Weathering Effects on Mechanical Properties of Recycled HDPE Based Plastic Lumber

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Abstract

Commingled recycled plastic lumber (RPL) decking was exposed to the environment for eleven years. The weathering effect is examined by performing mechanical property tests on the full size deck boards before and after the exposure. Flexural tests on the weathered deck boards were conducted with the exposed side and the unexposed side tested in tension. The flexural properties after weathering are compared to the original flexural properties. These data show the effect of weathering on recycled high-density polyethylene based RPL. A life cycle cost analysis (LCCA) is also presented to compare the cost of a wood deck versus an all RPL deck. The purchase, maintenance, and disposal costs are included.

Introduction

A deck was built in 1989 at Rutgers University composed entirely of RPL. The two by six inch deck boards used in the construction of the deck were a commingled recycled plastic material referred to as curbside tailings, NJCT. NJCT is defined as the rigid plastic containers, mainly bottles, which remain in the post-consumer plastic waste stream after the PET soda bottles and the natural HDPE milk and water containers are mined out [1]. The feedstock consists mostly of high-density polyethylene with no added ultraviolet stabilizers. Before installation of the NJCT deck boards, flexural properties were acquired by performing flexural tests in three point loading on the full size deck boards with a minimum 16:1 L:D ratio. After eleven years of outdoor exposure and use, the deck boards were removed and replaced by new RPL deck boards.

Flexural properties of the weathered NJCT deck boards were obtained by performing flexural tests in three point loading, for comparison to the original flexural properties, and four point loading. The tests were conducted using a MTS Model 810 servo-hydraulic test machine according to ASTM D796 and ASTM D6109 for plastic lumber, respectively. For the four point loading tests, deflection was measured directly using a draw wire transducer. Both the exposed side and unexposed side of the deck boards were tested in tension.

Observations

The outdoor exposure altered the surface of the samples. A white powder developed on the exposed side that whitened the exposed surface while the unexposed surface remained unaffected. The photograph in Figure 1 displays a comparison of the exposed and unexposed surface and the whitening effect. On the fracture surface, plastic chunks that did not melt are noticeable. These plastic pieces may act as stress raisers within the samples and are most likely not high-density polyethylene. It is likely that these plastic pieces are chunks of PET.

Results

The original flexural properties of the NJCT deck boards determined prior to weathering reveal a flexural modulus of 1,179 MPa and a flexural strength of 17.24 MPa.

The three-point load flexural property results disclose a slight modification in the mechanical properties due to weathering of the NJCT samples. Comparing the results in Table 1, the flexural properties when the exposed side was tested in tension, and Table 2, the flexural properties when the unexposed side was tested in tension, with the original mechanical properties, it is apparent that both the modulus and strength increased after the outdoor exposure. The modulus increased by 28 % from the original when the exposed side was tested in tension, as seen in Table 1, and increased by 25 % when the unexposed side was tested in tension, as seen in Table 2. The strength at three percent strain increased by 4 % from the original value, for both the exposed and unexposed side tested in tension.

The four point load flexural properties appear in Table 3 and Table 4 for the exposed and unexposed side tested in tension, respectively. The modulus of the NJCT samples increased by 25 % when the exposed side was tested in tension, Table 3, and by 27 % when the unexposed side was tested in tension, Table 4.

An interesting result of this study is the similarity between the flexural properties when tested in three point loading and four point loading. Comparing Table 1 with Table 3, the NJCT samples tested with the exposed side in tension, it is apparent that the modulus is almost the same, and the strength at three percent strain is identical. Comparing Table 2 with Table 4, the NJCT samples tested with the unexposed side in tension, it is also apparent that the flexural properties are nearly equivalent when tested in either three or four point load.

This improvement in the long term mechanical properties of the NJCT deck boards stimulated a study of the cost comparison of a section of boardwalk composed of all wood versus one composed of RPL over its lifetime.

Life Cycle Cost Analysis (LCCA)

A formal procedure to conduct Life Cycle Analysis, a cost comparison between the use of RPL and wood over the life of the structure, has been developed by the US Department of Energy (DOE) - Oak Ridge National Laboratory (ORNL) [2,3]. This procedure accounts for both tangible and intangible factors associated with various alternatives for recycling and disposal and provides a formal framework for evaluating and comparing alternatives. The basic parameters for LCCA includes the direct, indirect, recurring, nonrecurring and other related costs incurred or estimated to be incurred in the design, development, production, operation, maintenance, and support of an asset throughout its anticipated useful life span and through final disposal. Revenues such as user fees and salvage receipts are included as an offset to the cost.

The life cycle analysis methodology is divided into three phases: the Threshold Phase, the Life Cycle Analysis Phase, and the Decision Phase. In the first phase, the alternatives are evaluated based on the threshold criteria of protectiveness of human health and the environment, compliance with applicable or relevant and appropriate requirements (ARAR), and life cycle cost (LCC). Alternatives are eliminated from further consideration, if they fail to meet minimum standards, in terms of protectiveness of human health and the environment and compliance with ARAR, or those that are not within 25 percent of the LCC of the lowest cost alternative.

In the second phase, the Life Cycle Analysis Phase, the alternatives that meet the threshold criteria are evaluated on a comprehensive set of performance measures, and the results are tabulated in a Decision Summary Matrix. In the third phase, the Decision Phase, the alternatives are ranked using multi-attribute decision analysis, in which the results of the Life Cycle Analysis Phase are combined with weighting factors to produce an aggregate total score for each alternative. The alternative with the highest score becomes the preferred alternative under this methodology.

For comparison of a wood and RPL structure, the LCCA methodology is applied to an example case, a 5' x 10' section of a boardwalk with 2 x 10 joists 10" on center. A photograph of such a section that currently has RPL decking boards and wood joists is shown in Figure 2.

The first step in calculating the LCCA is to identify the alternatives. The options are a traditional wood structure made with southern pine or an all-RPL structure.

The second step is the identification of the life cycle duration for each alternative. This involves determining the useful design life and the time duration for which the structure is needed. The estimated design life for the example section of boardwalk is ten years for wood and forty years for RPL. The above assumptions for wood are based on discussions with personnel who are responsible for installing and maintaining structures such as those displayed in Figure 2 [4]. The expected life of RPL is based on the fact that RPL does not degrade structurally over time due to the effect of outdoor weathering, as shown by the data presented.

The third step is to identify the financial costs for each material type. The cost is comprised of three major categories: acquisition, maintenance and repair, and end-of-life cost. The initial cost of the material and installation for the boardwalk section is $291 for wood and $610 for RPL [4]. The primary cost difference between wood and RPL is the material cost. The cost of wood is $0.77 per board-foot while the cost of RPL is $1.50 per board-foot. The maintenance and repair costs are subject to some assumptions. Previous experience with the maintenance of wood structures indicate the need for staining the structure at a total cost of approximately $55, for such a section of a boardwalk, every 5 years or once during its service-life. The RPL structure is maintenance-free and does not incur any costs during its service life. The end-of-life cost for wooden structures requires shredding and disposal at a landfill. The RPL structure, on the other hand, is recyclable, and the various components are transported to the closest recycling site. Because this is a comparative cost analysis, costs common to both alternatives are not included, such as the salaries of the workers during installation, etc.

The fourth step is to identify the costs in each year. The costs incurred during each year were compiled for a wooden and RPL structure based on the above assumptions and data.

The fifth step is to identify the discount rate. For a 40-year project the real discount rate, R, is three and a half percent, as specified by the Office of Management and Budget Circular No. A-94, February 1997.

The sixth step is to calculate the LCCA. It is conducted over a period of forty years due to the life span of the RPL structure. During this time, the installation, maintenance, and disposal of four wooden structures is required. The most common method of LCCA uses the net present value method (NPV). In this method, the costs in each year are reduced to a common basis, utilizing present worth calculations (PW).

$$PW = (\text{Cost for Year Y})/(1+R)^{Y-1} \qquad [1]$$

In equation [1], R is the discount rate, and Y is the year. The total PW summed overall all years provides the LCC for the alternative.

Results of the LCCA

The results of the LCCA over a forty-year service life indicate that the cost of the wood structure is $883 versus $636 for RPL. It is important to note that the structure under consideration represents a small section of a larger boardwalk or platform and, therefore, the life cycle cost advantage for RPL would be significantly higher for a total structure.

A more formal and complete analysis including the Life Cycle Analysis, and Decision Phases, as well as a Sensitivity Analysis will be performed and reported at a later date.

Conclusion

Outdoor exposure of eleven years on recycled plastic lumber results in some weathering effects. The surface whitening is due to UV degradation on the sample surface. UV light may cause some minuscule surface degradation on high-density polyethylene of up to 0.003 inches/year [5]. The surface whitens but this does not affect the overall mechanical properties of the bulk material. Therefore, UV degradation is not much of a threat. However, the seasonal temperature changes occurring year after year, analogous to annealing a sample, induce a moderate increase in the mechanical properties. The increase in modulus and strength that has occurred with the NJCT samples after weathering is likely the result of annealing [6]. In the future, we plan to publish DSC data to verify this result. The temperature cycle of the seasons annealed the samples and produced an increase in the percent crystallinity. The reduction of amorphous regions and the increased crystallinity work together in stiffening the material. Hence, an increase in modulus and strength value at three percent strain is observed after the weathering exposure.

The improved flexural properties of the NJCT deck boards after weathering over the period of eleven years offers promising results concerning RPL. The lack of material property degradation, in conjunction with the LCCA results, catapults the industry into the twenty-first century. The intangible factors of LCCA, such as institutional preference, local public acceptance, environmental impact, and worker safety, and the fact that RPL is recycled and recyclable obviously indicates that RPL is the material of choice. RPL offers a beneficial alternative to treated wood.

References

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Table 1
Three-point bend flexural properties of the NJCT deck boards after weathering.
The exposed side was tested in tension.

SAMPLE	MODULUS (MPa)	SAMPLE FRACTURED	STRENGTH AT 3 % STRAIN (MPa)	ULTIMATE STRENGTH (MPa)
1A	1,658	NO	19.07	23.68
2A	1,474	YES	17.13	21.52
3A	1,385	YES	16.82	19.69
4A	1,477	NO	17.61	22.89
5A	1,568	YES	18.81	22.84
AVERAGE	1,512		17.89	22.12

Table 2
Three-point bend flexural properties of the NJCT samples after weathering.
The unexposed side was tested in tension.

SAMPLE	MODULUS (MPa)	SAMPLE FRACTURED	STRENGTH AT 3 % STRAIN (MPa)	ULTIMATE STRENGTH (MPa)
1B	1500	NO	19.10	24.03
2B	1410	YES	17.03	21.01
3B	1312	NO	16.87	21.04
4B	1512	NO	16.78	21.41
5B	1618	YES	19.03	22.39
AVERAGE	1470		17.76	21.98

Table 3
Four-point bend flexural properties of the NJCT samples after weathering.
The exposed side was tested in tension.

SAMPLE	MODULUS (MPa)	SAMPLE FRACTURED	STRENGTH AT 3 % STRAIN (MPa)
1-1	1500	NO	16.29
3-1	1454	NO	18.61
4-1	1403	NO	17.66
5-1	1625	NO	18.66
6-1	1449	NO	17.51
8-1	1413	NO	17.73
Average	1474		17.74

Table 4
Four point bend flexural properties of NJCT samples after weathering.
The unexposed side was tested in tension.

SAMPLE	MODULUS (psi)	SAMPLE FRACTURED	STRENGTH AT 3 % STRAIN (psi)
1-2	1541	NO	19.18
3-2	1553	NO	18.42
4-2	1455	NO	18.39
5-2	1503	NO	19.70
6-2	1355	NO	17.77
8-2	1610	NO	18.57
Average	1503		18.67

Figure 1
Comparison of the exposed surface (top) and the unexposed surface (bottom).

Figure 2
A typical structure -5' x 10' section of a boardwalk with RPL decking boards and wood joists.