Field and Laboratory Decay Evaluations of Wood–Plastic Composites

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Abstract

Experimental wood–plastic composites (WPCs) were made so that they matched the manufacturing process, dimensions, and water absorption of some commercial decking boards. WPC samples from selected formulations were divided into two identical groups. The first group was exposed in exterior conditions in Vancouver, British Columbia, and Hilo, Hawaii, at sun and shadow sites. Water absorption and biological activity were monitored by field inspection, density change measurement, and optical and scanning electron microscopy. The second group was used for soil block culture testing performed according to AWPA E10 (or ASTM D1413). Specimens were conditioned by immersion in water at room and elevated temperatures. Results of fungal decay activity are reported as specimen weight loss or corresponding density decrease. Observed density changes during field exposure and soil block culture testing are compared. Samples exposed to aggressive exterior conditions underwent decay, which was detected by microscopic inspection of board cross sections and calculated density decrease. Fruiting bodies of brown-rot decay fungi (*Dacryopinax spathularia*) were found on some sample surfaces during field inspections. The decay process of tested materials in the field seemed to require an initiation period dependent on exposure site. The shortest initiation time and the most aggressive environment for decay of WPC samples were found at the sunny site in Hilo. Laboratory soil block culture testing showed weight loss and density decrease of experimental WPCs to depend on conditioning. Correlations between laboratory test results and WPC performance in the field are described.

Experience within industry and academia related to decay of wood–plastic composite (WPC) materials subject to laboratory testing and exterior field exposure is limited and controversial. Data comparing laboratory test results with field performance for these composites are also lacking (Ibach et al. 2007, Manning and Ascherl 2007, Shirp et al. 2008). WPCs are used for many applications, and a large proportion (about two-thirds) is used for outdoor applications, e.g., decking, railing, fencing, and exterior covering applications, such as siding and trim. Design expectations for these new WPC products include long-term performance, consistent appearance, and dimensional stability (Smith and Wolcott 2006). Early laboratory and field studies indicated that the wood component in the WPC was susceptible to decay (Schmidt 1993; Morris and Cooper 1998; Laks and Verhey 2000; Mankowski and Morrell 2000; Verhey et al. 2001, 2003; Clemons and Ibach 2002; Ibach and Clemons 2002; Pendleton et al. 2002).

WPCs in outdoor applications are exposed to fluctuations of moisture, temperature, and ultraviolet radiation and to biological degradations (Fabiyi et al. 2005, Schauwecker et al. 2006). They were first thought to be very resistant to decay because of slow moisture transport into the material achieved by at least partial encapsulation of the wood by the polymer matrix (Naghipour 1996). However, it was found that the outermost layer was capable of reaching moisture levels high enough (around 25%) to initiate biological decay (Wang and Morrell 2004, Gnatowski 2009), and the presence of decay fungi fruiting bodies on WPCs has been described (Morris and Cooper 1998, Manning and Ascherl 2007, Laks et al. 2010).

WPCs have a thermoplastic-rich surface layer that is created during their processing (through extrusion, com-

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pression molding, or injection molding) that produces high levels of water repellency (Clemons and Ibach 2004). To simulate long-term field conditions in laboratory decay tests, it is necessary to expose WPCs to moisture conditions for long periods of time or at elevated temperatures, which ensures a moisture content (MC) high enough (around 25%) to support fungal growth (Ibach et al. 2004; Lopez et al. 2005; Shirp and Wolcott 2005; Manning and Ascherl 2007; Kim et al. 2008, 2009; Lomelí-Ramírez et al. 2009; Defoirdt et al. 2010; Fabiyi et al. 2011; Segerholm et al. 2012).

This article describes aboveground field studies that were performed on WPC lumber with known processing variables, blend components, additives, and amounts of each component. Failure in the form of decayed wood particles in the WPC was found after 28 months for some samples in the field, so this reproducible material could potentially be used as a negative specimen for soil block decay testing in the laboratory. The question is how WPC specimens will perform in the standard AWPA E10 (American Wood Protection Association 2007) or ASTM D1413 (ASTM International 2010) soil block test without modification and then with modification of the testing procedures. This information will allow for reliable assessment of the durability of new WPC materials.

The objectives of this study were to assess rate of decay observed during field exposure of selected WPC material and to correlate performance of field samples and results of laboratory soil block culture testing, particularly related to specimen conditioning prior to fungal exposure. This study was a portion of a larger evaluation and the samples described hereafter reflect the original identifications used; as such, labeling may not always be in consecutive order.

Materials and Methods

Material WPC #8 was formulated based on related research and matched the water absorption (WA) characteristics of some commercial WPC decking products available on the North American market in 2000 to 2002. The composition of experimental WPC #8 is shown in Table 1.

Boards were made to match the manufacturing process, dimensions, and WA of some selected commercial deck boards. The experimental WPC #8 was extruded as 25.4-mm (1-in.)-thick by 152.4-mm (6 -in.)-wide boards by the Composite Materials and Engineering Laboratory of Washington State University in Pullman. Raw materials were carefully batch blended and processed using a Milacron (Mount Orab, Ohio) 55-mm conical counter-rotating twin screw extruder with a Strandex (Madison, Wisconsin) die. The melt temperature was 180°C (357°F). Boards were initially cut into 1.83-m (6-ft)-long pieces. Each piece was marked with the date of manufacturing, formulation number, and sequential board number as it was made. Experimental boards were manufactured in November 2002.

Table 1.—Composition of experimental wood–plastic composite #8.

Component	Composition (wt%)
Wood flour pine[a]	65.93
HDPE resin[b]	24.06
UV stabilizer package[c]	6.01
Lubricants[d]	3.00
Talc[e]	1.00

[a] Wood flour grade 2020 (American Wood Fibers, Columbia, Maryland).
[b] High-density polyethylene B-53 35H flakes (Solvay, Brussels, Belgium).
[c] Tinuvin 770 (Ciba Geigy, Basel, Switzerland), 5 wt%; Tinuvin P (Ciba Geigy), 5 wt%; metal oxide pigments, 15 wt%; HDPE–resin B–53 35H flakes (Solvay) carrier, 75 wt%.
[d] Blend of zinc stearate (Ferro Chemical, Mayfield Heights, Ohio), 67 wt%; EBS Wax (GE Specialty Chemicals, Singapore), 33 wt%.
[e] Nicron 403 (Luzenac America, Inc., Three Forks, Montana).

Exterior exposure and samples collection

Experimental WPC #8 was exposed at two sites in different climatic zones: Vancouver, British Columbia, and Hilo, Hawaii, with Scheffer indexes around 50 and 350, respectively. Vancouver has annual average precipitation of 1,118 mm (44 in.); Hilo has annual average precipitation of 3,200 mm (126 in.). Board #8-2 was used as a control and was stored in a dry warehouse at room temperature and 30 to 60 percent relatively humidity, board #8-3 was exposed in Hilo, and board #8-4 was exposed in Vancouver. These 1.83-m (6-ft)-long boards were cut in half into two 0.91-m (3-ft)-long pieces and exposed in a horizontal position at two sites, in sun and in shadow, in each of the climatic zones. The shadow in Vancouver was mainly from a fence running east–west on the property border. The shadow in Hawaii was from trees. The site in Vancouver was set up on May 1, 2003, and the one in Hilo on November 18–19, 2004.

Collection at the Vancouver sites was carried out approximately every 2 years starting in February 2005, followed by collections in March 2007 and March 2009. Collections in Hilo were carried out approximately every 12 to 17 months starting in November 2005, and again in February 2007, March 2008, and March 2009.

Samples were collected by cutting 63 to 76 mm (2.5 to 3 in.) from the end of the exposed board at each site. The samples were instantly marked, wrapped tightly in plastic film, and refrigerated. Samples from Hawaii were shipped with dry ice by overnight courier. The MC at the ends of the exposed boards was evaluated independently, and this edge effect was relatively insignificant in regard to the overall MC distribution presented later in this article.

An additional set of samples approximately 32 mm (1¼ in.) in length was collected in Vancouver and Hilo in April and May 2010. These samples were used only for dimensional measurements after drying.

Field inspections

Each sample collection was photographically documented, except in March 2009 at the Vancouver sites due to time restrictions. Together with general views of the boards, areas of interest were magnified, such that surface defects or biological activity was also documented.

Microscopic inspection

Cross sections of field-exposed samples (section B) were inspected with a focus on potential wood decay and composite defects; a Leica MZ12 (Singapore) stereoscopic microscope (magnification up to ×300) equipped with a Leica DFC 320 digital camera was used. Areas of special interest were examined and documented using a Hitachi

S3000N scanning electron microscope (Japan) under variable pressure mode.

Water absorption and moisture content

Each sample collected in the field and subsequently frozen was cross-sectioned in the laboratory as shown in Figure 1. Special care was taken to avoid moisture dislocation or loss during handling. Cut frozen specimens were instantly sealed in preweighed plastic bags for initial weight measurements. By drying section B at 103°C to constant weight, the average WA for the tested board was established. With knowledge of the wood content, the MC of the wood was calculated. Section C was cut into thin wafers, with a target nominal thickness of 1 mm (0.039 in.). By wafering and drying section C at 103°C, WA and MC through the thickness of the board were found. To identify the distance of the locations of each wafer from the board surface, the thickness of each dry wafer was measured at five points and the average thickness was calculated. Thicknesses of each wafer were added together and subtracted from the measured dry thickness of sister section B. This difference was divided by the number of cuts used to waferize section C for calculation of the saw kerf. With knowledge of the average wafer thickness and kerfs, the distance of each wafer's center from the board surface was calculated.

Laboratory evaluations: moisture, density, and decay

Specimens of unexposed WPC #8 were tested for decay resistance by soil block cultures according to AWPA E10 (AWPA 2007) or ASTM D1413 (ASTM International 2010). Specimens 19 by 19 by 19 mm (¾ by ¾ by ¾ in.) were precisely cut with a band saw from an unexposed board and sanded to remove any saw blade ridges and any inaccuracy associated with blade drifting. A set of six specimens was obtained from one strip taken from the board cross section, as shown in Figure 2. Each specimen was individually marked based on its location within the board. Six sets of six such specimens were used for testing. Because the wood flour in the WPC was pine, the test fungus utilized was the brown-rot fungus *Gloeophyllum trabeum,* which is known to be more aggressive against softwoods. The test was carried out for 12 weeks.

Specimens were conditioned, steam sterilized at 100°C (212°F) for 20 minutes, and then inserted in the soil bottles. Two matching sets were tested with and without fungal exposure as follows:

1. No conditioning, no fungal exposure
2. No conditioning, fungal exposure
3. Conditioning A by water immersion at room temperature for 2 weeks, no fungal exposure
4. Conditioning A by water immersion at room temperature for 2 weeks, fungal exposure
5. Conditioning B by water immersion at 70°C for 5 days, no fungal exposure
6. Conditioning B by water immersion at 70°C for 5 days, fungal exposure

Results of fungal activity were reported as percentages of weight loss and corresponding percentages of density loss from leaching and decay to facilitate comparison with performance of samples from field exposure.

The AWPA E10 standard states that ''Failure to protect [wood based materials] is evidenced by loss of mass from the treated wood or wood based composite blocks, as indicated by a loss of weight.'' As such, weight loss was used in this article to represent mass loss in the relevant density calculations, which will be later described in the ''Density change calculations'' section.

Weight, dimensions, and density measurements

Laboratory samples.—Specimens were weighed before and after drying using an Ohaus Explorer Pro balance (Florham Park, New Jersey), with 0.001-g accuracy and computer interface, to determine the weight loss of the samples. The dimensions of ovendried (2 days at 103°C) specimens before and after soil block culture testing were also measured using a Mitutoyo Digimatic Indicator

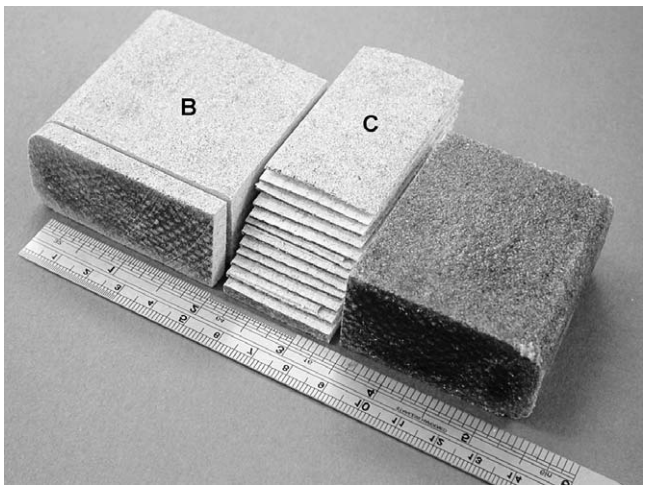

Figure 1.—Cross sections of collected field samples used for water absorption (B) and moisture content (C) measurements.

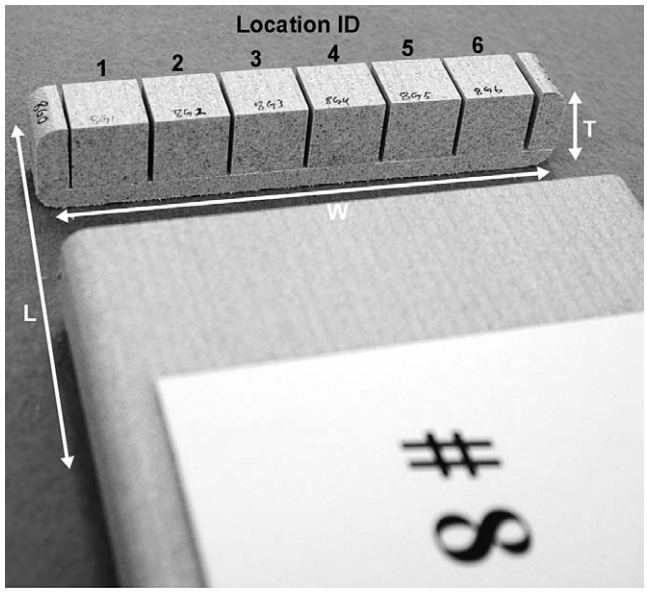

Figure 2.—Specimens cut from an unexposed wood–plastic composite board for soil block testing. L = *length;* W = *width;* T = *thickness.*

(Nakatsugawa, Japan) micrometer with ±0.001-mm accuracy. The thickness (T), width (W), and length (L) of specimens were recorded in correspondence to the board dimensions (see Fig. 2). Ratios of changes in width to changes in thickness ($\Delta W/\Delta T$) and changes in length to changes in thickness ($\Delta L/\Delta T$) were calculated for specimens after exposure to different water–temperature conditioning and soil block testing (described as 1 to 6 in the previous section). These measured weight and dimension values were used for density calculations. Based on the precise location of each specimen along the board, the density distribution in the board was also evaluated.

Field samples.—To calculate the density, specimens were weighed after drying at 103°C to constant weight using a Mettler PJ 300 balance (Greifensee, Switzerland; accuracy 0.001 g) with computer interface. The thickness and width of ovendried samples collected from the field were measured using a Mitutoyo calliper (Japan; accuracy ±0.01 mm) with computer interface. To calculate the volume of dried section B specimens without further cutting them, irregular cross sections with the rounded board edge on one side were photographed using a Nikon Coolpix 4500 digital camera (Japan). The cross-section images were then analyzed with ImagePro Express software (Media Cybernetics, Inc., Rockville, Maryland) to find the surface area of interest. The ImagePro Express program was calibrated for each specimen image based on the actual sample thickness measured with a calliper. This procedure allowed for dimensional measurements of the complex shapes of the samples without having to further cut the samples. Measurements by this method were used to determine the density of the samples without using a water immersion procedure. (Water immersion could be a questionable procedure, particularly with the increased composite porosity of the samples due to decay.)

To confirm similarities in dimensional changes between samples conditioned and tested in the laboratory and those weathered in the field, segments of the board containing the whole board cross section were collected in 2010. Thickness and width of these 2010 collection board segments were measured after drying using a digital calliper with computer interface and 0.01-mm accuracy. By comparing the dimensions of these board segments to reference unexposed boards, the ratios of changes in width to changes in thickness ($\Delta W/\Delta T$) for field samples were calculated.

Density change calculations

The density change of the tested WPC samples was determined by a series of calculations, with the assumption that relative dimensional changes in the tested WPC were proportional and did not depend on exposure conditions. This was confirmed by calculation of dimensional change ratios $\Delta W/\Delta T$ and $\Delta L/\Delta T$ for laboratory samples and $\Delta W/\Delta T$ for field-exposed samples. The average $\Delta W/\Delta T$ ratio for laboratory samples (0.437) was very similar to that for the field-exposed samples (0.440). A 2-tailed t test at 95% confidence level indicated that the $\Delta W/\Delta T$ ratios for laboratory and field-exposed samples were indeed not statistically different. Because of the good correlation between laboratory and field data, the laboratory-generated expansion ratios $\Delta W/\Delta T$ and $\Delta L/\Delta T$ were used to approximate volume expansion in the field data calculations.

As per AWPA E10, the mass of the wood-based materials was indicated by their weight during testing and analysis.

Initial reference density of unexposed samples was calculated from the simple equation

$$D_0 = \frac{M_0}{V_0} \tag{1}$$

where D_0 is ''reference density,'' the initial density of ovendried samples before testing; M_0 is initial dry mass of samples, measured prior to soil block culture testing or field exposure; and V_0 is initial dry volume of samples, measured prior to soil block culture testing or field exposure.

After exposure to decay either by soil block culture testing or in the field and subsequently dried, the exposed density of the samples was calculated as

$$D_e = \frac{M_e}{V_e} \tag{2}$$

where D_e is density of the samples after exposure to decay and drying; M_e is dry mass of exposed samples, measured after soil block culture testing or field exposure; and V_e is dry volume of exposed samples, measured after soil block culture testing or field exposure.

The observed decrease in density was a result of two independent processes: (1) dimensional changes of the board (as discussed previously) and (2) wood decay and, to a lesser extent, leaching of the composite wood components.

Unlike wood, which expands but also contracts upon exposure to moisture fluctuation and maintains similar volume after drying, WPCs undergo permanent dimensional changes during exposure to water, thus affecting the dry material density. The main interest in the evaluation, however, was to find density change caused mainly by decay. For this reason, density change caused by dimensional changes had to be taken into account in this evaluation. This was done for laboratory samples through calculations based on the equation

$$D_c = \frac{M_0}{V_e} \tag{3}$$

where D_c is the ''corrected reference density'' and M_0 and V_e are as defined earlier.

To calculate the density loss from decay and leaching only (ΔD), the final density of the exposed samples was subtracted from the ''corrected density'' of the sample before decay and results were presented as the percentage of change observed:

$$\Delta D = D_c - D_e = \frac{M_0}{V_e} - \frac{M_e}{V_e} \tag{4}$$

For field samples, corrected reference density D_c could be calculated as

$$D_c = \frac{D_0}{\beta} \tag{5}$$

where D_0 is reference density 1.101 g/cm^3 for ovendried WPC #8, and β is coefficient of volume expansion, which could be found as

$$\beta = (1 + \Delta T) \times \left(1 + \Delta T\left[\frac{\Delta W}{\Delta T}\right]\right) \times \left(1 + \Delta T\left[\frac{\Delta L}{\Delta T}\right]\right) \tag{6}$$

where ΔT is change in thickness, which was measured for each sample, and $\Delta W/\Delta T$ and $\Delta L/\Delta T$ were found by

dimensional change measurements of the laboratory samples (Table 2).

Based on Equations 1 and 3, the corrected reference density for field samples could be found as

$$D_0 = \frac{M_0}{V_0} \rightarrow M_0 = D_0 V_0 \tag{7}$$

$$D_c = \frac{M_0}{V_e} = \frac{D_0 V_0}{V_e} \tag{8}$$

$$D_c = \frac{D_0 V_0}{V_e} = \frac{D_0(1\times 1\times 1)}{(1+\Delta T)\times\left(1+\Delta T\left[\frac{\Delta W}{\Delta T}\right]\right)\times\left(1+\Delta T\left[\frac{\Delta L}{\Delta T}\right]\right)} = \frac{D_0}{\beta} \tag{9}$$

The difference in the corrected density calculation for laboratory samples compared with field samples was due to the different raw data available, and the methods used were selected based on their appropriateness in each case.

Results and Discussion

Field inspections

Selected photographs of WPC #8 boards exposed to exterior conditions in Vancouver and Hilo are shown in Figures 3 and 4. Inspection at the sunny site in Vancouver showed increasing black spotty discoloration on the surface of the samples, which intensified over time, particularly after spring 2004. No unusual material cracking or fungal fruiting bodies were seen until summer 2010 when the last inspection was carried out. Progressive surface damage in the form of fine cracks appeared after just a few months of exposure, likely due to sun radiation activity. At the shadow site during the first fall, heavy growth of algae on the board surface appeared and mold existence was difficult to distinguish. This algae presence was consistently observed afterward.

After 1 year of exposure at the sunny site in Hilo, the surface of the composite board of interest seemed to be relatively clean; however, signs of surface degradation in the form of microcracks were observed. After 28 months, many cracks parallel to the extrusion direction appeared on the surface, which was heavily covered by black mold that was microscopically identified as a mixture of different dematiaceous hyphomycetes. When microscopically examined, these cracks showed a depth of a few millimeters in some cases. Orange-colored fungal fruiting bodies also appeared in many locations on the board (Fig. 4) and could be seen again during inspection in March 2008. These orange fungal fruiting bodies were identified by a mycologist as most likely those of brown-rot decay fungus (*Dacryopinax spathularia*; Seifert 1983, Worrall et al. 1997). However, inspection of the site in 2009 showed the disappearance of this distinct sign of active fungal growth. At the shadow site, no cracks or fungal fruiting bodies were found until the last inspection in March 2009. However, heavy growth of algae and lichen had appeared during the first year of exposure and covered boards to such an extent that potential composite surface defects could not be examined afterward.

Optical and scanning electron microscopy

Select samples from the board of interest were subject to microscopic inspection, as described earlier. Hilo samples exposed in sun for 28 months showed distinct dark discoloration of wood particles, with the highest concentration near the board center. The optical microscope revealed signs of decay related to the dark brownish discoloration of lignin and fine fungal mycelia networks in some cavities left after the wood decayed (Fig. 5a). Further evaluation of this area under scanning electron microscopy showed wood that was clearly decayed and the presence of fungal mycelia (Figs. 5b and 5c). Brief microscopic inspection of the samples collected in 2008 and 2009 showed similar decay degradation but to a larger extent and spread across the whole board cross section.

Water absorption and wood moisture content

MC distribution inside the exposed board as measured from the upper surface of the board was calculated (Fig. 6). The wood MC reached 20 percent or higher for most of the tested samples regardless of time of exposure and location. Samples exposed for 40 months and longer in the sun location in Hilo and for 46 months and longer in both sun and shadow locations in Vancouver reached a wood composite MC from 25 percent up to about 50 percent. This indicated that most samples had a wood MC of over 25 percent, within the cross-section area, which was above the fiber saturation point at which decay can occur in wood. It could be expected that such high MC could initiate intense biological activity, including decay, and this was confirmed by our previous inspections and microscopic evaluation results.

Table 2.—Dimensional changes for dried wood–plastic composite #8 samples after soil block culture testing.

Conditioning[a]	Dimensional change (%)			$\Delta W/\Delta T$	$\Delta L/\Delta T$
	Thickness	Width	Length		
No conditioning, fungi	3.82	1.70	0.45	0.446	0.118
No conditioning, no fungi	3.87	1.67	0.38	0.431	0.097
Conditioning A, fungi	8.66	3.28	0.90	0.379	0.104
Conditioning A, no fungi	7.43	3.50	1.07	0.472	0.144
Conditioning B, fungi	8.03	3.40	0.66	0.424	0.082
Conditioning B, no fungi	9.20	4.31	1.36	0.469	0.148
Average (SD)	—	—	—	0.437 (0.034)	0.115 (0.026)

[a] Conditioning A = 2 weeks of soaking in water at room temperature; conditioning B = 5 days of soaking in water at 70°C.

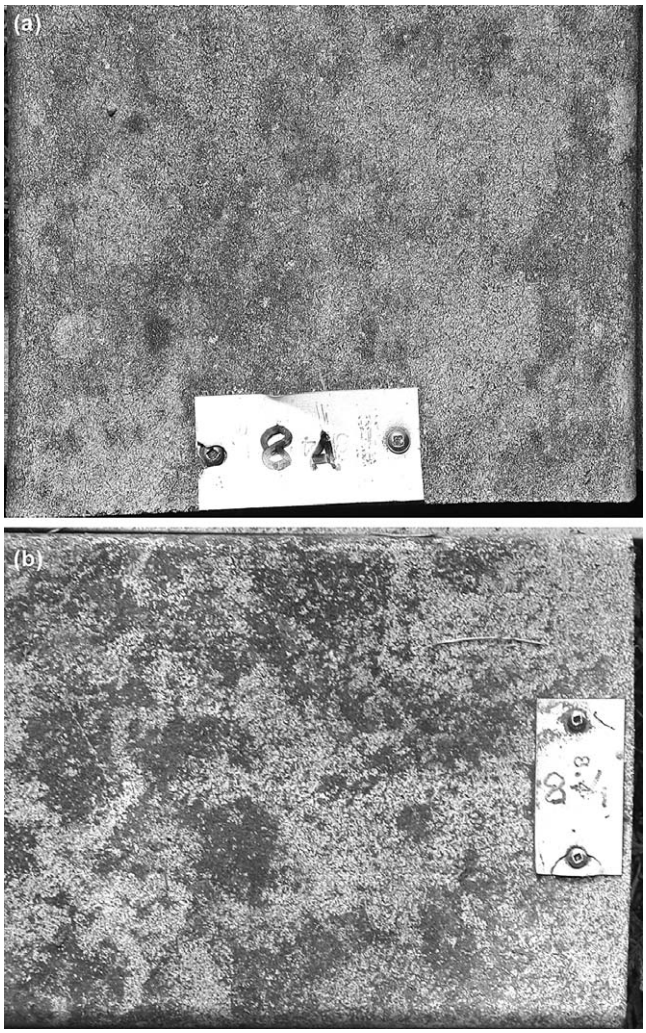

Figure 3.—Surface of wood–plastic composite #8 board, 152.4 mm (6 in.) wide. (a) Exposed at the sunny site in Vancouver, documented in 2008; note mold activity in the form of dark areas. (b) Exposed at the shadow site in Vancouver, documented in 2008; note algae activity in the form of green deposit.

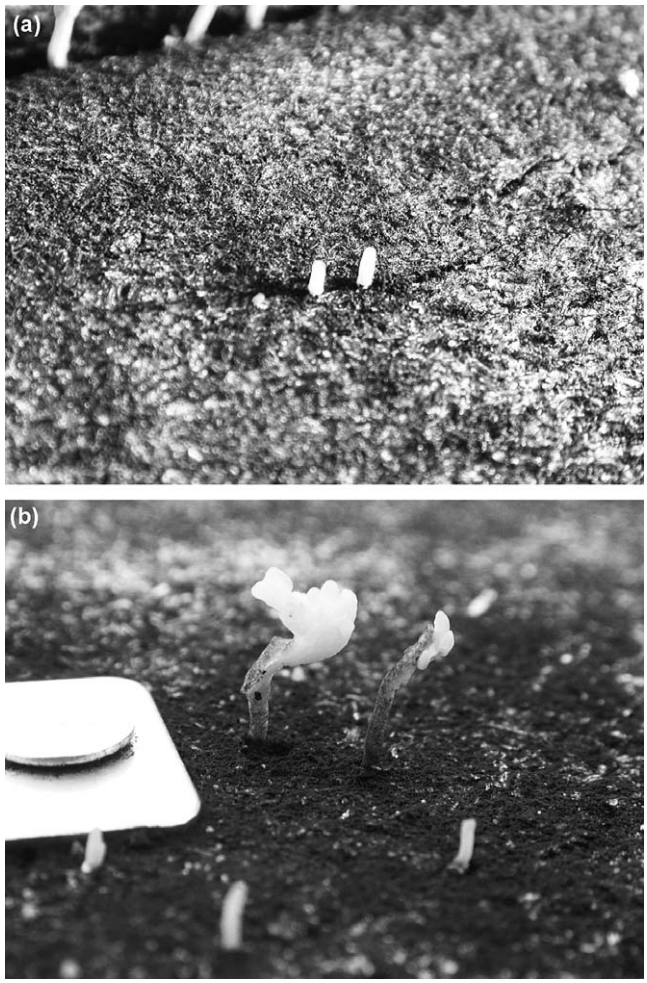

*Figure 4.—Surface of wood–plastic composite #8 board, 152.4 mm (6 in.) wide, exposed at the sunny site in Hilo. (a) Documented in 2007; note biological activity in the form of fungi fruiting bodies. (b) Documented in 2008; note the strong biological activity, including brown-rot fungi (*Dacryopinax spathularia*) fruiting bodies.*

Laboratory evaluations: moisture, density, and decay

The average total WPC weight loss of laboratory samples during soil block culture test is shown in Table 3. The data clearly indicate that weight loss depends on sample conditioning prior to exposure to fungi. Results could also be presented as a weight loss of the wood in the composite material because wood is the only WPC decaying component; it is assumed that polyethylene does not undergo the biological degradation process at these conditions. Calculated wood weight loss is also shown in Table 3.

Samples exposed to more aggressive moisture and heat conditioning showed greater weight loss. For example, specimens without conditioning showed a total WPC weight loss of only 4.75 percent (or 7.20% weight loss in wood), whereas specimens exposed to 5 days immersion in water at 70°C showed 12.88 percent total weight loss (or 19.54% weight loss in wood). Specimens of pine controls showed 47 percent weight loss, indicating the expected aggressive fungal activity. Identical samples exposed to test conditions without fungi showed lower weight loss, averaging 1.8 percent, which was likely due to wood extractive leaching.

Further data analysis included specimen density evaluation (Table 4). Specimen density analysis indicated that density loss due to fungal attack likely increased with decreasing composite density for samples without or with mild conditioning. For samples conditioned for 5 days in water at 70°C, the density of samples did not influence the density loss trend. The WPC board density may vary in cross section due to material cooling and shrinkage during manufacturing. This could lead to an area with slightly lower density inside the boards, which would be more sensitive to decay.

Specimens of WPC maintained their shape after completing the soil block culture test because of the presence of a plastic matrix that is known to be nondegradable, as opposed to wood, which disintegrates after decay. This allowed the presentation of soil block culture testing results not only as weight loss, but also as overall composite density loss, as shown in Figure 7. However, WPC overall density loss (of dried specimens) from soil block testing was

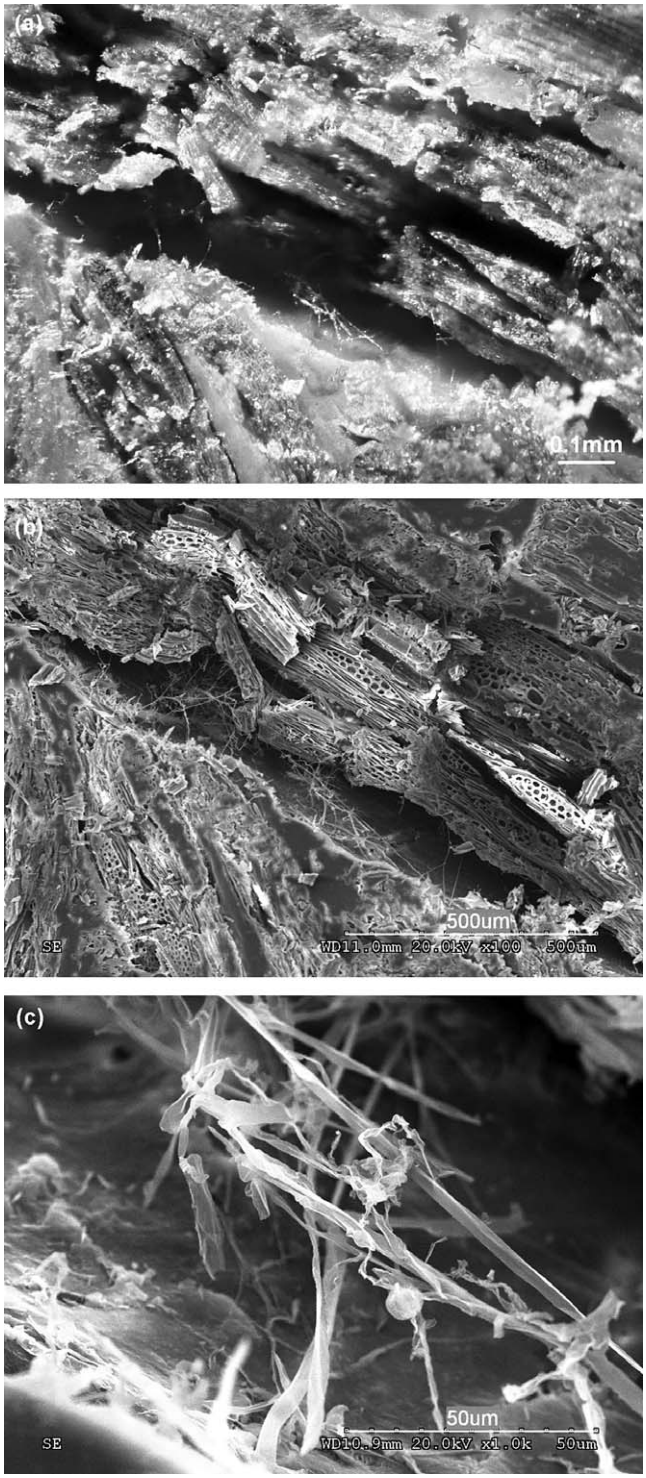

Figure 5.—Discolored cross section of wood–plastic composite #8 exposed at the sunny site in Hilo for 27 months. (a) Optical magnification of brown decayed wood particles with traces of white resin. (b) Scanning electron microscopy (SEM) image of the same area. (c) SEM image showing the magnified remains of decayed wood and fungal mycelia in the same area.

not only from decay but also from permanent dimensional changes (discussed in the next section). This issue was analyzed and will be discussed in the ''Density changes'' section. Presenting the results as WPC sample density facilitated the comparison of laboratory and field test results.

Dimensional stability

Laboratory exposure.—Permanent dimensional changes of oven-dried WPC exposed to moisture and elevated temperature in the laboratory by conditioning were studied using specimens from the soil block culture tests. Results for dimensional changes in laboratory samples, shown in Table 2, indicate significant permanent change in WPC dimensions after conditioning. These dimensional changes depended on their orientation with respect to the extrusion direction. The largest change of 9.2 percent was observed in the thickness for samples exposed to the soil block culture test without fungi presence after 5 days of immersion in water at 70°C. The same set of samples showed a width swell of 4.31 percent. The length direction expanded only 1.36 percent. It should be mentioned that the ratios of permanent dimensional changes in width to thickness ($\Delta W/\Delta T$) and length to thickness ($\Delta L/\Delta T$) were very similar within each ratio category, as shown by the low standard deviations presented in Table 2. Average ratios $\Delta W/\Delta T$ and $\Delta L/\Delta T$ were calculated as 0.437 and 0.115, respectively. The largest variability, in the range of 0.097 to 0.148, was observed for $\Delta L/\Delta T$; this was likely due to the dimensional changes in the board length direction being smaller (frequently well under 1%) and difficult to accurately measure.

Field exposure.—Table 5 summarizes dimensional changes in thickness and width of ovendried samples of WPC #8 collected in 2010 from the field. Historical data for thickness dimensional changes are shown in Figure 8. The presented data indicated that the tested WPC continued to permanently expand during the entire monitoring period. The largest dimensional changes in board thickness direction were observed in sun exposure in both Hilo (6.0%) and Vancouver (6.9%). The average $\Delta W/\Delta T$ ratio calculated for samples collected in 2010 was 0.440, which was almost identical to the average ratio (0.437) calculated based on laboratory testing, as described earlier.

Density changes

Laboratory exposure.—Distribution of density within the dried WPC board is presented in Figure 9. Specimens 2 and 5 showed slightly higher density, which could be explained by fast cooling of the board in combination with composite shrinkage during extrusion. The average density of an unexposed WPC board (#8) of interest was also accurately evaluated after drying to constant weight and found to be 1.101 g/cm^3. This value was later used in the evaluation of field samples. Figure 7 shows the overall density loss, which consists of both density loss from permanent dimensional changes and that from decay and leaching, for laboratory samples subject to conditioning and soil block culture testing. Table 5 and Figure 10 show the density loss due to leaching and decay for laboratory samples after soil block testing. In Figures 10 and 11, a horizontal line shows density loss from leaching to be 1.42 percent, which serves a baseline differentiating density loss from decay. This average leaching value was calculated based on the average density of samples exposed in Hilo for up to 12 months and in Vancouver for up to 46 months (Table 6), a period of time in which decay was assumed to be negligible.

Field exposure.—Measured density changes for WPC #8 exposed for different periods of time in Hilo and Vancouver are shown in Table 6. There was a continuous trend of

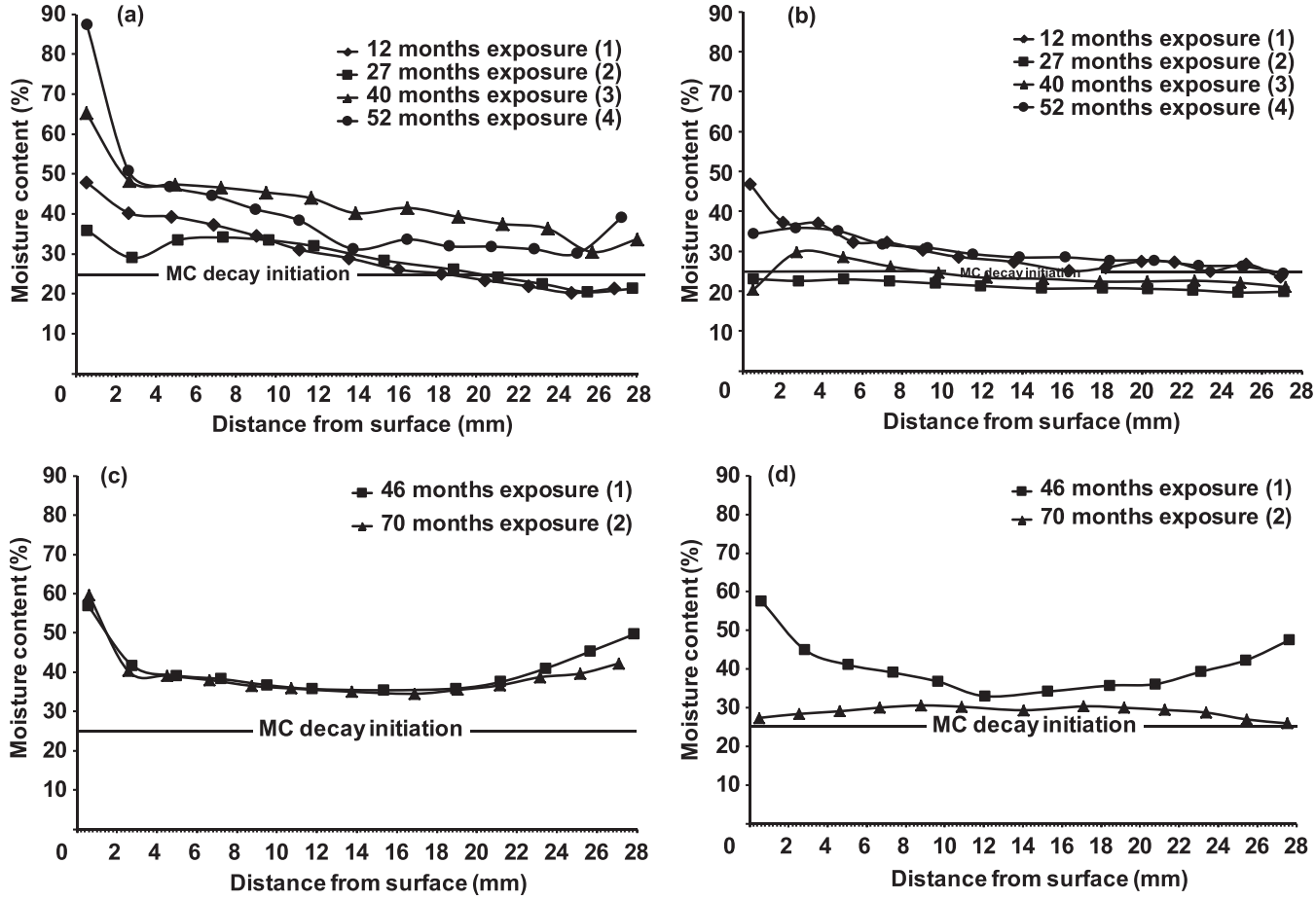

Figure 6.—Wood moisture content distribution in decking board as measured from the upper board surface of wood–plastic composite #8. (a) Exposed at the sunny location in Hilo for (1) 12 months, (2) 27 months, (3) 40 months, and (4) 52 months. (b) Exposed at the shadow location in Hilo for (1) 12 months, (2) 27 months, (3) 40 months, and (4) 52 months. (c) Exposed at the sunny location in Vancouver for (1) 46 months and (2) 70 months. (d) Exposed at the shadow location in Vancouver for (1) 46 months and (2) 70 months.

Table 3.—Weight loss of dried laboratory wood–plastic composite (WPC) #8 samples subject to soil block culture testing.

Specimen type (conditioning)[a]	Avg. (SD) total WPC wt loss (%)		Avg. (SD) wt loss in wood (%)	
	Fungi	No fungi	Fungi	No fungi
No conditioning	4.75 (0.15)	1.02 (0.04)	7.20 (0.23)	1.55 (0.07)
Conditioning A	8.59 (0.93)	1.62 (0.41)	13.03 (1.41)	2.46 (0.62)
Conditioning B	12.88 (4.64)	2.78 (0.12)	19.54 (7.04)	4.22 (0.18)
Pine controls	—	—	47.14 (7.85)	—

[a] Conditioning A = 2 weeks of soaking in water at room temperature; conditioning B = 5 days of soaking in water at 70°C.

Table 4.—Measured and calculated densities for dried wood–plastic composite (WPC) #8 laboratory samples exposed to soil block testing.

Specimen type (conditioning)[a]	Avg. (SD) measured density (g/cm^3)		Avg. (SD) overall density loss (%)		Avg. (SD) density loss from decay and/or leaching (%)	
	Fungi	No fungi	Fungi	No fungi	Fungi	No fungi
No conditioning	0.974 (0.003)	1.013 (0.003)	10.20 (0.20)	6.59 (0.17)	4.75 (0.15)	1.02 (0.04)
Conditioning A	0.887 (0.007)	0.946 (0.003)	18.06 (0.36)	12.55 (0.36)	8.59 (0.93)	1.62 (0.41)
Conditioning B	0.839 (0.035)	0.919 (0.004)	22.45 (3.29)	15.81 (0.27)	12.88 (4.64)	2.78 (0.12)

[a] Conditioning A = 2 weeks of soaking in water at room temperature; conditioning B = 5 days of soaking in water at 70°C.

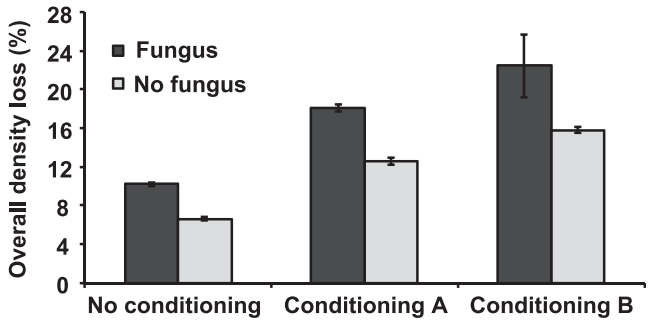

Figure 7.—Overall density loss of wood–plastic composite #8 laboratory samples after soil block testing. The overall density loss comprises both density loss from permanent dimensional changes and that from decay and leaching. Conditioning A = 2 weeks of soaking in water at room temperature; conditioning B = 5 days of soaking in water at 70°C.

decreasing WPC density during exposure to weathering. Sunny exposure sites also seemed to accelerate the rate of density decrease, and the change at Hilo was more aggressive than at Vancouver in this respect.

The coefficient of volume expansion and corrected density for field-exposed samples are shown in Table 6. Results indicate a decrease in corrected density for the majority of samples during the evaluated exposure period, regardless of climatic zone or sun–shadow exposure.

The calculated density loss from decay and leaching is shown in Table 6 and Figure 11. The corresponding weight loss could be assumed to be numerically equivalent to the density loss from leaching and decay once the loss

Table 5.—Dimensional changes for dried wood–plastic composite (WPC) #8 samples after field exposure (based on 2010 samples collection).

Climatic zone and location	Dimensional change (%)		
	Thickness	Width	$\Delta W/\Delta T$
Hilo, sunny	5.98	2.68	0.448
Hilo, shadow	4.98	2.34	0.470
Vancouver, sunny	6.87	2.99	0.435
Vancouver, shadow	4.58	1.87	0.409
Avg. (SD)	—	—	0.440 (0.025)

contribution from permanent dimensional changes was taken into account, as outlined by the equations in the ''Density change calculations'' section. Furthermore, weight loss values from leaching and decay for the wood inside the composite material were also calculated based on the known wood content of the WPC material and the assumption that wood is the only decaying component (Table 6). During field exposure, there was an initiation time period when no change in density or weight loss was observed. This initiation period was about 27 months for sun exposure and 40 months for shadow exposure in Hilo. This period was extended to about 70 months for both sun and shadow exposure in Vancouver.

For samples exposed in Hilo, only a small (~1.5%) density decrease occurred during the first year of exposure regardless of sun or shadow location, likely due to wood extractive leaching. No significant wood weight loss was expected. After the second year, the sample exposed in

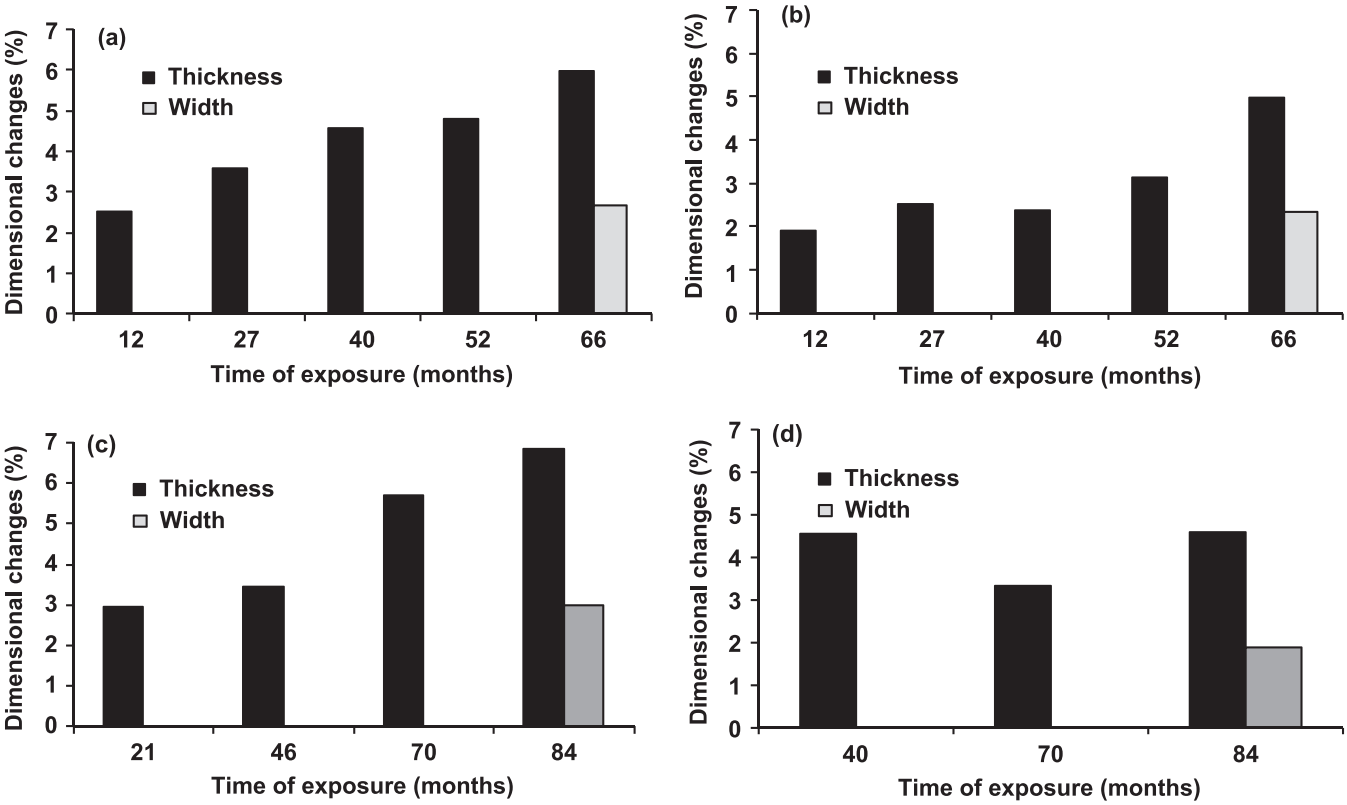

Figure 8.—Dimensional changes in wood–plastic composite #8 samples exposed at (a) the sunny location in Hilo, (b) the shadow location in Hilo, (c) the sunny location in Vancouver, and (d) the shadow location in Vancouver.

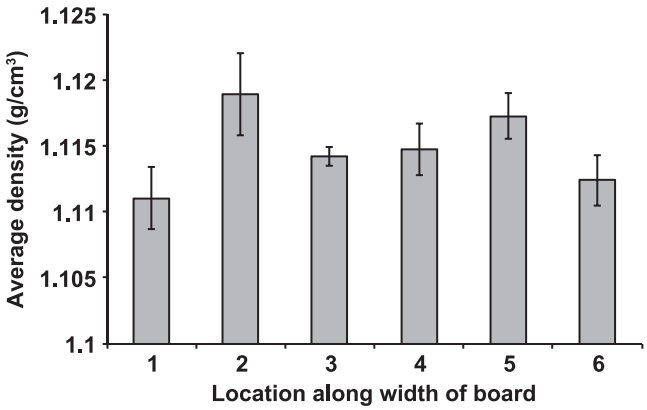

Figure 9.—Density distribution across the width of wood–plastic composite board #8 as measured for soil block test samples (locations correspond to those shown in Fig. 2).

shadow did not show any additional density decrease, but the sample exposed in sun showed a density decrease of 3.83 percent after the second year and 11.20 percent after 40 months of exposure in the field. This corresponded to 5.80 and 17.00 percent weight loss in wood, respectively. This decrease in density and weight loss in wood was very similar to the decrease in density of the soil block culture samples exposed to aggressive conditioning by immersion in water at 70°C for 5 days (12.88% total WPC weight loss or 19.54% weight loss in wood). The sample exposed in shadow showed a density decrease of 8.64 percent after 52 months, which corresponded to 13.11 percent weight loss in wood. The large density decrease in WPC samples exposed in sun was consistent with the results described earlier regarding decay found during sample inspection. Samples from Vancouver showed only a small density decrease, ~1.4 percent (or ~2.0% weight loss in wood), after 46 months of exposure, regardless of sun or shadow location. After 70 months, the sample exposed in shadow showed a density decrease of 2.96 percent (or 4.49% weight loss in wood), and the sample exposed in sun showed a density decrease of 4.54 percent (or 6.89% weight loss in wood), likely due to the initiation of the decay process.

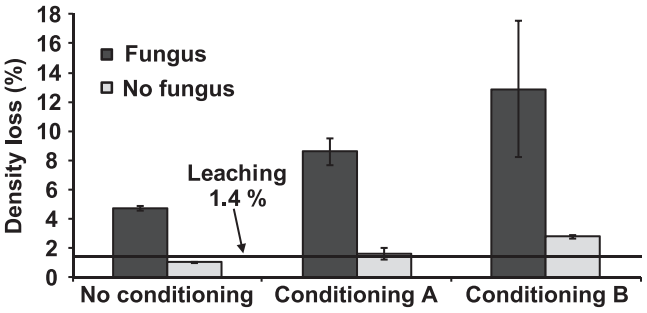

Figure 10.—Density loss from leaching and decay for wood–plastic composite #8 laboratory samples after soil block testing. The leaching value of 1.42 percent as calculated from field-exposed samples provides a baseline comparison for the soil block test results. Conditioning A = 2 weeks of soaking in water at room temperature; conditioning B = 5 days of soaking in water at 70°C.

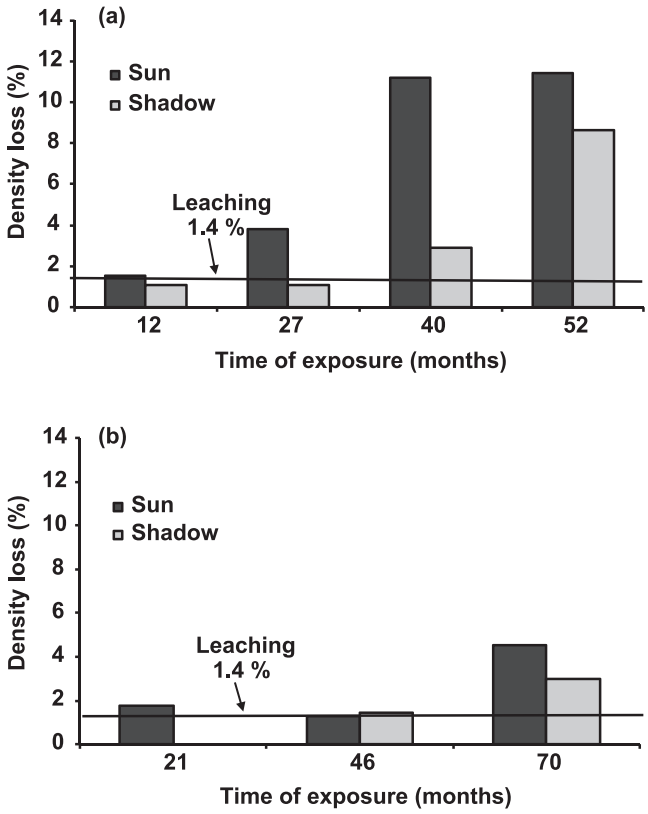

Figure 11.—Density loss from leaching and decay for wood–plastic composite sample #8 (a) exposed in Hilo and (b) exposed in Vancouver.

Conclusions

Laboratory soil block culture testing of WPC samples showed different decay rates, depending on conditioning prior to exposure to fungi. The lowest rate of decay was observed for nonconditioned samples, which showed 4.75 percent total weight loss or 7.20 percent weight loss in wood. Samples exposed to 2 weeks of water immersion at room temperature showed 8.59 percent total weight loss or 13.03 percent weight loss in wood. Samples conditioned for 5 days by water immersion at 70°C showed the highest total weight loss at 12.88 or 19.54 percent weight loss in wood. Based on the relatively small weight losses of the reference samples exposed to identical test conditions without fungal exposure, it was reasonable to expect that most weight loss during testing came from fungal activity and decay. The results confirmed published data with respect to the conditioning of samples (Clemons and Ibach 2004, Van Acker 2006).

Unlike with solid wood, quantitative evaluation of WPC decay could be expressed both in terms of weight loss and decrease in density because of the structural stability of the decayed WPC specimens. Decrease of WPC density may be a convenient way to compare the decay of laboratory and field samples. Evaluation of decrease in density from decay must be approached with caution, taking into consideration the ongoing WPC dimensional changes.

Rate of density decrease for the WPCs varied during field exposure. As expected, this rate depended on time of exposure, climatic zone, and exposure location (sun or shadow). Density decrease was most likely a result of fungal

Table 6.—Measured and calculated densities for dried wood–plastic composite (WPC) #8 samples exposed in Hilo and Vancouver.

Sample description							
Climatic zone	Exposure location	Months of exposure	Measured density (g/cm^3)	Coefficient of vol expansion	Corrected density (g/cm^3)[a]	Density or wt loss from leaching and decay (%)[b]	Wt loss in wood from leaching and decay (%)
Unexposed reference sample			1.101				
Hilo	Sunny	12	1.043	1.039	1.060	1.54	2.34
		27	1.003	1.056	1.043	3.83	5.80
		40	0.912	1.072	1.027	11.20	17.00
		52	0.907	1.076	1.024	11.41	17.31
	Shadow	12	1.058	1.029	1.070	1.10	1.67
		27	1.048	1.039	1.060	1.09	1.66
		40	1.031	1.037	1.062	2.92	4.42
		52	0.959	1.049	1.050	8.64	13.11
Vancouver	Sunny	12	1.126	—[c]	—	—	—
		21	1.034	1.047	1.052	1.77	2.68
		46	1.031	1.054	1.044	1.27	1.92
		70	0.964	1.091	1.010	4.54	6.89
	Shadow	46	1.013	1.072	1.028	1.43	2.17
		70	1.016	1.052	1.047	2.96	4.49

[a] Density of unexposed (reference) sample of WPC #8 corrected for dimensional changes expected in exposed boards. Dimensional changes were calculated based on field and laboratory data.

[b] Density or weight loss is numerically equivalent.

[c] Dashes = the specimen geometry for this sample could not be used for dimensional change measurements, and thus a corrected density could not be calculated.

activity (decay) and the effect of dimensional changes of the composite material. Regardless of the absence of decay fungus fruiting bodies, WPC may show a decrease in density most likely associated with the decay process.

During field exposure, there was an initiation time period during which no significant change in density or weight loss from decay was observed. After this period, rapid weight loss or density decrease of the WPC sample could be seen (most likely due to wood decay). The initiation period for the tested WPCs was 27 months for sunny exposure and 40 months for shadow exposure in Hilo (Scheffer index, ~350). This period was extended to about 70 months for both sunny and shadow exposure in Vancouver (Scheffer index, ~50). This also indicated that exposure in sun was more aggressive with respect to decay of the tested WPC samples than exposure in shadow.

Weathering of the WPC samples also led to significant permanent dimensional changes that, together with decay, contributed to a decrease in the composite density. The increase in dimensions was anisotropic and depended on orientation relative to the direction of extrusion. The greatest dimensional changes were associated with WPC board thickness, and the smallest changes were associated with board length. Graphs representing density as a function of time of exposure indicated a continuous decrease in density of samples during the entire test period of up to 6 years.

Laboratory and field results indicate that to simulate field performance of WPC using soil block culture testing, samples must be conditioned prior to exposure to fungi. This was mainly due to the very slow WA of WPCs in comparison to solid wood, for which the soil block culture test was designed. Conditioning depended on the climatic zone of field exposure and exposure time to be simulated. For example, results presented in this article show that the WPC sample exposed in the sun for 40 months in Hilo had a similar decrease in density related to decay (11.20%) as WPC samples of the same material conditioned in water for 5 days at 70°C (12.88%), which corresponded to weight loss in wood of 17.00 and 19.54 percent, respectively. Samples exposed in shadow for 52 months in Hilo showed a decay-related density decrease of 8.64 percent, similar to WPC samples of the same material conditioned for 2 weeks in water at room temperature (8.59%), which corresponded to weight loss in wood of 13.11 and 13.03 percent, respectively. In contrast, laboratory samples tested without conditioning showed a density loss from leaching and decay of less than 5 percent (4.75%), which corresponded to only 7.20 percent weight loss in wood. Simulating 70 months of sunny exposure in Vancouver did not require conditioning due to the longer initiation period for the decay process, but conditioning may be required if simulations of longer field exposures are desired.

Variability in material density of the WPC board may have contributed to the decay rate. During soil block culture testing, samples with lower initial density, exposed to either no conditioning or less aggressive conditioning, showed a trend of higher rates of decay. This trend was not detected for aggressively conditioned WPC.

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