Overall, orientation of wood fibers displayed significantly improved mechanical properties for both composites, at each fiber concentration. The highest flexural modulus (459,342 PSI) was achieved in the 50% wood fiber-PP Reclaim composite (lengthwise), 18% higher than the PP-wood fiber composite. Izod impact strength for both composites generally increased with an increase in fiber content. This suggests an increase in interfacial adhesion.

The PP Reclaim-wood fiber composite also displayed longer retention of interfacial strength under stress in both ambient and extreme environmental conditions.

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#### RECOMMENDATIONS

Since the PP Reclaim matrix offers excellent dimensional stability and improvements in mechanical properties, further research should be carried out in the areas of 1) improving fiber-matrix bonding at the interface, 2) the effect of the mixing apparatus, and 3) ultimate use for an injection molding composite.

The addition of Epolene wax (maleated propylene wax) to the pulp appears to improve bonding of the fiber-matrix interface when used as a coupling agent for 40% CTMP aspen fiber-PP composite. Results indicated an improvement in tensile strength by 35% (Raj et al., 1989). The similarity of the isotactic structures permits segmental crystallization to occur, whereas the carboxyl groups provide polar or chemical attachments to the cellulosic fibers (Woodhams et al., 1984).

It has also been shown that the average fiber length and fiber matrix bond are affected by the conditions under which the fibers are mixed into the polymer using a co-rotating twin screw extruder (Wall, 1989). The length of the mixing section is the most significant parameter.

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Additionally, compounds must be in granulated form to be capable of injection molding. Therefore, composite materials could be granulated prior to injection molding into tensile and impact bars to improve the accuracy of the mechanical properties and provide more precise end-use data. APPENDIX A

### APPENDIX A

Table 17. Actual composite composition by weight.

Treatments	Composite	Wood Fiber (g)	Matrix (g)
	30% Wood Fiber		
1	- Virgin PP	143.43	322.32
2	- PP Reclaim	206.18	630.00
	40% Wood Fiber		
3	- Virgin PP	173.94	256.47
4	- PP Reclaim	340.28	540.00
	50% Wood Fiber		
5	- Virgin PP	248.00	224.90
6	- PP Reclaim	450.00	424.84
7	100% Virgin PP		900.00
8	100% PP Reclaim		900.00

Table 18. Equations for Linear Regression.

## Mechanical Test

# Equation

Izod Impact Strength - PP Crosswise	y =	0.5209	+	7.686e03x
Izod Impact Strength - PPR Crosswise	y =	0.6413	+	6.176e03x
Tensile Strength - PP Crosswise	y =	26.748	-	0.23115x
Tensile Modulus - PP Crosswise	y =	48.827	+	1.1538x
Tensile Modulus - PPR Crosswise	y =	50.631	+	0.39252x
Tensile Modulus - PP Lengthwise	y =	50.760	+	1.3273x
Tensile Modulus - PPR Lengthwise	y =	50.318	+	0.65434x
Flexural Modulus - PPR Crosswise	y =	19.900	+	0.31456x
Flexural Modulus - PPR Lengthwise	y =	19.226	+	0.55580x

y = Mechanical Property x = Percent Wood Fiber APPENDIX B

### APPENDIX B

Table 19. Tensile strength data from tensile test  $(lb/in^2)$ .

	· · · · · · · · · · · · · · · · · · ·	Replications								
No.	. Composite	1	2	3	4	5				
1.	30% W-PP (LW)	2938.7	2971.9	3472.6	3372.6	2748.4				
2.	30% W-PPR (LW)	4024.0	3200.0	3506.4	3245.0	3371.9				
3.	30% W-PP (CW)	1975.9	2050.8	2016.0	2070.4	2182.3				
4.	30% W-PPR (CW)	2703.1	2271.3	2503.7	2425.6	2710.1				
5.	40% W-PP (LW)	3093.9	2172.7	2480.0	3800.0	<b>2696</b> .9				
6.	40% W-PPR (LW)	3131.8	2338.5	3861.1	2695.4	2151.1				
7.	40% W-PP (CW)	1728.0	1938.2	1998.3	1827.6	1523.9				
8.	40% W-PPR (CW)	1643.7	1524.8	1681.6	1622.2	1624.8				
9.	50% W-PP (LW)	2292.2	2593.8	2062.0	2310.9	2040.0				
10.	50% W-PPR (LW)	2186.4	2250.4	1856.5	3070.2	2516.0				
11.	50% W-PP (CW)	1343.2	1412.4	1430.7	1414.9	1177.3				
12.	50% W-PPR (CW)	1320.8	1308.5	1150.5	958.3	1455.6				
13.	100% PP	2741.9	2766.7	2451.6	2725.8	2409.8				
14.	100% PPR	2292.9	2469.7	2523.1	2297.1	2405.8				

- W = Wood Fiber
  PP = Polypropylene
  PPR = Polypropylene Reclaim
  LW = Lengthwise direction of the extrudate
- CW = Crosswise direction of the extrudate

				<u> </u>		
Var. No.	Composite	1	2	3	4	5
1	30% W-PP (LW)	8.15	6.30	8.30	6.75	7.45
2.	30% W-PPR (LW)	12.50	9.60	11.90	11.90	11.30
3.	30% W-PP (CW)	5.35	5.35	4.75	5.75	5.60
4.	30% W-PPR (CW)	8.85	5.95	7.25	7.20	8.80
5.	40% W-PP (LW)	6.50	8.35	7.50	8.00	6.60
6	40% W-PPR (LW)	6.85	5.00	6.65	5.55	5.35
7.	40% W-PP (CW)	4.55	4.75	4.70	3.90	2.80
8.	40% W-PPR (CW)	3.20	3.50	3.95	3.25	3.70
9.	50% W-PP (LW)	4.50	4.15	3.40	3.90	2.95
10.	50% W-PPR (LW)	3.35	2.85	3.70	5.30	4.45
11.	50% W-PP (CW)	2.55	2.80	3.60	2.80	2.05
12.	50% W-PPR (CW)	2.35	2.25	2.40	2.00	2.70
13.	100% PP	1055.50	911.50	699.50	369.40	411.35
14.	100% PPR	242.35	268.35	140.60	220.90	200.65

Table 20. Percent elongation data from tensile test (%).

W = Wood Fiber
PP = Polypropylene
PPR = Polypropylene Reclaim
LW = Lengthwise direction of the extrudate
CW = Crosswise direction of the extrudate

		Replications							
Var. No.	Composite	1	2	3	4	5			
1.	30% W-PP (LW)	98387	101562	100000	93548	96774			
2.	30% W-PPR (LW)	64800	67460	66935	58140	58594			
3.	30% W-PP (CW)	85714	90476	86400	84800	79032			
4.	30% W-PPR (CW)	68750	52713	56296	60800	58915			
5.	40% W-PP (LW)	100000	104545	98461	100000	103125			
6.	40% W-PPR (LW)	71212	68461	84733	86364	75573			
7.	40% W-PP (CW)	81600	97561	104132	81301	104065			
8.	40% W-PPR (CW)	74219	56391	68000	63492	55814			
9.	50% W-PP (LW)	93750	112308	128682	131250	129231			
10.	50% W-PPR (LW)	83333	91603	70992	91603	83969			
11.	50% W-PP (CW)	113600	119355	108800	105600	103226			
12.	50% W-PPR (CW)	75591	76613	69841	63636	78740			
13.	100% PP	54839	50000	40984	44355	54032			
14.	100% PPR	49643	55344	52692	50725	49635			

Table 21. Young's modulus of elasticity data  $(lb/in^2)$ .

W = Wood Fiber
PP = Polypropylene
PPR = Polypropylene Reclaim
LW = Lengthwise direction of the extrudate
CW = Crosswise direction of the extrudate

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<u> </u>	Replications												
Var. No.	Composite	1	2	3	4	5							
1.	30% W-PP (LW)	392336	408158	337443	293054	476838							
2.	30% W-PPR (LW)	294851	310233	294346	330386	284076							
3.	30% W-PP (CW)	260841	225714	223966	288401	247765							
4.	30% W-PPR (CW)	272638	312989	266140	281309	284221							
5.	40% W-PP (LW)	386381	324082	371219	375385	292293							
6.	40% W-PPR (LW)	470836	494770	406469	387240	486193							
7.	40% W-PP (CW)	386552	287697	360454	346385	289723							
8.	40% W-PPR (CW)	337490	301665	275321	338510	345471							
9.	50% W-PP (LW)	434393	411127	391764	431551	377575							
10.	50% W-PPR (LW)	475059	552302	448470	417412	403466							
11.	50% W-PP (CW)	296619	375117	358543	336900	340860							
12.	50% W-PPR (CW)	355598	364777	344568	367753	358334							
13.	100% PP	317153	346737	329668	290966	346005							
14.	100% PPR	215038	200573	203028	165277	194322							

Table 22. Flexural modulus of elasticity data  $(lb/in^2)$ .

W = Wood Fiber
PP = Polypropylene
PPR = Polypropylene Reclaim
LW = Lengthwise direction of the extrudate
CW = Crosswise direction of the extrudate

.

Table 23. Data from Izod impact test (ft.lb/in).

	Replications												
Var No.	Composite	1	2	3	4	5	6	7	8				
1.	30% W-PP (LW)	0.877	1.192	1.183	0.886	1.110	0.974	1.118	1.101				
2.	30% W-PPR (LW)	0.730	0.816	1.002	0.883	0.667	0.749	0.742	0.716				
3.	30% W-PP (CW)	0.766	0.741	0.803	0.656	0.735	0.791	0.877	0.619				
4.	30% W-PPR (CW)	0.645	0.766	0.779	0.779	0.864	0.914	0.830	0.816				
5.	40% W-PP (LW)	1.004	1.045	1.192	0.870	0.929	1.136	1.126	1.090				
6.	40% W-PPR (LW)	1.099	1.084	1.154	1.209	1.146	1.285	1.088	1.097				
7.	40% W-PP (CW)	0.797	0.943	0.592	1.118	0.667	0.735	0.772	1.025				
8.	40% W-PPR (CW)	0.978	0.891	0.829	0.859	0.936	0.863	0.747	0.854				
9.	50% W-PP (LW)	0.929	1.065	1.082	0.943	1.045	1.084	0.825	1.082				
10.	50% W-PPR (LW)	1.042	1.082	1.038	1.071	0.982	1.095	1.001	1.033				
11.	50% W-PP (CW)	0.760	0.779	0.816	1.609	0.882	0.741	0.877	0.974				
12.	50% W-PPR (CW)	1.030	0.914	0.893	1.091	0.944	1.001	0.936	0.907				
13.	100% PP	0.513	0.622	0.602	0.640	0.349	0.443	0.636	0.397				
14.	100% PPR	0.727	0.784	0.498	0.684	0.518	0.501	0.651	0.766				

W = Wood Fiber
PP = Polypropylene
PPR = Polypropylene Reclaim
LW = Lengthwise direction of the extrudate
CW = Crosswise direction of the extrudate

							Time					
NO.	0.017	0.1	0.2	0.5	1	2	5	20	50	100	200	500
<b>▲-1</b>	.003	. 005	.007	.009	.009	.013	.013	.015	.018	.023	.026	.033
-2	.001	.002	.003	.003	.006	.006	.006	.007	.009	.009	.011	.014
Avg	.002	.004	.005	. 006	. 008	.010	.010	.011	.014	.016	.019	.024
B-1	.002	.007	.010	.010	.010	.012	.015	.015	.018	.019	.022	.025
-2	.002	.003	.004	.004	.005	.006	.006	.006	.008	.008	.010	.010
Avg	.002	. 005	. 007	.007	. 008	.009	.011	.011	.013	.014	.016	.018
C-1	.009	.011	.012	.013	.014	.017	.017	.019	.022	.026	.028	.034
-2	.007	.008	.008	.009	.010	.010	.011	.011	.012	.014	.016	.019
Avg	.008	.010	.010	.011	.012	.014	.014	.015	.017	. 020	. 022	.027
D-1	.004	.006	.008	.008	.008	.010	.010	.012	.013	.014	.016	.018
-2	.002	.003	.004	.005	.005	.005	.005	.006	.007	.007	.008	.009
Avg	.003	.005	.006	.007	.007	.008	.008	.009	.010	.011	.012	.014
E-1	.012	.013	.013	.015	.015	.016	.018	.019	.021	.025	.026	.032
-2	.010	.011	.011	.011	.012	.013	.013	.013	.013	.016	.017	.020
Avg	.011	.012	.012	.013	.014	.015	.016	.016	.017	.021	. 022	.026
F-1	.011	.012	.013	.013	.013	.013	.013	.014	.014	.015	.016	.018
-2	.005	.006	.008	.009	.009	. 009	.010	.011	.011	.011	.013	.017
Avg	.008	. 009	.011	.011	.011	.011	.012	.013	.013	.013	.015	.018
G-1	.019	.021	.022	.025	.027	.031	.034	.038	.044	.048	.052	.062
-2	.014	.019	.021	.022	.022	.023	.029	.032	.037	.042	.046	.049
Avg	.017	.020	.022	.024	.025	.027	.032	.035	.041	.045	.048	.056
H-1	.017	.018	.019	.021	.023	.024	.027	.030	.031	.038	.040	.047
-2	.006	. 009	.012	.013	.015	.018	.020	.020	.023	.026	.031	.034
Avg	.012	.014	.016	.017	.019	.021	.024	.025	.027	.032	.036	.041

Table 24. Creep elongation data (in.) in ambient conditions.

A = 30% Wood Fiber-PP **B** = 30% Wood Fiber-PPR C = 40% Wood Fiber-PP **D** = 40% Wood Fiber-PPR E = 50% Wood Fiber-PP **F** = 50% Wood Fiber-PPR G = 100% PP H - 100% PPR

23°C, 37% Relative Humidity.

			-				rime		·····			
NO.	0.017	0.1	0.2	0.5	1	2	5	20	50	100	200	500
<u> </u>	.019	.020	.022	.024	.026	.030	.034	.039	.041	.045	.050	.064
-2	.043	.045	.047	.053	.055	.059	.065	.078	.087	.096	.106	.124
۸v	g .031	.033	.035	.040	.041	. 045	.050	. 059	.064	.071	.078	. 094
B-1	.031	.037	.038	.040	.044	.048	.054	.063	.072	.083	. 090	.105
-2	.036	.039	.041	.042	.046	.051	.056	.069	.077	.085	.094	.107
۸v	g.034	.038	.040	.041	.045	. 050	.055	.066	.075	.084	.092	.106
C-1	.018	.024	.028	.031	.032	.038	.048	.066	.083	.102	.133	. 208
-2	.022	.027	.028	.032	.036	.039	.048	.062	.078	.093	.116	.154
۸v	g.020	.026	.028	.032	.034	. 039	. 048	.064	.081	.098	.125	.181
D-1	.020	.022	.023	.024	.026	.028	.032	.041	.049	.056	.066	.083
-2	.012	.013	.017	.018	.019	.020	.024	.028	.039	.045	.055	.068
۸v	g .016	.018	.020	.021	.023	. 024	.028	.035	.044	.051	.061	.076
E-1	.026	.029	.033	.035								
-2	.015	.017	.018	.019	.022	.024	.030	.055				
Avş	g .021	.023	.026	.027	.022	. 024	.030	.055				
F-1	.001	.013	.014	.015	.024	.026	.029	.043				
-2	.019	.022	.024	.026	.027	.029	.032	.039	.047	.051	.061	.076
٨v	g .010	.018	.019	.021	.026	. 028	.031	.041	.047	.051	.061	.076
G-1	.042	.052	.057	.066	.076	.084	.097	.107	.116	.120	.123	.129
-2	.033	.045	.050	.057	.067	.078	.089	.101	.110	.116	.119	.123
٨vş	g .038	. 049	.054	.062	.072	.081	.093	.104	.113	.118	.121	.126
H-1	.050	.055	.060	.064	.071	.078	.090	. 099	.111	.115	.118	.129
-2	.038	.042	.047	.056	.061	.068	.077	.092	.098	.103	.107	.112
Avs	z.044	. 049	.054	.060	.066	.073	.084	.096	.105	.109	.113	.121

Table 25. Creep elongation data (in.) in extreme conditions.

37°C, 94% Relative Humidity.

A = 30% Wood Fiber-PP
B = 30% Wood Fiber-PPR
C = 40% Wood Fiber-PP
D = 40% Wood Fiber-PPR
E = 50% Wood Fiber-PPR
F = 50% Wood Fiber-PPR
G = 100% PP
H = 100% PPR

	Replications												
Composite	1	3	5	Average	8D								
30% Wood Fiber-PP	1.62	1.71	1.61	1.65	0.05								
30% Wood Fiber-PPR	1.49	1.39	1.36	1.41	0.07								
40% Wood Fiber-PP	2.89	2.51	2.98	2.79	0.25								
40% Wood Fiber-PPR	2.19	2.39	2.50	2.36	0.15								
50% Wood Fiber-PP	3.88	3.84	3.55	3.76	0.18								
50% Wood Fiber-PPR	3.10	4.65	3.83	3.88	0.78								
100% PP	0.09	0.11	0.11	0.10	0.01								
100% PPR	0.25	0.24	0.24	0.24	0.01								

Table 26. Water absorption data (%).

APPENDIX C

#### APPENDIX C

### Table 27. Two-way Analysis of Variance over variable 1 (Treatments) with values from 1 to 14 and variable 2 (Replications) with values from 1 to 5. Variable 3: Tensile strength.

### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Treatments	13	27723199.81	2132553.832	20.16	0.0000
Replications	4	470792.75	117698.187	1.11	0.3607
Error	52	5501681.31	105801.564		
Non-additivit	<b>y</b> 1	544904.98	544904.978	5.61	
Residual	51	4956776.33	97191.693		
Total	69	33695673.87			

Grand Mean = 2321.860 Grand Sum = 162530.210 Total Count = 70 Coefficient of Variation = 14.01%

Means for Tensile Strength

Treatments		Treatments			Treatments	<b>i</b>	
(Var.	No.)	Mean	(Var.	No.)	Mean	(Var. No.)	Mean
1		3100.84			2835.58		1355.70
2		3469.46	7		1803.20	12	1238.74
3	2	2059.08	8		1619.42	13	2619.16
4	2	2522.76	9		2259.78	14	2397.72
5	2	2848.70	10		2375.90		

### Table 28. Two-way Analysis of Variance over variable 1 (Treatments) with values from 1 to 12 and variable 2 (Replications) with values from 1 to 5. Variable 3: Percent elongation at break.

#### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Treatments	11	378.56	34.415	57.66	0.0000
Replications	4	3.53	0.882	1.48	0.2254
Error	44	26.26	0.597		
Non-additivit	<b>y</b> 1	3.00	2.999	5.54	
Residual	43	23.26	0.541		
Total	59	408.35			

Grand Mean = 5.462 Grand Sum = 327.700 Total Count = 60 Coefficient of Variation = 14.15%

Means for Percent Elongation

Treatments	3	Treatments		Treatments	
(Var. No.)	Mean	(Var. No.)	Mean	(Var. No.)	Mean
1	7.390	6	5.880	11	2.760
2	11.440	7	4.140	12	2.340
3	5.360	8	3.520	13	not used*
4	7.610	9	3.780	14	not used*
5	7.390	10	3.930		

\* Means for PP and PPR were not used because their percentages were greater than 100% (much higher).

### Table 29. Two-way Analysis of Variance over variable 1 (Treatments) with values from 1 to 14 and variable 2 (Replications) with values from 1 to 5. Variable 3: Tensile modulus.

### ANALYSIS OF VARIANCE TABLE

Source	Degrees Freedom	of	Sum of Squares	Sq	Mean Juare	F-va	lue	Proba	bility
Treatments	13	3122	26656706.4	7 24	02050515	.882	39.7	74 (	0.0000
Replications	4	2	7533121.0	9	11883280	.271	0.2	20 (	0.9391
Error	52	314	43425265.3	1	60450485	.871			
Non-additivit	<b>y</b> 1	16	64435095.1	41	64435095	.138	2.8	32	
Residual	51	297	8990170.1	8	58411571	.964			
Total	69	3441	7615092.8	7					

Grand Mean = 80615.957 Grand Sum = 5643117.000 Total Count = 70 Coefficient of Variation = 9.64%

Means for Tensile Modulus

Treat	ments		Treat	ments		Treat	ments	
(Var.	No.)	Mean	(Var.	No.)	Mean	(Var.	No.)	Mean
1	9	8054.2	6		77268.6	11		110116.2
2	6	3185.8	7		93731.8	12		72884.2
3	8	5284.4	8		63583.2	13		48842.0
4	5	9494.8	9		119044.2	14		51607.8
5	10	1226.2	10		84300.0			

### Table 30. Two-way Analysis of Variance over variable 1 (Treatments) with values from 1 to 14 and variable 2 (Replications) with values from 1 to 5. Variable 3: Flexural modulus.

### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Treatments	13	33692006.96	2591692.843	39.74	0.0000
Replications	4	556434.60	139108.649	1.03	0.4031
Error	52	7056235.01	135696.827		
Non-additivit	<b>y</b> 1	568562.39	568562.395	4.47	
Residual	51	6487672.62	127209.267		
Total	69	41304676.57			

Grand Mean - 3400.114 Grand Sum - 238007.959 Total Count - 70 Coefficient of Variation - 10.83%

Means (e+002) for Flexural Modulus

Treatments		Treatments			Treatments			
(Var.	No.)	Mean	(Var.	No.)	Mean	(Var.	No.)	Mean
1	38	15.658	6		4491.016	11		3416.078
2	30	27.784	7		3341.622	12		3582.060
3	24	93.374	8		3196.914	13		3261.058
4	28	34.594	9		4092.820	14		1956.476
5	34	98.720	10		4593.418			

## Table 31. Two-way Analysis of Variance over variable 1 (Treatments) with values from 1 to 14 and variable 2 (Replications) with values from 1 to 8. Variable 3: Isod impact strength.

### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Treatments	13	3.19	0.246	15.66	0.0000
Replications	7	0.11	0.016	1.04	0.4069
Error	91	1.43	0.016		
Non-additivit	y 1	0.01	0.015	0.95	
Residual	90	1.41	0.016		
Total	111	4.74			

Grand Mean = 0.885 Grand Sum = 99.171 Total Count = 112 Coefficient of Variation = 14.15%

Means for Impact Strength

Treatments		Treatments		Treatments	
(Var. No.)	Mean	(Var. No.)	Mean	(Var. No.)	Mean
	1 055	 <i>L</i>	1 1/5		
2	1.055	0 7	1.145	11	0.930
3	0.768	8	0.831	13	0.904
4	0.799	9	1.007	14	0.525
5	1.049	10	1.043	- ·	

### Table 32. One way Analysis of Variance grouped over variable 1 (Treatments) with values from 1 to 14. Variable 3: Tensile strength.

#### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Between Within	13 56	27723199.811 5972474.058	2132553.832 106651.322	19.996	0.0000
Total	69	33695673.869			

Coefficient of Variation = 14.07%

Var.	Ten	sile Strength (1b	./in <sup>2</sup> )			
1	Number	Sum	Average	SD	SE	
1	5	15504.200	3100.840	307.89	146.05	
2	5	17347.300	3469.460	332.19	146.05	
3	5	10295.400	2059.080	77.71	146.05	
4	5	12613.800	2522.760	187.52	146.05	
5	5	14243.500	2848.700	628.70	146.05	
6	5	14177.900	2835.580	684.60	146.05	
7	5	9016.000	1803.200	187.45	146.05	
8	5	8097.100	1619.420	57.98	146.05	
9	5	11298.900	2259.780	225.09	146.05	
10	5	11879.500	2375.900	453.63	146.05	
11	5	6778.500	1355.700	105.27	146.05	
12	5	6193.700	1238.740	190.43	146.05	
13	5	13095.810	2619.162	173.29	146.05	
14	5	11988.600	2397.720	102.56	146.05	
Total Within	70	162530.210	2321.860	698.82 326.58	83.52	

Bartlett's test

Chi-square = 47.208 Number of Degrees of Freedom = 13 Approximate significance = 0.000

## Table 33. One way Analysis of Variance grouped over variable 1 (Treatments) with values from 1 to 12. Variable 3: Percent elongation at break.

### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Between	11	378.564	34.415	55.456	0.0000
Within	48	29.788	0.621		
Total	59	408.352			

Coefficient of Variation = 14.42%

Var.	Elong	ation at Break (	(%)		
1	Number	Sum	Average	SD	SE
1	5	36.950	7.390	0.87	0.35
2	5	57.200	11.440	1.11	0.35
3	5	26.800	5.360	0.38	0.35
4	5	38.050	7.610	1.23	0.35
5	5	36.950	7.390	0.82	0.35
6	5	29.400	5.880	0.82	0.35
7	5	20.700	4.140	0.82	0.35
8	5	17.600	3.520	0.31	0.35
9	5	18.900	3.780	0.61	0.35
10	5	19.650	3.930	0.96	0.35
11	5	13.800	2.760	0.56	0.35
12	5	11.700	2.340	0.25	0.35
Total	60	327.700	5.462	2.63	0.34
Within				0.79	

Bartlett's test Chi-square = 15.833 Number of Degrees of Freedom = 11 Approximate significance = 0.000

## Table 34. One way Analysis of Variance grouped over variable 1 (Treatments) with values from 1 to 14. Variable 3: Tensile modulus.

### ANALYSIS OF VARIANCE TABLE

Source		Squares	Square	F-value	Probability
Between Within	13 56	31226656706.471 3190958386.400	2402050515.8 56981399.	882 42. 757	155 0.0000
Total	69	34417615092.871			

Coefficient of Variation = 9.36%

Var.	Tensile Modulus (lb./in <sup>2</sup> )				
1	Number	Sum	Average	SD	SE
1	5	490271.000	98054.200	3088.13	3375.84
2	5	315929.000	63185.800	4513.19	3375.84
3	5	426422.000	85284.400	4114.27	3375.84
4	5	297474.000	59494.800	5998.41	3375.84
5	5	506131.000	101226.200	2513.63	3375.84
6	5	386343.000	77268.600	7993.35	3375.84
7	5	468659.000	93731.800	11525.05	3375.84
8	5	317916.000	63583.200	7821.84	3375.84
9	5	595221.000	119044.200	16053.14	3375.84
10	5	421500.000	84300.000	8438.23	3375.84
11	5	550581.000	110116.200	6463.27	3375.84
12	5	364421.000	72884.200	6130.08	3375.84
13	5	244210.000	48842.000	6044.06	3375.84
14	5	258039.000	51607.800	2432.41	3375.84
Total	70	5643117.000	80615.957	22333.97	2669.42
Within				7548.60	

Bartlett's test

Chi-square = 27.033 Number of Degrees of Freedom = 13 Approximate significance = 0.000

### Table 35. One way Analysis of Variance grouped over variable 1 (Treatments) with values from 1 to 14. Variable 3: Flexural modulus.

#### ANALYSIS OF VARIANCE TABLE

1692.843 1 5940.529	.9.065 0	.0000
	1692.843 1 5940.529	1692.843 19.065 0 5940.529

Coefficient of Variation = 10.84%

Var.	Fle	<b>xural Modulus (lb.</b>			
1	Number	Sum	Average	SD	SE
1	5	19078.290	3815.658	701.45	164.89
2	5	15138.920	3027.784	180.38	164.89
3	5	12466.870	2493.374	267.51	164.89
4	5	14172.970	2834.594	179.88	164.89
5	5	17493.600	3498.720	400.62	164.89
6	5	22455.080	4491.016	489.34	164.89
7	5	16708.110	3341.622	439.30	164.89
8	5	15984.570	3196.914	301.21	164.89
9	5	20464.100	4092.820	247.09	164.89
10	5	22967.090	4593.418	589.22	164.89
11	5	17080.390	3416.078	293.96	164.89
12	5	17910.300	3582.060	90.43	164.89
13	5	16305.290	3261.058	231.80	164.89
14	5	9782.380	1956.476	185.66	164.89
Total	70	238007.959	3400.114	773.70	92.48
Within				368.70	

#### Bartlett's test

Chi-square = 25.592 Number of Degrees of Freedom = 13 Approximate significance = 0.000
## Table 36. One way Analysis of Variance grouped over variable 1 (Treatments) with values from 1 to 14. Variable 3: Izod Impact strength.

#### ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	Probability
Between	13	3.193	0.246	15.607	0.0000
Within	98	1.542	0.016		
Total	111	4.735			

Coefficient of Variation = 14.17%

Var.	Impact	t Strength (ft.)	lb./in.)				
1	Number	Sum	Average	SD	SE		
1	8	8.441	1.055	0.13	0.04		
2	8	6.305	0.788	0.11	0.04		
3	8	5.988	0.748	0.08	0.04		
4	8	6.393	0.799	0.08	0.04		
5	8	8.392	1.049	0.11	0.04		
6	8	9.162	1.145	0.07	0.04		
7	8	6.649	0.831	0.18	0.04		
8	8	6.957	0.870	0.07	0.04		
9	8	8.055	1.007	0.10	0.04		
10	8	8.344	1.043	0.04	0.04		
11	8	7.438	0.930	0.28	0.04		
12	8	7.716	0.964	0.07	0.04		
13	8	4.202	0.525	0.12	0.04		
14	8	5.129	0.641	0.12	0.04		
Total	112	99.171	0.885	0.21	0.02		
Within				0.13			

Bartlett's test

Chi-square = 43.554 Number of Degrees of Freedom = 13 Approximate significance = 0.000

# Table 37. Coefficients for the partitioning of the sum of squares among fourteen treatments into fifteen independent (orthagonal) comparisons.

	Treatments														
	Comparison	3PL	3RL	3PC	3RC	4PL	4RL	4PC	4RC	5PL	5RL	5PC	5RC	10P	10R
1.	Response to W	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	6	6
2.	30% W vs. All	- 5	- 5	- 5	- 5	2	2	2	2	2	2	2	2	2	2
3.	40% W vs. All	2	2	2	2	- 5	- 5	- 5	- 5	2	2	2	2	2	2
4.	50% W vs. All	2	2	2	2	2	2	2	2	- 5	- 5	- 5	- 5	2	2
5.	LW vs. CW	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	0	0
6.	30% LW vs. CW	-1	-1	1	1	0	0	0	0	0	0	0	0	0	0
7.	40% LW vs. CW	0	0	0	0	-1	-1	1	1	0	0	0	0	0	0
8.	50% LW vs. CW	0	0	0	0	0	0	0	0	-1	-1	1	1	0	0
9.	3PL vs. 3RL	-1	1	0	0	0	0	0	0	0	0	0	0	0	0
10.	3PC vs. 3RC	0	0	-1	1	0	0	0	0	0	0	0	0	0	0
11.	4PL vs. 4RL	0	0	0	0	-1	1	0	0	0	0	0	0	0	0
12.	4PC vs. 4RC	0	0	0	0	0	0	-1	1	0	0	0	0	0	0
13.	5PL vs. 5RL	0	0	0	0	0	0	0	0	-1	1	0	0	0	0
14.	5PC vs. 5RC	0	0	0	0	0	0	0	0	0	0	-1	1	0	0
15.	PP vs. PPR	0	0	0	0	0	0	0	0	0	0	0	0	-1	1

W - Wood Fiber, LW - Lengthwise, CW - Crosswise, and PL, RL, PC, RC -Polypropylene (PP) lengthwise, PP Reclaim (PPR) lengthwise, PP crosswise, and PPR crosswise, respectfully. Numbers 3, 4, 5, and 10 - 30%, 40%, and 50% wood fiber content, and 100% polymer, respectfully.

NOTE: Percent elongation for comparison number 1 was not tabulated due to exceedingly high values (>> 100%).

#### ORTHAGONAL COMPARISONS

1. Response to wood fiber.

	Tens. Strength	Elong. Tens. Mod.	Flex. Mod. Izod
Sum of Squares	406144.938	10775524133.038	7306012.264 1.705
Effect	31.097	-5065.176	-131.891 -0.050
Error	15.935	368.334	17.991 0.005
F value	3.808	189.106	53.744 108.369
Probability	0.056	0.000	0.000 0.000

**2**. 30% wood fiber content vs. the remaining treatments.

	Tens. Strengtl	h Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	6084932.107	185.754	473245165.491	3573796.395	0.064
Effect	-186.470	-1.244	1644.463	142.904	0.015
Error	24.687	0.072	570.621	27.871	0.007
F value	57.054	299.322	8.305	26.289	4.054
Probability	0.000	0.000	0.006	0.000	0.047

3. 40% wood fiber content vs. the remaining treatments.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod	Izod
Sum of Squares	57041.079	1.576	311701168.401	1506478.306	0.349
Effect	18.054	0.115	-1334.597	-92.782	-0.035
Error	24.687	0.072	570.621	27.871	0.007
F value	0.535	2.539	5.470	11.082	22.192
Probability		0.118	0.023	0.002	0.000

4. 50% wood fiber content vs. the remaining treatments.

	Tens. Strengt	h Elong.	Tens. Mod.	Flex. Mod	. Izod
Sum of Squares	7406994.267	153.115 7	141317677.041	7599772.876	0.453
Effect	205.732	1.130	-6388.077	-208.392	-0.040
Error	24.687	0.072	570.621	27.871	0.007
F value	69.451	246.728	125.327	55.905	28.795
<b>Probability</b>	0.000	0.000	0.000	0.000	0.000

5. Treatments in the lengthwise direction vs. treatments in crosswise.

	Tens. Strength	n Elong	. Tens. Mod.	Flex. Mod	. Izod
Sum of Squares	16492170.067	82.603	1400912768.067	9027884.595	0.595
Effect	-524.280	-1.173	-4832.033	-387.898	-0.079
Error	42.161	0.102	974.520	47.599	0.013
F value	154.636	133.105	24.585	66.411	37.809
Probability	0.000	0.000	0.000	0.000	0.000

6. Treatments with 30% wood fiber in lengthwise direction vs. 30% wood fiber content in the crosswise direction.

	Tens. Strength	Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	4942465.906	42.924	338697420.800	2870827.450	0.175
Effect	-497.115	-1.465	-4115.200	-378.869	-0.074
Error	73.024	0.176	1687.919	82.444	0.022
F value	46.342	69.168	5.944	21.118	11.106
Probability	0.000	0.000	0.018	0.000	0.001

7. Treatments with 40% wood fiber in lengthwise direction vs. 40% wood fiber content in the crosswise direction.

	Tens. Strength	Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	6393882.362	39.340	560729910.050	2632476.977	0.487
Effect	-565.415	-1.403	-5294.950	-362.800	-0.123
Error	73.024	0.176	1687.919	82.444	0.022
F value	59.951	63.392	9.841	19.365	30.950
Probability	0.000	0.000	0.003	0.000	0.000

8. Treatments with 50% wood fiber in lengthwise direction vs. 50% wood fiber content in the crosswise direction.

	Tens. Strength	Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	5208325.561	18.515	517337748.050	3562102.013	0.048
Effect	-510.310	-0.653	- 5085 . 950	-422.025	-0.039
Error	73.024	0.176	1687.919	82.444	0.022
F value	48.835	13.721	9.079	26.203	3.078
Probability	0.000	0.001	0.004	0.000	0.082

9. 30% wood fiber-PP in lengthwise vs. 30% wood fiber-PP Reclaim in lengthwise direction.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod	. Izod
Sum of Squares	339701.707	41.006	3039513296.400	1551863.500	0.285
Effect	184.310	2.025	-17434.200	-393.937	-0.133
Error	103.272	0.249	2387.078	116.594	0.031
F value	3.185	66.077	53.342	11.416	18.119
Probability	0.080	0.000	0.000	0.001	0.000

10. 30% wood fiber-PP in crosswise vs. 30% wood fiber-PP Reclaim in the crosswise direction.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	537497.981	12.656	1662758670.400	291077.754	0.010
Effect	231.840	1.125	-12894.800	170.610	0.025
Error	103.272	0.249	2387.078	116.594	0.031
F value	5.040	20.349	29.181	2.141	0.651
Probability	0.029	0.000	0.000	0.149	

11. 40% wood fiber-PP in lengthwise vs. 40% wood fiber-PP Reclaim in the lengthwise direction.

	Tens. Strength	Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	430.331	5.700 1	434916494.400	2461628.360	0.037
Effect	-6.560	-0.755	-11978.800	496.148	0.048
Error	103.272	0.249	2387.078	116.594	0.031
F value	0.004	9.185	25.182	18.108	2.355
Probability		0.004	0.000	0.000	0.128

12. 40% wood fiber-PP in crosswise vs. 40% wood fiber-PP Reclaim in the crosswise direction.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	84437.725	0.961	2272345204.900	52351.054	0.006
Effect	-91.890	-0.310	-15074.300	-72.354	0.019
Error	103.272	0.249	2387.078	116.594	0.031
F value	0.792	1.549	39.879	0.385	0.377
Probability		0.219	0.000		

13. 50% wood fiber-PP in lengthwise vs. 50% wood fiber-PP Reclaim in the lengthwise direction.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	33709.619	0.056	3017898584.100	626496.011	0.005
Effect	58.060	0.075	-17372.100	250.299	0.018
Error	103.272	0.249	2387.078	116.594	0.031
F value	0.316	0.091	52.963	4.609	0.332
Probability			0.000	0.036	

14. 50% wood fiber-PP in crosswise vs. 50% wood fiber-PP Reclaim in the crosswise direction.

	Tens. Strength	Elong	. Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	34199.103	0.441	3465554560.000	68875.087	0.005
Effect	-58.480	-0.210	-18616.000	82.991	0.017
Error	103.272	0.249	2387.078	116.594	0.031
F value	0.321	0.711	60.819	0.507	0.307
Probability			0.000		

### 15. 100% PP vs. 100% PP Reclaim.

	Tens. Streng	th Elong.	Tens. Mod.	Flex. Mod.	Izod
Sum of Squares	122591.390	563777.533	19124124.100	4254835.691	0.054
Effect	-110.721	-237.440	1382.900	-652.291	0.058
Error	103.272	25.794	2387.078	116.594	0.031
F value	1.149	84.740	0.336	31.299	3.413
Probability	0.288	0.000		0.000	0.068

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