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6. AUTHOR(S)
David B. Duncan
Randall L. Bickford

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Duncan Technologies, Inc.
P.O. Box 1150
Newcastle, CA 95658

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Materials research was performed to identify possible composite compositions and chemical treatments that would enhance the interfacial strength between paper fibers and the thermoplastic matrix. Screening tests were performed to select the most promising options. Tensile tests were performed on several composites made of paper and polystyrene or high density polyethylene. Economic and market analyses were performed to assess the viability of these composites as a product.

The data indicate that paper fibers are too weak to create a composite with suitable strength properties. In addition the available market is saturated and very difficult to compete in. The use of chopped glass fibers in a thermoplastic matrix as a fiberglass replacement may be a more promising strategy. Further investigation of this alternative is recommended.

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STRUCTURAL COMPOSITE CONSTRUCTION MATERIALS MANUFACTURED FROM MUNICIPAL SOLID WASTE

FINAL REPORT

APRIL 20, 1994

Contract No. DACA88-93-C-0013

Prepared for:
US Army Corps of Engineers
Construction Engineering Research Laboratory
2902 Newmark Drive
Champaign, IL 61812-1076

Prepared By:
Duncan Technologies, Inc.
P.O. Box 1150
Auburn, CA 95658
(916) 888-6522

ABSTRACT

Work was performed to assess alternatives and opportunities for the development of innovative construction materials made from recycled paper fiber and thermoplastic materials. The identification of such composites will create a stable market for recovered waste plastics and paper while providing a new material for applications. The goals were to identify methods and processes to produce composite materials with suitable properties and to evaluate the economics of the process and the markets they can compete in.

Materials research was performed to identify possible composite compositions and chemical treatments that would enhance the interfacial strength between paper fibers and the thermoplastic matrix. Screening tests were performed to select the most promising options. Tensile tests were performed on several composites made of paper and polystyrene or high density polyethylene. Economic and market analyses were performed to assess the viability of these composites as a product.

The data indicate that paper fibers are too weak to create a composite with suitable strength properties. In addition the available market is saturated and very difficult to compete in. The use of chopped glass fibers in a thermoplastic matrix as a fiberglass replacement may be a more promising strategy. Further investigation of this alternative is recommended.

FOREWORD

This research was performed for the US Army Construction Engineering Research Laboratory (USACERL) under Contract DACA88-93-C-0013, "Structural Composite Construction Materials Manufactured from Municipal Solid Waste" under SBIR Phase 1 Topic No. A93-029. The USACERL technical monitor was Mr. Richard G. Lampo.

The research was performed by Duncan Technologies, Inc., P.O. Box 1150, Newcastle, CA 95658.
Portions of the work was performed by Randall Bickford.

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1 INTRODUCTION

Background

The United States and many other nations of the world are facing a crises in the management of the waste products of modern life. Our ever increasing use of synthetic materials and disposable products has created a growing tide of garbage that can no longer be buried and ignored. One of the largest and fastest growing sources is municipal solid wastes (MSW), those disposable materials that are generated by day to day life. The Environmental Protection Agency (EPA) projects a MSW generation rate of 4.4 pounds/person/day [1.996 kg/person/day] by the year 2000.[1]

For many years, landfills and incineration were considered adequate processes for management of our waste products. However, the tremendous volume is overwhelming available landfill capacity. Incineration is an unacceptable alternative due to air quality concerns. Increasing awareness of long term environmental effects of our current waste management processes has generated a growing pressure for the recovery and reuse of resources. The Army, as a significant producer of MSW, faces the same problem. Figure 1 illustrates the distribution of MSW among current handling options. Many states are mandating a reduction of MSW flowing into landfills.

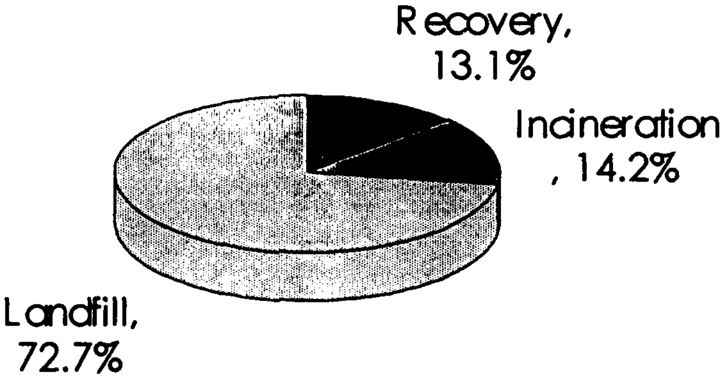

Figure 1. Current options for disposal of Municipal Solid Waste*

* Source: *Characterization of Municipal Solid Waste in the United States: 1990 Update*, United States Environmental Protection Agency, EPA/530-SW-90-042, June 13, 1990.

In order to increase the amount of MSW that is recovered and reused, stable and growing markets must be established for the materials. Products must be developed that not only utilize the recovered

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[1] *Characterization of Municipal Solid Waste in the United States: 1990 Update*, United States Environmental Protection Agency, EPA/530-SW-90-042, June 13, 1990.

resources, but do so in an economically viable manner to compete with products made from natural or virgin resources. In an effort to support the development of markets for recovered MSW, the Army Construction Engineering Laboratory is exploring the development of material systems to make use of these waste feedstocks while producing materials of equal or superior quality for the construction and rehabilitation of facilities. The work described in this report is a part of that effort and was performed under a Phase I Small Business Innovative Research program entitled "Structural Composite Construction Materials Manufactured From Municipal Solid Waste" by Duncan Technologies, Inc during the period from Sep 20, 1993 to Mar 20, 1994.

Objectives

The objective of the work described in this report is to assess alternatives and opportunities for the development of innovative construction materials made from recycled paper fiber and thermoplastic materials. Goals are to identify methods and processes to produce composite materials with suitable properties and to evaluate the economics of the process and the markets they can compete in.

Approach

In order to identify candidate materials, theoretical analyses were performed to determine the required compositions and component properties necessary to produce viable structural composites from paper fibers dispersed in a thermoplastic matrix. Techniques to enhance the bond strength between hydrophilic wood fibers and hydrophobic thermoplastics were developed. Test specimens were fabricated using candidate techniques and evaluated by mechanical testing. The preliminary design of a sub-scale pilot plant was completed to identify the requirements for large scale production of the composites in a production environment.

The market viability and economic feasibility of the proposed composites were evaluated. A market analysis was performed to identify current activity in this market and determine the competitive conditions faced in introducing a new composite construction material. An economic analysis of full scale production costs of the process for MSW recovery from a municipality of 1 million persons was performed.

2 MATERIALS RESEARCH

Literature Review

A thorough literature search and review was completed. Over thirty technical journal articles and reports spanning the fifteen year period from 1978 to 1993 were procured and evaluated. References reviewed focused on wood fiber composite research with high density polyethylene (HDPE) and polystyrene (PS). The majority of referenced work was based on virgin plastic and wood pulp fibers rather than recycled plastic and paper fiber.

The body of literature surveyed indicates significant beneficial effects from using chemical coupling agents to enhance fiber-to-matrix shear strength in wood fiber reinforced thermoplastic composites.[2] In some cases, tensile strength increased 30% or more when treated fibers were used. When untreated fibers were used, strength properties were often mildly degraded in comparison to unreinforced resins. Modulus increased 100% or more as the result of fiber reinforcement but was minimally effected by the use of coupling agents. Energy at yield was improved by as much as 100% while elongation was reduced on the order of 50% regardless of fiber treatment. The effort described in this report focused on the application of similar techniques to paper fiber in a thermoplastic matrix. The successful development of a useful composite from these materials could provide a good market for paper and plastics recovered from MSW.

Chemical Process Development

A number of steps were undertaken to identify potential composite compositions and their processing. Commercially available coupling agents were surveyed and the most promising and environmentally benign were selected for testing. An analytical model was developed and used to predict the properties of candidate composites. Simple bonding tests were performed to identify appropriate processing parameters and test initial paper/plastic bonding. When these tests failed to provide adequate discrimination data, laminated disks were produced and screened with qualitative shear, bend, and peel tests. The disk tests identified those processes that produced some amount of property enhancement. These most promising of these techniques were then used in the production of tensile test specimens. The tensile specimens were tested to failure and the data analyzed to assess the properties of the resulting composite. Each step of this process is detailed in the discussion that follows.

The development of the chemical process was aimed at exploring the application of chemical coupling agents in processes similar to those described in the literature to enhance tensile strength of the paper/plastic composite. A thorough review of commercial resin formulations suitable for coupling agent

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[2] Kokta, B.V.; Maldas, D.; Daneault, C.; Beland, P., *Polym. Composites*, 1990. 11(2), pp. 84-89; Maldas, D.; Kokta, B.V.; Daneault, C.; *J. Appl. Polym. Sci.*, 1989, 37, pp. 751-775; Maldas, D.; Kokta, B.V.; Raj, R.G.; Daneault, C.; *Polymer*, 1988, 29, pp. 1255-1265; Yam, K.L.; Gogoi, B.K.; Lai, C.C.; Selke, S.E.; *Polym. Eng. and Sci.*, 1990, 30, pp. 693-699; Dong, S.; Sapieha, S.; Schreiber, H.P.; *Polym. Eng. and Sci.*, 1993, 33, pp. 343-346; Raj, R.G.; Kokta, B.V.; Maldas, D.; Daneault, C.; *Polymer Composites*, 1988, 9, pp. 404-411; Emerging Technologies for Materials and Chemicals from Biomass, Rowell, R.M.; Schultz, T.P.; Narayen, R., Ed., ACS Symposium Series 476, 1992

preparations was completed.[3] Coupling agent effectiveness for cellulose based fibers depends on the ability to produce one or more of the chemical linkages shown in Figure 2. For acceptable economics, these linkages must be formed using low toxicity precursors and solvents requiring a minimum of processing. Product searches focused on anhydride modified alkyd, polyester, urethane and epoxy resin formulations with chemical characteristics suitable for bonding to both cellulose and recycled thermoplastics. The result of this review was the identification of cost effective, environmentally acceptable precursor materials for coupling agent synthesis.

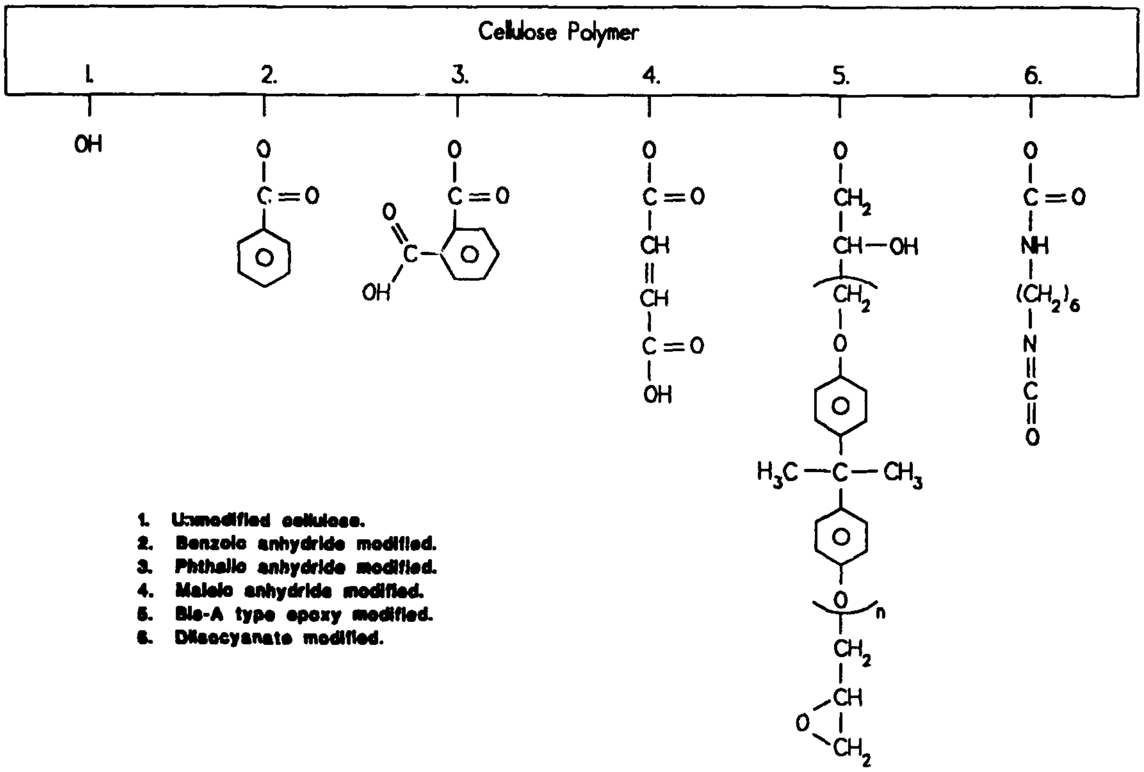

Figure 2. Primary Intermediates for Coupling Cellulose-Based Reinforcements to a Thermoplastic Matrix

Fiber-to-matrix shear strength enhancement in wood fiber/thermoplastic composites is accomplished by selecting coupling agents which form chemical bonds to cellulose and also engage the polymer matrix by chain entanglement or chemical bonding. Entanglement is enhanced by the development of low to medium molecular weight polymers grafted or strongly hydrogen bonded to the cellulose. Polyethylene matrices are inert to most reactive species but may be coupled by entanglement with low molecular weight polyolefin copolymers having groups reactive to cellulose. Commercially available maleated polypropylene waxes and maleated polybutadiene resins are suitable for coupling paper fiber to high density polyethylene (HDPE) to provide improved interfacial shear strength.[4]

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[3] The Chemistry of Organic Film Formers, Solomon, D.H.; John Wiley & Sons, 1967; Handbook of Adhesives, Skeist, I., Ed.; Van Nostrand Reinhold Company, 1977; Macromolecular Syntheses, Overberger, C.G., Ed.; John Wiley & Sons, 1963; Polymer Chemistry, Parker, D.B.; Applied Science Publishers Ltd, 1974.

[4] *Emerging Technologies,* Rowell, R.M.; Schultz, T.P.; Narayen, R.

Chemical bonding to the matrix resin will lead to higher interfacial shear strength and modulus than entanglement coupling. Anhydrides of the dicarboxylic acids, such as phthalic anhydride and maleic anhydride, are cost effective precursors of low toxicity suitable for initiating graft copolymers with cellulose.[5] Anhydrides are reactive with the hydroxyl side groups of cellulose to form esters as shown in Figure 3. Cross-linking of anhydride modified paper fiber to thermoplastics may be accomplished by the use of epoxy or diisocyanate reactions. A variety of anhydride cured epoxies are commercially available.[6] The epoxy and isocyanate functionalities are also reactive with cellulose as shown in Figure 2. Isocyanates suffer from handling problems due to toxicity. Dicarboxylic acid monoesters with cellulose may be further reacted with diols, such as ethylene glycol, to form short polyester side chains on cellulose as shown in Figure 3. Growth of long side chains is impractical due to competing polymer formation in the solvent phase.

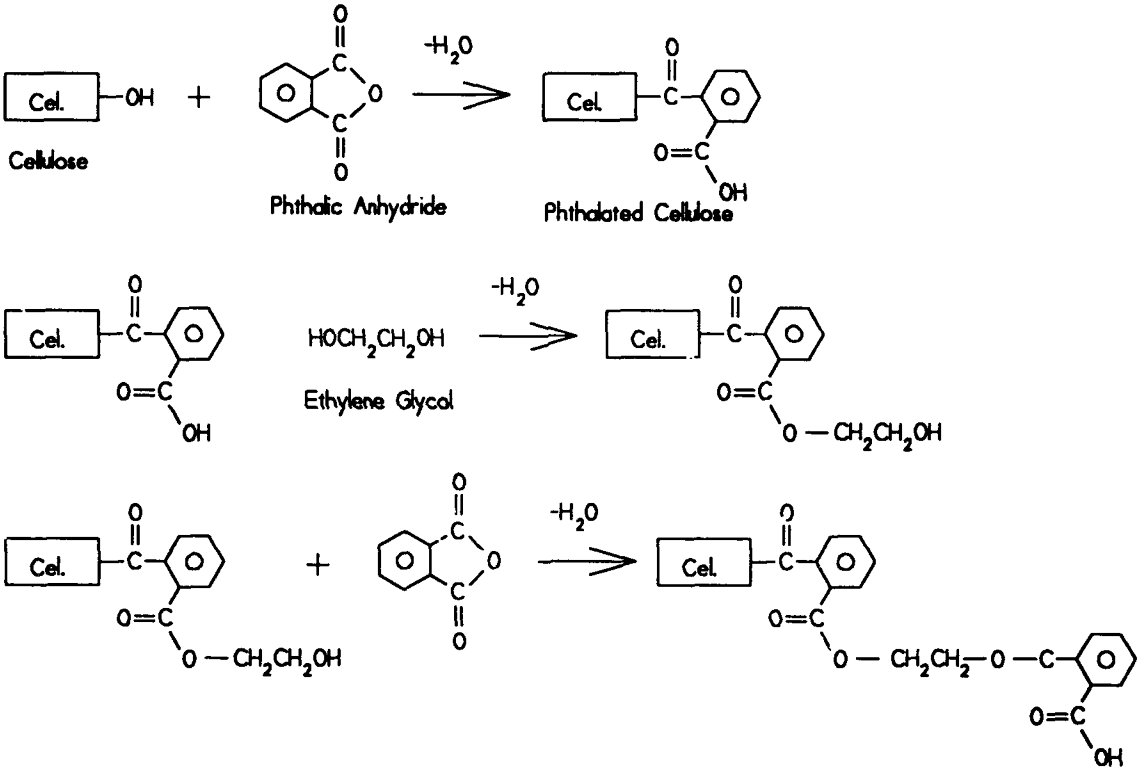

Figure 3. Chemical Modification of Cellulose by Phtalic Anhydride to form Ester Linkages

The unsaturated carbon-carbon bond in maleic anhydride offers additional synthetic options for polymer grafting to cellulose. The dicarboxylic acid monoester is formed as shown in Figure 4. The unsaturated alkene bond may then be polymerized by addition reactions with other alkenes, such as styrene, in the presence of free radical initiators, such as benzoyl peroxide.[7] Short chains may be grown by timing the order of reactant introduction; however, long chains are impractical due to competing polymerization of monomers in the solvent phase and the eventual probability of chain terminating reactions. Alternately, maleic anhydride copolymers may be prepared first followed by reaction of the adducted anhydride function

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[5] Chemistry of Organic Film Formers, Solomon.

[6] Handbook of Adhesives, Skeist, I.

[7] Macromolecular Syntheses, Overberger, C.G; Polymer Chemistry, Parker, D.B.

with cellulose. However, in this case steric hindrance will reduce cellulose hydroxyl activity. Maleic anhydride adducted styrene and polybutadiene resins are commercially available. These maleic anhydride adducted polymeric side chains will retain reactive anhydride groups useful for epoxy cross-linking reactions.

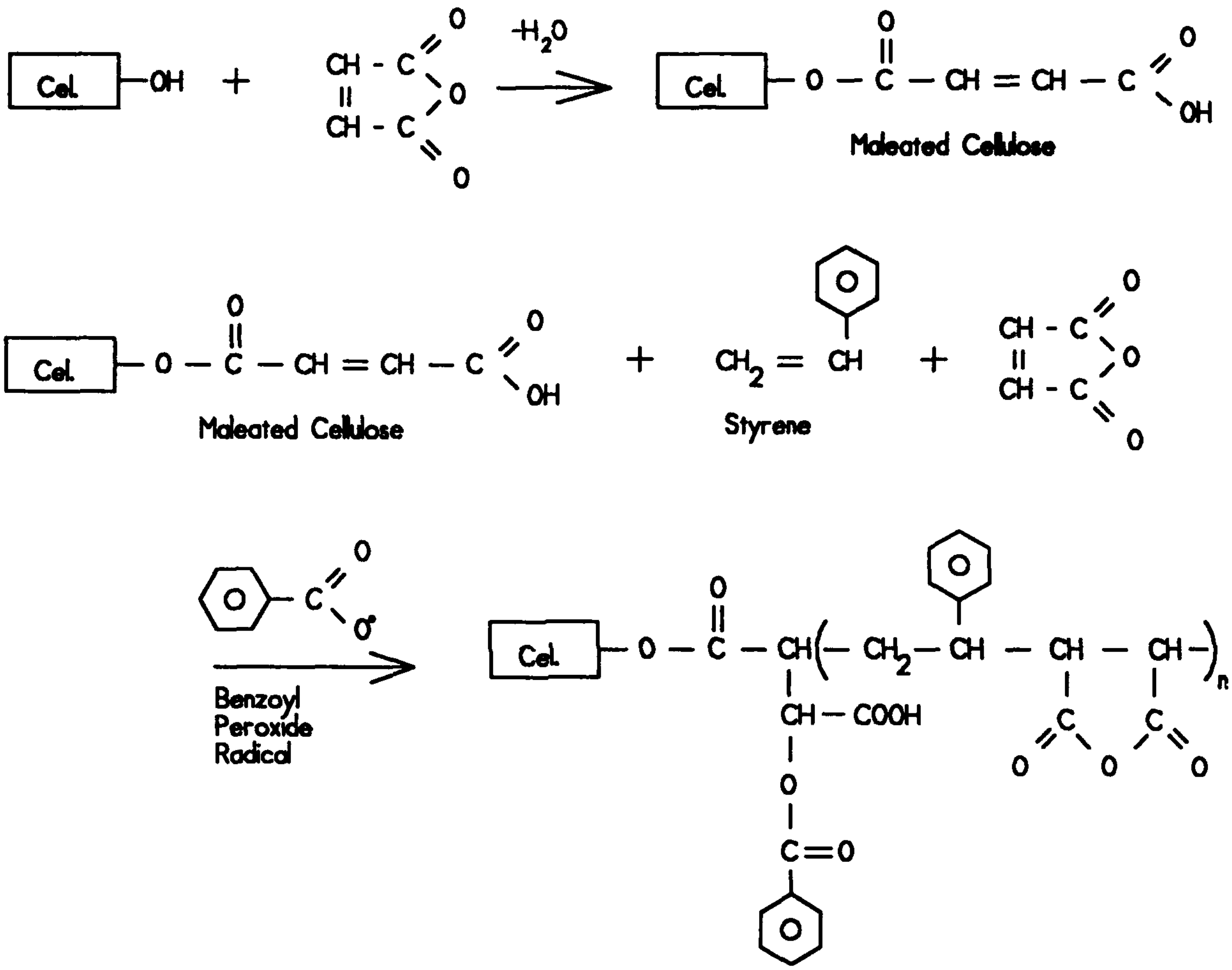

Figure 4. Modification of Cellulose by Maleic Anhydride followed by Polymerization with Styrene

Composite Property Modeling

A model was developed to predict the structural properties of candidate composites. Model development was limited by a lack of adequate paper fiber mechanical properties data. Paper properties located in the literature were characterized via sheet testing;[8] therefore, negligible data for single fiber mechanical properties were available.

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[8] Paper Structure and Properties, Bristow, J.A.; Kolseth, P.; Marcel Dekker, 1986

Properties of composites are highly dependent on fiber strength and geometry.[9] The length to diameter ratio determines the required bond strength between the fiber and matrix so that fiber failure rather than debonding determines the tensile strength. To determine paper fiber geometry, office paper was mixed with water in a laboratory blender to form a fiber slurry. Samples of the fiber were measured using a Gaether measurement microscope to determine length and diameter. Samplings of paper fiber diameters ranged from 0.010-mm to 0.035-mm depending on orientation of the ribbon like fiber. A fiber equivalent diameter of 0.015-mm was selected based on the estimated cross sectional area of typical fibers. Fiber lengths ranged from 0.5-mm to 3.0-mm. Average fiber length was estimated as 1.5-mm. This results in an average length to diameter ratio of 100:1; however, fiber curl may yield a lower effective length to diameter ratio, perhaps 50:1.

Property values and assumptions used for initial materials modeling are defined in Table 1. Candidate matrix materials included polystyrene (PS) or expanded polystyrene (EPS), high density polyethylene (HDPE), and polyethylene terephthalate (PET). Predictions of composite properties based on these values are presented in Table 2. The models used for pre-test predictions are summarized by equations 1 - 3.

$$L_c = \frac{\sigma_f d}{2\tau_c} \quad \text{with} \quad d = \sqrt{\frac{a^2 + b^2}{2}} \qquad \text{[Eq 1]}$$

$$\sigma_c = k\sigma_f v_f (1 - \frac{L_c}{2L}) + \sigma_m (1 - v_f) \qquad \text{[Eq 2]}$$

$$E_c = \eta\left\{k v_f E_f + E_m (1 - v_f)\right\} \qquad \text{[Eq 3]}$$

where:

L_c (mm) is the critical fiber length;

L (mm) is the weight averaged fiber length;

d (mm) is the fiber equivalent diameter;

a, b (mm) are the fiber semiaxis diameters;

τ_c (MPa) is the interfacial sheer stress;

σ (MPa) is the tensile strength of fiber (f), matrix (m), and composite (c);

E (GPa) is tensile modulus of fiber (f), matrix (m), and composite (c);

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[9] *Short Fiber Reinforced Composite Materials*, Sanders, B.A.,Ed.;ASTM Special Technical Publication 772, 1982; Short Fibre Reinforced Thermoplastics, Folkes, M.J.; Research Studies Press, John Wiley & Sons, 1982;

[10] Mechanical Properties of Reinforced Thermoplastics, Clegg, D.W.; Collyer, A.A.; Elsevier Applied Science Publishers, 1986.

v_f is the fiber volume fraction;

k is the fiber orientation effectiveness factor;

η is the short fiber effectiveness factor.

Table 1. Properties and Constants for Materials Modeling

	Property	Units	Value
Fiber:			
	Tensile Strength	MPa	400
	Tensile Modulus	GPa	20
	Equivalent Diameter	mm	0.015
	Weight Average Length	mm	1.5
	Density	kg/m**3	600
HDPE Matrix:			
	Tensile Strength	MPa	25
	Tensile Modulus	GPa	0.9
	Density	kg/m**3	950
PET Matrix:			
	Tensile Strength	MPa	60
	Tensile Modulus	GPa	3.5
	Density	kg/m**3	1350
PS Matrix:			
	Tensile Strength	MPa	50
	Tensile Modulus	GPa	2.5
	Density	kg/m**3	1050
Model Variables:			
	Volume Fraction	%	30
	Orientation Factor		0.3
	Short Fiber Efficiency Factor		0.9

Table 2. Pre-Test Predictions of Composite Properties

	Property	Units	Unmodified Fiber	Modified Fiber
HDPE-30 vol% Paper Fiber Composite:				
	Tensile Strength	MPa	26	46
	Tensile Modulus	GPa	2.2	2.2
	Density	kg/m**3	845	845
PET-30 vol% Paper Fiber Composite:				
	Tensile Strength	MPa	51	71
	Tensile Modulus	GPa	3.8	3.8
	Density	kg/m**3	1125	1125
PS-30 vol% Paper Fiber Composite:				
	Tensile Strength	MPa	44	64
	Tensile Modulus	GPa	3.2	3.2
	Density	kg/m**3	915	915

After tensile testing of candidate materials was completed, the test data was used to update the model with measured values. Tensile property test results were used to define best fit parameters for paper reinforced PS and HDPE material models. Tensile test results were not available for PET because it was not selected for the tensile tests due to early indications of unsuitability for the task during screening tests. Best fit values are reported in Table 3 for Paper, PS, and HDPE. Properties predicted based on best fit parameters are reported in Table 4. The greatest differences between pre-test and post-test predictions are the effects of much lower apparent strength and higher apparent density of the paper fiber.

Table 3. Best Fit Model Properties and Constants Based On Experimental Results

	Property	Units	Value
Paper Fiber:			
	Tensile Strength	MPa	30
	Tensile Modulus	GPa	18
	Effective Diameter	mm	0.02
	Effective Length	mm	0.3
	Density	kg/m**3	1650
HDPE Matrix:			
	Tensile Strength	MPa	21
	Tensile Modulus	GPa	0.5
	Density	kg/m**3	950
PS Matrix:			
	Tensile Strength	MPa	38
	Tensile Modulus	GPa	1.4
	Density	kg/m**3	1047
Interfacial Shear Strength:			
	Unmodified Fiber	MPa	0.1
	Modified Fiber	MPa	10
Model Variables:			
	Fiber Orientation Factor	0.3	
	Short Fiber Efficiency Factor	0.9	

Table 4. Best Fit Model Predictions of Composite Properties

	Property	Units	Unmodified Fiber	Modified Fiber
HDPE-16 vol% Paper Fiber Composite:				
	Tensile Strength	MPa	17	19
	Tensile Modulus	GPa	1.2	1.2
	Density	kg/m**3	1060	1060
PS-18 vol% Paper Fiber Composite:				
	Tensile Strength	MPa	31	31
	Tensile Modulus	GPa	1.9	1.9
	Density	kg/m**3	1150	1150

Preliminary Screening Test Results

A number of paper treatment techniques were surveyed and tested in order to identify the most promising options. Initial coupling agent screening tests were performed to qualitatively assess fiber-to-matrix bond enhancement using treated paper sheet bonded to plastic film to form shear test specimens.

Paper sheets were water and acid washed prior to drying under vacuum at 150° C. Acid washing removes surface extractive oils and has been shown in the literature to improve fiber adhesion in bonded fiber board.[11] Nitric acid washes in the range 0.1-M to 0.5-M were evaluated. An acid concentration of 0.1-M provides an acidic wash solution with negligible strength degradation in the treated paper sheet.

Using the washed paper samples, plastic-to-plastic and plastic-to-paper bonding experiments were performed to study bonding effects and identify processing parameters. Initial bonding runs were performed at 150° C and 3-MPa pressure. This temperature proved to be too high, causing polyethylene (PE) and PS to flow excessively, bonded to themselves, and adherent to the paper. After further tests, processing parameters of 115° C at 3.5-MPa for PE and 100° C at 3.5-MPa for PS were selected for paper-to-film bonding. Higher temperatures produced paper adherence levels which caused peel specimens to fail within the paper sheet. All processing began with a ramp of 15 - 20 minutes to process temperature, 15 minutes at temperature, followed by a cool down ramp of 15 - 30 minutes to handling temperatures (below 70° C).

Bonding tests using PET film failed to successfully pressure bond PET to itself or paper at conditions up to 230° C at 5-MPa. Temperatures above 190° C were found to significantly degrade paper tear strength. These results indicate PET is inappropriate for the process under investigation, and it was omitted from further testing. PET processing should be further evaluated for composite applications using other reinforcements. It has adequate strength for many structural applications and it's moderate stiffness can be considerably enhanced by compounding with a high modulus particulate such as pulverized MSW glass.

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[11] *Emerging Technologies*, Rowell, R.M.; Schultz, T.P.; Narayen, R.; Young, R.A.; Philippou, J.L.; Barbutis, J.; *Bonding and Molding of Chemically Modified Whole Wood Fibers*, presented at International Chemical Congress, Am. Chem. Soc., Honolulu, HI, December, 1989

After processing parameters were identified, tests were performed to evaluate chemical treatment of the paper fibers. Dried, acid washed paper strips were refluxed in xylene containing suitable concentrations of coupling reagent to react with the available hydroxyl functionality of cellulose. The hydroxyl equivalent value used was 1E-03 gmoles per gram of paper based on literature data for acetylation of wood by acetic anhydride. [12]

Treated paper strips were compression bonded to plastic film. After bonding, the paper was peeled awary from the film to study the quality of the bond. The condition of the paper fibers and the amount of pull out from the plastic was observed. Results of these test are reported in Table 5. This particular screening approach proved fruitless. None of the tests resulted in adequate discrimination from the baseline untreated paper. It is suspected that the process temperatures were too low for significant chemical or physical bonding to occur. However, as reported above, higher temperatures resulted in adhesion exceeding paper tear strength which also prevented effective discrimination.

Table 5. Material Screening Peel Tests Did Not Provide Adequate Process Discrimination

Substrate	Treatment	Result
Polyethylene (PE)		
	None	Baseline
	Acid washed (AW)	Negligible effect
	Benzoic anhydride	Negligible effect
	Phthalic anhydride	Negligible effect
	Maleic anhydride	Negligible effect, paper weakened
	Maleic anhydride plus epoxy	Negligible effect, paper weakened
	Maleic anhydride adducted polypropylene wax (E-43)	Negligible effect
	E-43 plus epoxy	Negligible effect
	Polyazelaic polyanhydride (PAPA)	Negligible effect
	PAPA plus epoxy	Negligible effect
Polystyrene (PS)		
	None	Baseline
	Acid washed (AW)	Negligible effect
	Benzoic anhydride	Possible improvement
	Phthalic anhydride	Negligible effect
	Maleic anhydride adducted polystyrene	Negligible effect
	Maleic anhydride adducted polypropylene wax (E-43)	Reduced adherence
	E-43 plus epoxy	Reduced adherence
	Polyazelaic polyanhydride (PAPA)	Reduced adherence
	PAPA plus epoxy	Reduced adherence

A second round of screening tests was performed in which paper disks were compression laminated to plastic film. This was performed by stacking alternating layers of plastic film disks and paper disks and heating them under pressure. Laminating was performed at 170° C and 5-MPa for both PE and PS.

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[12] Emerging Technologies, Rowell, R.M.; Schultz, T.P.; Narayen, R.; Rowell, R.M.; in *Proceedings of the Composite Wood Products Symposium*; Burton, R.J.; Tarlton, G.L., Eds.; Rotorua, New Zealand, 1990, pp. 57-67.

All processing began with a ramp of 15 - 20 minutes to process temperature, 30 minutes at temperature, followed by a cool down ramp of 15 - 30 minutes to handling temperatures (below 100° C).

Qualitative shear, bend and peel tests were performed on the laminated disks. Peel tests were performed by manually peeling off layers of the laminate. Bend tests consisted of manually bending the disk to the point of failure (breaking it in half). For shear testing, a pie slice section of the disk was cut using tin shears. In each case, the disk was examined under a microscope to observe the resulting state of the fibers and film. Improved wetting of the paper sheet and enhanced fiber-to-plastic adhesion were apparent in a number of cases. Treatments tested and resulting observations are summarized in Table 6 and Table 7. These experiments provided adequate discrimination from the baseline untreated paper to down select to the most promising fiber treatments for tensile bar testing. Weight percent data reported in Table 6 and Table 7 identify the level of additive used relative to total weight of a hypothetical composite containing 20 wt% fiber.

Table 6. Laminated Disk Tests Identified Effective Fiber Treatments for Improved Interfacial Bonding to HDPE

Substrate	Treatment	Result
Polyethylene		
	None (acid washed)	Baseline. Fibers loosely adherent. Not wetted.
√ (= selected for tensile testing)	1.6 wt% maleic anhydride adducted polybutadiene plus 0.5 wt% epoxy	Very good adherence to PE. Paper fibrous char. retained. Improved peel strength. Improved wetting & translucence.
√	3.3 wt% maleic anhydride adducted polypropylene wax	Good adherence to PE. Paper waxy throughout with fibrous character.
√	3.3 wt% maleic anhydride adducted polypropylene wax plus 0.5 wt% epoxy	Very good adherence to PE. Paper waxy and dense with less fibrous character.
	0.3 wt% maleic anhydride adducted polypropylene wax plus 0.1 wt% epoxy	Improved adherence. Not as effective as 3.3%
	1.0 wt% polyazelaic poly-anhydride plus 1.6 wt% epoxy	Negligible improvement. Paper sheet strongly bonded to self. Fiber character lost.
	0.3 wt% polyazelaic poly-anhydride plus 0.5 wt% epoxy	Negligible improvement. Paper sheet strongly bonded to self. Fiber character lost.
	1.0 wt% phthalic anhydride	Negligible improvement. Paper adherent to self.
	1.0 wt% phthalic anhydride plus 1.9 wt% epoxy	Negligible improvement. Paper adherent to self.
	1.0 wt% maleic anhydride	Improved adherence. Paper sheet notably degraded.
	1.0 wt% maleic anhydride plus 0.5 wt% epoxy	Good adherence. Paper sheet notably degraded.

Table 7. Laminated Disk Tests Identified Effective Fiber Treatments for Improved Interfacial Bonding to PS

Substrate	Treatment	Result
Polystyrene		
	None (acid washed)	Baseline. Fibers loosely adherent. Not wetted.
	1.6 wt% maleic anhydride adducted polybutadiene plus 0.5 wt% epoxy	Negligible improvement. Paper adherent to self.
√ (selected for tensile testing)	1.6 wt% maleic anhydride adducted polybutadiene plus 0.01 wt% benzoyl peroxide	Good adherence. Fiber character retained.
√	1.0 wt% maleic anhydride adducted polystyrene	Good adherence and wetting. Fiber character retained.
√	1.0 wt% maleic anhydride adducted polystyrene plus 0.7 wt% epoxy	Very good adherence and wetting. Fiber character retained.
√	1.0 wt% phthalic anhydride	Good adherence and wetting. Fiber character retained.
√	1.0 wt% phthalic anhydride plus 1.9 wt% epoxy	Good adherence and wetting. Fiber character retained.
	1.0 wt% maleic anhydride	Improved adherence. Paper sheet notably degraded.
	1.0 wt% maleic anhydride plus 0.5 wt% epoxy	Good adherence. Paper sheet notably degraded.

Tensile Property Test Results

On the basis of the preliminary screening results, the most promising treatments were selected and tensile specimens were prepared for evaluation of material properties. Compression molding tooling for manufacture of ASTM D638 Type I specimens was designed and fabricated. Materials used for specimen production were extruded several times to enhance mixing. The extruded material was then compression molded under temperature. PS specimen compositions are summarized in Table 8. HDPE specimen compositions are summarized in Table 9. Four PS specimens were tested per composition. Four unreinforced and five reinforced HDPE specimens were tested per composition. A total of 32 PS and 32 HDPE specimens were tested.

All tensile bars produced were compounded with 25 wt% fiber in the polymer matrix. Tensile bars of unreinforced PS weighed 7.9-g and were known to have a density of 1.047-g/cm^3. Tensile bar volume was therefore 7.55-cm^3. Paper filled tensile bars weighed 8.7-g. From these data, the apparent fiber density is calculated as 1.65-g/cm^3. This calculation agrees well with a xylene volumetric displacement measurement which gave 1.5-g/cm^3 for the dried bulk fiber.

Fiber density data enables an improved volume fraction determination for 25 wt% fiber composites. PS composite density was calculated as 1.15-g/cm^3 with 18 vol% fiber. Tensile bars of unfilled HDPE weighed 6.1-g and 25 wt% composite specimens weighed 7.0-g. HDPE matrix density is known at 0.950-g/cm^3. Composite density is calculated as 1.06-g/cm^3 with 16 vol% fiber.

Paper fiber volume fraction is plotted versus composite density for PS and HDPE in Figure 5. Calculated relations for glass fiber volume fraction versus density in PET-fiberglass composites are also shown. Figure 6 displays weight fraction to volume fraction relations for these three composites.

Table 8. Polystyrene Composite Formulations for Tensile Property Testing

Interfacial Agent	I/F Agent wt% In Composite	Crosslinking Agent	C/L Agent wt% In Composite
None (control)	-	None	-
Maleic anhydride adducted polybutadiene	1.0	Benzoyl peroxide (initiator)	0.006
Maleic anhydride adducted polystyrene	1.0	None	-
Maleic anhydride adducted polystyrene	1.0	Epoxy (diglycidal ester of bisphenol A type)	0.7
Phthalic anhydride	1.0	None	-
Phthalic anhydride	1.0	Epoxy	1.8

Table 9. Polyethylene Composite Formulations for Tensile Property Testing

Interfacial Agent	I/F Agent wt% In Composite	Crosslinking Agent	C/L Agent wt% In Composite
None (control)	-	None	-
Maleic anhydride adducted polybutadiene	1.0	Benzoyl peroxide (initiator)	0.006
Maleic anhydride adducted polybutadiene	1.0	Epoxy (diglycidal ester of bisphenol A type)	0.3
Maleic anhydride adducted polypropylene	1.0	None	-
Maleic anhydride adducted polypropylene	1.0	Epoxy	0.2

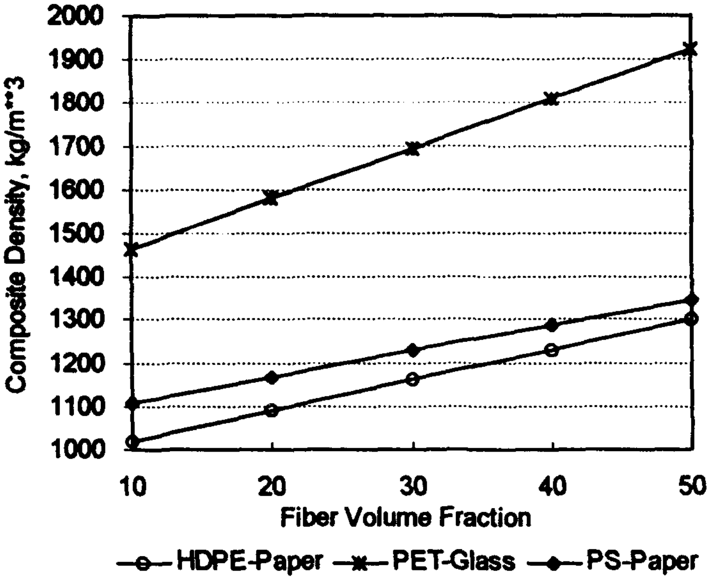

Figure 5. Composite Density vs. Fiber Volume Fraction

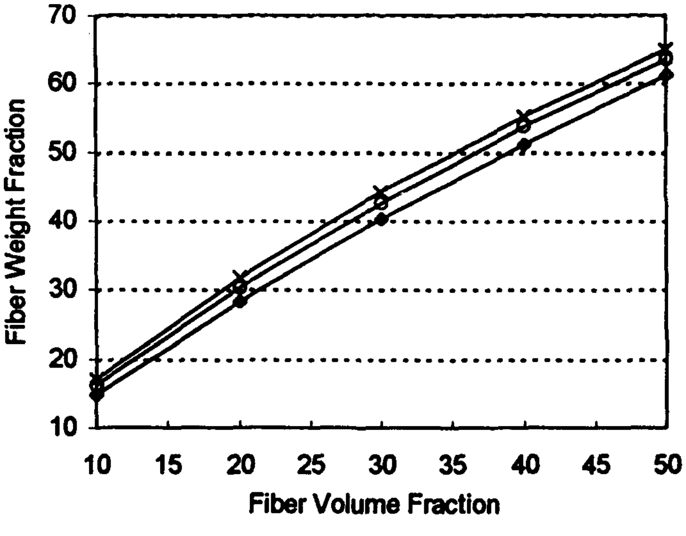

Figure 6. Composite Fiber Weight Fraction vs. Volume Fraction

Tensile test results for PS-paper composites are summarized in Figure 7. Actual test data are included as Appendix A. Paper fiber did not effectively strengthen PS composites because of its low strength. Apparent tensile strength of the fiber was on the order of 30-MPa. Strength of the PS matrix was measured at 38-MPa. Visual examination reveals that fibers are broken off rather than pulled out of the fracture surface in both control and treated specimens. This means coupling agents can provide no strength enhancing effect for PS-paper fiber composites. All treated specimens performed consistently with the control at an average tensile strength of 21-MPa.

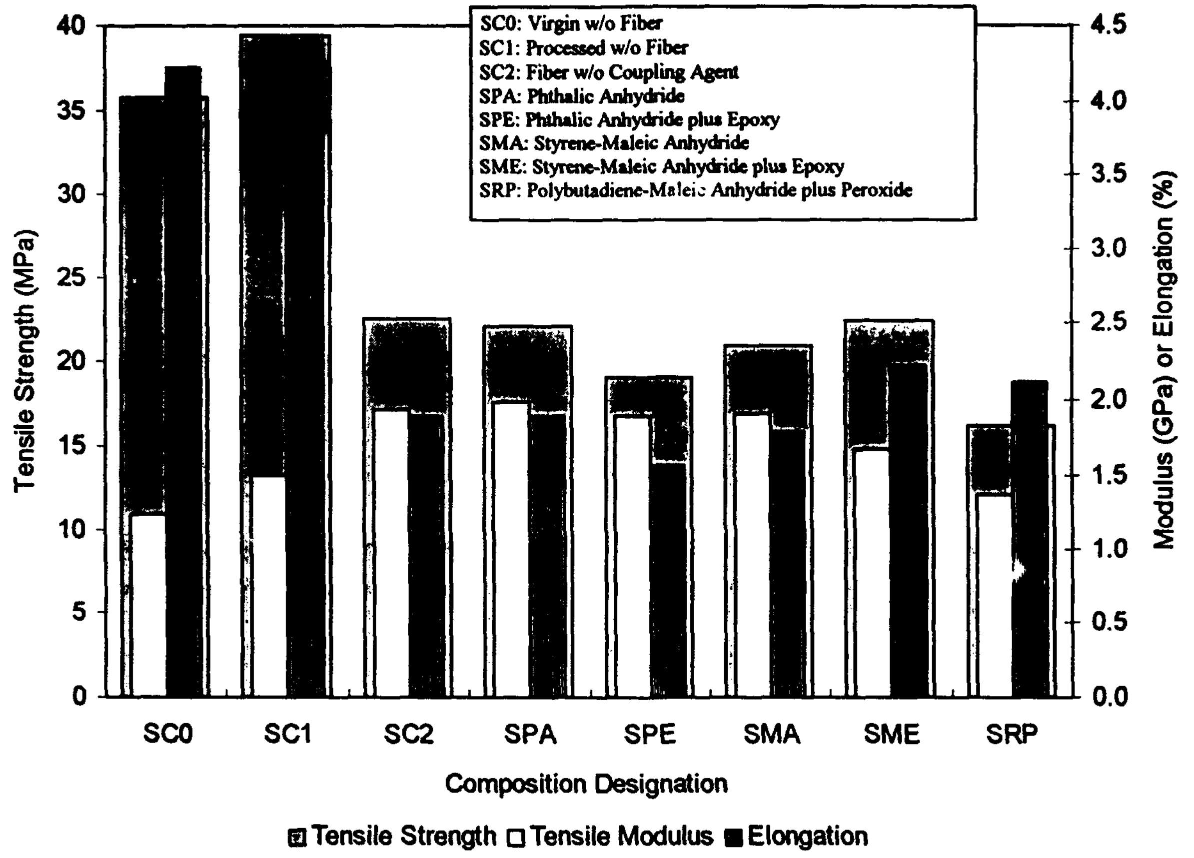

Figure 7. Tensile Test Results for PS-Paper Fiber Composites

Considered as a group, these data provide a statistically significant measurement of the strength, modulus and elongation of paper filled polystyrene. Modulus improvements were classic for a filled composite. The PS matrix modulus was measured at 1.4-GPa. With 18 vol% fiber, the composite modulus measured 1.9-GPa. The apparent paper fiber modulus was 18-GPa. The elongation at break was 4% for the matrix and 1.9% for the filled composite.

Tensile test results for HDPE-paper composites are summarized in Figure 8. Actual test data are included as Appendix B. HDPE matrix yield strength was measured at 21-MPa. Fiber pull-out was observed in the fracture surfaces. The effect of fiber treatment was apparent in the tensile strength data. Because of random fiber orientation and low fiber strength the composite yield strength was only 14-MPa for untreated fiber and 19-MPa for the most effective treatment. At treatment levels of 1%, coupling agents increased paper composite strength between 10% and 35%.

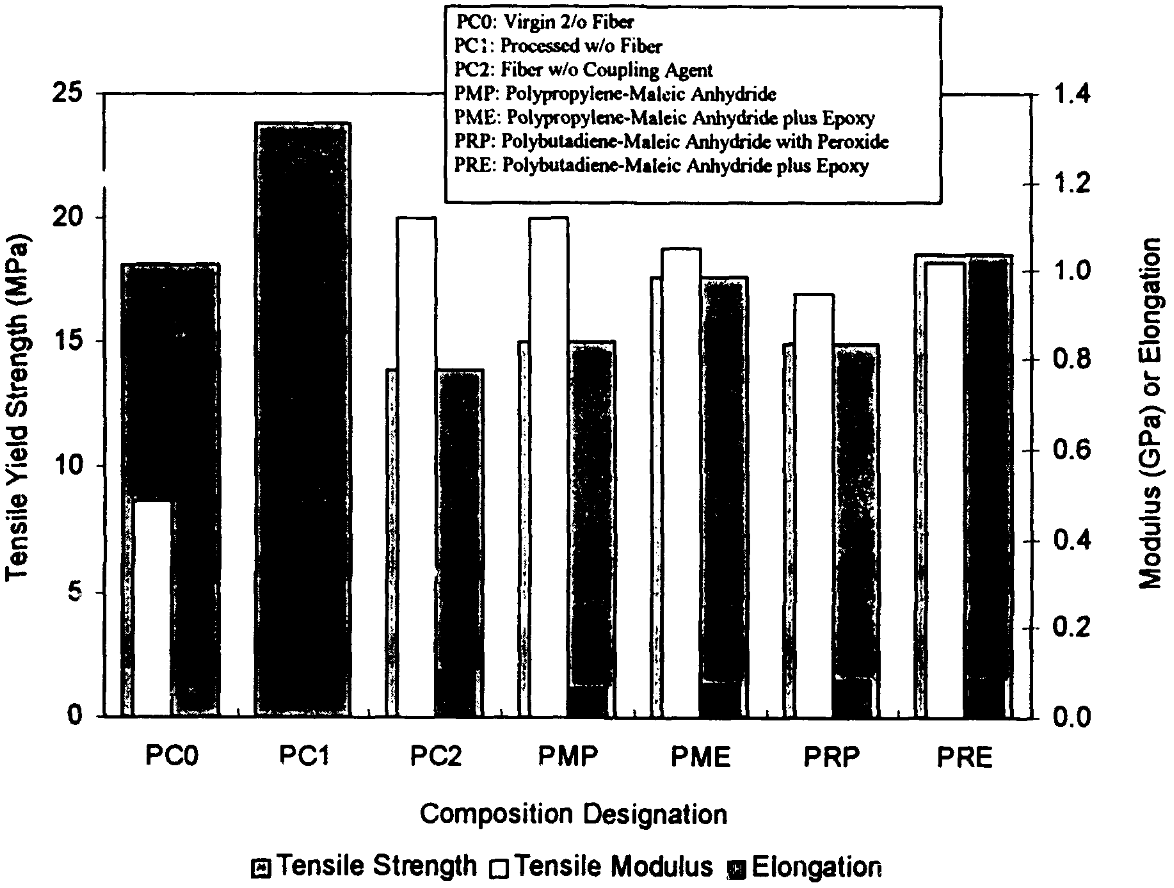

Figure 8. Tensile Test Results for HDPE-Paper Fiber Composites

Modulus and elongation data obtained for unreinforced HDPE were not meaningful due to difficulties experienced in testing. A typical literature value for modulus of HDPE is 0.5-GPa at a density of 0.95-g/cm^3.[13] Composite specimens displayed a modulus of 1.1-GPa at 16 vol% fiber. The HDPE composite modulus also fits an apparent paper fiber modulus of 18-GPa. Elongation at break was measured at 0.08% for the composite.

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[13] Strength and Fracture of Engineering Solids, Felbeck, D.K.; Atkins, A.G.; Prentice-Hall, 1984

Summary of Materials Research Results

The data indicates that the paper fibers used in the composite have much lower strength than handbook values for cellulose fibers. This is presumed to be an indication that chemical and mechanical processing used in the manufacture of paper greatly reduce the tensile strength of the wood-based fibers. Literature values for wood fiber strength are one to two orders of magnitude greater than the apparent paper fiber strength observed.[14] In order to be useful, structural PS or HDPE composites made from 100% MSW recoverable constituents will require a much higher strength fiber reinforcement. An alternative might be to use raw wood fibers from ground whole wood reclaimed from pallet or construction waste. This combination is currently in use in plastic wood products.

The anhydride-based coupling agents investigated appear to be effective in improving fiber to HDPE matrix bonding. In particular, anhydride-based polymer grafting to cellulose with epoxy cross-linking is a promising coupling agent technology.

PS applications are particularly important for MSW reduction since markets for reclamation of this resin have been slow to develop. PS-paper composites demonstrate properties suitable for non-structural sheathing applications. The PS composite has a honey brown color and a textured, light diffusing opacity. It might be used for interior sheathing board or equipment enclosures and non-load bearing shade or cover structures including roll-up garage door panels and carports.

HDPE-paper properties suggest non-structural sheet or sheathing applications similar to those recommended for PS-paper composite. HDPE-paper and PS-paper composite products may be readily produced using conventional extrusion and injection molding techniques.

PET composites require processing temperatures which preclude wood-based fiber reinforcements. Chopped fiberglass reinforcement is commonly used in high performance virgin PET applications. Reclaimed PET resin demands a higher market price than HDPE and PS because technology exists to reuse PET in original packaging applications. Local production of reclaimed PET sheet using structural chopped fiberglass may be a viable alternative for production of a structural material.

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[14] Mechanical Properties, Collyer, A.A.; Czarnecki, L.; White, J.L.; *J. Appl. Polym. Sci.*, 1980, 25, pp. 1217-1244.

3 MANUFACTURING PROCESS DEVELOPMENT

A preliminary design of a production line process to produce composites from recycled PS and HDPE was performed in order to evaluate the feasibility of transferring the laboratory techniques tested to large scale production. Initial efforts focused on the sizing and economics of a sub-scale pilot plant.

Preliminary Sizing of Sub-Scale Pilot Plant

When selecting process equipment for a new product, the preliminary study must be sufficiently detailed to ensure profitable production. Pilot plant studies are normally performed to establish the controlling process factors. These factors in turn drive the production economics. The pilot plant studies are used to select and install equipment which will operate in quantity production at minimum over-all cost.

Preliminary design and analysis of a 1/20th scale pilot plant facility was completed. Such a facility would be appropriate for converting HDPE or PS/EPS recoverable from MSW into useful sheet product for a town or Army instaallation of 17,000 persons. The pilot plant was sized for production of 250-kg of composite per day in single shift operations. Pilot plant sizing is summarized in Table 10.

Table 10. Pilot Plant Sizing for 250-kg/day Production

	Units	HDPE	PS/EPS
Composite Production Rate	kg/hr	40	40
Productive Hours per Year	hr	1250	1250
Extruder Efficiency	kg/hr/hp	2.0	3.0
Extruder Size	hp	20	13
Installed Power	kW	15	10
Screw Diameter, Typical	mm	50	50
Barrel L/D Ratio, Typical		25:1	25:1
Maximum Operating Pressure	Mpa	70	70
Maximum Sheet Width	m	1.0	1.0
Maximum Sheet Thickness	mm	6.0	6.0

The pilot plant consists of fiber and plastic preprocessing equipment, composite compounding equipment, sheet extrusion equipment, and post forming equipment. Auxiliary equipment are required for loading and handling feedstocks and finished product. Floor space for production, warehousing and administrative activities is necessary. A preliminary layout for the pilot plant is defined in Figure 9. Equipment required is summarized in Table 11.

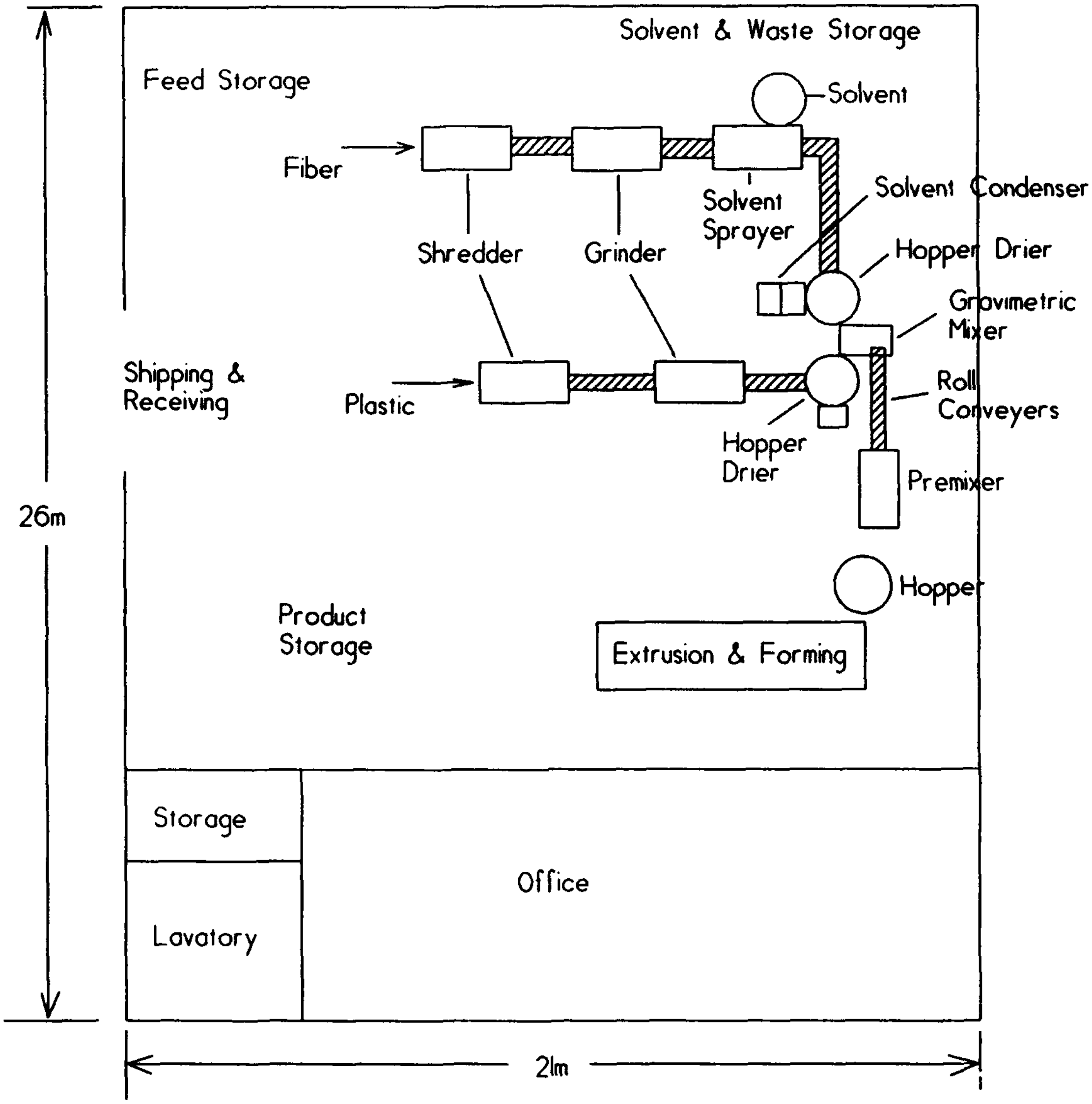

Figure 9. Preliminary layout for pilot processing plant.

Table 11. Pilot Plant Equipment Summary

Equipment	Qty	Size
Shredder	1	15 kW
Grinder, Wood Waste	1	15 kW
Grinder, Plastic	1	15 kW
Spray Chamber/Conveyor	1	2 m^3/hr
Hopper-Drier	2	2 m^3
Gravimetric Mixer	1	50 kg
Mixer / Pellatizer	1	30 kW
Hopper	1	2 m^3
Extruder	1	15 kW
Sheet Take Off	1	1 m
Pneumatic Shear	1	5 mm

Fiber Preprocessing

Reclaimed paper fiber is available in bulk from established paper reclamation facilities or brokers. Capital equipment for paper fiber reclamation and deinking favors large, regionally centralized processors. This is largely due to the chemical processing and waste handling issues associated with fiber reclamation from waste paper. These facilities produce fiber suitable for manufacture of 'new' paper goods.

It is possible that mechanically shredded raw waste paper could be used as feedstock instead of washed, reclaimed fiber for producing a filled plastic composite. The effects of the inks present in raw paper on the composite are unknown at this time and would need further investigation. Simple mechanical shredding enables the use of very low cost feed and is more suitable for local composite production. Eliminating wash and deink processing eliminates the toxic waste handling requirement and dramatically reduces the energy requirement to dry the fiber.

Mechanical processing equipment selected for pilot plant studies will be equally effective for producing wood fiber from MSW pallet or construction waste. The strength properties of reclaimed wood fiber are believed to be one to two orders of magnitude higher than those observed for paper fiber, as discussed earlier. Wood fiber enhanced with coupling agents may provide reinforcement properties suitable for structural composite applications. All elements of the pilot plant design are suitable for wood fiber composite processing.

Moisture content of reclaimed fiber will typically range from 10% to 20% by weight. The fiber will be stored and dried in hopper dryers to approximately 1% moisture by weight prior to treatment with acid anhydride coupling agents. Conventional hopper dryers are readily available for controlling the moisture content of bulk materials such as paper and plastic.[15]

Fiber treatment with interfacial coupling agents was accomplished in the laboratory using solvent immersion for reagent transport and solvent reflux for residence time at reaction temperatures. The drawbacks of batch immersion processing include significant solvent absorption by the fiber mass. Absorbed solvent must be subsequently evaporated and recovered requiring additional process equipment and substantial energy penalties.

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[15] Product literature for plastics hopper-driers, Novatec, Inc., Baltimore, MD

Similar reaction temperatures and residence times may be accomplished in a continuous process using a fluidized bed reactor. In such a reactor, untreated fiber is continuously fed to the fluidization chamber. A solvent solution of the treatment reagent is injected into the fiber mass with the heated fluidization air stream. The solvent evaporates on contact with the heated fiber bed thereby coating the fibers with reagent. Input fiber is continuously added and treated fiber removed from the reactor at a rate appropriate for the statistical residence time of the reactor. Solvent is recovered from the fluidization air flow using a condenser and recycled with addition of additional reagent. A closed air flow system eliminates solvent losses and environmental emissions.

The significant disadvantage of a fluidized bed reactor is the need for design, manufacture and operations support of the necessary equipment. The fluidized bed reactor requires pressurized feed hoppers and screws, solvent pumps, blowers, condensers, and cyclones each of which contribute to plant acquisition and production costs. An alternative meriting further study is reactive extrusion processing wherein the fiber and treatment reagents are reacted with adequate temperature and residence time during composite compounding operations.

Reactive extrusion processing greatly simplifies fiber treatment processing. Fibers may be dry mixed with powdered reagents or spray coated with solvent solutions at ambient temperatures and pressures. If solvent spray coating is selected, conventional drying equipment may be used for solvent recovery with far fewer complications than a fluidized bed reactor. Reactive extrusion processing was selected for pilot plant design. Further laboratory study is merited prior to final design selection.

Pilot plant designs presume the capability to produce and compound treated fiber composites. Fiber treatment improves load transfer across the fiber-matrix interface to enable effective utilization of the fiber strength in the composite material. The data gathered for this effort indicate that paper fiber is too weak to reinforce PS and serves only as a modulus enhancing filler. It is therefore unnecessary to treat paper fiber for PS-paper composites. Paper fiber treatments are marginally beneficial in HDPE-paper composites due to very low fiber strength. Composites produced from higher strength wood fibers recoverable from MSW, however, should from interfacial bond enhancement.

Plastic Preprocessing

Recycled HDPE and PS/EPS plastic will be purchased in bulk from recyclers or brokers. Materials are typically sorted and baled. Baled material will be shredded, washed and granulated using conventional plastics recovery equipment. Granulated plastic will be dried using hopper dryers. Plastic will require drying to less than 1% moisture if reactive extrusion processing is used, otherwise up to 5% moisture is acceptable.

Compounding Methods

Dry bulk mixing and extrusion methods for compounding plastic with dried paper fiber were evaluated in the materials testing effort. Dry bulk mixing followed by hot pressing offers the simplest fabrication approach for sheet material. However, the most effective approach was found to be extrusion wherein the polymer is melted and intimately mixed with the dispersed fiber. Extrusion is more effective because the extremely low bulk density of paper fiber makes it difficult to obtain a uniform dry mix. Dry bulk mixing was improved using finely pulverized plastic but uniformity of fiber distribution was clearly better after extrusion processing.

In production, extrusion (melt) compounding eliminates the need to finely grind or pulverize the plastic. Room temperature production of fine plastic powders for dry mixing was shown to be ineffective due to the tendency of the plastic pellets to ball up and melt in the grinding mill. Cryogenic processing of HDPE and PS was evaluated for powder production. Plastic pellets were chilled by immersion in liquid nitrogen prior to introduction into the mill. Cryogenic processing was found to significantly improve pulverization rates of PS. HDPE, however, remained difficult to process at liquid nitrogen temperature, tending to flow and smear rather than pulverize.

Extrusion processing also provides temperatures and residence times sufficient to consider reactive fiber treatment in situ during the mixing and sheet forming process, e.g., reactive extrusion. Reactive extrusion significantly simplifies the production process by eliminating the separate fiber-coupling agent reaction step. Process optimization studies are necessary to determine if reactive extrusion can provide equivalent interfacial strength enhancement to improve composite properties.

It may be preferable to premix and pelletize the fiber and plastic prior to feeding the material to a conventional sheet forming line. This is because a non-uniform feed rate or density can cause extruder surging leading to reduced equipment life and poor product uniformity.[16] A number of manufacturers make premixing stations suitable for this preprocessing. A batch mixer size of 0.2-m^3 (50-gal) working capacity and 25-kW power was selected for the pilot plant. Evaluation of premixed versus bulk mixed feed effects on product quality and uniformity will be an important pilot plant activity.

Sheet Forming

Conventional plastic extrusion equipment is well suited to production of fiber reinforced HDPE and PS sheet. Sheet extrusion of high viscosity fiber reinforced plastic is a good processing selection since resistance of the long horizontal sheet die is low compared to other die forms.[17] Sheet extrusion lines are commercially available as turn-key systems in the 20-hp size required for pilot plant studies.[18] This enables process development to proceed using well established designs with a substantial production data base. The primary elements of a commercial thermoplastic sheet extrusion line are illustrated in Figure 10.

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[16] Plastics Extrusion Technology, Griff, A.L.; Reinhold Plastics Applications Series, 1968

[17] Plastics Extrusion, Griff

[18] Product literature for plastic sheet extrusion systems, Welex, Inc., Blue Bell, PA

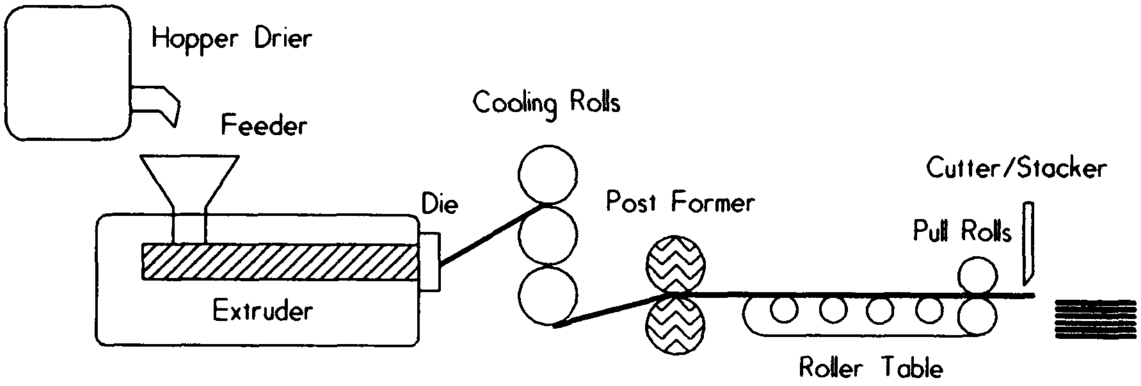

Figure 10. Commercial thermoplastic sheet extrusion line.

At least one manufacturer makes a turn-key sheet extrusion line customized for continuous compounding of ground paper or wood waste with plastic. This system uses two converging extruders to uniformly feed melted polymer to the fiber transport screw. Over twenty of these systems are in operation, primarily in Europe. One system has been recently installed in the United States (Lancaster, SC)[19].

Post Forming and Handling

Sheet extruded composite is well suited for continuous post forming into flats, corrugated panels, channel and other contours. Most manufacturers of sheet extrusion equipment offer integrated systems for sheet handling, post forming, embossing, and laminating.

After leaving the extruder die, the still molten material is drawn through polished metal cooling rolls which solidify the sheet and provide thickness control. Embossing of surface textures or laminating of surface films is normally combined with this process step. Post formers for corrugated sheet follow the primary cooling rolls. The formed sheet is then drawn across a roller table which provides additional cooling at a controlled rate. At the end of the table, the sheet reaches the pull rolls which feed the product to cutters, stackers and other handling equipment.

4 ECONOMIC ANALYSIS

An economic analysis was performed to verify commercial feasibility of the a production process to manufacture paper/plastic composite sheet stock. Analyses were performed for both the pilot plant and production plant sizings.

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[19] *B.G. Plast Product Brochure,* Via V. Bellini, 1/3, 20095 Cusano Milanino (Milano, Italy), represented in US by Tex America, 4717 Sweden Rd., Charlotte, NC 28273. (704)-552-5404, Fax (704) 552-5854.

Pilot Plant Economics

Pilot plant production economics were evaluated using methods described below. Cost factors for pilot plant production are summarized in Table 12. Bulk, unprocessed paper or wood waste and plastic feeds are assumed. Fiber is produced by mechanical shredding, and then dried and spray coated with an interfacial bond enhancing reagent for reactive extrusion. Plastic is shredded, washed, granulated and dried. Fiber and plastic are premixed and pelletized. The product form is flat sheet produced by extrusion.

Table 12. Cost Factors for Pilot Plant Production

Factor	Units	HDPE	PS/EPS
Composite Production Rate	kg/hr	40	40
Productive Hours per Year	hr	1250	1250
Cost of Plastic Feed	$/kg	$0.20	$0.15
Cost of Paper Feed	$/kg	$0.10	$0.10
Cost of Additives	$/kg	$4.20	$4.20
Additive as Weight Percent	%	1.0%	1.0%
Cost of Solvent	$/kg	$1.00	$1.00
Solvent to Additive Ratio	%	2000%	2000%
Solvent Recovery Factor	%	99.0%	99.0%
Ratio Line to Extruder Power	%	125%	125%
Cost of Electricity	$/kW/hr	$0.11	$0.11
Cost of Labor	$/hr	$22.50	$22.50
Number of Operators per Line	-	2	2
Maint and Supplies, % Inst Cost	%/yr	5%	5%
Equipment Capital Cost	$	$525,000	$525,000
Installation/Start-Up Cost	$	$75,000	$75,000
Total Installed Capital Cost	$	$600,000	$600,000
Facility Lease Costs	$/yr	$5,000	$5,000
Property Tax and Insurance Rate	%/yr	2%	2%
Sales Expense, % of Feed Cost	%	20%	20%
General and Administrative Ratio	%	15%	15%
Assets Employed	$/yr	$634,097	$633,589
State and Federal Income Tax Rate	%	50%	50%

Product economics are summarized in Table 13. Economic analyses consider two cases. In the first case, fiber and plastic feeds are purchased from recyclers or brokers at market price and processed using labor at commercial wage rates. Because the labor required to run a small extrusion line is similar to labor for a much larger line, labor contributes a high share of product cost in pilot plant operations.

Table 13. Summary of Pilot Plant Processing Economics

		Commercial Production		On Base Production	
	Units	HDPE	PS/EPS	HDPE	PS/EPS
Cost of Feedstocks	$/kg	$0.194	$0.169	$0.044	$0.044
Cost of Electricity	$/kg	$0.051	$0.034	$0.051	$0.034
Cost of Labor	$/kg	$1.872	$1.872	$1.872	$1.872
Cost of Maint and Supplies	$/kg	$0.525	$0.525	$0.525	$0.525
Depreciation Expense, 10 yr SL	$/kg	$1.200	$1.200	$1.200	$1.200
Cost of Facility Lease	$/kg	$0.100	$0.100	$0.000	$0.000
Property Tax & Insurance Expense	$/kg	$0.240	$0.240	$0.240	$0.240
Sales Expense	$/kg	$0.039	$0.034	$0.000	$0.000
G&A Expense	$/gk	$0.389	$0.385	$0.366	$0.366
Production Cost, $/kg		$4.610	$4.559	$4.058	$4.041
Gross ROA, $/kg @ 20.0%		$2.536	$2.534	$0.000	$0.000
Market Price, $/kg		$7.146	$7.093	$4.058	$4.041
$/m^2 @ 6-mm thick		$51.838	$54.561	$29.440	$31.086
$/ft^2 @ 0.25-in thick		$5.097	$5.365	$2.894	$3.056

At an Army installation, 'captive' production economics may be calculated differently. In the second case (Table 13), fiber and plastic materials are recovered from an on-base collection facility. These materials are then available at negligible additional cost to the base processing facility. The composite product produced is used internally to provide cost avoidance for materials otherwise procured in performance of base maintenance and construction. In this case fiber and plastic feed costs, facility lease, sales expense, insurance and property taxes, and return on assets employed (profit) are not considered in the analysis. Remaining production costs are recovered in whole or part by procurement cost avoidance for alternative materials. Labor costs, included in Table 13, for production and general and administrative expense may also be deducted for captive applications if the net effect on base operations is negligible.

Production Facility Sizing

The production plant economic analysis was based on preliminary sizing of a production facility suitable for handling MSW plastic and wood fiber waste in quantities generated by a municipality of 1 million persons. Production facility sizing is summarized in Table 14.

Table 14. Production Plant Sizing for Municipality of 1 Million Persons

	Units	HDPE	PS/EPS
Total Recoverable Resin	kg/yr	8.36E+06	4.18E+06
Recovery Factor for Composite Feed	%	10%	10%
Total Composite Production	kg/yr	1.67E+06	8.36E+05
Productive Hours per Year	hr/yr	1500	1500
Composite Production Rate	kg/hr	1115	557
Extruder Efficiency	kg/hr/hp	2.0	3.0
Extruder Size	hp	557	186
Installed Power	kW	416	139
Screw Diameter, Typical	mm	150	120
Barrel L/D Ratio, Typical	-	25:1	25:1
Maximum Operating Pressure	Mpa	70	70
Maximum Sheet Thickness	mm	6.0	6.0
Maximum Sheet Width	m	1.5	1.5

U.S. Environmental Protection Agency (EPA) data indicate an estimated per capita MSW generation of 1.9-kg/day.[20] Of this, 8% is plastic waste. The plastic fraction contains 1/3 to 2/3 (here assumed 50%) post consumer packaging waste. Packaging fractions by resin are 30% for HDPE, 15% for PS/EPS, and 8% for PET.[21] A recovery factor of 10% was assumed for sizing the facility. These factors were used to calculate the total available plastic feedstock per year per 1 million persons.[22]

A composite consisting of 50% by weight resin was assumed for sizing studies. Facility sizing assumes single shift operations with 1500 productive hours per year. Resulting machine sizes are well within the capability of available turn-key production systems.[23] Multiple shift operations require trade offs between higher labor costs and lower acquisition (depreciation) costs for smaller machines. Initial trades favor large machines.

Extruder sizing was based on production experience data for HDPE and PS resins.[24] Extruder efficiency is typically expressed in terms of kilograms output per hour per horsepower. Efficiencies for HDPE range from 2 to 3.5-kg/hr/hp. Efficiencies for PS range from 3 to 5-kg/hr/hp. The low end of each range was selected to account for inefficiencies due to fiber content. A 400-kW (550-hp) class machine is indicated for HDPE- 50% fiber composite processing at a 1100-kg/hr production rate. A 150-kW (200-hp) class machine is indicated for PS- 50% fiber composite processing at a 550-kg/hr production rate.

Economic Factors

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[20] *Decisionmaker's Guide to Recycling Plastics,* United States Environmental Protection Agency, Region X Solid Waste Program, EPA 910/9-91-008, December 1990.

[21] EPA 910/9-91-008.

[22] EPA 910/9-91/008.

[23] Product literature, Welex, Inc.

[24] Product literature, Welex, Inc.; Plastics Extrusion, Griff.

Economic factors used to estimate unit production costs were based on current trade data, vendor pricing for materials and equipment, process relationships, and typical estimating factors for other direct and indirect costs. Economic factors selected are summarized in Table 15.

Table 15. Economic Factors for MSW Processing

	Units	HDPE	PS/EPS
Cost of Plastic Feed	$/kg	$0.20	$0.15
Cost of Paper Feed	$/kg	$0.10	$0.10
Cost of Additives	$/kg	$4.00	$4.00
Additive as Weight Percent	%	1.0%	1.0%
Cost of Solvent	$/kg	$1.00	$1.00
Solvent to Additive Ratio	%	2000%	2000%
Solvent Recovery Factor	%	125%	125%
Cost of Electricity	$/kW-hr	$0.11	$0.11
Cost of Labor	$/hr	$22.50	$22.50
Number of Operators per Line	-	2	2
Maint and Supplies, % Inst Cost	%/yr	5%	5%
Equipment Capital Cost Per Line	$	$1,175,000	$1,025,000
Installation & Start Up Cost	$	$625,000	$625,000
Total Installed Capital Cost	$	$1,800,000	$1,800,000
Facility Lease Costs	$/yr	$15,000	$15,000
Property Tax and Insurance Rate	%/yr	2%	2%
Sales Expense, % of Feed $	%	10%	10%
General and Administrative Ratio	%	15%	15%
Assets Employed	$/yr	$1,942,668	$1,733,544
State and Federal Income Tax Rate	%	50%	50%

Feedstock Costs

February 1994 trade data for HDPE prices range from $0.07 to $0.25 per kilogram for natural material and $0.01 to $0.07 per kilogram for colored material. PS prices range from $0.01 to $0.15 per kilogram. PET prices range from $0.13 to $0.18 per kilogram for soft drink containers and $0.01 to $0.18 for other PET. Resin costs of $0.20/kg for HDPE and $0.15/kg for PS were selected for economic modeling.[25]

Waste paper prices range from $50 to $150 per metric ton ($0.05 to $0.15 per kilogram) depending on grade. Prices for wood pallet and construction wood waste are unavailable since no significant market exists. Fiber cost was estimated at $0.10/kg for economic modeling.[26]

Treatment reagent prices were based on vendor data for maleated polypropylene. Current pricing for maleated polypropylene is $3.87/kg in five metric ton quantities.[27] The total cost of additives used for economic modeling was $4.00/kg. Estimated reagent requirements are 17-mt/yr for HDPE and 8-mt/yr for PS at an additive to composite ratio of 1% by weight. Solvent prices were estimated at $1.00/kg with 99% solvent recovery and reuse. Combined total solvent use for HDPE and PS lines is estimated at 5-mt/yr.

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[25] Plastic Recycling Update, Resource Recycling, February 1994

[26] DTI phone survey.

[27] Product literature and pricing for plastic aditives, Eastman Chemical Company, Kingsport, TN.

Plant and Equipment Costs

Plant and equipment costs were estimated based on discussions with equipment vendors. Vendor representatives provided varying degrees of fidelity ranging from order of magnitude data to costs for specific items of equipment. Only major equipment items could be estimated because of available schedule and the conceptual nature of the plant design.

Production Costs

Variable production costs include labor, electricity, maintenance and supplies, sales expense, and general and administrative expense. Fixed costs include facility lease cost, depreciation expense, property taxes and insurance.

Production labor costs were estimated at $15.00/hr plus 50% for fringe benefits and employer paid taxes. Lower labor costs are possible depending on facility siting and local economic factors. Cost estimating factors used for extruder operations are 1 operator per extrusion line plus 1/3 person for feed handling, 1/3 person for engineering and maintenance, and 1/3 person direct supervision.[28] Labor costs were based on 40-hr/week and 52-week/yr. Line operation for 30-hr/week and 50-week/yr (1500-hr/yr) was assumed in facility sizing.

Plant electricity consumption was estimated at 125% of extruder installed power. Grinding, drying, and mixing operations consume the additional power. Local utility rates of $0.11/kW-hr were used for estimating costs on the basis of 1500-hr/yr production.[29]

Standard estimating factors for maintenance and supplies range from 4% to 10% of capital equipment cost.[30] A 5% factor was selected for estimating maintenance and supplies cost. Sales expense was estimated at 10% of feedstock costs. General and administrative expense was estimated at 15% of variable costs.

Facility lease costs were estimated at $16.10/m2 ($1.50/ft^2). Production facility space requirements were estimated at 930-m2 (10,000-ft^2) per line. These factors yield a fixed lease cost of $15,000/yr/line.

Depreciation expense, property taxes and insurance were based on estimates of the total installed equipment cost reported. Ten year straight line depreciation was used for economic analysis. Property tax and insurance were calculated at 2% of installed equipment cost per year.

Production Unit Costs

Production unit costs were estimated from the preceding data. Cost breakouts per kilogram of finished product are tabulated in Table 16.

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[28] Plastics Extrusion, Griff

[29] Sacramento Municipal Utility District, Sacramento, CA. 3/94

[30] Chemical Engineers' Handbook, Perry, R.H.; Chilton, C H., Eds.; McGraw-Hill, 1973

Table 16. Production Costs for MSW Processing

	Units	HDPE	PS/EPS
Cost of Feedstocks	$/kg	$0.194	$0.169
Cost of Electricity	$/kg	$0.051	$0.034
Cost of Labor	$/kg	$0.056	$0.112
Cost of Maint and Supplies	$/kg	$0.035	$0.061
Depreciation Expense, 10 yr SL	$/kg	$0.108	$0.197
Cost of Facility Lease	$/kg	$0.009	$0.018
Property Tax & Insurance Expense	$/kg	$0.022	$0.039
Sales Expense	$/kg	$0.019	$0.017
G&A Expense	$/gk	$0.042	$0.051
Production Cost, $/kg		$0.534	$0.697
Gross ROA, $/kg @ 20.0%		$0.348	$0.622
Market Price, $/kg		$0.883	$1.319
$\$/\text{m}^2$ @ 6-mm thick		$6.403	$10.144
$\$/\text{ft}^2$ @ 0.25-in thick		$0.630	$0.997

Plastic and fiber raw materials contribute the greatest share of finished product cost. Raw materials contribute 20% to 25% of product cost. Finished product cost and profitability will therefore be sensitive to the stability of these costs. In contrast, data from trade journals and individuals trading in recycled materials indicate that wide fluctuations in price and supply typify the market for recycled paper and plastic waste. Price volatility will make high volume production facilities a risky investment. Long term contracts or partnerships should be established with municipal solid waste agencies to ensure stable pricing and supply.

Coupling agents, solvents and other additives add 15% to 20% to product cost. The results of the materials research indicate coupling agents are not merited for paper fiber filled materials, especially PS. Coupling agents would be appropriate for wood fiber reinforced materials. Other additives may include colors and processing aids. The dispersed fiber should provide effective UV protection to the composite.

Labor and depreciation expenses contribute the next largest share of product cost. These elements may be traded during facility sizing to provide optimum utilization of capital equipment.

A gross margin value per unit production was added to arrive at the market prices shown in Table 16. The gross margin was calculated to provide a 15% return on assets employed (ROAE) after taxes. The value of assets employed was calculated as the total installed equipment cost plus two months operating expenses.

Profitability and Return on Assets Employed

The economic analysis identifies costs and defines market pricing required to provide an acceptable return on investor capital. Profitability calculations assume that the material produced can be sold wholesale at the market price per unit shown in Table 16. This implies sales of .23 million square meters of 6-mm HDPE composite sheet (2.34-Mft^2 @ 0.25-in) or .11 million square meters of 6-mm PS composite sheet (1.11-Mft^2 @ .25-in) per year.

Gross unit margins added to production costs in Table 16 were selected to provide a 15% after tax return on assets employed (ROAE). ROAE provides an important measure of an investors real return on capital. Minimum acceptable ROAE is dependent on the risk and potential return from alternate investments (opportunity cost) available to the investor. Most corporations target 15% ROAE as a minimum acceptable return on capital. Many will not consider investments with less than 20% ROAE.

Yearly sales costs and profitability are summarized in Table 17. Gross sales minus production costs provide gross margin which is subject to income taxes. Taxes are estimated at a 50% rate. Net profit is calculated after taxes. Net profit to sales of approximately 20% is required to provide a ROAE of 15%. Inversely, this translates to approximately 75% mark-up to cost.

Table 17. Production Economic Analysis Summary

	Units	HDPE	PS/EPS
Gross Sales	$/yr	$1,476,142	$1,102,784
Production Cost	$/yr	($893,341)	($582,721)
Gross Margin	$/yr	$582,800	$520,063
Federal/State/Local Taxes	$/yr	($291,400)	($260,032)
Net Profit After Taxes	$/yr	$291,400	$260,032
Net Profit to Sales	%	19.7%	23.6%
Return on Assets Employed	%	15.0%	15.0%
Cash Flow	$/yr	$471,400	$425,032
Investment Recovery Point	yr	4.1	4.1

Cash flow is the sum of net profit after taxes and depreciation. Depreciation contributes to cash flow via its contribution to production cost without recurring cash expense. At 15% ROAE, the capital recovery point for this investment occurs at 4.1 years. If the assumed sales could be achieved and the facility productive life is assumed equal to the 10 year depreciation life, an $1,800,000 investment in the HDPE facility would return a total after tax profit of $2,771,000.

5 MARKET ANALYSIS

Market Assessment

The Plastics Recycling Foundation, Washington, D.C., and the Institute for Scrap Recycling Industries, Washington, D.C., were contacted to identify sources of recycled material, current feedstock pricing, products and producers of other recycled goods, and reference resources for similar work. Excellent materials and references were obtained from these non-profit foundations which enabled an accurate assessment of the current market for recycled plastic product forms.

Vendors of a variety of recycled goods were contacted for product information. Primary focus was placed on vendors whose products are oriented toward wood and construction material substitutes. The wide variety of product lines and applications found indicate a healthy and expanding market for recycled materials.

Most currently available recycled wood substitute products are 100% plastic (HDPE/PET) formed as non-structural lumber, benches, tables, decking, car-stops, or bricks. Sheet stock products are hard plastic sheets used for livestock pens and other agricultural applications. Primary product features of these materials are durability and low maintenance. The lumber products can be sawed and worked like wood and use standard fasteners. They are generally heavier than wood and more flexible. The materials offer some compressive strength, but poor shear and tensile strength. When used as structural members such as load-bearing columns, joists or beams, additional reinforcements and special designs are necessary to compensate for the plastic wood's limited loadbearing capacity. Mobil Chemical Company manufactures a product called Trex™ which is a wood-polymer composite made of 50% post-consumer plastic and 50% sawdust.[31] The material is marketed for applications similar to plastic lumber, but exhibits more "wood-like" surface characteristics when sanded, painted, or stained. A small number of other vendors offer some fiber reinforcement in their plastic wood products.

Another market segment for recycled plastics is expanded and extruded polystyrenes. These materials are used for insulation board, sheathing, and roofing systems. These products utilize post-consumer resins from the food services industries. The structural improvements offered by a composite or laminate material would expand the market for a variety of new applications.

A literature search was performed to identify existing information on markets for wood and plastic wood products. A number of on-line databases were searched. The best search results were obtained from the Applied Science & Technology Index[32], the Wilson Business Periodicals Index[33], PTS Prompt[34], NTIS Bibliographic Index[35], and CA Search[36]. These references were analyzed for information on current and future demand for both synthetic and natural wood products. The goal of this task was to assess market opportunities by surveying competing products and relative pricing. Knowledge of existing and emerging markets combined with evaluation of composite material properties will help define the best opportunities

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[31] Trex™, Wood-Polymer Composite, Mobil Chemical Co., Composite Products Division.

[32] *Wilson Applied Science & Technology Index*, Produced by: The H.W. Wilson Co., 950 University Ave., Bronx, NY 10452.

[33] *Wilson Biological & Agricultural Index*, Produced by: The H.W. Wilson Co., 950 University Ave., Bronx, NY 10452.

[34] *PTS Prompt*, Predicasts, Online Services Department, 11001 Cedar Ave., Cleveland, OH 44106, (800)-321-6388.

[35] *National Technical Information Service*, 5285 Port Royal Road, Springfield, VA 22161

[36] *CA Search*, Chemical Abstracts Service, P.O. Box 3012, Columbus, OH 43210

for development of product forms. Since the project goal is production of alternative construction materials, market surveys were focused on construction related applications. The most recent pricing information available was used. Price quotes were obtained from distributors, vendor literature, articles and reports.

Market Acceptance

The efforts of this project were directed at producing a composite material that exhibits properties similar to wood construction materials, especially sheet stock like plywood. A number of factors must come into play in order to produce a product that can successfully compete with traditional wood construction products. Foremost, the material must exhibit acceptable physical properties for the application. Beyond this basic tenant, the manufacturing process must be efficient enough to produce the material at an economical price. If the production price is higher than wood equivalents, the product must offer significant additional features that justify its added cost such as improved durability or enhanced thermal properties. Achieving these goals is only half the battle.

Standards for application of material used in building construction must be developed and approved for use by national and local building codes. Fire testing is likely to be required for any structural or building interior applications. This type of testing can be very costly. The building industry must be educated as to its use. Long term application of the material must be successfully demonstrated to reduce builders' risk in using a new technique. A manufacturer must actively participate in developing design and application guidelines and getting the material approved for use.

Compatibility with the remainder of the standard building process must be demonstrated. This issue can create subtle problems that are difficult to anticipate. For example, many of the engineered woods present a problem in that they are produced with a different moisture content than standard wood products. Therefore, they go through a different transition than other wood in a structure as they come to moisture content equilibrium in the structure. This can cause buckling and other sizing problems when different materials are used together. Additional problems can arise if use of the product affects the way other parts of the construction process are implemented. Radically different procedures for installation of plumbing or electrical systems in the resulting structure can present an barrier to a new product's acceptance.

The ability to easily adapt a new material to existing manufacturing processes and industries is also an important aspect in the successful development of a market for a new product. The engineered wood products described below enjoy a distinct advantage because they are an offshoot of the existing lumber industry and utilize existing facilities and distribution channels. A completely new process requires a high initial investment in facility capital and development of handling and distribution channels.

Wood and Plywood Products

The most common building material for residential structures is wood. Residential construction consumes two thirds of the lumber used by the construction industry. Nearly 85% of the wood used to construct a home is used for framing, with the balance being plywood used for sheathing.[37]

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[37] *Building with Alternatives to Lumber and Plywood*, NAHB Research Center, Homebuilder Press, 1994

In recent years, the price of wood products has risen sharply due to a number of factors. A primary factor is the supply of timber for harvest. From a strictly biological standpoint, US forests can supply the nation's timber needs. In spite of the biological capability, laws, regulations, and court orders may cause a shortage of supply. The Northwest timber harvest has been cut severely due to environmental battles. Other areas of the country are also being affected and timber harvests are falling. Exports to Japan and other countries also siphon off huge amounts of available timber. Other factors include the lack of large dimension logs from old growth forests and stricter design specifications to meet earthquake and other safety codes.[38][39]

While prices are rising, wood remains one of the cheapest materials available and enjoys the advantages of a well established market with developed standards. Current pricing for plywood around $0.39 - $0.42 per square foot.[40]

Wood Alternatives

Engineered Wood Products

Traditional wood products make very inefficient use of the raw log, generating large amounts of scrap that at one time was discarded. New processes utilize small diameter timber and wood that was previously discarded to gain up to 80% usage of a log. Engineered products generally provide more consistency, better properties, and more flexibility in dimensions that natural wood products.[41]

In general, most engineered alternative wood products are more expensive to produce than their natural corollary. An exception is oriented strand board which is a plywood alternative for sheathing applications and costs $0.35 to $0.40 per square foot.[42] It is less expensive than plywood to produce because it is made from abundant, fast growing trees. Logs are cut into strands and the strands are blended with a resin and mechanically oriented in layers. The resulting product is very similar to plywood, but is has a lower moisture content and as a result absorbs moisture and does not hold up well when exposed to the weather.

Another engineered wood sheathing material is laminated fiberboard structural sheathing. This is made of from fibrous plies laminated and covered with foil or polyethylene. The material is made into large thin sheets that works well as a sheathing but does not provide a nail base. Costs range from $0.11 to $0.20 per square foot.[43]

A variety of alternatives to structural lumber are being produced. These include glue-laminated lumber, laminated veneer lumber, parallel strand lumber, and I beams made from flanges grooved with plywood webs. All of the engineered lumbers enjoy the advantage of better overall quality and strength and the ability to manufacture to any length. They are used for beams, headers, columns, joists, and rafters. Light gauge structural steel studs are also seeing increasing use in framing.

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[38] *Loss of NW timber too great for other forests to make up.*,Forest Industries, v. 118, Jan.-Feb. '91, p.16

[39] *Lumber prices beat up builders.*,ENR, v. 228, June 29 '92, p. 40-41.

[40] Based on phone survey by DTI personnel of local lumber distributers.

[41] *Building with Alternatives,* NAHB

[42] *Building with Alternatives,* NAHB

[43] *Building with Alternatives,* NAHB

While all of these products offer a variety of advantages over traditional wood products, most incur a higher initial cost. Glue-laminated lumber costs $4.00 to $5.50 per liner foot for a 4" x 12" and around $9.00 per linear foot for a 6" x 12". Laminated veneer lumber in 2" x 4" costs $2.50 to $4.00 per linear foot. Parallel strand lumber averages $5.00 to $7.50 per linear foot in a 4" x 12". An I-beam equivalent of a 2" x 12" costs $1.00 to $1.50 per liner foot.[44] Acceptance of these materials in local building codes is scattered at best because the use of an unproven material presents an unacceptable risk to most small builders. In addition, builders are not knowledgeable of the proper use and installation of the materials. Many of them require special engineering analysis of a structure's design.

Sheet and Sheathing

A great deal of effort has been put into developing a variety of composite replacements for structural wood products. A number of these materials present the opportunity to make use of municipal solid waste and recovered raw materials from various industrial processes.

The US Forest Product's Laboratory has been using structural panels for a number of years. These panels come in a variety of forms known as stressed-skin or structural sandwich panels. The typical panel being produced today is made of two stiff skins made of a material such as plywood or oriented strand board separated by a thick core of expanded or extruded polystyrene or rigid polyurethane. The panels offer many advantages including quicker construction time, good strength, and outstanding insulating properties. The panels require a radically different construction process than used with traditional materials. They are subject to insect infestation and in some cases have caused overheating problems in roof sheetings. These panels show a much higher price, averaging $8.75 to $11.00 per square foot. However, they can replace a number of components including sheathing, insulation, and to a large extent framing lumber.

Foam panels and laminated foam panels are another common alternative for sheathing and roofing applications where insulation is required. Amoco makes an extruded polystyrene foam board useful in exterior sheathing, wall systems, foundation insulation, roofing, and siding underlayment. This insulation is made with a minimum of 50% post consumer waste.[45] A number of other companies make a variety of expanded polystyrene insulation panels that are used in insulation and roofing systems.[46]

Thermoplastics are seeing increased usage in a variety of products. The large supply of recyclable plastics is a factor in the development of these products. Sheet stock made from recycled plastics is available in flat and corrugated panels. Many are made from polyethylene although some products are able to utilize co-mingled plastics. For the most part these materials are rare in standard construction applications. However, they do offer some advantages in certain environments. Their toughness, durability, and impermeability make them ideal for agricultural environments where they are used in animal housing and other farm construction. Prices for large sheets in nominal 1/4" thickness range from $1.00 - $1.50 per square foot.

Thicker plastic sheeting is used in plastic palettes. These palettes are much more durable than standard wood palettes and don't splinter but cost about three times more. Current plastic wood palettes

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[44] *Building with Alternatives,* NAHB

[45] AmoFoam™, Amoco Foam Products Co., 375 Northridge Rd., Suite 600, Atlanta, GA 30350-32397

[46] EPS Roofing Systems, AMF Corporation, Box 246, Excelsior, MN 55331, (612)-474-0809

costs from $40 - $60 each. Despite their cost, the continuing increases in lumber prices combined with longer life is bringing more companies to consider this as a viable alternative.[47]

A number of groups are evaluating the use of various plastic panels and composite structures for use in both temporary and permanent housing. Increased interest has been driven by natural disasters like Hurricane Andrew, the growing problem of shelter needs for the homeless population, and the need to reduce the ever rising tide of consumer waste.[48] Besides the more obvious approaches utilizing plastics containers and papers, a number of companies are looking at unique and creative alternatives. One company uses the wastes from leg cutouts in disposable diaper manufacture as a supply stream. Another is turning used carpet into plastic wood.[49]

Plastic Lumber

A number of recent development efforts have been focused on the creation of plastic lumber to substitute for wood lumber products. The resulting materials come in two basic forms: plastic only, and plastic enhanced with wood fillers. Plastic lumber is extruded as lumber, timber, and posts. It's durability, impermeability, and lack of maintenance requirements make it ideal for marine, decking, and landscaping applications. The material is being widely used in a number of outdoor products such as picnic tables and park benches. It's graffiti resistance and ease of cleaning make it particularly appealing for these applications. Manufacturers have achieved a product that can be handled and worked using standard wood working tools and fasteners. Mobil Chemical Company has marketed a product called Trex with mixed results™.[50] It is a wood-polymer composite made from reclaimed plastic and wood waste. The product is widely distributed on the East coast and is becoming available in the West.

Ideally, plastic wood products should offer better control of consistency and defects than a natural material like wood. To date, manufacturing processes have produced problems with defects and compositional variations. These problems result in variations of properties that can be very similar to those of natural wood. The current line of products offer good compressive strength, but to date are suitable only for limited load bearing applications. In addition, producers have had difficulty in creating materials consistent structural properties. Manufacturers recommend a maximum of 18"-20" maximum unsupported spans. Prices for 2x6 plastic lumber range from $1.20 - $1.90 per linear foot, 2x4 lumber is $0.90 - $1.20 per linear foot. For comparison, current retail prices for common Douglas Fir studs are $0.32 per linear foot for 2x4's, $0.53 per linear foot for 2x6's, and $1.32 per linear foot for 2x12's.[51]

The plastic lumber industry is still in a fledgling state, but has the potential to blossom into a growing industry. However, there is much disagreement on the assessment of market opportunity for this product. The New York State Energy Research and Development Authority recently issued a study concluding that several barriers will inhibit growth of the plastic lumber market, including cost, unpredictable performance, and lack of specifications.[52] Members of the industry are working to overcome these barriers. A great deal of research and development effort has been directed at development of the product and efforts are continuing to overcome the structural limitations. The recent formation of the

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[47] *Wood prices make plastic pallet-able. Industrial Pallet: Mfrs plastic pallets using plastic lumber from Custom-Pac Extrusions.*, Plastic News, November 8, 1993, p. 21.

[48] *Plastic houses get their day in Florida sun.*, Plastics News, September 14, 1992, p. 1.

[49] *Business and the Environment: Roll out timber carpet.*, Financial Times (London) November 4, 1992, p. 18.

[50] Trex™, Mobil Chemical

[51] Phone quote from Lumberjack, Auburn, CA 6/14/94.

[52] *Plastic Lumber News*, Resource Recycling's Plastics Recycling Update, Vol. 7, No. 2, February 1994, p. 1.

Plastic Lumber Trade Association is an indicator of the high level of activity and increasing market potential.[53] The group will focus on promoting market awareness of the product and developing standards of tests and grading of the products. The new ASTM Section D-20.05.03 on "Manufactured Recycled Plastic Lumber and Shapes" is working on specifications and test methods for plastic lumber products. Task groups have been formed to work on "Terminology", "Test Methods", and "Performance Standards" for plastic lumber products.

Alternative Markets

While the initial focus of this effort was targeted at development of a replacement for lumber products, there may be reason to look at other types of applications. The survey of existing and emerging products indicates that lumber substitutes suffer from two major problems. The majority of wood substitutes are two to three times more expensive than natural wood products. This is due to the combined effects of competition with an abundant natural resource and expensive manufacturing processes. The key to commercial success with plastic and other alternative lumber products is the development of radically more efficient production methods. In addition, the product quality must be improved. Development of materials with consistently reproducible properties is essential. Improvement in structural properties is also needed. An exception to this is the engineered wood products that take the basic strengths of natural wood and enhance them through design.

Alternative strategies to competition in the plywood market might be to position a new composite to compete with higher valued products. One possibility is the fiberglass market. Fiberglass panels are frequently used in a variety of sheathing type applications. While it offers a number of desirable properties, fiberglass suffers from degradation from solar exposure and embrittlement with age. The use of a thermoplastic matrix to replace the resin, would offer many of the same desirable properties and add the durability and life of plastics.

The raw material costs of fiberglass production are split roughly 50/50 between fiber and resin by weight. Average prices for chopped stranded fiber are \$0.80 - \$1.20 per pound. Typical resin prices are \$0.80 - \$0.90 per pound.[54] In addition, the resins require expensive curing processes and the use of environmentally hazardous chemicals. Replacement of the resins with recycled thermoplastics would provide a similar material at a much lower cost. This competitive price advantage would provide a much more viable market possibility.

The properties of the composites developed during this effort may also make it a viable alternative to formed metal sheeting. The plastic composite can be formed by a rolling process and shaped in corrugated shapes similar to those used as an exterior sheathing. The ability to produce translucent panels would also have some interest for skylights.

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[53] *Plastic lumber to have trade group,* Plastics News, August 2, 1993., p. 3.

[54] Based on vendor contacts by DTI personnel. 3/94.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Composites made from recycled paper fiber in a matrix of thermoplastic resin do not have suitable properties for structural construction applications. Chemical techniques can be employed to provide some enhancement of the bond between the paper fibers and plastic matrix, but the paper fibers do not have enough strength to produce a composite with suitable properties. In order to produce a material with adequate strength, fibers of greater strength must be employed. The use of raw wood fibers in place of paper should provide improved properties but would still require chemical processing to overcome the problems of mixing hydrophillic cellulose and hydrophobic thermoplastics. The requirement for chemical treatment increases costs and complexity due to waste handling requirements. Many commercial ventures are currently exploring producing and developing wood fiber filled plastic woods with only mixed success due to a combination of factors including inconsistent physical properties, high prices, and poor market acceptance. Although natural wood prices are rising, it remains a very inexpensive material with the advantages of long established use, a large established industrial base, and outstanding properties for construction applications.

The use of glass fibers to enhance the strength of a matrix material has a long history in the form of fiberglass. However, the thermoset resins used for the matrix in fiberglass are environmentally hazardous and their use has come under ever increasing restriction in recent years. Substitution of a recycled thermoplastic matrix in place of the thermoset resin appears to be a viable opportunity for a useful composite. There are many favorable factors that make this an area of interest.

A glass fiber and thermoplastic composite utilizes the same concept found in fiber filled polywood products, but glass fiber is much stronger and more importantly, provides consistent and predictable properties. The compatibility problems found in mixing cellulose and plastic might possibly be avoided because glass and thermoplastics are hydrophobic, making them more compatible. However, some existing thermoplastic composites still require surface treatments ("compatiblizers") to enhance the wetting of the glass by the plastic matrix. A thermoplastic/glass composite would compete in the market place against products that are much higher valued than the natural wood products that plastic woods compete against. Roughly 50% of the cost of fiberglass is in the resin. Replacement of this expensive, toxic matrix with a thermoplastic matrix from recycled MSW offers a good market for reclaimed thermoplastics and the prospect of producing a material with reduced costs. Composites based on glass fiber have a pre-established market of well-known applications that currently utilize standard fiberglass including shower stalls, translucent panels, water tanks, corrosive handling hardware, etc.

In order to provide a viable market for recycled MSW materials, new composites must have superior physical properties, competitive production costs, and favorable market opportunities. The work performed during this program indicated that these goals are not likely to be achieved using recycled paper and plastic. However, a combination of factors indicate that composites based on glass fiber and recycled thermoplastic may be a viable alternative. Development of such composites hold the possibility of addressing the dual objectives of providing a market for recovered MSW and offering innovative construction materials.

Recommendations

To further explore possible alternatives for new construction materials based on recycled MSW the following recommendations are made:

1. Development of composite materials based on glass fiber in a recycled thermoplastic matrix should be explored.

2. The economics of a production process to produce either structural or skylight panels based on a composite from chopped glass fibers and thermoplastics should be examined.

3. Potential applications where thermoplastic composites could replace thermoset composites should be assessed.

4. Assess throughput and environmental benefits in switching existing fiberglass/thermoset resin products to fiberglass/thermoplastic and how this change would affect plant economics, community acceptance, potential for localized production, and localized job impact.

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APPENDIX A: TENSILE PROPERTY TEST RESULTS FOR PS

Test Approach

Tensile testing was performed per ASTM D638. The 13-mm wide specimens were tested with an initial grip separation of 114-mm. The rate of grip separation was 51-mm per minute, except as noted in the attached test report. Strength, elongation and 1% secant modulus were calculated per ASTM D638.

Test Results

Tensile test results are described by the tensile laboratory reports attached herewith.

APPENDIX B: TENSILE PROPERTY TEST RESULTS FOR HDPE

Test Approach

Tensile testing was performed per ASTM D638. The 13-mm wide specimens were tested with an initial grip separation of 114-mm. The rate of grip separation was 51-mm per minute, except as noted in the attached test report. Strength, elongation and 1% secant modulus were calculated per ASTM D638.

Test Results

Tensile test results are described by the tensile laboratory reports attached herewith.

Consolidated Engineering Laboratories Report

March 2, 1994

Ms. Judy Duncan, Vice President
Duncan Technologies, Inc.
Box 1150
Newcastle, CA 95658

CEL #5957
Report #01

Dear Ms. Duncan:

Re: Results of Testing the Tensile Strength of Eight 125-mil Polystyrene Samples Submitted by Duncan Technologies

Summary: All specimens were tested for tensile strength and modulus. Average sample tensile strengths varied between 2,343 and 5,715 psi, while average sample moduli varied between 178,125 and 287,200 psi.

Eight 125-mil (nominal thickness) polystyrene samples were submitted by Duncan Technologies for tensile strength testing. These samples were received by CEL on Monday afternoon, February 28, 1994. The samples were given CEL identification numbers 5957-1 through 5957-8 respectively. An inventory of the samples presenting the notations on the individual specimens as they were received and the thickness of the specimens is presented in appendix.

Testing of tensile strength was performed in accordance with ASTM D638, Specimen Type I, dumbbell. These 0.5-inch-wide specimens were tested with an initial grip separation of 4.5 inches. The rate of grip separation was 0.2 inch per minute (ipm). Four specimens were tested per sample. The results of this testing are presented in Tables 3 and 4, enclosed.

REVIEWED BY: **SOPHIE LAGACE,**
SENIOR LABORATORY TECHNICIAN

REVIEWING ENGINEER: CHRIS N. KAVALERIS, R.C.E.

REGISTERED PROFESSIONAL ENGINEER
CHRIS N. KAVALERIS
No. CE33179
Exp. 6/30/94
CIVIL
STATE OF CALIFORNIA

Enclosures

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TABLE 1: INVENTORY OF SAMPLES

SAMPLES SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957
SAMPLE SIZE: ASTM D638 Type I dumbbell, 0.5 in. wide and 6.5 in. long
DATE RECEIVED: 02/28/94
MATERIAL: POLYSTYRENE

Sample number	Client's notations on individual specimens	Details	Thickness, mils
5957-1	SC0-6 to 9	---	129.5, 121.1, 118.2, 117.6
5957-2	SC1-1 to 4	---	117.2, 120.6, 117.6, 116.9
5957-3	SC2-1 to 4	With approximately 10% wood particles	119.2, 119.0, 119.1, 118.6
5957-4	SPA-1 to 4	With approximately 10% wood particles	118.6, 119.1, 119.7, 120.1
5957-5	SPE-1 to 4	With approximately 10% wood particles	119.2, 118.7, 117.7, 118.0
5957-6	SMA-1 to 4	With approximately 10% wood particles	120.1, 120.9, 118.7, 117.8
5957-7	SME-1 to 4	With approximately 10% wood particles	121.2, 121.3, 117.8, 117.8
5957-8	SRP-1 to 4	With approximately 10% wood particles	117.9, 119.4, 118.1, 117.4

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TABLE 2: 1% SECANT MODULUS (ASTM D638, Modified)

Material Polystyrene	Date Tested March 1, 1994	Test Temperature 71.9 F	Project No. 5957	
Tested by Steve Knudsen	Cross-Head Speed 0.2 ipm	Test Specimen D638 Type I dumbbell	Gauge Length 2.25 in.	
Load Cell 5000 pounds	Full Scale Load 500 pounds	Initial Grip Separation 4.5 in.	Chart Speed 20 ipm	Width 0.5 in.

Sample	Specimen number	Cross-head extension at break, in.	Thickness, mil	Load at 1% elongation, units	Load at 1% elongation, lbs.	Stress at 1% elongation, psi	1% secant modulus, psi
5957-1	1	0.09	129.5	23.1	115.50	1,782	178,200
	2	0.10	121.1	22.0	110.00	1,815	181,500
	3	0.10	118.2	20.9	104.50	1,768	176,800
	4	0.09	117.6	20.7	103.50	1,760	176,000
5957-2	1	0.09	117.2	25.0	125.00	2,133	213,300
	2	0.08	120.6	25.7	128.50	2,131	213,100
	3	0.09	117.6	26.0	130.00	2,211	221,100
	4	0.07	116.9	25.6	128.00	2,188	218,800
5957-3	1	0.04	119.2	28.2	141.00	2,366	236,600
	2	0.04	119.0	34.2	171.00	2,874	287,400
	3	0.04	119.1	35.4	177.00	2,970	297,000
	4	0.05	118.6	35.7	178.50	3,010	301,000
5957-4	1	0.04	118.6	35.6	178.00	3,002	300,200
	2	0.05	119.1	34.0	170.00	2,852	285,200
	3	0.04	119.7	34.8	174.00	2,905	290,500
	4	0.04	120.1	32.8	164.00	2,729	272,900
5957-5	1	0.04	119.2	32.4	162.00	2,718	271,800
	2	0.04	118.7	32.1	160.50	2,702	270,200
	3	0.03	117.7	32.0	160.00	2,716	271,600
	4	0.03	118.0	33.7	168.50	2,856	285,600
5957-6	1	0.04	120.1	34.5	172.50	2,870	287,000
	2	0.05	120.9	33.3	166.50	2,752	275,200
	3	0.04	118.7	32.6	163.00	2,744	274,400
	4	0.03	117.8	31.9	159.50	2,708	270,800

NOTE: The 1% secant modulus is calculated by dividing the stress at 1% elongation by the strain, i.e., 1%. The one percent elongation is based on an assumed gauge length of 2.25 inches, which represents the reduced section of the specimen. The stress at 1% elongation is determined by dividing the load at 1% elongation by the cross-sectional area of the test specimens.

CEL/March 2, 1994
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Data checked by: Sophie Lagacé

TABLE 2: 1% SECANT MODULUS (ASTM D638, Modified) - Continued

Material Polystyrene	Date Tested March 2, 1994	Test Temperature 71.9 F	Project No. 5957	
Tested by Steve Knudsen	Cross-Head Speed 0.2 ipm	Test Specimen D638 Type I dumbbell	Gauge Length 2.25 in.	
Load Cell 5000 pounds	Full Scale Load 500 pounds	Initial Grip Separation 4.5 in.	Chart Speed 20 ipm	Width 0.5 in.

Sample	Specimen number	Cross-head extension at break, in.	Thickness, mil	Load at 1% elongation, units	Load at 1% elongation, lbs.	Stress at 1% elongation, psi	1% secant modulus, psi
5957-7	1	0.05	121.2	34.4	172.00	2,838	283,800
	2	0.05	121.3	28.0	140.00	2,306	230,600
	3	0.05	117.8	27.7	138.50	2,351	235,100
	4	0.05	117.8	26.0	130.00	2,207	220,700
5957-8	1	0.04	117.9	22.8	114.00	1,932	193,200
	2	0.05	119.4	24.1	120.50	2,018	201,800
	3	0.05	118.1	23.8	119.00	2,014	201,400
	4	0.05	117.4	23.3	116.50	1,985	198,500

NOTE: The 1% secant modulus is calculated by dividing the stress at 1% elongation by the strain, i.e., 1%. The one percent elongation is based on an assumed gauge length of 2.25 inches, which represents the reduced section of the specimen. The stress at 1% elongation is determined by dividing the load at 1% elongation by the cross-sectional area of the test specimens.

CEL/March 2, 1994
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Data checked by: Sophie Lagacé

TABLE 3: TENSILE STRENGTH OF 125-mil (NOMINAL) POLYSTYRENE SAMPLES
SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957

	CEL ID number 5957-1 Client sample SC0				CEL ID number 5957-2 Client sample SC1			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1	129.5	5,035	4.00	178,200	117.2	5,990	4.00	213,300
2	121.1	5,219	4.44	181,500	120.6	5,788	3.56	213,100
3	118.2	5,228	4.44	176,800	117.6	6,276	4.00	221,100
4	117.6	5,272	4.00	176,000	116.9	4,808	3.56	218,800
Avg.=	121.6	5,188.5	4.22	178,125	118.1	5,715.1	3.78	216,575
SD =		105.1		2,427		637.3		4,009
CV =		2.0%		1.4%		11.2%		1.9%

	CEL ID number 5957-3 Client sample SC2				CEL ID number 5957-4 Client sample SPA			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1	119.2	2,827	1.78	236,600	118.6	3,314	1.78	300,200
2	119.0	3,227	1.78	287,400	119.1	2,779	2.22	285,200
3	119.1	3,342	1.78	297,000	119.7	3,542	1.78	290,500
4	118.6	3,693	2.22	301,000	120.1	3,139	1.78	272,900
Avg.=	119.0	3,272.2	1.89	280,500	119.4	3,193.5	1.89	287,200
SD =		356.9		29,818		321.8		11,378
CV =		10.9%		10.6%		10.1%		4.0%

	CEL ID number 5957-5 Client sample SPE				CEL ID number 5957-6 Client sample SMA			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1	119.2	2,961	1.78	271,800	120.1	2,798	1.78	287,000
2	118.7	3,050	1.78	270,200	120.9	3,515	2.22	275,200
3	117.7	2,396	1.33	271,600	118.7	3,184	1.78	274,400
4	118.0	2,636	1.33	285,600	117.8	2,632	1.33	270,800
Avg.=	118.4	2,760.7	1.56	274,800	119.4	3,032.3	1.78	276,850
SD =		301.4		7,235		396.7		7,032
CV =		10.9%		2.6%		13.1%		2.5%

NOTE:
Performed in accordance with ASTM D638, Specimen Type I dumbbell, testing speed 0.2 inch per minute.
Elongations are based on a gauge length of 2.25 inches.
SD = Standard deviation, psi.
CV = Coefficient of variation (SD/Avg.), %.

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TABLE 4: TENSILE STRENGTH OF 125-mil (NOMINAL) POLYSTYRENE SAMPLES
SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957

	CEL ID number 5957-7 Client sample SME				CEL ID number 5957-8 Client sample SRP			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1	121.2	3,952	2.22	283,800	117.9	2,265	1.78	193,200
2	121.3	3,001	2.22	230,600	119.4	2,337	2.22	201,800
3	117.8	3,056	2.22	235,100	118.1	2,396	2.22	201,400
4	117.8	2,963	2.22	220,700	117.4	2,376	2.22	198,500
Avg.=	119.5	3,242.9	2.22	242,550	118.2	2,343.5	2.11	198,725
SD =		474.4		28,150		58.1		3,966
CV =		14.6%		11.6%		2.5%		2.0%

	CEL ID number 5957- Client sample ID				CEL ID number 5957- Client sample ID			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1								
2								
3								
4								
Avg.=								
SD =								
CV =								

	CEL ID number 5957- Client sample ID				CEL ID number 5957- Client sample ID			
Spec. no.	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi	Thickness mil	Tensile strength, psi	Elongation at break, %	Modulus psi
1								
2								
3								
4								
Avg.=								
SD =								
CV =								

NOTE:
Performed in accordance with ASTM D638, Specimen Type I dumbbell, testing speed 0.2 inch per minute.
Elongations are based on a gauge length of 2.25 inches.
SD = Standard deviation, psi.
CV = Coefficient of variation (SD/Avg.), %.

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Consolidated Engineering Laboratories Report

March 8, 1994

Ms. Judy Duncan, Vice President
Duncan Technologies, Inc.
Box 1150
Newcastle, CA 95658

CEL #5957
Report #02

Dear Ms. Duncan:

Re: Results of Testing the Tensile Strength of Seven 125-mil High Density Polyethylene Samples Submitted by Duncan Technologies

Summary: All specimens were tested for tensile strength and modulus. Average sample tensile strengths at yield varied between 2,000 and 3,450 psi, while average sample moduli varied between 137,300 and 269,000 psi.

Seven 125-mil (nominal thickness) high density polyethylene (HDPE) samples were submitted by Duncan Technologies for tensile strength testing. These samples were received by CEL on Friday afternoon, March 4, 1994. The samples were given CEL identification numbers 5957-9 through 5957-15 respectively. An inventory of the samples presenting the notations on the individual specimens as they were received and the thickness of the specimens is presented in Table 1 in appendix.

Testing of tensile strength at yield and at break was performed in accordance with ASTM D638, Specimen Type I, dumbbell. These 0.5-inch-wide specimens were tested with an initial grip separation of 4.5 inches. The rate of grip separation was 0.2 inch per minute (ipm), except for specimens no. 2, 3 and 4 from sample 5957-10 (PC1) and specimen no. 1 from sample 5957-11 (PC2) which were tested at 2 inch per minute. Four specimens were tested per sample for samples 5957-9 (PC0), 5957-10 (PC1) and 5957-11 (PC2); five specimens were tested per sample for samples 5957-12 (PRP), 5957-13 (PMP), 5957-14 (PRE) and 5957-15 (PME). The results of this testing are presented in Tables 3 to 5, enclosed.

As discussed with S. Lagacé on the phone, it should be noted that samples 5957-9 (PC0) and 5957-10 (PC1) were tested with various chart and crosshead speeds in an effort to determine the most suitable testing parameters. Because of these variations, the graph lengths varied considerably, making it very difficult to extract reliable values for the strength at break and the modulus of elasticity. In addition, the specimens also varied significantly in behavior, particularly concerning the elongation at break, making the moduli values obtained almost meaningless.

If you should need any other information, please do not hesitate to contact us at (510) 460-5100.

Sincerely,

Sophie Lagacé

REVIEWED BY: SOPHIE LAGACE,
SENIOR LABORATORY TECHNICIAN

REVIEWING ENGINEER: CHRIS N. KAVALARIS, R.C.E.

REGISTERED PROFESSIONAL ENGINEER
CHRIS N. KAVALARIS
No. CE33[illegible]
Exp. 6/30/94
CIVIL
STATE OF CALIFORNIA

Enclosures

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TABLE 1: INVENTORY OF SAMPLES

SAMPLES SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957
SAMPLE SIZE: ASTM D638 Type I dumbbell, 0.5 in. wide and 6.25 in. long
DATE RECEIVED: March 4, 1994
MATERIAL: HIGH DENSITY POLYETHYLENE (HDPE)

Sample number	Client's notations on individual specimens	Details	Thickness, mils
5957-9	PC0-1 to 4	---	106.8, 105.4, 105.7, 105.4
5957-10	PC1-1 to 4	---	106.7, 105.0, 105.7, 106.1
5957-11	PC2-1 to 4	With paper fiber fill	106.4, 105.3, 106.7, 103.6
5957-12	PRP-1 to 5	With paper fiber fill	106.9, 105.7, 105.3, 106.5, 109.8
5957-13	PMP-1 to 5	With paper fiber fill	108.2, 105.7, 106.4, 107.0, 105.3
5957-14	PRE-1 to 5	With paper fiber fill	106.8, 104.7, 105.0, 106.9, 107.0
5957-15	PME-1 to 5	With paper fiber fill	106.9, 106.2, 106.8, 105.7, 107.3

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TABLE 2: 1% SECANT MODULUS (ASTM D638, Modified)

Material High Density Polyethylene	**Date Tested** March 7-8, 1994	**Test Temperature** 70 F	**Project No.** 5957	
Tested by Steve Knudsen	**Cross-Head Speed** 0.2 ipm / *2 ipm	**Test Specimen** D638 Type I dumbbell	**Gauge Length** 2.25 in.	
Load Cell 5000 pounds	**Full Scale Load** 500 pounds	**Initial Grip Separation** 4.5 in.	**Chart Speed**	**Width** 0.5 in.

Sample	Specimen number	Cross-head extension at break, in.	Thickness, mil	Load at 1% elongation, units	Load at 1% elongation, lbs.	Stress at 1% elongation, psi	1% secant modulus, psi
5957-9	1	0.90	106.8	3.6	18.00	336	33,708
	2	1.14	105.4	4.4	22.00	419	41,746
	3	0.15	105.7	0.3	1.50	28	2,838
	4	0.25	105.4	0.8	4.00	76	7,590
5957-10	1	8.28	106.7	20.4	102.00	1,907	191,190
	2						
	3						
	4	4.65	106.1	36.8	184.00	3,472	346,843
5957-11	1						
	2	0.07	105.3	18.7	93.50	1,781	177,588
	3	0.08	106.7	15.1	75.50	1,411	141,518
	4	0.10	103.6	17.6	88.00	1,692	169,884
5957-12	1	0.08	106.9	14.5	72.50	1,355	135,641
	2	0.08	105.7	14.6	73.00	1,377	138,127
	3	0.07	105.3	15.6	78.00	1,486	148,148
	4	0.07	106.5	15.3	76.50	1,430	143,662
	5	0.08	109.8	13.3	66.50	1,209	121,129
5957-13	1	0.06	108.2	16.7	83.50	1,546	154,344
	2	0.06	105.7	18.2	91.00	1,717	172,185
	3	0.06	106.4	17.7	88.50	1,670	166,353
	4	0.06	107.0	16.8	84.00	1,570	157,009
	5	0.06	105.3	17.2	86.00	1,638	163,343

NOTE: The 1% secant modulus is calculated by dividing the stress at 1% elongation by the strain, i.e., 1%. The one percent elongation is based on an assumed gauge length of 2.25 inches, which represents the reduced section of the specimen. The stress at 1% elongation is determined by dividing the load at 1% elongation by the cross-sectional area of the test specimens.

CEL/March 8, 1994
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Data checked by: Sophie Lagacé

TABLE 2: 1% SECANT MODULUS (ASTM D638, Modified) - Continued

Material High Density Polyethylene	Date Tested March 8, 1994	Test Temperature 70 F	Project No. 5957
Tested by Steve Knudsen	Cross-Head Speed 0.2 ipm	Test Specimen D638 Type I dumbbell	Gauge Length 2.25 in.

Load Cell 5000 pounds	Full Scale Load 500 pounds	Initial Grip Separation 4.5 in.	Chart Speed 20 ipm	Width 0.5 in.

Sample	Specimen number	Cross-head extension at break, in.	Thickness, mil	Load at 1% elongation, units	Load at 1% elongation, lbs.	Stress at 1% elongation, psi	1% secant modulus, psi
5957-14	1	0.08	106.8	14.8	74.00	1,383	138,577
	2	0.07	104.7	15.0	75.00	1,429	143,266
	3	0.09	105.0	16.0	80.00	1,524	152,381
	4	0.08	106.9	16.8	84.00	1,570	157,156
	5	0.09	107.0	15.8	79.00	1,477	147,664
5957-15	1	0.07	106.9	16.0	80.00	1,495	149,673
	2	0.09	106.2	17.4	87.00	1,642	163,842
	3	0.05	106.8	15.2	76.00	1,421	142,322
	4	0.07	105.7	16.7	83.50	1,575	157,994
	5	0.06	107.3	16.2	81.00	1,514	150,979

NOTE: The 1% secant modulus is calculated by dividing the stress at 1% elongation by the strain, i.e., 1%. The one percent elongation is based on an assumed gauge length of 2.25 inches, which represents the reduced section of the specimen. The stress at 1% elongation is determined by dividing the load at 1% elongation by the cross-sectional area of the test specimens.

CEL/March 8, 1994
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Data checked by: Sophie Lagacé

TABLE 3: TENSILE STRENGTH OF 125-mil (NOMINAL) HDPE SAMPLES SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957

CEL ID number 5957-9
Client sample PC0

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1[a]	106.8	164.0	3,071			0.90	33,708
2[a]	105.4	163.0	3,093			1.14	41,746
3[a]	105.7	124.0	2,346			0.15	2,838
4[a]	105.4	107.5	2,040			0.25	7,590
Avg. =	105.8	139.6	2,637.6			0.61	21,471
SD =			528.4				19,155
CV =			20.0%				89.2%

CEL ID number 5957-10
Client sample PC1

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1[a]	106.7	168.0	3,149			8.28	191,190
2[abc]	105.0	188.0	3,581			3.90	
3[abc]	105.7	188.5	3,567			0.52	
4[ab]	106.1	186.5	3,516			4.65	346,843
Avg. =	105.9	182.8	3,453.1			4.34	269,017
SD =			204.6				110,063
CV =			5.9%				40.9%

CEL ID number 5957-11
Client sample PC2

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1[abc]	106.4	102.0	1,917			0.15	
2	105.3	95.0	1,804	75.0	1,425	0.07	177,588
3	106.7	104.5	1,959	95.0	1,781	0.08	141,518
4	103.6	121.5	2,346	120.0	2,317	0.10	169,884
Avg. =	105.5	105.8	2,006.5	96.7	1,840.6	0.10	162,997
SD =			235.3		449.1		18,996
CV =			11.7%		24.4%		11.7%

NOTES:

Performed in accordance with ASTM D638, Specimen Type I dumbbell, testing speed 0.2 inch per minute.

SD = Standard deviation, psi

CV = Coefficient of variation (SD/Avg.), %

[a] Stress at break could not be calculated from the graph with enough precision.

[b] Tested at 2 inch per minute.

[c] Modulus could not be calculated from the graph with enough precision.

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TABLE 4: TENSILE STRENGTH OF 125-mil (NOMINAL) HDPE SAMPLES SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957

CEL ID number 5957-12
Client sample PRP

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1	106.9	111.5	2,086	109.5	2,049	0.08	135,641
2	105.7	116.5	2,204	112.5	2,129	0.08	138,127
3	105.3	111.5	2,118	110.0	2,089	0.07	148,148
4	106.5	125.0	2,347	123.5	2,319	0.07	143,662
5	109.8	111.5	2,031	55.0	1,002	0.08	121,129
Avg. =	106.8	115.2	2,157.3	102.1	1,917.5	0.08	137,341
SD =			123.4		522.3		10,284
CV =			5.7%		27.2%		7.5%

CEL ID number 5957-13
Client sample PMP

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1	108.2	105.0	1,941	40.0	739	0.06	154,344
2	105.7	105.5	1,996	43.5	823	0.06	172,185
3	106.4	129.0	2,425	129.0	2,425	0.06	166,353
4	107.0	116.0	2,168	110.0	2,056	0.06	157,009
5	105.3	124.0	2,355	121.5	2,308	0.06	163,343
Avg. =	106.5	115.9	2,177.1	88.8	1,670.2	0.06	162,647
SD =			213.1		822.9		7,175
CV =			9.8%		49.3%		4.4%

CEL ID number 5957-14
Client sample PRE

Specimen number	Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1	106.8	133.5	2,500	130.0	2,434	0.08	138,577
2	104.7	141.0	2,693	138.5	2,646	0.07	143,266
3	105.0	149.5	2,848	146.5	2,790	0.09	152,381
4	106.9	152.0	2,844	150.0	2,806	0.08	157,156
5	107.0	140.0	2,617	135.0	2,523	0.09	147,664
Avg. =	106.1	143.2	2,700.3	140.0	2,640.1	0.08	147,809
SD =			149.5		162.9		7,317
CV =			5.5%		6.2%		5.0%

NOTES:
Performed in accordance with ASTM D638, Specimen Type I dumbbell, testing speed 0.2 inch per minute
SD = Standard deviation, psi
CV = Coefficient of variation (SD/Avg.), %

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TABLE 5: TENSILE STRENGTH OF 125-mil (NOMINAL) HDPE SAMPLES SUBMITTED BY DUNCAN TECHNOLOGIES, NEWCASTLE, CA
CEL PROJECT #5957

CEL ID number 5957-15
Client sample PME

Specimen number		Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
1		106.9	134.0	2,507	130.0	2,432	0.07	149,673
2		106.2	157.0	2,957	155.0	2,919	0.09	163,842
3		106.8	115.5	2,163	113.0	2,116	0.05	142,322
4		105.7	144.0	2,725	144.0	2,725	0.07	157,994
5		107.3	129.5	2,414	128.0	2,386	0.06	150,979
Avg.	=	106.6	136.0	2,553.0	134.0	2,515.6	0.07	152,962
SD	=			302.5		312.2		8,241
CV	=			11.8%		12.4%		5.4%

CEL ID number 5957-
Client sample

Specimen number		Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
Avg.	=							
SD	=							
CV	=							

CEL ID number 5957-
Client sample

Specimen number		Thickness, mil	Load at yield, lbs	Stress at yield, psi	Load at break, lbs	Stress at break, psi	Elongation at break, %	Modulus, psi
Avg.	=							
SD	=							
CV	=							

NOTES:
Performed in accordance with ASTM D638, Specimen Type I dumbbell, testing speed 0.2 inch per minute.
SD = Standard deviation, psi
CV = Coefficient of variation (SD/Avg.), %

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