ELSEVIER Resources, Conservation and Recycling 23 (1998) 243–258

resources, conservation and recycling

Long-term engineering properties of recycled plastic lumber used in pier construction

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Accepted 5 May 1998

Abstract

Plastic lumber manufactured using post consumer waste plastic has been proposed as an acceptable material for use in the construction of docks, piers and bulkheads and is touted to outlast conventional wood products due to its strength, durability and resistance to rot. This study examines the long-term engineering properties of plastic lumber manufactured using post consumer waste plastic (TRIMAX, Ronkonkoma, NY). Plastic lumber profiles were used in the decking of a pier built in West Meadow Creek, Old Field, NY during December 1995. Samples of plastic lumber were removed from the deck of the pier periodically over a two-year period and returned to the laboratory for testing. Results of engineering tests showed the in-plane compression modulus (260 ± 30 MPa), dimensional stability and the Shore D surface hardness (60 ± 2) of plastic lumber removed from the pier remained similar to or greater than their pre-placement values. In contrast, significant changes in the modulus of elasticity of plastic lumber were measured with prolonged weathering. The modulus of elasticity of plastic lumber initially decreased from 1370 Pa to 750 Pa following 12 months weathering, a decrease equal to 45% of its pre-placement value and then increased during the second year to close to its initial value. The high variability in the modulus of elasticity should restrict the use of plastic lumber profiles to non-load bearing structural applications. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Recycling; Plastic; Plastic lumber; Piers; Engineering testing

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0921-3449/98/$ - see front matter
PII S0921-3449(98)00024-X

1. Introduction

Plastic lumber is currently one of the major products manufactured using commingled waste plastic collected in municipal recycling programs. Typically, 50% or more of the feedstock used for plastic lumber manufacturing is composed of polyolefins (high density polyethylene (HDPE), low density polyethylene (LDPE) and polypropylene (PP)) [1]. Polyolefins act as adhesive and encapsulate high-melt plastics and additives (fiberglass, wood fibers) within a rigid structure. Other additives are typically incorporated into the extruded mixture to enhance the appearance or performance of the lumber product. These additives include foaming agents, UV stabilizers, and pigments. Previous research and testing programs have shown the engineering properties of plastic lumber profiles are sufficient to allow for their use in a variety of applications [2–4]. Plastic lumber is currently used in products including marine piling, pier and dock surfaces, fences and park benches.

Plastic lumber is widely marketed as an alternative to chromated copper arsenate (CCA) pressure treated lumber for marine applications. Plastic lumber is designed to outlast conventional wood products and is claimed to possess beneficial properties such as high strength, durability and resistance to rot. Plastic lumber is also marketed as an environmentally preferable material to CCA treated wood lumber. As the plastic lumber has a smooth, dense hard surface resistant to damage due to marine borers, it does not need to be treated with preservatives prior to use in the marine environment. Recent studies have shown that the release of copper, chromium and arsenic from CCA treated wood is continuous in the marine environment [5–7]. CCA treated wood has also been identified as a source of contamination in marine sediments and biota [8–10]. In contrast, the leaching of metal and organic contaminants from plastic lumber in river water was shown to be low and no highly toxic compounds were identified [11].

Several recent laboratory studies show that the engineering properties of plastic lumber are inferior to wood lumber and recommend restrictions on how the lumber should be used in marine construction [4,12,13]. Plastics are susceptible to damage due to UV radiation and deformation under constant load and the testing of lumber profiles from structures following prolonged weathering is critical to evaluating the its long-term structural properties. The extent to which the engineering properties of plastic lumber profiles are subject to deterioration due to weathering in the marine environment is not well known.

The objectives of our study were to: (1) measure the initial engineering properties of plastic lumber profiles for use in pier construction; and (2) to measure changes in the engineering properties of the plastic lumber profiles as the pier structure weathered in the marine environment. A fixed pier (1.2 x 9.1 m) built at the West Meadow Conservation Center, Old Field, NY was partially constructed using plastic lumber profiles supplied by TRIMAX, Ronkonkoma, NY. A series of engineering tests were conducted on both the plastic lumber prior to pier construction and on plastic lumber profiles collected from the completed pier over a 19 month period. Plastic lumber testing included dimensional stability, Shore D hardness, compression modulus and modulus of elasticity. The engineering properties of the plastic lumber profiles were then compared with the results of other studies to assess the plastic lumber for pier construction.

2. Materials and methods

2.1. TRIMAX lumber manufacturing process

TRIMAX manufactures plastic lumber using a continuous extrusion process with post consumer waste plastic as the primary additive. TRIMAX purchase bales of HDPE that have been shredded into flake, primarily from milk and water jugs, shampoo and detergent bottles, for use as feedstock. TRIMAX lumber also contains twenty percent recycled fiberglass.

TRIMAX used two new twin-screw machines purchased from Berstoffand, Werner, and Pfleiderer [14]. The extruders push the melted feedstock through one of several different die shapes to create various lumber dimensions. When the lumber has adequately cooled and solidified, it is cut to the desired length.

2.2. Pier construction

The pier was constructed in West Meadow Creek in Stony Brook Harbor, NY (Fig. 1). The pier was designed primarily for use as a dock for the loading and unloading of passengers aboard a pontoon boat used in support of the educational activities at the Marine Conservation Center located at this site.

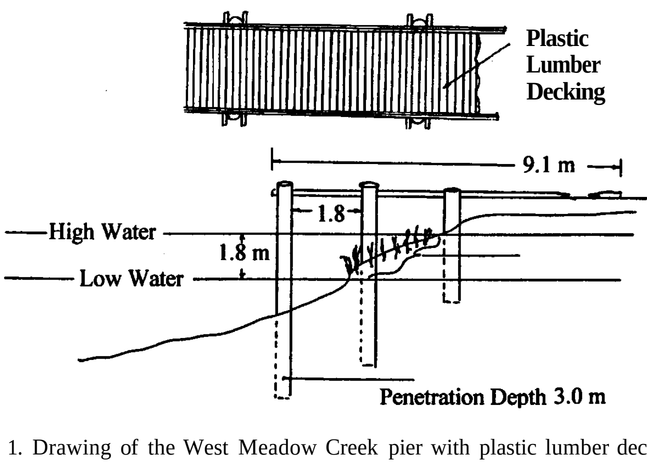

Fig. 1. Drawing of the West Meadow Creek pier with plastic lumber decking.

Table 1
Matrials list for the fixed pier

Number	Dimensions	Description	Material
12	20.3 cm x 6.1 m	Piles	CCA treated southern pine[a]
10	7.6 x 25.4 cm x 3 m	Girders	CCA treated southern pine
12	7.6 x 20.3 cm x 4.9 m	Joists	CCA treated southern pine
45	5 × 15.2 cmx2.4 m	Decking	TRIMAX plastic lumber
20	1.9 x 35.6 cm	Timber bolts with nuts and washers	
1 22.5 kg box	7.6 cm	Galvanized deck screws	

[a] Chromated copper arsenate (CCA) treated southern yellow pine.

The materials used in the construction of the pier included both TRIMAX plastic lumber and CCA pressure treated wood (Table 1). The CCA pressure treated lumber and piling was obtained from Port Lumber, Riverhead, NY. The piling, girders and joists were CCA treated wood and the pier decking was plastic lumber. The contractor chosen for the pier construction was Great South Beach Construction, NY. The plastic lumber profiles were a uniform grey color. The girders and joists were secured to the pilings using timber bolts with nuts and washers. The plastic lumber decking was secured to the CCA treated wood cross members using 7.6 cm galvanized screws. Each 5 x 15.2 cm x 1.2 m plastic lumber plank was secured using two screws at four locations along the length of the board. Construction of the pier was completed on December 14, 1995.

The framework of the pier consists of five piles (20.3 cm x 6.1 m) equally spaced on each side along the length of the 9.1 m pier. Sections of plastic lumber (7.6 x 25.4 cm x 1.2 m) were used as cross members used to support the deck structure. The 7.6 x 25.4 cm x 1.2 m plastic lumber cross members were obtained by trimming the tongue portion off 7.6 x 25.4 cm x 3.0 m tongue and groove sheathing. The plastic lumber cross members were fastened to the piling using 1.9 x 35.6 cm timber bolts with nuts and washers. The deck frame was constructed using 7.6 x 20.3 cm CCA treated lumber to construct four equally spaced parallel beams running the length of the 9.1 m pier. The plastic lumber decking was fastened to these beams using two 7.6 cm galvanized decking screws to each of the four CCA lumber beams.

2.3. Lumber sampling

Each piece of plastic lumber decking was uniquely labeled to allow for identification of the location of the sample along the pier surface. Plastic lumber samples were sampled on eleven occasions during the period February 1996 to December 1997 (Table 2). Two lumber profiles were collected from the pier during each sampling event. The collected lumber profiles were replaced by similar unweathered plastic lumber profiles cut to the same dimensions.

2.4. Engineering properties of plastic lumber

2.4.1. Dimensional analysis

Dimensional analysis involved replicate measurements of the length, width and thickness of each sample to the nearest 1.6 mm. Each lumber profile was cut to a length of 1.2 m by the contractor at the time of the pier construction. All dimensional analysis measurements were made in the laboratory at room temperature.

2.4.2. Modulus of elasticity

Modulus of elasticity (MOE) was measured according to ASTM standard method E 855-90, Standard Test Method for Bending Testing of Metallic Flat Materials for Spring Applications Involving Static Loading, using a four point bending fixture. Samples from the lumber were cut into 26.4 x 3.8 x 1.3 cm bars. In order to consider any directionality of the mechanical properties into consideration, bars were cut in two different directions: parallel (in-plane) and perpendicular (cross-section) to the long surfaces. A total of five samples were prepared from each lumber profile. The tests were conducted using a servo-hydraulic Instron (Model 8500) testing machine with a four point bending attachment. The distances of the inner and outer support spans were set at 70 and 210 mm, respectively. The rate of movement of the cross head to the machine was 0.5 mm s^{-1} and the deflection and corresponding load applied to the sample was recorded. The bending modulus was calculated using the following equation:

$$E_b = [P(3L^2 - 4a^2)/4bh^3\delta] \quad (1)$$

Where; E_b = bending modulus (Pa); L = span between supports (m); b = specimen width (m); h = specimen thickness (m); P = load (N); δ = deflection (m); and a = half the difference between the support and load applicators (m). Modulus was determined using the initial slope of the load versus deflection (P versus 6) curves.

Table 2
Sampling schedule for engineering tests performed on the lumber profiles from the West Meadow pier

Sampling event	Date	Sample numbers	Time (months)
1	February 28, 1996	58, 65	2
2	April 15, 1996	34, 38	4
3	June 17, 1996	9, 11	6
4	July 24, 1996	21, 24	7
5	August 8, 1996	34, 41	8
6	September 6, 1996	13, 14	9
7	November 11, 1996	35, 36	11
8	January 17, 1997	19, 26	13
9	March 17, 1997	20, 27	15
10	July 7, 1997	31, 40	19
11	December 3, 1997	46, 48	24

2.4.3. Compression modulus

ASTM standard method 695-91, Standard Test Method for Compression Properties of Rigid Plastics was used for measuring compressive properties of plastic lumber. The tests were conducted using an Instron (Model 8500) Universal Testing machine. Lumber samples were cut to 3.3 cm diameter cylinders having a thickness of 3.3 cm. Samples were cut in two different directions, parallel and perpendicular to the long surfaces, in order to consider the directionality of the mechanical properties. A total of five samples were prepared for each lumber profile. The test consists of loading the specimen into the machine and compressing the specimen at a uniform and relatively low rate of straining (0.1 mm s^{-1}). The applied load and the corresponding compressive displacement of the sample were recorded. After a total vertical distance of 30 mm was traversed, the load was removed. A stress versus strain plot of the compression test was completed for each test, from which the slope of the elastic portion was taken as the compression modulus of elasticity.

2.4.4. Durometer hardness

A 'D'-type durometer was used to conduct surface hardness tests according to ASTM standard method D2240, Standard Test Method for Rubber Property-Durometer Hardness. The testing was done by placing the indenter tip of the 'D'-type durometer firmly into the material making sure that the instrument was seated flat. The tests were conducted with a hold time of 10 s. During the testing, the standard requirement that a minimum thickness of 6 mm for the test specimen and at least 12 mm from any edge was met. The hardness value was read off the dial gauge on the instrument, which is inversely related to the penetration of the indicator into the material. Ten measurements were taken for both the surface and interior of the lumber specimen.

3. Results and discussion

3.1. Use and appearance of West Meadow pier

The pier was not heavily trafficked during the two-year monitoring period. Passenger boat trips were most frequent during May–October (4–6 trips/week) and decrease in frequency during the fall and winter months (< 1 trip/week). The pier was constructed to provide a platform above the waterline at high tide however, the pier was completely submerged periodically during storm events or at times of extreme high tides. Other major factors affecting the weathering of the plastic lumber on the pier include seasonal temperature changes and changes in UV intensity. During the 2-year exposure period, the pier has been subjected to two summer cycles, where the highest temperatures and UV intensities would be expected.

Frequent visual inspections of the pier indicated that the plastic lumber was in very good condition. No obvious warping, discoloration or cracking of the plastic lumber decking was noted.

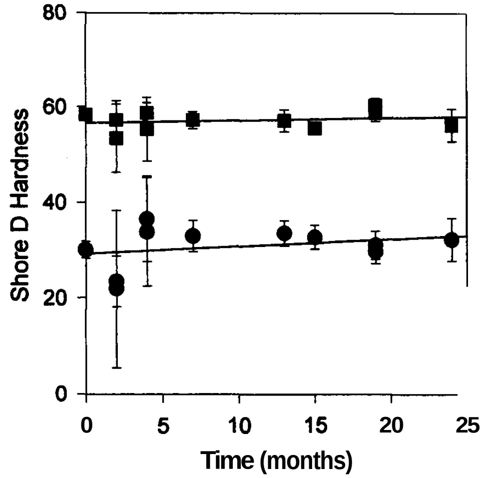

Fig. 2. Shore 'D' hardness measurements for both exterior and interior surfaces of plastic lumber profiles collected from the West Meadow pier over 24 months. (●) Inside cross sectional surface; (■) outside exterior surface.

3.2. Dimensional stability

Dimensional stability was assessed by measuring the length, width and thickness of each lumber profile following removal from the pier. Length measurements show that the lumber lengths remain close to the initial 1.2 m length, generally within 1.6–3.2 mm of the specified length. The lumber samples were nominally 5 x 15.2 cm, and the actual size reported by TRIMAX is 3.8 x 14 cm. Measurements of the lumber width over time showed that the samples were consistently 4.8–6.4 mm less than the specified value. Similarly, lumber thickness was close to the specified value of 3.8 cm. Three measurements were taken along each lumber sample to measure cup, which is a measure of the deviation in the face of a piece from a straight line drawn from edge to edge of the lumber piece. For 15.2 cm nominal widths, a cup of 3.2 mm is specified. Results show that cup measurements for these lumber profiles removed from the pier deck over time were within TRIMAX specifications.

3.3. Durometer hardness

Results of the durometer hardness tests show that the surface hardness of the plastic lumber is approximately 60 ± 2 on the Shore 'D' scale (Fig. 2). Surface hardness measurements were made both in-plane and cross-sectional directions. The initial surface hardness on the exposed cross-sectional surface was lower (30 ± 2), and individual measurements varied considerably over the surface (22 ± 16 to 36 ± 9) (Fig. 2). The measured variation was due to the porous internal structure that becomes denser towards the surface of the lumber. In contrast, the external surface of the lumber was characterized by a thick, very dense layer. As a result, the durometer hardness measurements show the relatively uniform surface hardness of the plastic lumber samples. In addition, the surface and cross sectional shore 'D' hardness of the plastic lumber samples did not change during the 24 month exposure period (Fig. 2).

The TRIMAX plastic lumber profiles tested had internal voids located in the center of the profile cross section. The presence of these voids is most likely a result of the differential cooling of the polymers in the exterior and interior portions of the lumber and the presence of moisture in the plastic used in the manufacture of the lumber [1]. The presence of moisture in the plastic may be due to retained atmospheric moisture, or moisture retained from washing or separation processes. When the plastic is heated in the extruder, the water vaporizes forming bubbles in the mix. As the extruded lumber cools, the vaporized moisture is trapped within the lumber [4].

3.4. Compression modulus

The compression modulus of the plastic lumber was measured in both the cross-sectional and in-plane axes. The compression modulus measured in-plane (192 MPa) was on average six to eight times the measured cross-sectional compression modulus (24 MPa) (Fig. 3). Similar differences, though not as great, are reported in the TRIMAX literature for compression testing results in each of these respective planes. Although differences were measured, the compression modulus in each respective plane did not change with time. Following 19 months, the in-plane (264 MPa) and cross-sectional (48 MPa) compression moduli remained similar to their initial values of 192 and 24 MPa, respectively. However, the 24 month measurements showed significant increases in both the in-plane (417 MPa) and cross-sectional (170 MPa) compression moduli (Fig. 3).

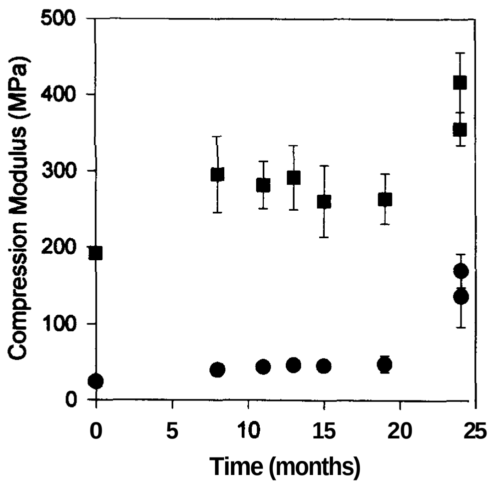

Fig. 3. Compression modulus measurements for both cross-sectional and in-plane dimensions for plastic lumber collected from the West Meadow pier over a 24 month period. (●) Cross section; (■) in-plane.

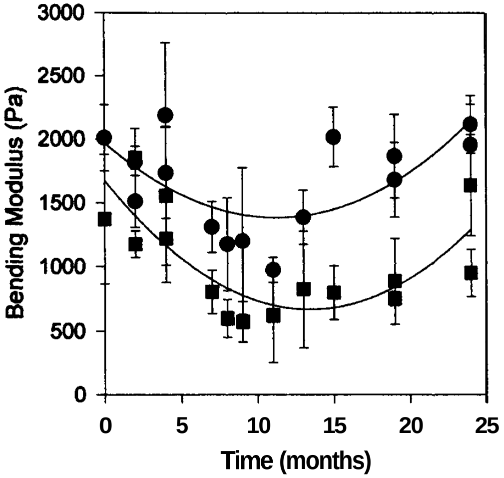

Fig. 4. Bending modulus measurements for both cross-sectional and in-plane dimensions for plastic lumber collected from the West Meadow pier over a 24 month period. (●) Cross section; (■) in-plane.

It is important to note that a major modification in the mechanical testing system was performed prior to the 24 month measurements. The improvement involved the installation of a higher resolution load and displacement detection system, which may have affected the results obtained. On the other hand, the 24 month samples were more difficult to cut and contained higher amounts of moisture than previously tested samples. Hence, the increases in the compression moduli at 24 months may be related to changes and/or variability in the material properties of the lumber profiles.

3.5. Bending modulus

Results show that the initial bending modulus was higher in the cross sectional direction (1860 Pa) as compared to the in-plane direction (1400 Pa) (Fig. 4). Results also show a high degree of variability in the bending modulus for replicate plastic lumber profiles measured in each respective direction at each sampling time. These measured variations in the bending modulus ranged from 10–40% (Fig. 4).

Changes in the bending modulus were also measured for plastic lumber sampled from the pier over time. The bending modulus measured in the in-plane direction was found to continuously decrease with time (Fig. 4). After 19 months exposure, the in-plane bending modulus of the plastic lumber decreased to 750 Pa from an initial value of 1370 Pa. Although the bending modulus measured in the cross sectional direction was similar at 0 and 19 months, considerable variation was measured in the bending modulus over time. The bending modulus measured in the cross sectional direction decreased to almost 50% of its initial value during the summer months (July–September; months 7–9). However, significant increases in both the in plane (1640 Pa) and cross-sectional (2120 Pa) bending moduli were measured for the lumber profiles tested at 24 months (Fig. 4).

A clear trend is not shown in the data for the two-year period. Changes measured in the cross sectional bending modulus may be a reflection of the heterogeneity of the material rather than a change in the initial lumber properties due to weathering. In addition, the comments for the 24 month compression modulus measurements are also valid for the bending modulus. In either case, the large variations in the bending modulus measured in this study must be accounted for in designing structures to be built using plastic lumber profiles.

3.6. Comparison to other measured engineering properties

The engineering properties of plastic lumber profiles vary depending on the composition of the lumber (Table 3). Manufacturers are currently using materials including virgin plastics, post-consumer plastics, a variety of plastic mixtures (HDPE, LDPE, PET, PP and PS), and additives including wood and glass fibers. Some of the poorest engineering properties were measured for lumber samples manufactured using a mixture of post-consumer waste plastic (Rutgers, 100% Curb Tailings). The use of a single polymer (HDPE) and a glass fiber additive resulted in significantly better engineering properties for the TRIMAX plastic lumber profiles. Results also show that the use of glass and wood fiber additives significantly improves the modulus of elasticity for plastic lumber. The modulus of elasticity for plastic lumber manufactured without fiber additives ranged from 79000–173000 psi (545–1193 MPa). With the addition of wood or glass fibers, the modulus of elasticity ranged from 146000–653000 psi (1007–4502 MPa), a 2–4-fold increase.

Although the engineering properties of plastic lumber have improved with the use of additives, they are inferior to those of wood lumber. The modulus of elasticity of wood lumber is 10 times that of plastic lumber, compressive strengths are two to three times that of plastic lumber and the specific gravity of wood lumber is two to three times less than that of plastic lumber [12].

3.7. Recent studies concerning the engineering properties of plastic lumber

A survey of the published literature identified several recent studies where engineering testing of plastic lumber was completed [4,12,13]. These studies were selected for review here as they were conducted by independent third parties and replicate lumber samples were tested. In addition, the methods used in these studies were the same ASTM methods used in our study.

4. Zarillo and Lockert, 1993

Studies completed at the Florida Institute of Technology (FIT), Melbourne, FL were designed to examine the feasibility of using commingled plastic lumber in marine construction [4]. Results of the engineering tests conducted at FIT showed that the basic engineering properties of the plastic lumber depended on factors including the raw materials used in the manufacture of the lumber, the amount of

Table 3
Engineering properties of plastic lumber products

Product	Composition	Specific gravity	Compressive strength (psi)	Modulus of elasticity (psi)	Tensile strength (psi)	Hardness	Source
TRIMAX	HDPE/ Glass fibers	0.75 (D198)	1740	450 000	1250		TRIMAX literature
TRIMAX	HDPE/Glass fibers	0.80			1189	60 (Shore 'D')	SUNY at Stony Brook
Lumber last	Commingled recycled plastic	0.86 (D792)	3755 (ultimate) (D198)	140 000 (D790)	1453 (ultimate) (D198)	1436 lbs (D143)	www.lumberlast.com
Earth care recyclemaid	Post-consumer milk jugs	0.79 (Density)	3205 (D695)	93 000–102 500 (D790)	2550 (D638)	64/65 (Shore 'D')	ww.ecpl.com
Hammer's plastic	80%HDPE/ 20%LDPE	2708	89 814				[4]
	HDPE/LDPE (20PSGF)	4247	527 000				
	HDPE/LDPE (40PS20GF)	3514 (D695)	653 000 (D790)	1793 (D638)			
Superwood Selma, Alabama	33%HDPE/ 33%LDPE/ 33%PP	0.82–0.87	3468 (D695)	146 171 (D790)	1793 (D638)		[4]
California recycling company	100% Commingled	44 942	81 717				
	10% Polypropylene	48 713	79 319				
	50% HDPE	55 150 (D695)	92 636 (D790)				[13]
RPL-A	HDPE/Glass fibers		2000				[12]
RPL-B	49% HDPE/51% wood fiber	2000					[12]

Table 3 (Continued)

Product	Composition	Specific gravity	Compressive strength (psi)	Modulus of elasticity (psi)	Tensile strength (psi)	Hardness	Source
Rutgers University	100% Curb tailings	0.944	3049	89 500			[3]
	60% Milk bottles 15% Detergent bottles 15% Curb tailings 10% LDPE	0.883	3921	114 800			[3]
	50% Milk bottles 50% Densified PS	0.806 (D792)	4120 (D695)	164 000 (D790)			[3]
Earth care products	HDPE	0.909 (D792)		173 439 (D790)			www.ecpl.com
BTW Recycled plastic lumber	Post-consumer	0.88–1.01	1840–2801	162 000			BTW/Hammers brochure
White cedar		0.31	3960	800 000			[15]
Red oak		0.63	6760	1 800 000			[15]

psi Pounds per square inch (1 psi = 6894.76 Pa).
ASTM American Society for Testing and Materials, Annual Book of Standards, Section 8, Plastics, Philadelphia, PA. (Method No.).

voids in the cross section, the test temperature, and the rate at which loads were applied to the test specimens. The FIT study examined the engineering properties of plastic lumber supplied by Hammer's Recycling (Iowa Falls, IA) and Superwood (Selma, AL) (Table 3). Tests conducted on the plastic lumber included flexure, compression, creep, friction, biofouling and UV degradation. Large variations (30%) were measured among replicate lumber samples even when test parameters were controlled and even greater variability in engineering properties were measured when comparing lumber from one manufacturer with that of another. In addition, the stiffness and strength of unreinforced plastic lumber is much less than that of wood. Plastic lumber had 1/10 the stiffness, 1/2 the strength, twice the weight and twice the cost of wood lumber.

FIT built a 1 5.2 m long, 2.1 m high bulkhead attached to a 1.8 m wide deck. The bulkhead and deck were almost exclusively constructed using 5 x 15.2 cm commingled plastic lumber. The bulkhead was constructed accounting for the reduced mechanical properties of the plastic lumber. As a result, nearly twice as much plastic lumber was required to build the structure. The FIT researcher's report that the contractor was pleased with the quality of the plastic lumber. However, the plastic lumber was more difficult to cut and screw than wood lumber. The FIT researchers concluded that even though the plastic lumber was higher cost and requires more material to build a comparable wood structure, the promise of a 50 year or longer expected lifetime may make plastic lumber cost competitive with conventional CCA treated wood lumber. The FIT plastic lumber bulkhead and deck structure was constructed to allow monitoring of the engineering properties of the plastic lumber. To date, results of engineering testing conducted on this structure have not been reported.

5. Smith and Kyanka, 1994

Smith and Kyanka [12] conducted a laboratory study at the SUNY College of Environmental Science and Forestry examining the engineering properties of recycled plastic lumber in comparison to wood lumber. Two plastic lumber products were examined: (1) lumber manufactured from extruded HDPE with a foaming agent and 20% fiberglass to enhance strength and (2) a mixture of 49% HDPE and 51% wood particle fibers. These engineering properties of these plastic lumber samples were compared to nominal 5 x 15.2 cm southern pine (0.4 pcf CCA).

A determination of the modulus of elasticity for the three lumber materials showed that the modulus of elasticity of wood lumber was 5 times greater than the fiberglass reinforced plastic lumber and 10 times that of the HDPE-wood particle composite lumber (Table 3). The flexibility of the plastic lumber may be somewhat compensated by decreasing the span distance between supporting members, a corresponding increase in materials needed for supporting members would increase costs. Compressive strength testing showed that the strength of wood was at least five times that of the plastic lumber formulations and the compressive strength of the plastic lumber formulations decreased with increasing temperature. These testing results once again raised the concern of excessive creep in plastic lumber due to constant load in the presence of elevated temperature possibly leading to product failure.

6. RW. Beck and Associates, 1993

R.W. Beck and Associates [13] completed an assessment of plastic lumber produced by the California Recycling Company (CRC). The feedstock for plastic lumber manufacture was obtained from the New Stanton, CA materials recovery facility. A compositional analysis of the plastic processed at the facility showed that approximately 70% of the plastic was HDPE with lesser amounts of PP, LDPE, PET and uncoded plastics. The plastic was also shredded and granulated at the MRF prior to shipment to the CRC where it was extruded to form 5 x 15.2 cm x 3.7 m 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.

The engineering and environmental properties of the plastic lumber were examined to determine strength, creep, serviceability, biological compatibility with fouling organisms and toxicity of the plastic lumber. The tests were selected to characterize the behavior of plastic lumber for marine applications. Results of the studies showed that the plastic lumber produced by CRC has significant creep characteristics. R.W. Beck and Associates recommends that continuous loads be kept minimal, unless deflection is not an important consideration. Concern was also expressed that high temperatures in the plastic resulting form sunlight exposure in the summer months may increase the rate of creep and result in mechanical failure. In addition, the compressive strength and flexural strength was found to be far lower that that of CCA treated wood lumber (Table 3). The stiffness of the lumber samples tested were less than 1/10 that of wood lumber. Glass fiber reinforcement of the plastic lumber was recommended as a way of increasing the engineering properties of the plastic lumber.

7. Summary of plastic lumber engineering properties

Results of our study agree well with previous studies showing that the major obstacle to the use of plastic lumber profiles in marine construction is the low modulus of elasticity. A variety of additives have been incorporated into plastic lumber (glass fibers, wood fibers, polystyrene) and have been shown to increase the stiffness of the lumber (Table 3). Other additives including UV stabilizers and plasticizers may also improve the performance of plastic lumber in service. However, the low modulus of elasticity ($<$ 10% of wood value), compared to wood lumber, will ultimately limit the use of plastic lumber in many load bearing applications.

It is also clear that the engineering properties of plastic lumber vary depending on the composition of the polymers and additives used in lumber manufacture. The differences in engineering properties of plastic lumber produced by different manufacturer's highlights the need for the development of a grading system for differentiating the quality of plastic lumber. In addition, results of this study and the FIT study show that the engineering properties of plastic lumber from the same manufacturer may vary up to 30%. Therefore, extensive testing of plastic lumber is required to develop specifications for the use of plastic lumber in marine construction. The low modulus of elasticity results in the need for additional support members, ultimately resulting in the need to use far more material to build plastic lumber structures compared to comparable wood structures. The lack of long-term testing of plastic lumber from structures in service calls into question the manufacturers' claims that plastic lumber will have a service life of greater than 50 years. This is particularly true considering the variability in the engineering properties of plastic lumber profiles and the results of our study showing large variations in the bending modulus of plastic lumber profiles weathered for 2 years.

Acknowledgements

This research project was supported by a grant from the New York State Energy Research and Development Authority to the Research Foundation of SUNY. We thank the Ward Melville Heritage Organization for their assistance in the siting and permitting process. We thank Tony Noto, TRIMAX Lumber for donating the plastic lumber for pier construction. We thank SUSB undergraduate students Jonathan Gutleber, Steve Depalo, Sapna Shah and Luis Zarate for their assistance in performing the engineering tests. We also thank MSRC graduate students Chongle Zhang and Sharon Two-Axe for their assistance in sampling and literature collection activities. This manuscript is MSRC contribution No. 1118.

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