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EVALUATION OF RECYCLED PLASTIC LUMBER FOR MARINE APPLICATIONS

By

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulation of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This publication is part of a series of publications for the Municipal Solid Waste Innovative Technology Evaluation (MITE) Program. The purpose of the MITE program is to: 1) accelerate the commercialization and development of innovative technologies for solid waste management and recycling, and 2) provide objective information on developing technologies to solid waste managers, the public sector, and the waste management industry.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

PREFACE

The Municipal Solid Waste Innovative Technology Evaluation (MITE) Program is managed by the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD). The purpose of the MITE program is to: 1) accelerate the commercialization and development of innovative technologies and programs for solid waste management and recycling, and 2) provide objective information on developing technologies and programs to solid waste managers in the public and private sectors.

These goals are met by selecting, through a competitive process, technologies and programs that have submitted proposals to EPA through its annual solicitation. Once selected, EPA, with the cooperation of the technology developer, formulates a plan which evaluates the costs, effectiveness, and environmental impacts of the technology. Each project consists of a field demonstration and an associated evaluation. The MITE program is administered by the Solid Waste Association of North America (SWANA). SWANA coordinates an Advisory Committee review as well as assisting in the formulation of the evaluation plans.

The technology developer, California Recycling Company (CRC), in conjunction with Morrow Associated Enterprises, manufactured the materials tested in this program. The evaluation was conducted at the Florida Institute of Technology and Rutgers University. The MITE program seeks to gather environmental and cost information on new and developing technologies. This report presents the results of this evaluation.

A limited number of copies of this report will be available at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268. Requests should include the EPA document number found on the report's cover. When the supply is exhausted, additional copies can be purchased from the National Technical Information Service, Ravensworth Building, Springfield, Virginia 22161, 703/487-4600.

ABSTRACT

This report presents an evaluation of the recycled plastic materials (RPM) produced by California Recycling Company (CRC). This evaluation is performed under the Municipal Solid Waste Innovative Technology Evaluation (MITE) Program of the U.S. Environmental Protection Agency (EPA) Risk Reduction Laboratory. The lumber is produced from difficult-to-market post consumer plastic materials which have been recovered from a mixed municipal solid waste stream at CR Transfer's New Stanton material recovery facility (MRF).

R. W. Beck and Associates assessed the composition of the plastic made into plastic lumber. This plastic was shredded and granulated followed by air elutriation to remove paper labels at the New Stanton MRF. The material was transported to CRC, Los Angeles, where it was formed into 2 in. x 6 in. by 12 ft dimensional plastic lumber at mixtures ranging from 100% commingled plastic to 50% commingled blended with 50% industrial regrind plastic. The continuous extrusion process used a foaming agent to impart a lighter core to the plastic lumber.

A battery of tests was performed on the RPM to determine strength, creep, serviceability, biological compatibility, and toxicity of the plastic lumber. These tests were selected to characterize the behavior of the material for marine applications.

The findings show that the plastic lumber produced by CRC has significant creep characteristics which must be adequately addressed by appropriate architectural design when using this material. Flexural stiffness properties are less than 1/10 that of wood. The plastic lumber shows excellent nail and screw retention ability compared to wood. Biological testing has indicated a far lower toxicity for the plastic than for chromium copper arsenate (CCA) treated wood.

A limited life cycle analysis was performed to compare CCA-treated wood with the recycled plastic lumber created. The analysis takes into account lifetime and environmental impacts of the manufacture of CCA-treated wood and recycled plastic lumber.

This report was submitted in fulfillment of Cooperative Agreement CR 818238 with the Solid Waste Association of North America (SWANA). The report was completed by R. W. Beck and Associates under subcontract to SWANA. This report covers a period from September/91 to August/93 and work was completed as of March/93.

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Sea Urchin Fertilization experiments were performed by Pedrick Weiss of the New Jersey Medical School. All other tests were performed by Charles R. Lockert under the supervision of Gary Zarillo of FIT.

SECTION I

INTRODUCTION

The Environmental Protection Agency (EPA) through the Municipal Solid Waste Innovative Technology Evaluation Program (MITE) is funding the evaluation of a new process to produce "Recycled Plastic Materials" (RPM). The plastics targeted are from residential and commercial waste streams. Special emphasis is placed on using "lower value" plastic waste, or plastic waste in which the more marketable plastics have been removed. The RPM formed from these plastics is envisioned as a substitute for wood dimensionable lumber, such as 2 in. x 6 in. and 4 in. x 4 in. cross section lumber.

The company manufacturing the RPM used in this evaluation is California Recycling Company (CRC). The CRC manufacturing plant is located in Los Angeles, California. Process and equipment design was performed by Morrow Associates Enterprises, Inc.

PLASTICS IN THE WASTE STREAM

Plastic is defined as "any of various nonmetallic compounds, synthetically produced, usually from organic compounds by polymerization, which can be molded into various forms and hardened, or formed into pliable sheets or films, fibers, flexible or hard foams, etc., for commercial use." From this broad definition comes plastic's inherent recycling dilemma — there are many plastic resins, sometimes different types for the same end use (which are incompatible), making it difficult to economically recover and recycle plastic. Sorting the plastic by resin type is difficult to do automatically, and currently the markets for secondary plastic are only strong for soft drink bottles (polyethylene terephthalate, or PET) and milk jugs (natural high density polyethylene, or HDPE). Other resins have less recycling value. This leaves a large portion of the plastic waste stream without an economic alternative to landfilling or incinerating.

According to a recent EPA study (Franklin and Associates, 1992), plastic discards contributed 9.1% of solid waste by weight in 1988. This represents about 14 million tons per year of plastic of which roughly 70% are found in nondurable and packaging applications. Concentrating on and recycling this portion of the plastic waste stream is the focus of this project.

COLLECTION STRATEGIES

Two main methods are followed for collecting plastics from the waste stream. Commingled solid waste can be collected as a single stream and processed at a centralized facility to remove the recyclable material. In this scenario, the centralized processing facility can be designed and operated to extract and sort the plastic which is marketable. Non-marketable plastic is not recovered, but could be at a later date as markets improve for these materials.

The other method of collecting plastic is through source separation. Here, the waste generator is instructed what to separate from the waste stream. The recyclable materials can be curbside collected or taken by the waste generator to a drop-off location. Recyclables can be kept separate or commingled in various combinations, for subsequent sorting at a material recovery facility (MRF). For plastics, source separation programs generally accept only specific products, such as PET and natural HDPE. However, if markets exist for other resins, the program could be modified to accept other plastic containers.

RECYCLED PLASTIC

Thermoplastics, the plastics which comprise all of the common consumer packaging and nondurables, can be remelted and reformed for a wide range of non-food contact applications. If proper separation, washing, and processing of the resins are accomplished, many products can be made. The amount of recycled plastic in the new products can range up to 100% depending on the application. Products currently manufactured with recycled plastic include bags, detergent and motor oil bottles, carpet fiber, and slip sheets (substitute for pallets).

Plastic lumber is the generic term given for making dimensional wood and steel substitutes from post consumer, or industrial, scrap plastic. One or more plastic resins can be used, along with various additives for color, strength, or density reduction. Color additives can add to aesthetic quality. Strength additives can include fiberglass, particular plastic resins, and wood/fiber. Density reduction can be attained using foaming agents which create air spaces in the middle of a cross section of plastic lumber. Density can also be reduced by forming plastic with hollow, or ribbed, internal cross sections.

Plastic lumber cannot compete with conventional building materials on a strength basis, but it has certain characteristics which can make it competitive for specific applications. Included in this list are:

- Weather resistance
- Biological resistance
- Salt water resistance
- Environmental compatibility
- Reuse of waste materials

These characteristics can make plastic lumber especially competitive as a substitute for chromium copper arsenate (CCA) treated lumber for marine applications. This evaluation focused on marine applications as a market niche for the plastic lumber created from a specific process and manufacturer of plastic lumber. Marine applications include docks or piers, bulkheads, and boardwalks. Laboratory and field testing can determine values of the properties which are relevant in these applications. Short-term testing can also be used to infer long-term performance of the plastics.

TECHNOLOGY DESCRIPTION

There are three main steps in producing plastic lumber: collecting the material or feedstock, shredding and granulating, and forming into the end product. There are aspects to the CRC process which make it somewhat unique. These will be detailed in the individual operation descriptions.

Feedstock

The feedstock for CRC comes from the New Stanton, California, mixed waste MRF. This facility receives approximately 750 tons/day of municipal solid waste (MSW). The material is sent through a large trommel which sorts the waste by size onto conveyors. Plastics are hand picked from the larger size fraction of MSW. The PET and natural HDPE are recovered for separate recycling. The hand pickers are instructed to take out all other plastic containers, plates, and objects. These are sent by conveyor to a shredder/granulator. CRC requires at least 70% of the plastic delivered to them be from HDPE containers. This can be ensured through selective picking from the conveyor.

Composition Analysis

The plastic was not washed before it was granulated. The bottles, for the most part, did not contain liquids. Visually, there was only a minimal amount of non-plastic material going to the granulator. Occasionally an aluminum can would be transported to the granulator. After granulation, the plastic appeared clean, even though no washing was performed. Paper labels and contamination were removed in an air elutriation system explained below.

The composition of plastics from the New Stanton facility going to CRC was determined by a composition audit. The Quality Assurance Project Plan (QAPjP) for this project stipulated taking ten 50-lb grab samples of the mixed plastic destined for CRC; 11 samples were taken with a total weight of 633.8 lbs. The samples were taken from the conveyor leading up to the plastics granulator. All the plastics on this conveyor were picked over the course of about 10 hours distributed over 2 days.

Plastics from the conveyor were placed in 30-gal trash cans. Each can weighed from 5-10 lbs when full. Five to ten trash cans were required for a single waste composition sample. The trash cans were dumped onto a tarp where they were sorted into 16 separate bins representing the seven resin codes commonly used in packaging and their major product types. The bins were tared and weighed on a digital platform balance.

Table 1.1 shows the average composition of the plastics based on the 11 samples. The relative standard deviation (RSD) is calculated according to Section 8.0 of the QAPjP. The 90% confidence interval is calculated from the standard deviation and the sample size. As can be seen, the RSD is greater than 50% for most of the components. This is expected since the number of components is large and the amount of each type is generally small. This illustrates the heterogeneity of the MSW stream and the variability of the plastic composition with respect to the components as sorted.

The sample size was selected in order to obtain a reasonable accuracy of the composition with respect to HDPE, the resin with the largest overall fraction. CRC specifies at least 70% of the plastic from the New Stanton MRF be HDPE. Table 1.2 shows the composition condensed into the seven resin categories. The RSD and 90% confidence intervals are shown. As is indicated, the RSD for HDPE is 12.7%, well below the QA objective of 50%. As seen, the RSD for the other resins is greater than 50%. This is again due to the relatively large variation in the plastic waste stream and the small percentages of these resins.

TABLE 1.1 PLASTIC COMPOSITION BY TYPE OF PACKAGING

Component	Resin	Average Composition	RSD	90% Confidence Interval (+\-)	Relative % Error (+\-)
PET, other bottles and jars	1	1.5%	174.2%	1.5%	100%
PET rigid containers	1	1.2%	68.0%	0.5%	39%
PET soda bottles	1	0.1%	262.6%	0.1%	150%
HDPE colored blow-molded bottles	2	44.5%	17.4%	4.4%	10%
HDPE injection-molded containers	2	24.9%	30.9%	4.4%	18%
HDPE opaque blow molded bottles	2	2.3%	165.2%	2.1%	95%
Polyvinyl chloride bottles	3	0.6%	85.4%	0.3%	49%
Polyvinyl chloride containers	3	0.1%	214.3%	0.1%	123%
LDPE composite containers	4	0.6%	94.4%	0.3%	54%
LDPE bottles	4	1.0%	258.9%	1.4%	148%
LDPE containers	4	0.6%	96.8%	0.3%	55%
Polypropylene containers	5	8.0%	75.4%	3.5%	43%
Polystyrene containers	6	1.0%	66.1%	0.4%	38%
Polystyrene foam, other packaging	6	1.8%	198.7%	2.1%	114%
Polystyrene food products	6	1.3%	45.8%	0.3%	26%
Uncoded plastic or plastic labeled #7	7	10.7%	46.1%	2.8%	26%

TABLE 1.2 FEEDSTOCK COMPOSITION BY RESIN

Component	Resin	Average	RSD	90% Confidence Interval (+\-)	Relative % Error (+\-)
PET	1	2.9%	86.1%	1.4%	49.3%
HDPE	2	72.1%	12.7%	5.3%	7.3%
PVC	3	0.7%	62.1%	0.2%	35.6%
LDPE	4	2.2%	128.6%	1.6%	73.7%
Polypropylene	5	7.7%	81.2%	3.6%	46.5%
Polystyrene	6	4.2%	97.1%	2.3%	55.7%
Uncoded	7	10.4%	48.6%	2.9%	27.9%

The 90% confidence interval for HDPE is 5.3%, which indicates that the mean of the entire plastic waste stream from this MRF should be from 66.8 to 77.4% with 90% confidence. Strictly speaking, therefore, the composition could have less than the 70% HDPE specified. This can have a significant influence on the runability of this feedstock in the extruder, and the resulting strength of the plastic lumber which is made.

Approximately 1,000 lbs of plastic was shipped to CRC, of which 633.8 lbs was sampled. Of the 750 tons/day of MSW received at the MRF, approximately 1 to 2 tons of plastic is collected and shipped to CRC. This is less than the theoretical composition of plastic tailings in the waste.

Granulation

Shredding and granulation of the feedstock is done at the MRF. The shredder is an Allegheny using a 50-hp motor. The granulator is made by Formost and has a pair of 50-hp motors. The granulator has a nameplate capacity of 1 ton/hr but reportedly has been proven to only accept 0.6 ton/hr or approximately 14 tons/day. The plastic is first shredded and then cut up in a high-speed granulator to a size of about 10 mm. The air elutriation system uses a stream of air to separate the lighter material from heavier plastic pieces. It forces lighter weight granulated material into a separate container for disposal.

Extrusion

The continuous extrusion "line" consists of a Reifenhauser twin screw extruder; a die to form the dimensions of the plastic lumber; a vacuum "calibrator" which uses a vacuum to pull the extruded plastic against the sides of a perforated mold; and a wet calibrator, in which water flows over the die to cool the plastic down before it finally leaves the extrusion line. This system is unique in that it has been designed specifically for a post-consumer feedstock. Due to the proprietary nature of this design, specific features of the extrusion line will not be detailed.

Product Types

Products can be varied according to the properties and shapes required by the marketplace. CRC can manufacture 2 in. x 6 in. and 4 in. x 4 in. dimensional lumber with a hollow core or a foam core. The hollow core has a ribbed cross section which provides some extra strength, without adding greatly to the weight. The core is made by using a foaming agent which essentially produces a gas in the interior of the plastic lumber as it is formed. This creates a rigid foam-like interior which lightens the overall weight without causing a substantial loss in compressive or flexural strength.

The foam core lumber was chosen for this evaluation because the market for foam core was stronger for CRC, and the development of the foaming technique was more reliable at the time of producing the plastic lumber for this study. The hollow core is lighter but is seen to be more difficult to fasten, as the wall thickness is about 3/16 in. The foam core achieves some weight saving over a solid cross section, but still has enough structure to allow for screws and nails to be used for fastening during construction. This is seen to be an advantage when substituting for wood without having to change building practices.

Applications

The applications for this plastic lumber will depend on its properties, which this study attempts to characterize. The testing protocol attempts to give information both for general properties as well as specific ones important in marine applications. Marine applications can include:

- Decking for boardwalks and boat docks
- Stationary and movable piers
- Bulkheads which can control beach erosion
- Sea walls

- Pilings
- Pier impact protectors
- Railings for various platforms

Of these applications, some will demand higher strength material than others. For instance, railings and deckings will require less strength and creep resistance than will pilings and bulkheads which will have a more constant load placed upon them.

OTHER AVAILABLE TECHNOLOGIES

There are two major methods for making plastic lumber. The first method is a continuous extrusion process where the molten plastic is passed through a die and then cooled by a water spray or bath, as used by CRC. The second method is a molded process where the molten plastic is extruded into a mold and then cooled in the mold. The following sections describe a few of the available processes.

The ET-1 and Superwood Processes

These processes are derived from a plastic lumber system developed and patented by Lankhorst Recycling LTD of the Netherlands. Granulated plastics (and in some instances densified film plastics) are fed into an extruder where they are melted. The extruder then pumps the molten plastic into a sealed mold under low pressures, until the mold is filled and pressurized. The filled mold then rotates down into a cooling water bath, and later back out as other molds are sequentially filled. The finished product is air-ejected from the molds.

An Irish company called Superwood International, LTD, paid Lankhorst Recycling for the right to build and sell plastic lumber systems using the concept of rotating molds. Although Superwood International went out of business in 1991, plastic lumber companies still use the process and systems sold to them by Superwood.

Advanced Recycling Technology, LTD (ART) of Belgium also began selling a system with rotating molds which moved from a filling station to a submerged cooling station to an ejection station. ART called its system the ET-1 system. After a patent battle between ART and Lankhorst Recycling, ART signed a licensing agreement in 1992 giving it the right to sell its ET-1 system in several North American and European countries including the United States, Canada, Germany, France, and England.

Several generations of ET-1 systems have been designed and sold by ART. The systems vary in their output depending on the model and processing conditions, but may range from 300 lbs/hr per line for older models to 700 lbs/hr for newer models. The Superwood systems will have outputs similar to the older ET-1 models. This compares with an observed rate of approximately 500 lbs/hr for the CRC foamed core material, which is made by a continuous extrusion process.

Low-pressure molding systems such as Superwood, ET-1, and other systems without rotating molds all produce similar solid profiles. The molding process does not have the ability to produce hollow profiles as a continuous extrusion system can, nor can a molded process produce very long profiles. Internal voids are common, but can be controlled by keeping wet plastic or foamed plastics such as expanded polystyrene out of the feedstock. Other techniques such as pressurizing the molds with the molten plastic will minimize the creation of voids while helping to maintain dimensional stability upon cooling. The slow nature of the mold filling process, however, usually results in lumber profiles which have at least some variation in density from one end of the profile to the other. This happens because the first plastic to enter the mold is partially cooled by the time the final plastic enters the mold, so it is not easily pressurized. The variation in density will result in profiles where one end may have more voids and less stiffness than the other end of the profile.

Low pressure molding systems also usually produce a coarse fibrous surface texture on their profiles. This fibrous texture is visually pleasing since it gives the plastic lumber a wood-like appearance. The texture is a result of the slow molding process. When molten plastic enters the mold, it begins to solidify, beginning first with the low melting point plastics such as low-density polyethylene (LDPE). Other plastic continues to enter the mold, pushing the partially solidified LDPE along. As it is pushed along, friction with the mold wall elongates it into strings, resulting in the fibrous texture. The CRC plastic lumber formed has a smooth surface due in part to the higher speed of the sliding motion in the molds.

The Mobil and AERT Processes

The Mobil Chemical Company and Advanced Environmental Recycling Technologies, Inc. (AERT) both make continuously extruded plastic lumber products that contain wood fibers. Mobil purchased a company called Riverhead Milling, acquiring the plant, process, and the product trademark Timbrex™. The company is now known as the Composite Products Division of Mobil Chemical Company, although the product is still referred to as Timbrex™. Details about either the Mobil or AERT processes are difficult to obtain at this time.

Mobil refers to its product as a wood-polymer composite. Mobil uses mostly hardwood fiber wastes from the furniture industry for the wood fraction in its product. The plastic fraction comes from film plastics, mostly LDPE from grocery sacks or other sources, and may include some HDPE film as well. Mobil does not use plastic that has been collected from the public in curbside programs in its product. Timbrex™ contains up to 50% wood, is a very pleasing brown color, and looks similar to wood, only without knots or grain. Timbrex™ appears to be very solid, with good dimensional uniformity and no voids. The controlled plastic feedstock, wood fibers, and low processing temperature allowed by using LDPE all contribute to its good quality.

AERT also makes its product from both plastic and wood wastes, and like Mobil, prefers to call it a composite material. AERT calls its product MoistureShield™, and sells it to the building products industry, where it is made into window and door sills, and drawer tracks for furniture. AERT uses finely ground cedar wood waste fiber for the wood fraction of its product. The plastic fraction comes from post-consumer grocery bags, HDPE containers, and LDPE film from recycled LDPE-coated milk cartons. MoistureShield™ appears to have a higher fraction of wood in it than Mobil's product does. MoistureShield™ is a very pleasing brown color, and looks similar to wood, only without knots or grain. It appears to be very solid, with good dimensional uniformity and no voids. It smells like cedar wood.

AERT has submitted six patent applications for its product processing and film reclamation technologies. The films are compressed and forced through a die to form dense pellets. The film plastics have not been melted in forming the pellets, so the pellets can be broken apart. Film densification systems used by other plastic lumber producers include heat to melt and densify film plastics before they enter the extruder.

Comparison Between Molded and Continuous Extrusion Systems

Continuous extrusion systems take up more space than molded lumber systems, because the continuous extrusion systems must have a long, straight cooling section. As the length of the cooling section on a continuous extrusion system is reduced, the extruder output must also be reduced to allow time for the extruded plastic to cool. This can reduce the greater theoretical capacity that a continuous extrusion system can have down to the capacities of molded systems. The time spent in cooling the extruded profile also will affect its dimensional uniformity. Although the exterior of a continuously extruded profile can be quickly cooled, the interior may still be hot. This temperature gradient will result in the creation of voids, and profile faces which contract inward toward the center of the profile as it cools. The slower cooling rates of molded lumber systems usually help those systems achieve greater dimensional uniformity.

In summary, continuous extrusion systems lend themselves to producing plastic lumber profiles which are of a wide range of lengths and are hollow or foamed in their interior. This is very advantageous from a weight-saving standpoint. Molded lumber systems can produce thicker and heavier profiles, and may be more forgiving of dirty or inconsistent feedstock. Molded systems have in the past been generally less expensive to purchase and easier to operate. These cost advantages may be erased as advances are made in continuous extrusion technology.

SECTION II

EVALUATION OF THE TECHNOLOGY

Five separate types of plastics manufactured by CRC were tested. All were made with a blowing agent to give them a foam core. The blowing agent is composed of a powder which is mixed in the plastic in small quantities. As the plastic is extruded, the blowing agent produces gas bubbles which achieve two results: 1) the bubbles displace plastic in the core of the material, which increases strength to weight ratio and 2) the gas forces the plastic against the mold which then precludes the need for a vacuum in the calibrator.

The five different types of plastic manufactured for this evaluation were 100% commingled 2 in. x 6 in., 4% polypropylene industrial regrind added, 10% polypropylene industrial regrind added, 50% HDPE industrial regrind added, and 4 in. x 4 in. with 50% HDPE industrial regrind added. The manufacture of the 2 in. x 6 in. material was observed.

The reason for adding polypropylene is to evaluate its effect on improving the modulus of elasticity. It has been found that adding up to 35% polystyrene can improve the modulus dramatically. Polystyrene, however, is more difficult to collect since it is usually in foam form and thus not thought to be as practical an additive as polypropylene. Adding 50% HDPE can assure a more consistent and marketable product, as this material is clean and consistent.

Table 2.1 describes testing methods.

TABLE 2.1 TESTING METHODS

Parameter	Method	Method Title	Method Type	Source Reference
Holding strength of nails and screws	ASTM D1761	Standard Test Methods for Mechanical Fasteners in Wood	Mechanical	ASTM[1]

TABLE 2.1 TESTING METHODS (cont.)

Parameter	Method	Method Title	Method Type	Source Reference
Resistance to deformation by flexural stress	ASTM D2990	Standard Test Methods for Tensile, Compressive and Flexural Creep and Creep-Rupture of Plastics	Mechanical	ASTM(1)
Strength of the profiles when force is applied in compression	ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics	Mechanical	ASTM(1)
Strength of profiles in bending	ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	Mechanical	ASTM(1)
Friction of the profiles, while wet and dry	ASTM D4521	Standard Test Method for Coefficient of Static Friction of Corrugated and Solid Fiberboard	Mechanical	ASTM(1)
Loss of surface layers due to UV	ASTM G53	Standard Practice for Operating Light- and Water-Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials	Light	ASTM(1)
Bioassay of the profiles	EPA 1008	Sea Urchin Fertilization and Embryolarval Test	Biological	EPA(2)
Biofouling of the profiles	ASTM D3623	Standard Method for Testing Antifouling Panels in Shallow Submergence	Biological	ASTM(1)

(1) American Society for Testing and Materials. Annual Book of Standards. ASTM. Philadelphia, PA. Sections 4, 6, 8, 14, 15.

(2) U.S. Environmental Protection Agency. "Short Term Methods for Establishing the Chronic Toxicity of Effluents and Receiving Waters to Marine and Estuarine Organisms," EPA 600/4-87/028, Environmental Monitoring Systems Lab, Cincinnati, Ohio, May 88, p239-272.

A series of tests as set forth in the QAPjP was performed on the plastic made at CRC. The tests can be divided into two groups: physical testing and environmental testing. Results from these tests are given below.

PHYSICAL TESTING

The physical tests used were standard ASTM tests. Charles R. Lockert, P.E., of the Florida Institute of Technology Department of Oceanographic Engineering performed the tests under the supervision of Gary Zarillo, Ph.D. A summary of each test is given along with results of the tests.

Creep Tests

Creep tests are designed specifically for measuring long-term movement in plastic materials due to a continuous force placed on the materials. If one places a weight on the center of a span of plastic lumber supported only on two ends, the material will flex somewhat initially. Over time this flex will increase due to the unraveling of the polymeric entanglements of the plastic. This phenomenon is called creep and can be important in certain applications of plastic lumber.

ASTM D 2990, "Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics," was used and the tests measured the change in deflection of the plastic lumber over a period of 1,000 hrs.

Sample Preparation

Thirty-two-inch-long samples were cut from nominal 2 in. x 6 in.'s using an electric miter saw. Samples were placed in test jigs under no load, but at test temperature, for a minimum of 72 hours prior to loading.

Test Conditions

Room temperature tests were conducted with the temperature varying between 74-76°F and humidity between 65-67%. Elevated temperature of 140°F was conducted between 139-141°F and a humidity of 100% (submerged in heated water).

Apparatus--

The creep test jigs were constructed out of readily available materials. Figure 2.1 shows a schematic of a single test jig. The 2 in. x 3 in. steel tubing is fastened to a fixed stand, and the middle 1/2 in. x 30 in. section can move freely through this tubing. The basic idea is to apply a force to

the center of a 24 in. span of 2 in. x 6 in. plastic. The deflection is then measured with a digital caliper at set intervals of time. For the higher temperature tests, the plastic is immersed in a hot water bath which is controlled to 140°F. A more extensive description is given in the ASTM procedure.

Verification of Creep Test Jigs with Delrin

Verification of the creep test jig was accomplished by testing a virgin material and comparing test results with those published by the manufacturer. E. I. DuPont's Delrin 150 was chosen for the test. A Delrin rod 1-1/2 in. in diameter was cut to a length of 32 in. Three rods under an identical load were tested simultaneously. Figure 2.2 shows a comparison between the Delrin mean test results and the published results at 1,250 psi. The expected Delrin results were taken from *Modern Plastics*, "Guide to Plastics," 1985.

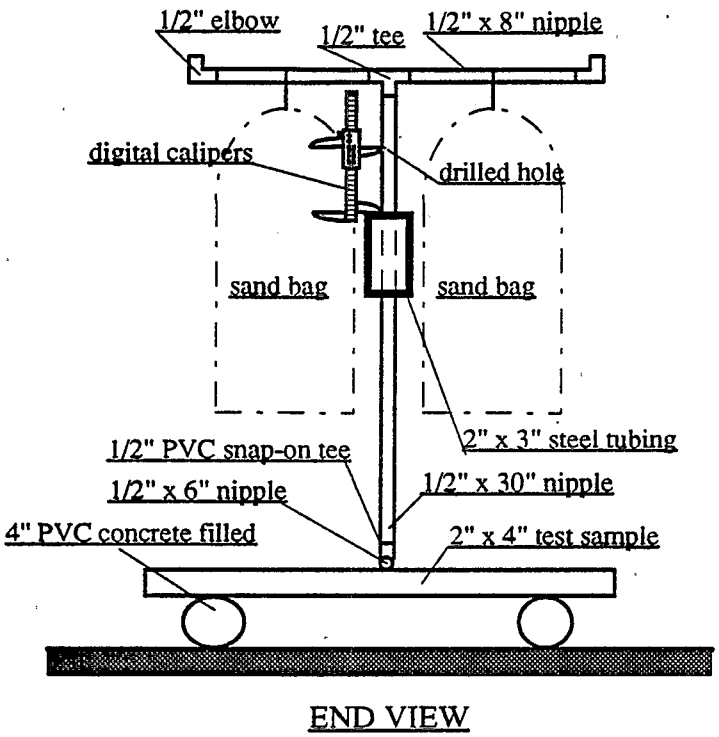

Figure 2.1 Individual sample in cut away of dry test jig.

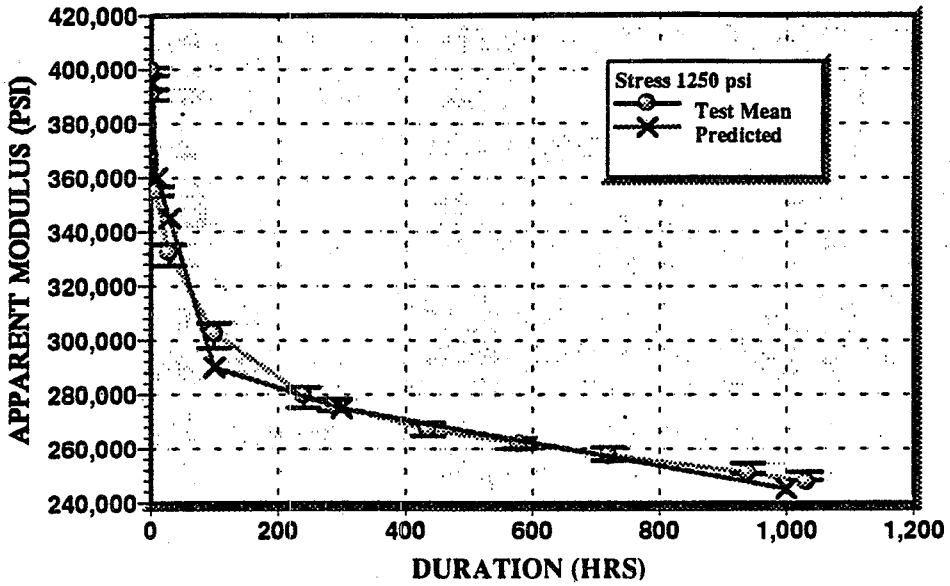

Figure 2.2 Delrin predicted vs. mean test values.

The small variation between test samples, as well as the 5% or less error between predicted and test values, provided assurance the test jig and accompanying procedure were reliable.

Results

The results of these tests are shown in plots of the apparent modulus of elasticity versus time for each plastic type, loading, and temperature. The apparent modulus in pounds per square inch (psi), is given in the following equation:

$$E = \frac{PL^3}{48\Delta I}$$

where:

E	is the apparent modulus in psi
P	is the constant load in lbs
L	is the distance in in. between supports
Δ	is the deflection of the sample in in.
I	is the moment of inertia in in^4

By plotting the log of the modulus versus the log of time, the data points form a relatively straight line in most cases. From these plots comparisons can be made between the different feedstock "recipes" used to make the plastic lumber. The creep behavior can also be predicted over longer

periods of time by extrapolating the plots beyond the time examined in the tests.

Figures 2.3 to 2.10 show the results of the creep tests under room and elevated temperatures. The elevated temperature runs were conducted at 140°F. Due to the variability of the materials it is shown that the creep is not as strongly correlated with weight as it should be. That is, the material variability from one piece to another is likely greater than the change in creep due to a different force being applied to the material. Figure 2.11 compares the four plastic formulations for a 100-lb load at room temperature.

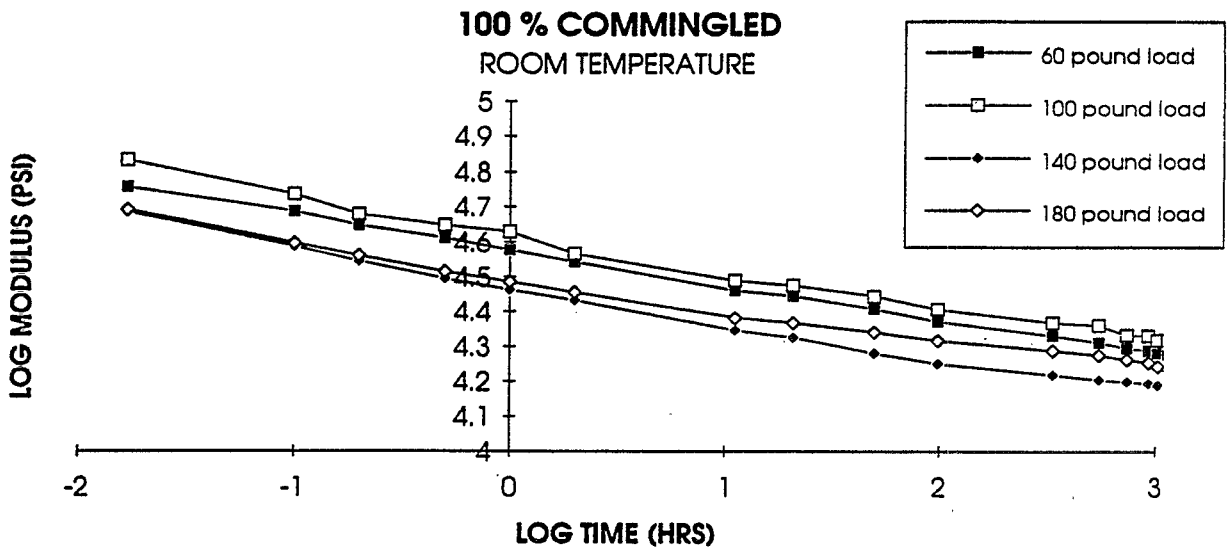

Figure 2.3 Creep test results - commingled plastic at room temperature.

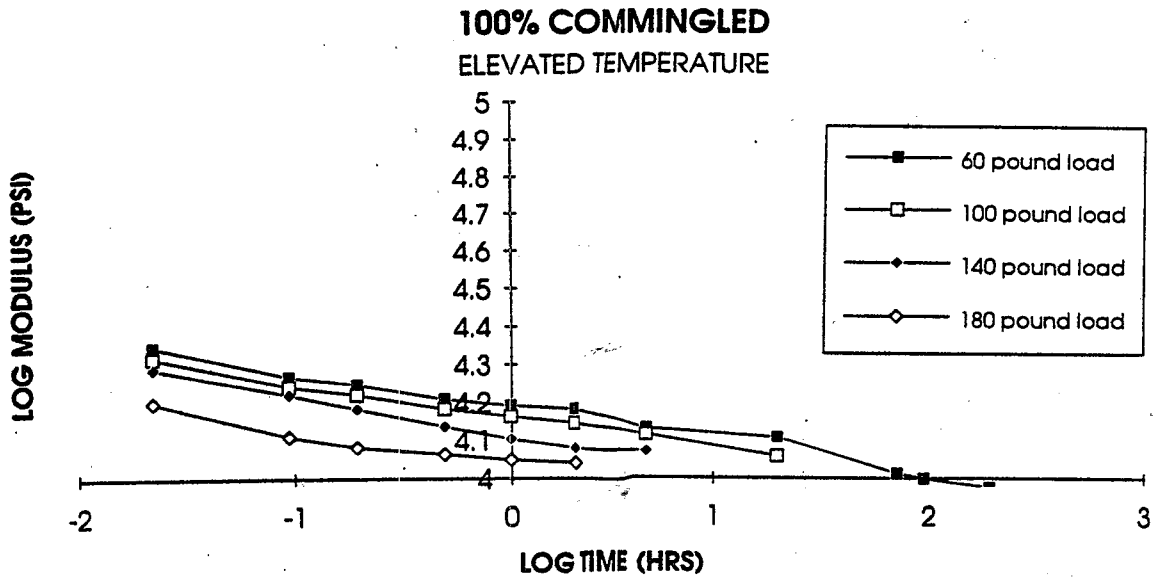

Figure 2.4 Creep test results - commingled plastic at elevated temperature.

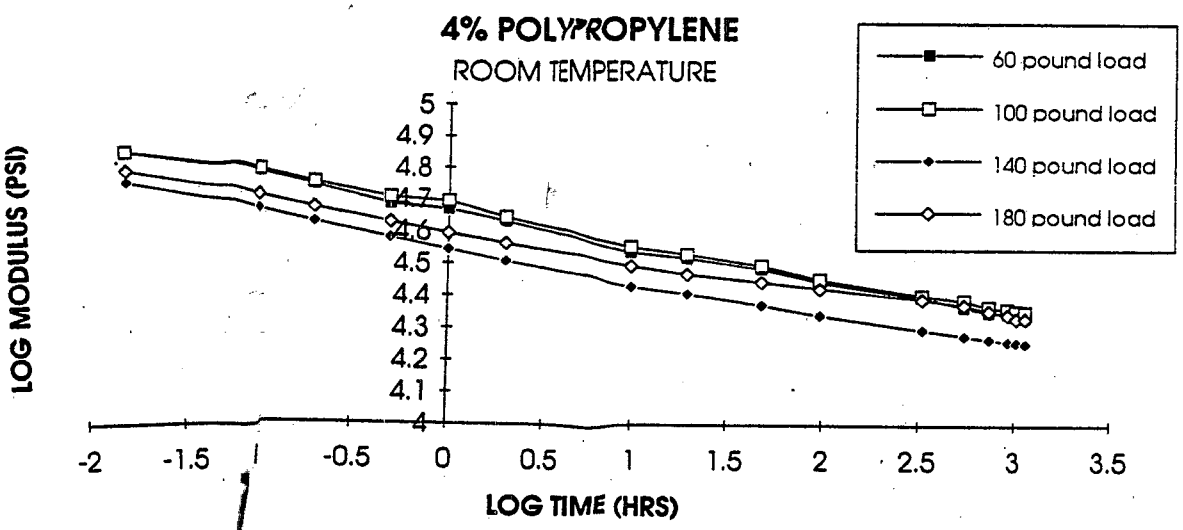

Figure 2.5 Cre test results - 4% polypropylene plastic at room te rature.

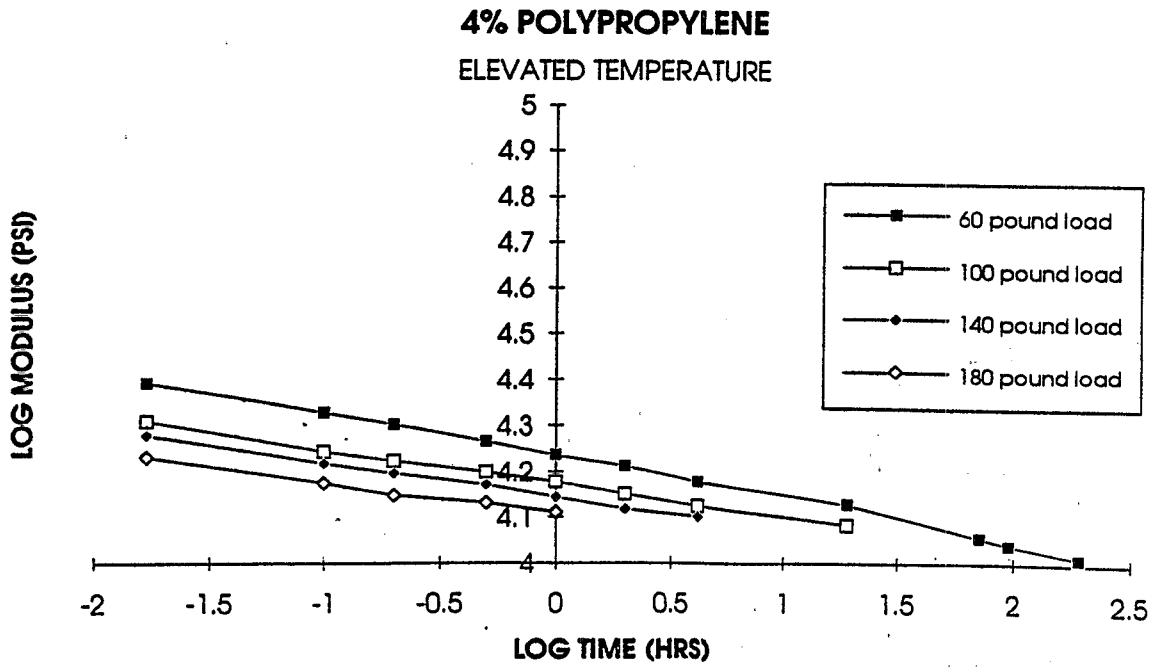

Figure 2.6 Creep test results - 4% polypropylene plastic at elevated temperature.

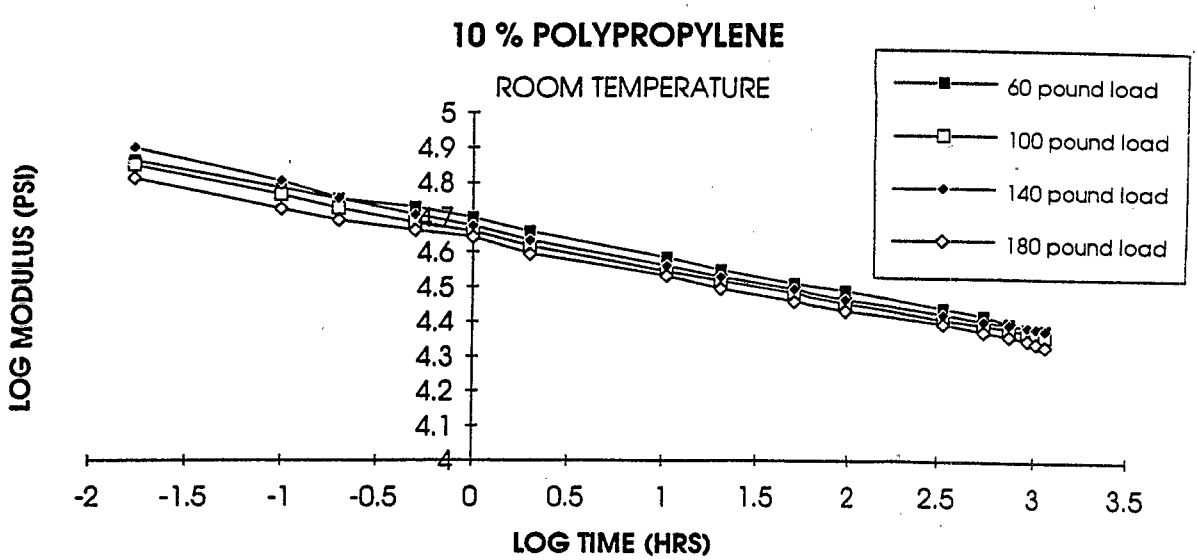

Figure 2.7 Creep test results - 10% polypropylene plastic at room temperature.

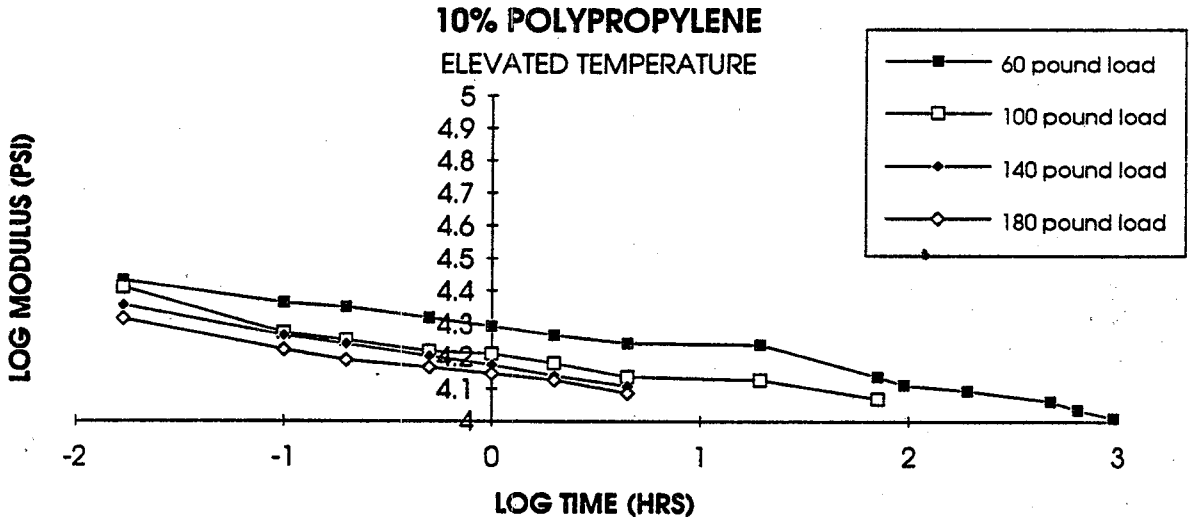

Figure 2.8 Creep test results - 10% polypropylene plastic at elevated temperature.

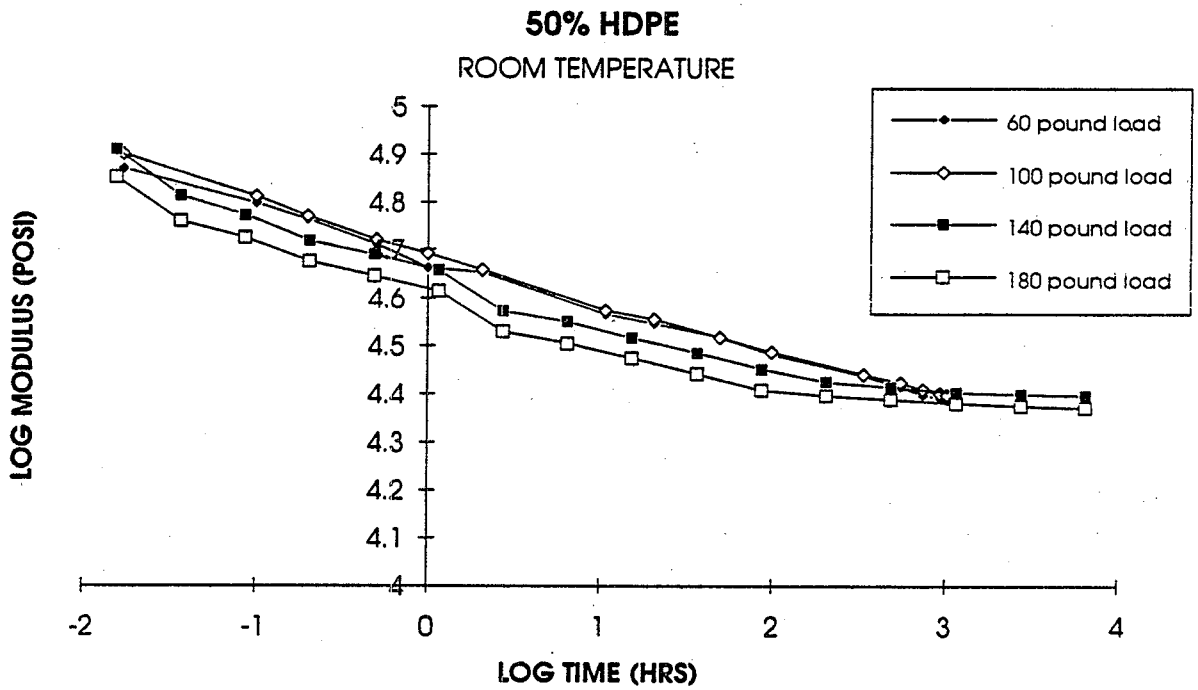

Figure 2.9 Creep test results - 50% HDPE plastic at room temperature.

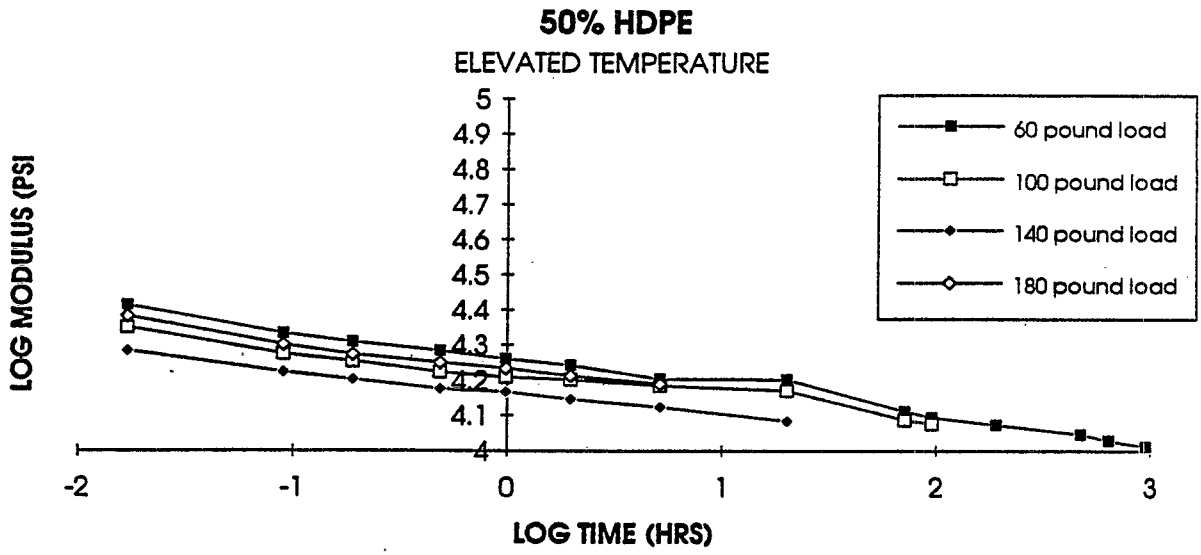

Figure 2.10 Creep test results - 50% HDPE plastic at elevated temperature.

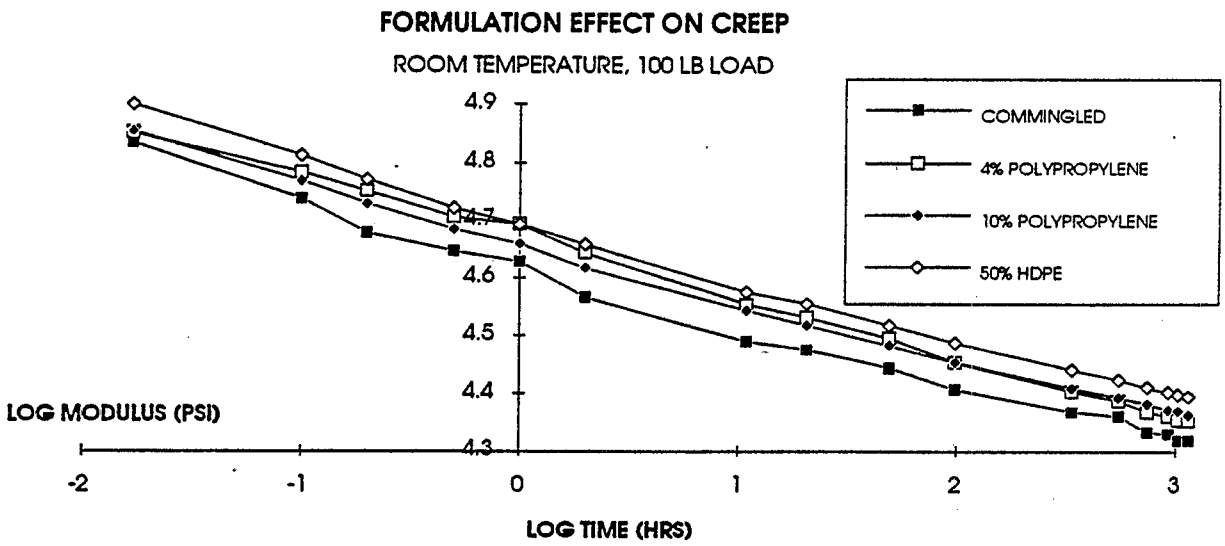

Figure 2.11 Comparison of four plastic formulations - 100-lb load at room temperature.

Flexure Tests

Flexural modulus is a measure of the stiffness of a material. It is important in that it will determine the span length of supports underneath decking among other things. This length is generally about 24 in. for 2 in. x 6 in. wood but will be expected to be less for the more flexible plastic studied here. Flexural testing followed the ASTM method D 790, "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials." Tests were performed on 2 in. x 6 in. lumber only.

Basic test procedure--

Flexure tests were performed using the Baldwin universal test machine in simply supported three point bending as shown in Figure 2.12. This machine is designed to apply a load on a material by gradually compressing it between a moving plate and a fixed plate. A maximum deflection of 3 in. is allowed with this test apparatus. None of the samples failed prior to bottoming out on the jig. As such, no ultimate strength could be calculated. Increasing the strain rate from 0.01 in./in./minute (used in testing) to 0.1 in./in./minute still did not cause failure. As a 3 in. deflection is greater than the 5% maximum strain in the outer fibers that ASTM allows, increasing the maximum allowable deflection would be of no use. The Baldwin load cell, an instrument which measures the force applied to the material, measured load while a digital extension indicator measured deflection. A corrected load and deflection were calculated to account for the preloading to ensure the sample was tight against the supports and loading nose. The secant modulus of elasticity was calculated between each data point and the beginning data point to best reflect a comparable value with wood. The secant modulus is the load divided by the deflection.

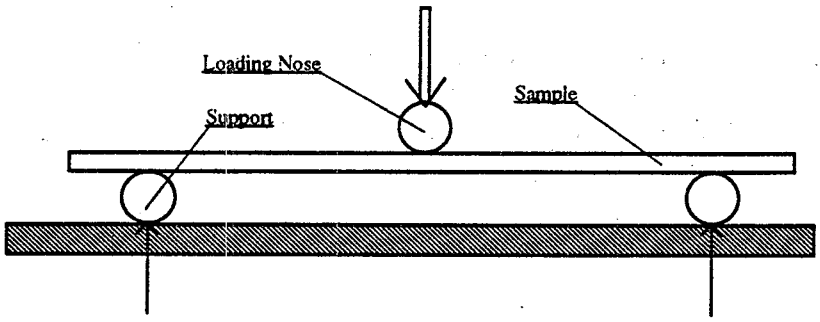

Figure 2.12 Flexure test jig.

Results--

The flex test, as indicated, did not show the ultimate strength of the material, as the material was elastic enough not to fail within the specified range of deflection of 3 in. Flexural modulus was calculated. Generally the tangent modulus calculated is at the first part of the stress versus strain curve, where the slope is constant. For the plastic, the initial portion of the curve was not linear. Therefore the secant modulus for each part of the curve was calculated and found to vary linearly with stress. Secant modulus is the absolute stress divided by the strain, instead of the change in stress divided by the change in strain. The secant modulus versus load was linearly regressed to yield an equation for each test.

The secant modulus equations allow calculation of strains and deflections for loads in the expected service environment of up to 500 lbs. The coefficient and constant statistics of these equations are summarized for the four 2 in. x 6 in. plastic compositions in Table 2.2.

TABLE 2.2 SECANT MODULUS EQUATIONS STATISTICS

Sample	Coefficient	Constant	RSD Coefficient	RSD Constant	Completeness
100% Commingled	-88	81,717	6.8%	7.1%	95%
4% Polypropylene	-106	86,951	2.5%	3.6%	90%
10% Polypropylene	-73	79,319	13.5%	3.8%	90%
50% HDPE	-85	92,636	9.8%	4.6%	90%

A graph of the four average equations is given in Figure 2.13. This demonstrates the higher modulus of the 50% HDPE formulation. Also to be noted is the greater stiffness of the 10% polypropylene plastic lumber at higher loadings. A single factor analysis of variance (ANOVA) performed on the data demonstrated the distinct statistical difference in flexural modulus of the four formulations.

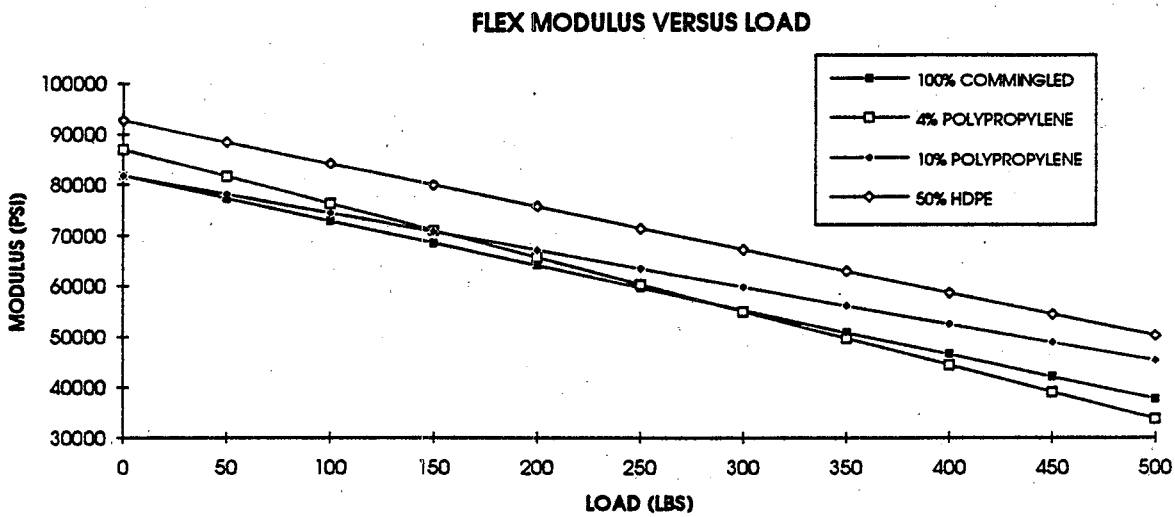

Figure 2.13 Plot of flex modulus for the four formulations of RPM.

Compression Tests

Compression testing is important in determining the structural characteristics of the plastic lumber. A structure composed entirely of plastic lumber will be under compression, tension, and flexural force at various points due to the loads caused by the weight of the structure and loads from external forces and weights. Therefore, a reasonable structural design will require values for these parameters, including variability of the material. The tensional strength was not measured in this study; however, as it is going to play a smaller role in design of marine applications, it can be estimated using flex and compression data if required. The ASTM test D 695*, "Compressive Properties of Rigid Plastics," was followed.

Basic test procedure--

Samples were placed between the bed and lower cross arm of the Baldwin universal test machine. The bed and cross arm provided flat and parallel surfaces. No provisions for pivoting of the sample were made. The sample was compressed at a cross head rate of 0.01 in. per minute. Deflection of the sample was recorded using a Mitutoyo Digimatic Indicator. The extension indicator and load indicator were interfaced with an IBM PC that recorded load and deflection data at approximately 500-lb intervals throughout the test. The cross head movement was continuous until sample failure.

The maximum load prior to failure was used to calculate ultimate strength. A corrected load and displacement were calculated to account for the 200- to 300-lb preload placed on the sample to ensure the sample was tight with the bed and cross arm. Secant modulus of elasticity was calculated

between adjacent data points throughout the test. An average modulus of elasticity was calculated for all like samples by averaging the maximum individual secant modulus of each sample. Figure 2.14 below indicates the arrangement of the test jig used.

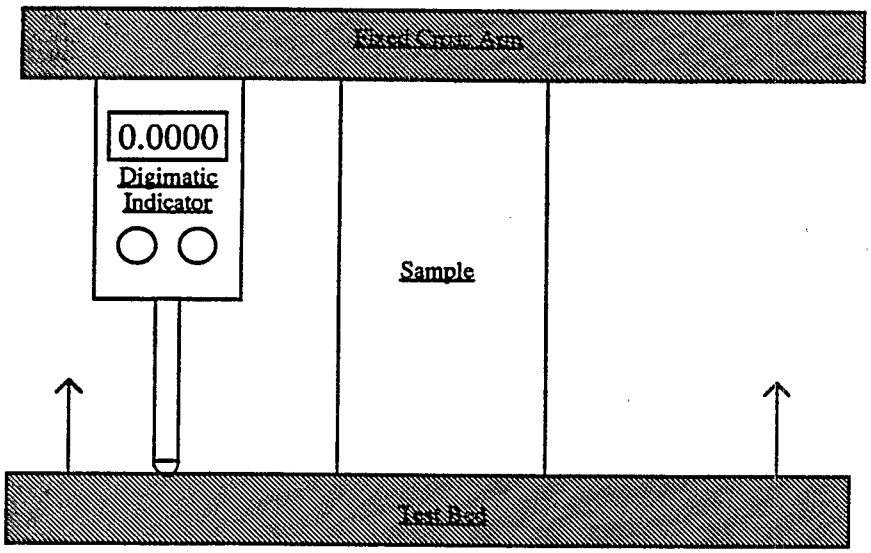

Figure 2.14 Compression test jig.

Results

Results from the tests are summarized in Table 2.3. It appears that the samples with 50% industrial regrind HDPE show the smallest relative standard deviation from the average. This is expected, since the HDPE should be very consistent in its characteristics. It also looks like polypropylene addition does not result in significant increases in compressive strength. This is verified by ANOVA which does not show a statistically significant difference between the 100% commingled and 10% polypropylene formulations.

TABLE 2.3 COMPRESSIVE MODULUS OF RPM

Sample Type	Number	Completeness	Average Compressive Modulus (psi)	Standard Deviation (psi)	RSD	90% Confidence Interval (+\-)
100% Commingled	19	95%	44,942	7,315	16%	2,910
4% Polypropylene	8	89%	42,163	4,788	11%	3,208
10% Polypropylene	10	100%	48,713	7,874	16%	4,882
50% HDPE	10	100%	55,150	3,743	7%	2,508
50% HDPE 4 in. x 4 in.	10	100%	33,697	3,449	11%	3,288

Static Friction Tests

Static friction testing can give an indication of how well the plastic lumber will function as a decking material. ASTM D 4521, "Coefficient of Static Friction of Corrugated and Solid Fiberboard," was performed on both plastic and CCA-treated wood for comparison. Wet testing was performed as well as dry to evaluate applications where surfaces may be periodically wet.

Basic test procedure--

Two-inch x 6 inch x 6 inch samples were clamped to the inclined plane as shown in Figure 2.15 below. The inclined plane is raised at a rate of 0.5 degree per second until the shoe or block placed on the sample begins to slide. The inclined plane is raised by the cross arm of the Baldwin test machine. This provided a very smooth and controlled rate of lift. When the block or shoe begins to slide, inclining is stopped and the angle of incline is noted. The angle of incline is provided by the protractor placed at the pivot point of the incline plane. The test is repeated three times and the angle of incline on the third lift is used to calculate the coefficient. The coefficient of static friction is equal to the tangent of the incline angle at which sliding begins.

Plastic samples and CCA-treated wood samples were tested. The first test of each sample was determining a coefficient of friction between the sample and itself. This involved sliding a 2 in. x 6 in. x 6 in. block of the same sample material and determining the coefficient of static friction. Then a tennis shoe was placed on the sample and a coefficient between the sample and tennis shoe was determined. The procedure is repeated for a rubber-soled

boat shoe. All three tests, sample block, tennis shoe, and boat shoe are repeated under wet or moist conditions. Water from a spray bottle is squirted on the sample face and the bottom soles of the shoes. Sufficient water is used to ensure saturation, evident by standing water on the sample surfaces. The plane is inclined three times as before with fresh water being applied to the sample between lifts. Fresh water is used to replace the water that has run off as the result of being inclined. The angle of the third lift is used in calculations.

The same procedure was used with the wooden samples using a wooden block, and the same tennis and boat shoe. After all the dry runs, water was squirted on the samples to simulate wet, rainy conditions. It should be pointed out, no water was squirted on the sample during the actual inclination process. It was placed only on the horizontal sample before each lift.

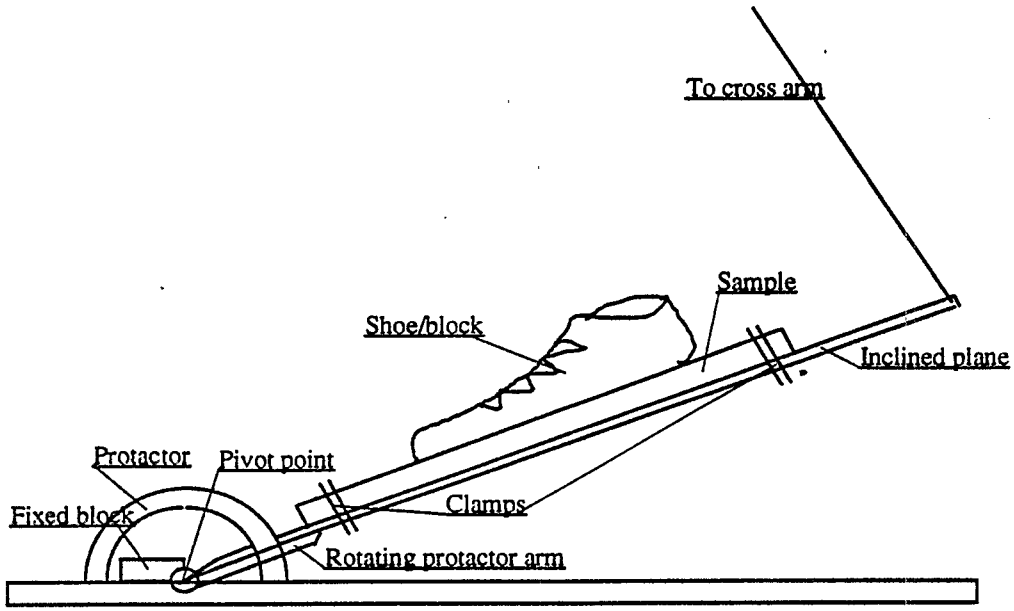

Figure 2.15 Inclined plane friction test jig.

Results

Table 2.4 shows a summary of the test results for plastic and wood samples. The coefficient of friction statistics for the material tested against itself, a used and a new tennis shoe, and a used and a new boating shoe were determined. A new Sperry Topsider™ boat shoe and a new Converse Chuck Taylor™ tennis shoe were used. Only 100% commingled plastic was

tested, since a substantial difference was not expected for the other plastic compositions.

The results show that the plastic is significantly more slippery than wood, especially under wet conditions. It appears that the old tennis and boat shoes show an increase in the coefficient of friction with a wet surface. However, this phenomenon does not occur with new tennis and boat shoes. This has been verified statistically by ANOVA. Also for plastic, the tennis shoe coefficient is always greater than the boat shoe, while for wood, this is only true for the new shoe tests.

TABLE 2.4 COEFFICIENT OF FRICTION USING MATERIAL AGAINST ITSELF, OLD AND NEW TENNIS AND BOAT SHOES

Sample	Average Coeff	STD Deviation	RSD
Dry Plastic			
Plastic	0.222	0.012	5%
Old tennis shoe	0.583	0.014	2%
New tennis shoe	0.8	0.019	2%
Old boat shoe	0.541	0.014	2%
New boat shoe	0.6	0.031	5%
Wet Plastic			
Plastic	0.241	0.018	7%
Old tennis shoe	0.600	0.023	4%
New tennis shoe	0.7	0.011	2%
Old boat shoe	0.563	0.576	4%
New boat shoe	0.545	0.022	4%
Dry Wood			
Wood	0.631	0.138	22%
Old tennis shoe	0.700	0.092	13%
New tennis shoe	0.933	0.015	2%
Old boat shoe	0.862	0.064	7%
New boat shoe	0.876	0.016	2%
Wet Wood			
Wood	0.948	0.113	12%
Old tennis shoe	0.872	0.021	2%
New tennis shoe	0.804	0.015	2%
Old boat shoe	0.994	0.035	3%
New boat shoe	0.785	0.029	4%

Mechanical Fasteners in Plastic Lumber

Testing the ability of the plastic lumber to hold nails and screws is important in ascertaining whether the plastic can be fastened using conventional nails and screws. ASTM D 1761, "Mechanical Fasteners in Wood," was followed.

Nail: #16d galvanized deck nails were driven manually using a carpenter's claw hammer. One nail was driven into each sample. Nails were driven in the geometric centriod of the 3.5 in. x 5.5 in. face and the 1.5 in. x 3.5 in. face. All nails were driven into to an uncut manufactured surface. The nails were driven to a penetration depth of 2.2 in. The 2.2 in. penetration in the 5.5 in. face therefore penetrated both the top and bottom faces of the sample. Nails remained in untested samples for 15 to 22 days to allow relaxation of the plastic around the nails and screws.

Screw: One #10 galvanized deck screw was placed in each sample. Screws were placed in the center of the 5.5 in. face and the 1.5 in. face. Pilot holes were drilled to one-half the screw penetration depth and with a diameter 70% of the screw root diameter. Pilot holes were drilled and the screws were inserted using an electric drill press. Screws were driven to a penetration depth of 2.4 in. The 5.5 in. face screw penetrated both the top and bottom faces. Screws remained in the untested samples for 15 to 22 days.

Basic test procedure--

The maximum load in pounds required to pull out the nails and screws vertically was determined with the use of a Baldwin universal test machine. Figure 2.16 below describes the test jig and setup used in both cases.

The bottom cross arm remained stationary while the top cross arm moved upward. The rate of cross arm movement was 0.1 in. per minute. The maximum load during removal of the fastener was recorded.

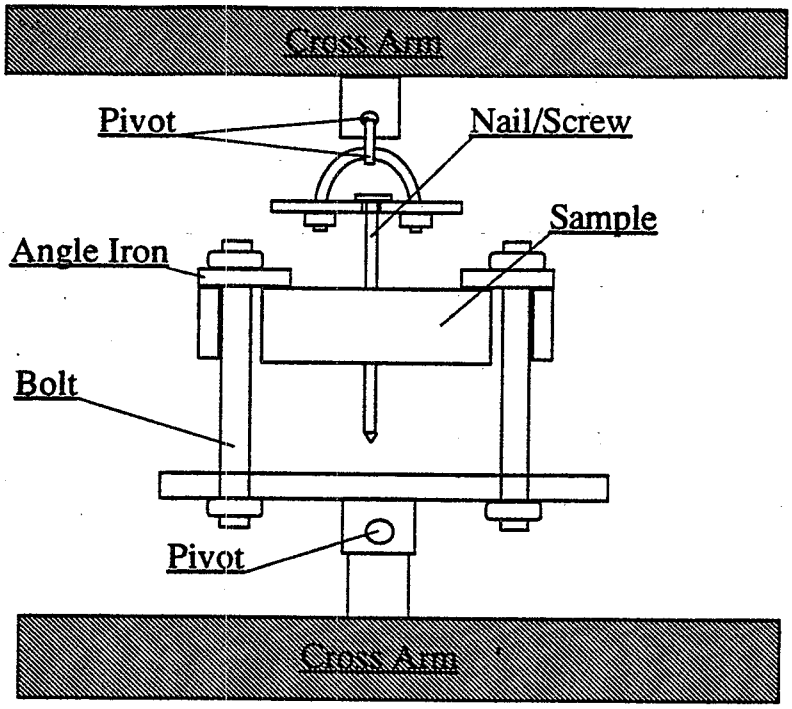

Figure 2.16 Nail and screw pullout test jig.

Results

The results indicate that the resistance to nail pullout, as shown in Table 2.5, is somewhat variable and not well correlated with the composition. In fact the 100% commingled and the 50% industrial regrind HDPE added have better average pullout resistance than the polypropylene samples. The standard deviations of data suggest, however, that the samples may not be significantly different in pullout resistance. This has been verified by a single factor ANOVA on the edge-driven nails. However, the face pullout tests were significantly different according to the statistical ANOVA test.

It is also noted that the nails going through the 5.5 in. face appear to be more difficult to remove than through the edge. This is not corroborated statistically by ANOVA.

TABLE 2.5 NAIL PULLOUT TEST RESULTS SUMMARY

Sample	Side	Average Nail Pullout (lbs)	STD Deviation (lbs)	RSD	90% Confidence Interval (lbs)		Completeness
100% Commingled	Edge	264.6	53.7	20%	295.7	233.5	100%
	Face	241.8	56.4	23%	274.5	209.1	100%
4% Polypropylene	Edge	209.6	42.8	20%	236.1	183.0	90%
	Face	257.6	28.3	11%	274.0	241.2	100%
10% Polypropylene	Edge	213.6	65.4	31%	251.5	175.7	100%
	Face	234.0	43.0	18%	260.7	207.3	90%
50% HDPE	Edge	276.4	89.0	32%	328.0	224.8	100%
	Face	334.6	81.8	24%	382.0	287.2	100%

The screw pullout test results are shown in Table 2.6. In these tests, the face-directed screws are less strongly held than the edge screws for three of the four composition types. This is corroborated by 2 factor ANOVA which indicates significant differences between the different formulations and the different angles of penetration. It could mean that more of the threads see plastic with the edge-driven screws, since the screws do not penetrate all the way through from this angle.

TABLE 2.6 SCREW PULLOUT TEST RESULTS SUMMARY

Sample	Side	Average Screw Pullout (lbs)	STD Deviation (lbs)	RSD	90% Confidence Interval (lbs)		Completeness
100% Commingled	Edge	629.4	81.7	13%	676.8	582.0	100%
	Face	511.4	38.3	7%	533.6	489.2	100%
4% Polypropylene	Edge	478.4	89.7	19%	530.4	426.4	100%
	Face	524.4	60.9	12%	559.7	489.1	100%
10% Polypropylene	Edge	625.4	76.4	12%	669.7	581.1	100%
	Face	472.0	80.3	17%	518.6	425.4	100%
50% HDPE	Edge	694.2	190.4	27%	804.6	583.8	100%
	Face	605.8	72.1	12%	647.6	564.0	100%

UV TESTS

ASTM G-53, "Operating Light and Water Exposure Apparatus (Fluorescent UV Condensation Type) for Exposure of Nonmetallic Materials," was performed to test the effect of UV light on the plastic. The effect studied was loss of thickness which would be caused by further polymerization and oxidation of the plastic lumber surface. The experiment was designed to accelerate ambient conditions by using UV lamps.

Forty samples were prepared with ten samples coming from types 2A, 2C, 2D, and 3A material.

Test Conditions

Samples were exposed to a UVCON Ultra Violet/Condensation Screening Device utilizing eight UVA-340 sun lamps with peak emission at 340 nm and range between 365 nm and 295 nm (Figure 2.17). New sunlamps were installed at the beginning of the tests. After 400 hrs, one lamp was replaced in each bank of four and the others were rotated as outlined in the ASTM test and shown in

Figure 2.19. Samples were exposed in a cycle of 8 hrs of exposure followed by 4 hrs of non-exposure. This resulted in a sample exposure of 16 hrs a day. Samples were rotated every 2 to 3 days using the horizontal rotation method recommended by ASTM (Figure 2.18). During the exposure cycle, the test chamber temperature was maintained at 50°C, while it returned to room temperature during off cycles. No condensation testing was performed. Samples were exposed to the UV/Elevated Temperature combination for a total of 544 hrs.

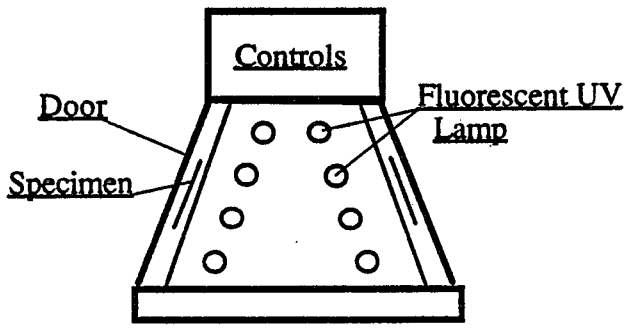

Figure 2.17 UV test chamber cross section.

Basic test procedure--

Samples were cut and allowed to sit in the air-conditioned lab for 48 hrs. The samples were then measured using digital calipers. The width and thickness of each sample was recorded to the nearest thousandth of an inch. This measurement was actually an average of several readings along the sample length. Although the samples were cut square, the release of internal stresses upon cutting coupled with the non-square manufactured face produced samples with varying width and thickness. The variation was ±0.007 in. Samples were then placed into the UV chamber and exposed to UV and a temperature of 50°C for 8 hrs and then 4 hrs of no UV and room temperature.

Every 2 to 3 days the samples were rotated horizontally as outlined in the ASTM test and shown in Figure 2.18 below. After 400 hrs, two of the sunlamps were replaced and the others were rotated as outlined in the ASTM test (Figure 2.19). After a total UV/Elevated Temperature combination of 544 hrs, the samples were removed and allowed to cool to room temperature for 72 hrs. At the end of 72 hrs the samples were measured using the same digital calipers to determine any change of dimensions.

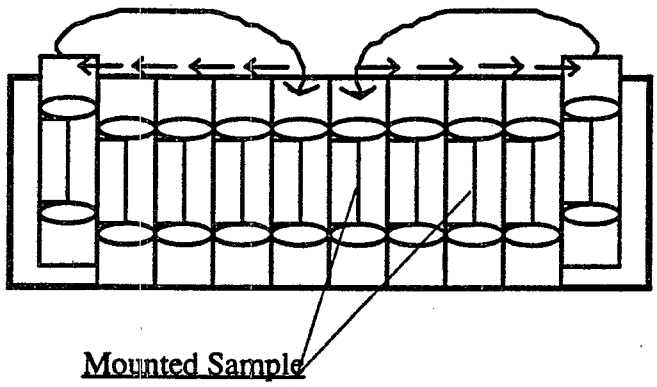

Figure 2.18 Horizontal sample rotation.

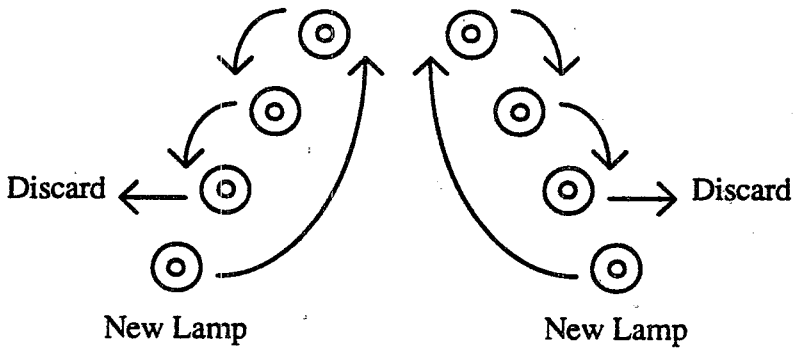

Figure 2.19 Lamp replacement and rotation.

Results

No change in dimensions was detected after exposure that was outside of the ±0.007 in. error. The internal stress release straining coupled with the curved manufactured surfaces makes precise measurements of the samples impossible.

ENVIRONMENTAL TESTING

Biofouling Tests

Biofouling of panels is generally directed at coatings which resist the attack of biological organisms in the sea. In this evaluation, the test was used to demonstrate the compatibility of the plastics with marine life.

Biofouling is thus a measure of the absence of toxicity in the plastic lumber as compared with untreated lumber controls. ASTM D 3623, "Antifouling Panels in Shallow Submergence," was followed. The test was performed from 8/28/92 to 12/17/92 in the Florida Institute of Technology (FIT) Exposure Platform, Indian River Lagoon, Grant, Florida.

Sample preparation--

Two inch x 6 in. x 18 in. long samples were cut using an electric miter saw. A 1/4 in. hole was drilled in each corner of the samples to attach the sample to exposure frames with the use of nylon tie strips.

Test conditions--

Samples were attached to a PVC exposure frame which was, in turn, submerged to a minimum depth of 10 in. to 12 in. The exposure platform is in the middle of the Indian River Lagoon with a surrounding water depth of 8 to 10 ft. The lagoon has direct access to the ocean through Sabastian Inlet approximately 10 miles south. The lagoon contains brackish water with all the biofouling organisms normally associated with coastal biofouling in this area.

Test procedure--

As shown in Figure 2.20, PVC frames were constructed and plastic lumber samples were attached to these frames with the use of nylon tie strips. The samples were arranged so that at least a 1/2 in. gap remained between adjacent samples and between the PVC frame. The frames had two levels of samples. The top level held the top on the sample 10 in. to 12 in. below the water surface while the bottom level had the top of the samples approximately 3 ft below the surface. Four different types of plastic lumber were tested as well as untreated southern pine. Five samples of each type were exposed. The five samples were arranged on four exposure frames, such that every type had three samples in the top level and two samples in the lower level. Photographs of the samples and frames were made prior to exposure and approximately every 30 days for a total exposure time of 90 days. In addition to the photographs, estimations as to the type, percent coverage, and number of the various biofouling organisms were recorded for the same 5.5 in. x 18 in. face on each inspection date.

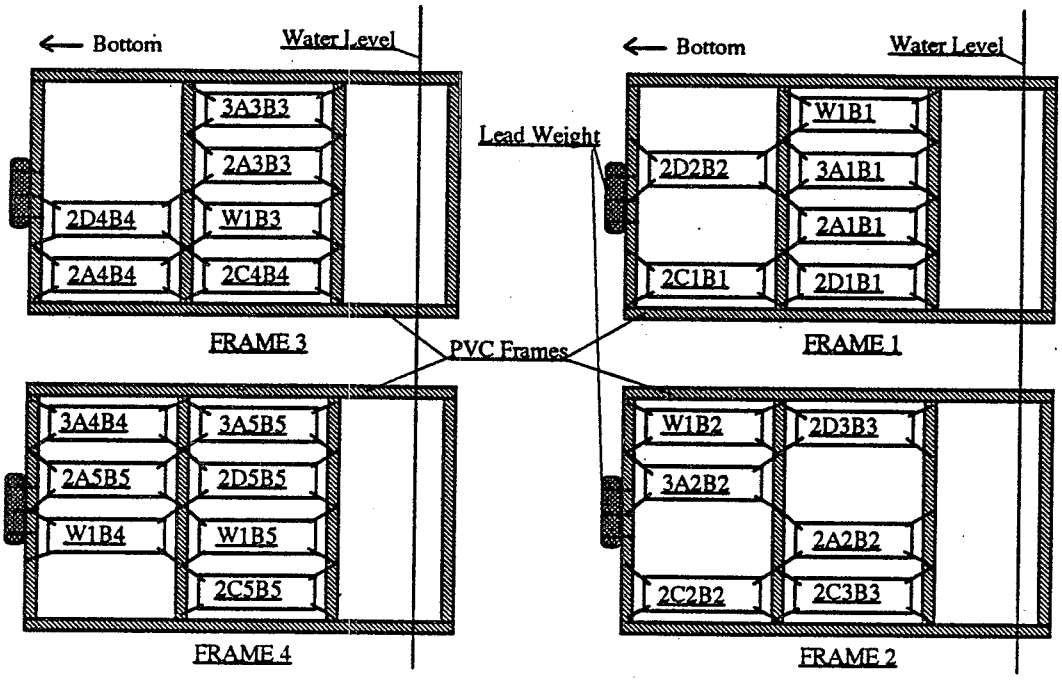

Figure 2.20 Biofouling test frames and sample layout.

Results

Results from this test are summarized in Table 2.7.

Figure 2.21 shows the results of Exposure Frame 1 which contains all of the plastic compositions and one 2 in. x 6 in. untreated wood length.

The wood length is on the left portion of the frame. It is seen from the table and figure that the wood panel has a similar degree of fouling, but does not have the barnacles which cover the plastic samples. This may be due to the surface characteristics of the plastic, extractives from the wood which irritate the barnacles, or other phenomena. In any event, it appears that the plastic is easily biofouled and does not deteriorate in the short span of this test.

TABLE 2.7 BIOFOULING AFTER 4 MONTHS OF EXPOSURE IN INDIAN RIVER LAGOON
(Averages of Five Boards Each)

Formulation	Fouling	Slime	Algae	Green Algae	Brown or Red Algae	Encrusting Bryozans	Non-encrusting Bryozans	Barnacles	Barnacles	Poly-chaetes
	%	%	%	% of Total Algae	% of Total Algae	No.	No.	%	No.	No.
Commingled	98	76	80	29	51	1.4	0	54	102	1.4
3A - 4% Polypropylene	97.4	78	83	29	54	1	0	51	117	1.4
2D - 10% Polypropylene	99.8	74	82	32	50	0	0	44	70	0.2
2A - 50% HDPE	98	78	78	32	46	3	0	66	205	1.8
Untreated Wood (pine)	96.8	85	89	58	31	0	0	5.6	7.8	0

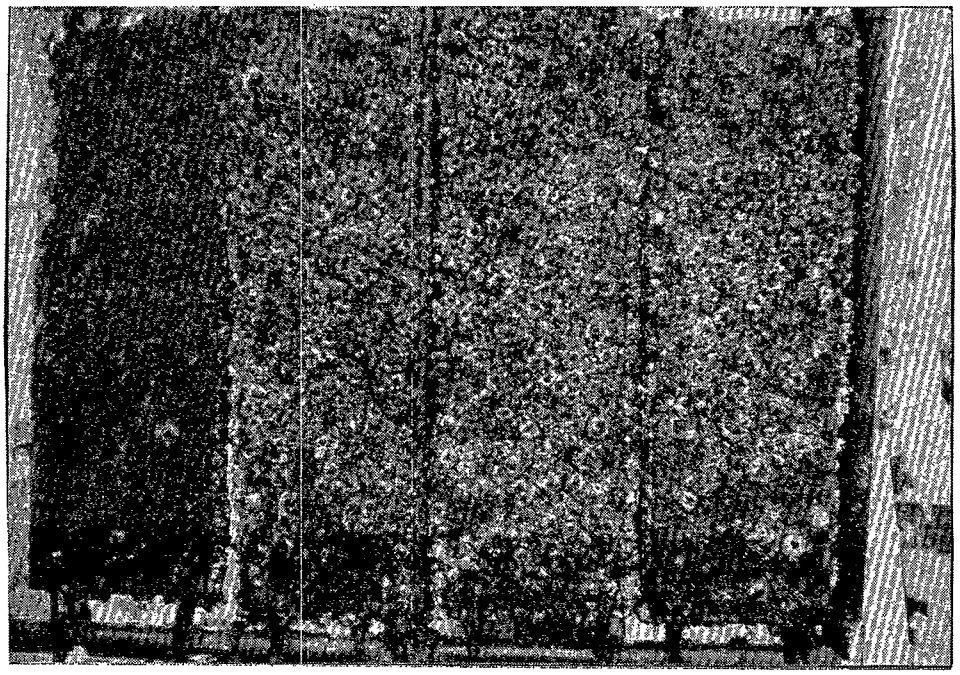

Figure 2.21 Top portion of exposure frame after 111 days of exposure.

SEA URCHIN FERTILIZATION TEST

This test is used to characterize the toxicity of plastic with respect to a sensitive sea animal, the Sea Urchin. The bioassay followed was EPA Test Method 1008, Sea Urchin Fertilization. In addition, longer term monitoring of the larval growth of the fertilized gametes was also performed.

Sample Preparation

A piece of RPL 1-1/2 in. x 5-1/2 in. x 12 in. (representing a standard piece of "dimensional" 2 in. x 6 in. lumber) was received in June. The material submitted for testing was prepared on Nov. 2 as follows (the end product included the original surface):

- Four 1 x 1 cm strips were cut (by radial table saw) from one edge along the 12 in. length.
- Each strip was cut into 1 x 1 x 0.5 cm blocks using a band saw.
- One 1 x 1 x 10 mm strip was cut from each block with a stainless steel razor blade.

- The 1 x 1 x 10 mm strips were cut down to:
  - -- Size A: 1 x 1 x 1, yielding 6 mm² surface area
  - -- Size B: 1 x 1 x 2, yielding 10 mm² surface area
  - -- Size C: 1 x 1 x 4.5, yielding 20 mm² surface area

Thus, each piece has its longest surface from the original surface of the plank, each piece consists of 1 mm depth from that surface, and the sampling is spread out over the entire length of the plank. See Figure 2.22.

These prepared pieces were stored in glass vials at room temperature (24°C) and under fluorescent lamps (≈ 9 hrs/day).

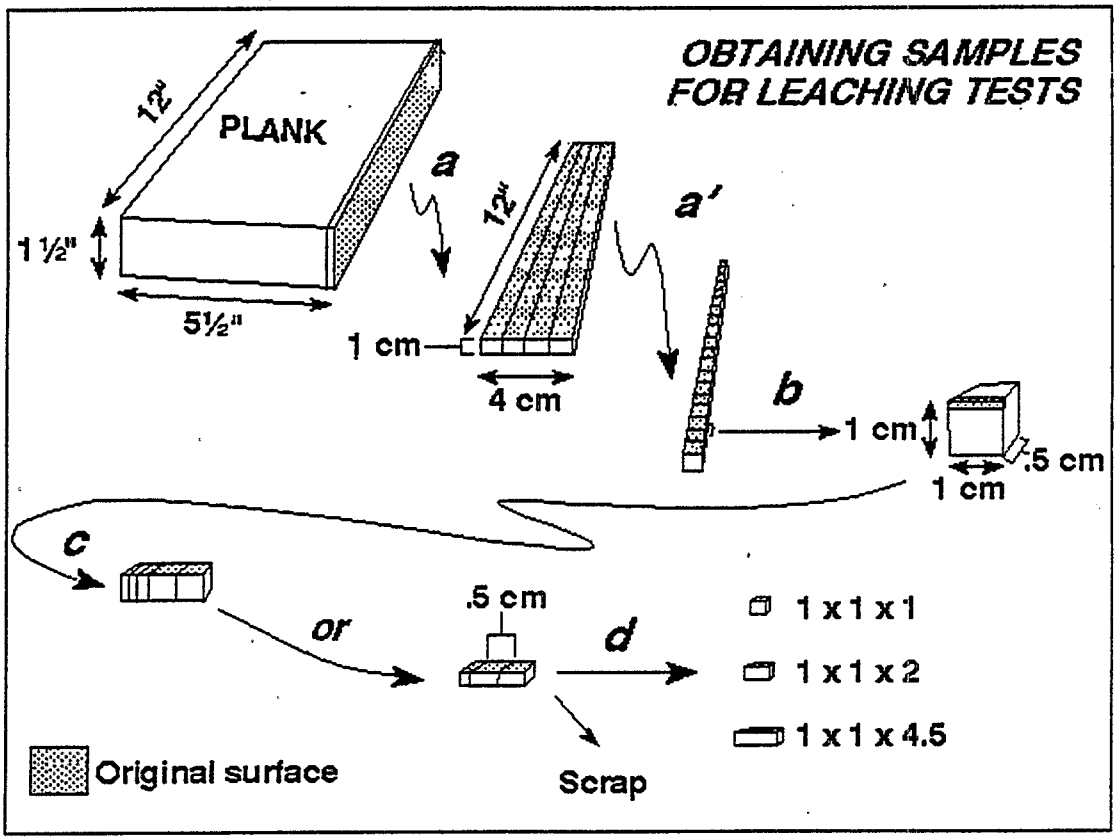

Figure 2.22 Plastic preparation for leaching testing.

Leaching Procedure

Sea water was collected from Gardiner's Bay (Eastern Long Island, New York) on the incoming tide. The water was transported in seasoned (well-used)

polyethylene carboys to the laboratory and stored cold (4°C) and aerated. For 48 hrs prior to use, this water was stirred with activated charcoal in a glass carboy at 24°C. The leaching was performed for one week (it has been demonstrated that the results of the assays were similar with leaching for 1, 2, and 3 weeks - Weis, et al., 1992). The leaching was done in standard vials (liquid scintillation vials, borosilicate glass, Kimball Corp.) at 20° ±0.1°C, dark, in an incubator, with twice daily hand agitation. The materials, water volumes, and ratios are presented in Table 2.8.

TABLE 2.8 LEACHING PROTOCOL

RPL Piece	Dimensions (mm)	Surface Area (mm^2)	Water Volume (L)	Surface/ Volume Ratio (cm^2/L)
Size A	1 x 1 x 1	6	20	3
Size A	1 x 1 x 1	6	10	6
Size B	1 x 1 x 2	10	10	10
Size C	1 x 1 x 4.5	20	10	20
Size C	2 of 1 x 1 x 4.5	20 x 2	10	40

The lowest surface/volume ratio used was the result of having the smallest replicable unit of plastic that could be used, and the maximum volume of water that could be contained in the standard test vials required by the EPA method. This ratio was two to three times that of the maximum environmental exposure found in completely developed residential canals on the Atlantic and Gulf Coasts.

SEA URCHIN PREPARATION

QA Procedures

The quality assurance procedure involves testing fertilization with 0-4.0 mg/L of detergent dodecyl sulfate (SDS) added to the test vials. Probit analysis, using a BASIC program included in the EPA manual, indicated the EC_{50} (50% fertilization rate for a determined concentration of SDS) and spontaneous response rates (SRR) (level of fertilization below which a toxic effect is measured) both with 95% confidence intervals (CI_{95}).

Results

For the first assay, the fertilization success was 74.2% ±8.41 for the controls. Probit analysis demonstrated an EC_{50} for SDS at 1.55 (1.12 to 1.99 CI_{95}) and an SRR of 70-85%. All the leachates had fertilization successes of 82-91% better than controls and clustered about the predicted upper limit of the SRR. It is noted that the plastic leachate causes a small rise in fertilization over the controls. This indicates hornesis, a low level of toxicity increasing metabolic rates. These data suggest no effect of plastic on fertilization.

For the second assay, the fertilization success was 90.4 ±5.32% for the controls. Probit analysis demonstrated an EC_{50} of 1.46 (1.16-1.79 CI_{95}) and an SRR of 91.4 (86.1 to 96.6 CI_{95}). The RPL-exposed larvae were again unaffected, all the fertilization rates were within the SRR.

On the third assay, since the lowest SDS reference exposure and all of the RPL exposures yielded >90% fertilization, the fertilization results of control replicates A, B, and C were interpreted as due to contamination of the vials. With this massaging of data, probit analysis gave an EC_{50} of 2.25 mg/L SDS (1.91 to 2.63 CI_{95}) and an SRR of 88.9 to 96.3%. All the RPL exposures were within this SRR, indicating no effect.

In three assays of RPL, there were no acute effects (fertilization success), even at the highest ratio of surface area to water volume. A summary of the assay test data is presented in Table 2.9.

TABLE 2.9 SUMMARY OF ASSAY TEST DATA

Surface/Volume	Assay 1	Assay 2	Assay 3
SRR (cm^2/L)	77.2	91	92.6
Control (0)	74.2	90.4	94.5
3	82.3	91.8	95.3
6	84.0	9.0	93.8
10	84.3	91.6	94.3
20	89.3	94.8	95.3
40	91.0	93.0	95.8

SECTION III

MATERIAL COMPARISON

PHYSICAL COMPARISON

Comparisons with wood can be made by using values for wood properties found in the literature. A summary of various properties is given in Table 3.1. Included are comparisons for flexural modulus, compressive ultimate strength, and nail and screw pullout resistance.

TABLE 3.1 COMPARISON OF PROPERTIES BETWEEN PLASTIC AND WOOD

Property	Plastic	Wood
Flexural Modulus	80,000-90,000	800,000-1,700,000(1)
Compressive Modulus		
Ultimate Strength (psi)	1,000-1,200	800-1,900 (parallel to grain) 600 (perpendicular to grain)(1)
Nail Pullout Strength (lbs)	200-300	≈100(2)
Screw Pullout Strength (lbs)	500-600	≈200(2)

(1) Western Wood Products Association.
(2) Uniform Building Code, 1988.

From this comparison, it is apparent that the flexural modulus is the limiting property of the CRC plastic lumber. The ultimate strength of the plastic is similar to wood. Surprisingly, the nail and screw pullout strength is greater for plastic than wood. This does not, however, take into consideration elevated temperatures and the effect of creep over time which affects plastic more severely than wood.

LIMITED LIFE CYCLE ANALYSIS OF RECYCLED PLASTIC LUMBER AND CCA-TREATED LUMBER

Methodology

A life cycle analysis (LCA) examines all the costs associated with a specific material or product through its entire useful life. These "cradle to grave" analyses attempt to quantify the energy used and environmental impacts resulting from:

- Acquiring the raw material.
- Transporting it to the point of manufacture.
- Processing the raw material into a product.
- Transporting the product to the point of use.
- Disposal of the product after its useful life is complete.

The difficulty in doing these analyses stems from a number of factors, including:

- Too much detail - the analysis can suffer due to trying to incorporate too much data, especially data which are unreliable or inaccurate.
- Not enough detail - leaving out important energy uses or environmental impacts.
- Unfair methodology - the methodology may unfairly sway the results due to assumptions used or the level of detail agreed upon.
- Inability to accurately convert environmental impacts into economic costs, such as loss of natural resources (like fossil fuel or minerals) and land use (opportunity cost).

The limited LCA attempted in this analysis avoided some of these pitfalls, but at the expense of yielding an absolute result. That is, the analysis which follows is meant to look at the major energy and environmental costs associated with plastic lumber and CCA-treated lumber, but will not be all encompassing, and does not assign costs to environmental impacts. The two materials were compared, looking at the energy required by them in their lifetimes, how long they will last, and the air emissions associated with their life cycle.

This LCA does not go "one step back" in the analysis. Many LCAs include in the calculation of impacts the environmental damage caused by producing the fuel used to produce energy for manufacturing or transportation. Assume that

these will be small compared to the impacts of burning this fuel. Furthermore, no consideration was given to the impacts of building facilities or equipment to process and transport the products. These impacts are also generally assumed to be small per ton of material produced.

Recycled Plastic Lumber

Inherent in the analysis of plastic lumber is the assumption that the recycled plastic has already cycled through its originally intended lifetime. This means that the energy and impacts associated with producing the original plastic feedstock are not included. By doing this, the plastic's "first" lifetime as a container or other object bears the costs associated with the original plastic feedstock acquisition, transportation, and manufacturing. Once this lifetime is complete, the plastic which is not currently recyclable is essentially a waste, which has no inherent value. Further, the costs of disposal of this waste, including garbage collection, landfilling, or incinerating, and the environmental impacts associated with this disposal, are also borne by the plastic in its first lifetime. There will be a cost associated with separating out the nonrecyclable plastic from the waste stream, which is where the analysis begins.

Plastics Acquisition

Acquisition of the plastic will be by either curbside collection of the separated plastics, or by separation of the plastics from MSW at a MRF. In the case of curbside collection of separated plastics, it is possible to separate the contribution to energy and associated truck emissions which result from the plastic portion of the recyclables collected. For standard garbage collection and subsequent separation of the plastics, energy and environmental impacts from transportation are assumed to be negligible as the waste would be picked up and taken to a landfill or incinerator if it were not taken to the MRF. The energy and environmental impacts at the MRF for plastics are assumed to be small.

For a curbside collection approach, the top of Table 3.2 gives the energy used and environmental impacts resulting from the trucks used in collection.

Transport

Transporting the plastic from the MRF to manufacturer is not calculated since the plastic would normally go directly to a landfill if it were not separated at a MRF or collected by curbside collection.

Manufacture

The manufacture of the plastic includes granulation of the plastic, and extrusion. Table 3.2 shows the various economic, energy, and environmental costs attributed to this process.

TABLE 3.2 LIFE CYCLE COSTS OF PLASTICS

Plastics Acquisition (Curbside)		
Energy (Truck Fuel)	1,182,000 Btu/ton[1]	358 Btu/foot
Environmental (Truck Emissions)[2]		
SO_x	0	0.00
NO_x	344	0.10
Particulates	25	0.01
HC	82	0.02
CO	243 g/ton	0.07 g/foot
Manufacturing of Plastic Profiles		
Granulation Of Plastics[3]		
Shredder	50 hp	38 kW
Grinder	100 hp	75 kW
Capacity	0.6 tph	
Electricity Rate		188 kWh/ton
		0.5 kWh/foot
EQUIVALENT BTU RATE		1,962,323 Btu/ton
		1,619 Btu/foot
Extrusion Of Plastics		
Throughput	500 lbs/hr/line	
Lines	2	
Availability	0.9	
Lineal density	1.65 lbs/foot	
Capacity	3942 tons/yr	Equivalent Btu Rate
Electrical rate	1104 kWh/ton	11,554,160 Btu/ton
	0.91 kWh/foot	9,532 Btu/foot

(continued)

TABLE 3.2 LIFE CYCLE COSTS OF PLASTICS (continued)

Environmental (electricity from coal power plants)(2)		
SO_X	0.037 lbs/kWh	16.80 g/kWh
NO_X	0.0112	5.08
Particulates (PM10)	0.0427	19.39
HC	0.000053	0.02
CO	0.00032	0.15

(1) Koch, 1992.
(2) Compilation of Air Pollution Emission Factors, 1985.
(3) Energy use based on design.

Transport to End Use

It is assumed that this transportation is local for the most part and therefore small compared to transportation from a wood lumber mill to the end use which can be hundreds of miles, depending on the source of the lumber.

Construction

Construction costs are a function of not only the cost of building but also the cost of maintaining or renewing a structure over the time frame of interest. One-time construction costs and impacts will be more expensive than wood since plastic used for decking will require more support underneath (joists) to prevent excessive deflection. From the evaluation it was determined that the joist spacing should be less than wood construction dictates. However a major factor in life cycle analysis is the lifetime of the plastic versus that of wood under equivalent environmental conditions. If a marine structure must be renewed every 5 years for wood and only every 10 years for plastic, all of the life cycle costs for wood will be multiplied by two to compare with an equivalent life for plastic.

Unfortunately the information needed to determine absolutely the lifetime of the plastic is not available from the testing program. The testing program was limited to short-term laboratory tests which do not adequately predict long-term performance in the field. If the assumption is made that creep is the important factor in terms of lifetime, the creep testing data can be used to determine the amount of deflection expected for the plastic lumber over time. By then assuming a maximum deflection which can be tolerated, the time to reach this deflection can be determined, and hence the plastics lifetime.

Cost of construction is estimated to be more expensive per square foot for a plastic boardwalk versus a wood one. It is assumed that environmental

impacts and energy use during construction are small compared to the other activities in the life cycle.

CCA-Treated Lumber

Acquisition

Impacts during acquisition of lumber are due to use of gasoline and diesel-powered engines for cutting trees and loading onto trucks. Proper forest management is assumed, which minimizes environmental impacts. Table 3.3 gives the energy and estimated air emissions resulting from this activity. Impacts are given on the basis of tons of oven dried lumber.

TABLE 3.3 LIFE CYCLE COSTS OF WOOD

Tree Acquisition	943,000 Btu/ton(1)	4 gal gas	
Environmental(2)		2 gal diesel	
SO_x	0 g/gallon	0 g/ton	0 g/foot
NO_x	5.26	21.04	0.016306
Particulates	1.8	7.2	0.00558
HC	713	2,852	2.2103
CO	1,618	6,472	5.0158
Tree Transport(1)	250,000 Btu/ton	100 miles	15 ODT/truck
Environmental(2)			
SO_x	0 g/mile	0 g/ton	0.00 g/foot
NO_x	11.44	76	0.06
Particulates	0.7	5	0.00
HC	2.52	17	0.01
CO	8.53	57	0.04
	Linear Density 1.55 lbs/ft		
Lumber Manufacture(1)			
Electricity	786,000 Btu/ton	74 kWh/ton	600.21 Btu/ft
Environmental(2)			
SO_x	0.0002 lb/kWh	7 g/ton	0.01 g/ft
NO_x	0.004	134	0.10
Particulates	0.0067	225	0.17
HC	0.0022	74	0.06
CO	0.0333	1,119	0.87

(continued)

TABLE 3.3 (continued)

Steam Heating	4,060,000 Btu/ton	560 lbs wood/ton lumber	
Environmental(2)	3,147 Btu/foot		
SO_X	0.15 lb/ton chips	19 g/ton lumber	0.01 g/foot
NO_X	2.8	356	0.28
Particulates	5	636	0.49
HC	1.7	216	0.17
CO	25	3178	2.46
Lumber Transport(1)	125,000 Btu/ton	500 miles	30.00 ODT/truck
Environmental(2)			
SO_X	0 g/mile	0 g/ton	0.00 g/foot
NO_X	11.4	38.1	0.03
Particulates	0.7	2.3	0.00
HC	2.5	8.4	0.01
CO	8.5	28.4	0.02

(1) Boyd, 1976.
(2) EPA, 1985.

Transportation to Lumber Mill

The distance between the cutting area and the lumber mill is assumed to be 100 miles. It is assumed that the wood is green, roughly 50% by weight moisture. Therefore, moisture is accounted for in the shipping of wood to the mill. Although a large portion of the wood from the tree will be used for energy, pulp, or other wood products, it is assumed that impacts will accrue to these uses, and not to the lumber.

Lumber Manufacture--

Manufacture of lumber at the lumber mill demands steam and electricity. It is assumed that the energy required for this process comes from wood byproducts such as bark and hog fuel (waste wood). Thus the environmental emissions are derived from wood-fired power plant data, which tend to have relatively low sulfur, NO_X, and particulate emissions compared with a coal-fired plant. The other advantage to burning wood, which is not accounted for by this analysis, is that the impacts due to harvesting the trees for lumber are shared by the wood used to create energy for the lumber mill. In fact, there would be a net energy surplus if all of this non-lumber wood went to

create energy. This simplified analysis does not credit wood for this environmental advantage.

Transportation to End Use

A distance of 500 miles from the lumber mill to the community where the lumber will be bought and used was assumed.

Comparison

Table 3.4 shows the comparison of energy and environmental impacts associated with life cycles for plastic and CCA-treated wood lumber. Since the lifetimes of the two materials in a marine application are different, these values need to be adjusted to make a fair comparison. The economic costs will also need to be adjusted.

TABLE 3.4 LCA ANALYSIS OF CCA-TREATED 2 IN. BY 6 IN. WOOD VS. PLASTIC

	Acquisition G/foot	Transport G/foot	Manufacturing G/foot	Total G/foot
Lumber				
SO_x			0.02	0.02
NO_x	0.02	0.00	0.38	0.40
Particulates (PM10)	2.21	0.00	0.67	2.88
HC	0.01	0.06	0.22	0.29
CO	0.00	0.00	3.33	3.33
Energy (Btu/foot)	730	193	3,755	4,680
Plastic				
SO_x	0.00		23.29	23.29
NO_x	0.10		7.05	7.16
Particulates (PM10)	0.01		26.88	26.89
HC	0.02		0.03	0.06
CO	0.07		0.20	0.28
Energy (Btu/foot)	358		11,151	11,509

Environmental Impacts

The bioassays and biofouling experiments that were run can be compared with similar experiments performed on CCA-treated wood and recycled plastic. In previous sea urchin fertilization experiments, Weis, et al. ("Toxicity of Construction Materials in the Marine Environment: A Comparison of Chromated-Copper Arsenate-Treated Wood and Recycled Plastic," *Archives of Environmental Contamination and Toxicology*, 1992) showed that CCA-treated lumber 1/10 the area of plastic test samples was far more toxic to fertilization and development. Weis and Weis ("Construction materials in estuaries: reduction in the epibiotic community on chromated copper arsenate (CCA) treated wood," *Marine Ecology Progress Series*, vol. 83: 45-53, 1992) found that CCA-treated wood during biofouling experiments showed significant decreases in number and biodiversity of species adhering or fouling compared to recycled plastic and untreated wood. The biofouling on CCA-treated wood had many times the levels of copper, chromium, and arsenate than did that on recycled plastic or untreated wood.

The results indicate that the CRC recycled plastic lumber behaves reasonably close to previous studies of recycled plastic for biofouling and sea urchin testing. Sea urchin experiments for plastic showed no impact on fertilization and no correlation between plastic concentration on development of the embryos. The biofouling experiments showed the plastic to be fouled with a greater diversity of species than even untreated wood. These results cannot be compared directly with previous work in different locales, but they point to the general biological compatibility of the plastic in marine environments.

DURABILITY/LIFETIME

Wood

Tests have been performed on CCA-treated lumber used in marine environments (cite literature). These tests are generally multi-year tests which are designed to show the resistance of treated wood to wood-borers. Lifetimes of the wood are dependent on the site of the construction. Different species of wood-borers live in different regions and degrade specific types of wood at different rates. Lifetimes for exposed wood can be as little as 1 year and greater than 20 years, depending on the specific environment.

The lifetime of freeze-thaw cycles may have a large effect on longevity of CCA-treated lumber in northern climates. Boardwalks have been found to have a life span of as little as 2 years in marine environments.

Plastic

For recycled plastic lumber, the limited testing performed here cannot accurately predict its lifetime. Only extensive field testing of actual applications can demonstrate the expected longer wear of plastic over wood. The two tests performed to demonstrate longevity are the creep tests and UV test.

Creep

Creep is a phenomenon of plastic which causes the plastic to deform over time under a continuous load. The rate of deflection with a continuous load occurs at an exponential rate; therefore, the load will cause a larger change in deflection in the first month than in the next 12. The deflection may not be permanent as the material can recover over time after the load is removed.

Creep must be adequately addressed in design of construction in order to avoid excessive deflection or failure of the plastic under a load. There are no construction guidelines for plastic lumber, and it would be recommended that continuous loads be kept minimal, unless deflection is not an important consideration. For instance, a bulkhead will have a continuous load, but may not be objected to if the plastic lumber bows outward over time, as long as the soil is adequately retained. In the case of decking, as long as heavy objects are not placed on the plastic lumber for long periods of time, creep should not be a problem.

UV Testing

The UV resistance of the plastic was shown to be good based on the short amount of testing performed. This test simulates and accelerates the exposure of plastic to UV. UV has a tendency to cause the surface of plastic to become embrittled by promoting additional polymerization of the plastic. This can result in a loss of the surface layers which absorb the UV radiation. The laboratory simulations showed that the rate of loss is negligible, and should not have a substantial influence on the lifetime of the recycled plastic.

It should be noted that the UV testing performed did not monitor other properties in the plastic which may have changed or remained constant due to the UV exposure. These could include flex testing, creep, and compressive strength. These were not performed due to the expectation that these properties would also not change significantly and the fact that the plastic lumber would be of such small dimensions to fit in the exposure tester as to not represent real properties of the full size lumber.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, some preliminary conclusions concerning the usefulness of CRC's RPM can be made. It is important to note that tests were not performed on actual field applications, which greatly restricts the ability to make conclusions about the RPM's practical performance. Using engineering judgment and laboratory results, inferences can be drawn about the expected performance of this material in real world applications. Engineering estimates are no replacement for long-term testing of RPM in field use. Only field testing can produce results which will confirm a new material's ability to withstand environmental conditions, various forces, and other difficult to simulate effects.

The benefit of the MITE evaluation is to generate an independent analysis of key properties which can then be compared to other building materials. As such, the ASTM and EPA tests provide a benchmark for this material, as well as other plastic materials to be produced in the future. When linked with results from field testing, the laboratory tests will have even greater usefulness.

CONCLUSIONS

The conclusions are divided into five categories: Cost, Environmental Impacts, Lifetime, Physical Strength, and Friction. Most results fit in one particular category, although there is some overlap. For instance, strength characteristics are related to time due to the creep phenomenon. These then will impact the ultimate lifetime of the material.

Cost

The price charged by CRC for their 2 in. x 6 in. foamed core RPM is approximately $1.00/ft in larger quantities.

Compared with CCA-treated wood, the price is greater for the plastic. However, wood prices have been increasing rapidly. It is difficult to make an absolute judgment as to whether the RPM is more cost effective than wood without designing, constructing, and testing a real world application where the RPM would serve as a substitute for wood.

Environmental Impacts

From the sea urchin experiments, it can be concluded that the RPM would not hinder fertilization at practical surface to volume ratios. CCA-treated wood has been shown to reduce fertilization of sea urchins. In environmentally sensitive areas, RPM could have a distinct environmental, and thus marketing, advantage.

The biofouling experiments demonstrated the compatibility of the RPM with the ecosystem in the marine environment of Melbourne, Florida. There did not appear to be any indication of toxic behavior of the RPM, even though the RPM was produced from unwashed post consumer plastic, suggesting that the extrusion process may sterilize the plastics and vaporize detergents and oils. The biodiversity was greater for RPM plastic than even untreated wood.

Lifetime

The lifetime of plastics would be difficult to predict from the laboratory testing alone. Proper design will be necessary to ensure that creep does not become a limiting factor. Resistance to UV and marine environments should be better than wood. High temperatures which could be generated in the plastic from sunlight will increase the rate of creep as seen in the results of the elevated temperature creep experiments. Reflective coatings may reduce temperature adequately. The relatively low conductivity of plastic will produce a significant temperature gradient in the plastic. This temperature gradient was not duplicated in the laboratory, but its effect on creep could perhaps be predicted by modeling. Field testing is needed on actual plastic lumber applications before a final judgment can be made with respect to lifetime of the plastic.

Physical Strength

Strength may be the key to RPM acceptance in most marine applications. While RPM has many advantages over CCA-treated wood, its strength will determine in what application it will ultimately be used. Strength over time will determine its lifetime in a given application.

The compressive and flexural strength of the RPM was found to be far lower than that of CCA-treated wood. This makes its use for structural applications impractical without some type of modification of the plastic recipe, or construction design. A glass fiber reinforced RPM was an originally planned material sample, but this was not manufactured by CRC in time for testing.

Non-structural uses such as decking material on docks, piers, and boardwalks; railings; pier impact protection; benches and tables; and movable piers

seem to be best suited to the RPM tested. These applications generally have small and infrequent loads and thus strength requirements which can be attained through proper design.

The plastic property known as creep is an additional characteristic which requires attention in designing for a specific application. Creep causes the plastic to move over time in the direction in which constant force is applied. The result is a deflection of the plastic. Thus proper design using plastic lumber must take creep into account.

Friction

Friction is an important property when designing a platform such as a boardwalk or dock. The tests demonstrated that the CRC plastic lumber does not have as high a coefficient of friction as wood. A surface treatment can be applied to the plastic to enhance this coefficient. While at CRC, a process to apply an epoxy which had sand mixed in for "traction" was observed. Paint does not adhere to the plastic without some type of surface preparation.

RECOMMENDATIONS

Further exploration may lead to increased acceptance and use of recycled plastic lumber in general and the tested material in particular. First, field testing of the RPM is needed to demonstrate its performance under real applications. This testing must be done over a long period of time in a variety of typical applications and locations. In conjunction with field and continued laboratory testing is development and refinement of the manufacturing process. There are many variables including additives, washing of the plastic, control over the mix of plastics, processing temperatures and speeds, and shape configurations which could potentially lead to enhanced properties. Finally, market research could be performed to increase market penetration.

Field Testing

Performance of the RPM in the field was not done in this study. Field performance testing would demonstrate the material's effectiveness under real world applications. Certain problems can be discovered through longer term use in a combination of environmental conditions that cannot be foreseen and modeled in the laboratory.

Widespread acceptance of the RPM as a building material can be further obtained with demonstrations of its use over long periods of time. While scientific reports such as this one can provide useful data for purposes of comparing materials, practical demonstrations of the use of the materials will help gain public acceptance.

From a construction standpoint, the material must be accepted by the construction industry as a viable alternative. This will require properties which are both reasonable and consistent. Construction codes may need to be altered to allow substitution of plastic for conventional building materials in some cases. Since the architects and building contractors are, in most cases, responsible for a structure's performance, they must be able to rely on the performance of a building material. RPM acceptance by architects and contractors can be bolstered by a demonstration program using RPM for various construction projects.

Environmental effects can be verified with field testing. Especially of interest here is the effect of various animals on the plastic's lifetime. Woodborers are among the chief causes of deterioration of treated wood in marine applications. The plastic should be highly resistant to such organisms. Environmental impacts can also be further quantified through a field testing program.

New Formulations

As the material manufactured here represents a relatively new process and product, there is room for engineering improvements. Depending on the application, strength can be improved through the use of various additives, or by altering the feedstock composition. It should be noted, however, that the 100% commingled plastic formulation tested in this study represents probably the least expensive and most recyclable option. Additives, control of the feedstock composition, washing of the feedstock, etc., will add to the cost of manufacturing the plastic.

At the time of taking samples for testing, the hollow-core RPMs were not being produced. Samples of these observed from a trial in Austria looked intriguing. The melting of the plastics appeared more uniform, although perhaps due to the fact that the feedstock was from source-separated post-consumer waste. The hollow core retains much of the strength of the foam core with the added advantage of potential for adding concrete or steel rebar to give structural integrity.

Other shapes could be produced using different dies and molds. The Florida Institute of Technology has done some research on the strength of various shapes, each of the same cross sectional area. Shapes like I-beams have more flexural strength than simple hollow cores.

Consistency

Consistency of properties, as mentioned before with respect to construction, is important to sales. Consistency can perhaps better be maintained once the process is optimized, and the feedstock is controlled to some

reasonable specifications of composition and cleanliness. A minimal testing program could be put in place to maintain feedstock and product quality. At a minimum, the flexure and compression strength should be tested each time the product is switched and at regular intervals thereafter.

Other Properties

Properties such as friction, and others which are found to be important after a thorough field testing program, should be examined to see if modifications or enhancements can be made. In particular for friction, a research and testing program designed to try various surface treatments and their wear resistance and friction characteristics should be performed.

MARKET RESEARCH

For a relatively new product such as RPM, marketing must work side by side with customer feedback, and research and development. There are three areas where marketing can play a key role: finding applications for the plastic, determining barriers to market penetration, and strategic planning to overcome these barriers.

Applications

The marine applications mentioned in this study are general and can be better defined and specified through market research. For instance, plastic lumber may find a niche in areas which have more concentrated use of CCA-treated wood in relatively still water. In these cases, plastic's negligible toxicity will be a clear advantage over wood, as leaching of metals from wood may have an environmental impact which is unacceptable. It would be worthwhile to study the advantages and disadvantages of plastic to identify market niches.

Barriers

Market research can identify barriers to the proliferation of plastic lumber. These could include perceptions about plastic's characteristics based on poorly made or inappropriately designed products by other manufacturers. It is important to determine why perceptions exist in order to try to change them.

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GLOSSARY

Acute toxicity	Toxicity of a material which causes reproductive failure in the sea urchin fertilization test.
Baldwin Universal Machine	Apparatus for performing physical tests on the material.
Blow-molded plastic	Forming process generally used to create plastic bottles; plastic is blown out against a two-piece mold which is pulled off after cooling, leaving a seam around the length of the bottle.
Biofouling	Propensity of different species of marine organisms to adhere to the material.
Chronic toxicity	Toxicity which affects the growth of the sea urchin after it has been fertilized.
Compressive strength	The ability of a material to resist deflection caused by a force that pushes the material inward.
Creep	Movement of a material over time due to a continuous force applied to the material.
Flex	The bending of a material; in this study caused by a force at the middle of a span of plastic lumber that is supported on its ends.
Injection molded	Forming process for plastic containers; plastic is injected into a mold; a small raised point on the center of the bottom of the container is observed.
Life cycle analysis	Evaluation which accounts for all costs and impacts of a material or product from its raw material extraction to its ultimate disposal.
Modulus of elasticity	Slope of the stress - strain curve at low stress; measures the strength of a material in the regime where elastic behavior occurs (no permanent deformation).
Secant modulus of elasticity	Similar to modulus of elasticity except measures the slope of the stress-strain curve from the origin to the load of interest (about 500 lbs for this study).

Static friction	A measure of resistance to movement of the surface of a material fitted against either the same material or a different one such as a shoe sole.
Strain	A deformation, or change of dimension in the direction perpendicular to a stress placed on a material.
Stress	Force applied to a material which tends to strain or deform it.

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