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Laboratory and environmental decay of wood–plastic composite boards: flexural properties

Rebecca Ibach[a], Marek Gnatowski[b], Grace Sun[b], Jessie Glaeser[c], Mathew Leung[b] and John Haight[c]

[a]Forest Products Laboratory, USDA Forest Service, Madison, WI, USA; [b]Polymer Engineering Company Ltd, Burnaby, BC, Canada; [c]Center for Forest Mycology Research, USDA Forest Service, Madison, WI, USA

ABSTRACT

The flexural properties of wood–plastic composite (WPC) deck boards exposed to 9.5 years of environmental decay in Hilo, Hawaii, were compared to samples exposed to moisture and decay fungi for 12 weeks in the laboratory, to establish a correlation between sample flexural properties and calculated void volume. Specimens were tested for flexural strength and modulus, both wet and dry, at 23°C and 52°C. Some specimens degenerated to only 15% of original flexural strength. UV radiation had no impact on flexural properties of field-exposed boards; loss occurred mainly on the side opposite to the sun-exposed surface. The mechanism of the aging process on colonization of WPC by fungi was examined and is consistent with development of slow crack growth in the polyethylene matrix combined with wood decay by fungi. Wood particle decay, moisture, and elevated temperature were the major factors causing composite degradation, indicated by accumulation of voids and a severe decrease in flexural properties. To simulate long-term field impact (including decay) on WPC flexural properties in the laboratory, conditioning of specimens in hot water for an extended period of time is required. Exposure to water (70°C/5 days) was adequate for simulating long-term composite exposure in Hawaii of $4 \times 15 \times 86$ mm^3 specimens.

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1. Introduction

Wood–plastic composites (WPCs) are a class of relatively new materials, employed extensively to manufacture deck boards, fences, playground structures, and elements of exterior doors and windows. The rising popularity of WPC in exterior construction, particularly across North America, has increased the interest in testing its long-term durability. Durability testing can be conducted under controlled laboratory conditions, but limited knowledge of the correlation between accelerated laboratory testing and in-service performance of WPCs makes drawing comprehensive conclusions difficult (Morrell *et al*. 2009). Until laboratory testing can be correlated with long-term exterior durability, long-term performance of WPC products will remain the subject of scientific controversy.

Commercial WPC products are generally made by an extrusion process, blending dry wood flour and thermoplastic resins, adding lubricants, pigments, mineral fillers, coupling agents, biocides and stabilizers (Gardner and Murdock 2010, Lam 2010, Hanawalt 2012). Some researchers from industry and academia expected that encapsulation of wood particles in plastic such as polyethylene, polypropylene, or polyvinyl chloride would bring the required water-resistance to the wood components (Schirp *et al*. 2008, Morrell *et al*. 2009). Decay resistance was expected from WPCs because of the anticipated low water absorption (WA).

Low WA was an important requirement for one of the first large scale uses of WPCs – replacement elements of walkways in the Florida Everglades National Park in 1992. A few years after installation, fruiting bodies of decay fungi were observed growing on the WPCs along these walkways (Morris and Cooper 1998). Also, the presence of deformed WPC boards was reported, likely due to excessive moisture absorption.

Exposure tests of WPCs have been conducted in Asia (Taib *et al*. 2010, Darabi *et al*. 2012, Zhao *et al*. 2012, Chaochanchaikul *et al*. 2013, Ebe and Sekino 2015), Australia (Li 2000), Europe (Oberdorfer and Golser 2005, Butylina *et al*. 2012a, 2012b, Kallakas *et al*. 2015), and North America and Hawaii (Verhey *et al*. 2003, Anon. 2005, Lopez *et al*. 2006, Schauwecker *et al*. 2006, Manning and Ascherl 2007, Gnatowski 2009, Ibach *et al*. 2013, 2016, Fabiyi and McDonald 2014, Gnatowski *et al*. 2014, Sun *et al*. 2014, 2015). Most of these exposure tests were carried out for a limited period of time, usually not exceeding one year, and only on the rare occasion were the tested composites left in the field for extended periods of 3–10 years. This extended exposure still may not be sufficient for drawing conclusions about long-term WPC performance in comparison to the expected WPC exterior service period, which may reach decades under varied, often harsh, climatic conditions. Many test sites were in locations with a relatively mild climate with limited decay fungi activity, but sites near Hilo, Hawaii, were known to be effective in the evaluation of decay resistance of treated, wood-based products. A fair amount of published data came from those sites near Hilo with annual rainfall about 3300–5000 mm, depending on the exact location (Manning and Ascherl 2007). These exposures may be treated as accelerated testing for other locations in the world, particularly when fungal decay is a concern and the Scheffer climate

CONTACT Rebecca Ibach ribach@fs.fed.us

index can be calculated and taken into consideration (Scheffer 1971).

Verhey *et al*. (2003) exposed WPC stakes below and above ground for a period of up to one year near Hilo and observed a large loss in the flexural properties of the WPCs that were attributed mainly to a significant increase in moisture content (MC). Basidiomycete fungi were not detected. WA in WPCs was also found by other researchers to be a major cause of decreased flexural properties in laboratory and field exposure experiments (Clemons and Ibach 2002, 2004, Lopez *et al*. 2006, Ibach *et al*. 2007, Gnatowski 2009, Morrell *et al*. 2009, Machado *et al*. 2016). Commercial and experimental WPC boards with wood content of 50–65% exposed near Hilo and Vancouver (BC, Canada) had a significant amount of WA (Manning and Ascherl 2007, Gnatowski 2009). During these studies, the MC above wood fiber saturation (∼25–30%) was detected with the highest at the surface of the boards and lowest in the center. These observations led to the conclusion that the surface of the exposed boards allowed water entry and made the WPC vulnerable to decay. Similar WA patterns and the presence of free water were found on magnetic resonance (MR) images of WPC decking boards, including co-extruded products with plastic capping (Gnatowski *et al*. 2014). The largest free water concentration was visible on the MR images at the board support areas, around the fastening grooves, along the water drip zone and at the cut ends. These data question the use of co-extruded cappings for the protection of WPC decking boards against water entry, which instead may create a favorable environment for potential fungal decay.

Fungal decay of WPC boards near Hilo was caused by a variety of decay fungi, and fruiting bodies on the board surfaces were observed after 1.5–4 years of exposure (Manning and Ascherl 2007). Another investigation involved samples cut from commercial WPC boards that were exposed near Hilo for 10 years (Schauwecker *et al*. 2006). Some environmental deterioration of the composite was found within a 5 mm zone from the surface of the samples, likely due to WA, but the presence of decay fungi or signs of their activity were not detected. Some researchers suggested the use of biologically active additives (biocides) to control fungal activity, including decay. Zinc borate was found to be effective in this application and is used commercially in some WPCs (Clemons and Ibach 2004, Manning and Ascherl 2007).

Recently, the relationship between field decay and a laboratory decay resistance test was determined based on the testing of experimental WPC boards exposed in Hilo and Vancouver, as well as from laboratory evaluation of this composite for fungal decay resistance (Ibach *et al*. 2013). It was confirmed that conditioning the WPC samples prior to fungal exposure in the laboratory was necessary. In the field, an induction time was required to initiate fungal colonization before wood weight loss occurred. These findings may explain the deficiencies in some laboratory evaluations of WPC for fungal decay resistance.

To fairly compare laboratory testing with exterior exposure, the damaging effect of solar UV radiation, if any, must also be taken into consideration. The measurement of photo-oxidation has been well-described in literature, and infrared spectroscopy was found to be an effective measuring tool (Zerbi *et al*. 1989, Colom *et al*. 2000, Stark and Matuana 2004, Gnatowski *et al*. 2007). This effect can be detected as polymer photo-oxidation.

The objective of this study was to determine whether there is a correlation between the flexural properties for laboratory- and field-exposed and decayed WPC decking boards and develop laboratory methods that can be applied to reliably predict durability of WPCs in service.

2. Materials and methods

2.1. Exterior exposure, inspection, and collection of WPC boards

Twenty-seven randomly selected commercial decking WPC boards of different grades, made by seven different manufacturers, were purchased from a building materials outlet. Each board was cut into three segments, one was kept as a reference sample and the other two were used for exterior exposure. These segments will be henceforth referred to as "boards".

The reference board was used for characterization of the material and for preparation of samples for laboratory decay testing. The two other boards were exposed in a horizontal position outside near Hilo, Hawaii starting in November 2004. For each grade, one of the boards was exposed in semi-shadow under an *Albizia* tree for most of its exposure (Shadow) while the second board was exposed in an open area under full sunlight (Sun). Boards were periodically inspected and tested. Interim laboratory testing evaluated WA and distribution, the presence of environmental damage, including the appearance of decay fungi fruiting bodies, examined the board surface and cross-sections using a microscope, and for selected samples, assessed composite oxidative degradation. Following the inspection after 8 years of exposure in November 2012, one set of boards (shadow and sun) out of six sets that showed distinct signs of decay in the form of fungal fruiting bodies was selected for a more comprehensive study (Sun *et al*. 2015, Ibach *et al*. 2016). In June 2014 (after 9.5 years of exposure) a final field inspection was carried out at both exposure sites and the remains of the boards were taken for evaluation, including fungal identification by DNA sequencing, mechanical testing, and photo-degradation analysis.

2.2. Fourier transform infrared spectroscopy

Photo-oxidation of WPC was measured from infrared spectra of randomly selected field-exposed (Sun) sample surfaces, as well as from fresh surfaces after gradual removal of material by sanding off 0.10, 0.31, 0.52 and 0.73 mm thick layers of the composite. The surface of specimens taken from the interior of the tested WPC board (14.5 mm) was used as a reference. An Avatar 370 spectrometer (Thermo Nicolet, Madison, WI) equipped with a multiple reflectance ZnSe crystal with a 45° angle of incidence (Harrick Scientific Products, Pleasantville, NY) was used for acquisition of Fourier transform infrared (FTIR) spectra. Spectra consisting of 128 scans were acquired, each with the focus on bands around: 1715 cm^{-1} (C=O stretching), 2910 cm^{-1} (-CH- stretching). This pair of bands was used for characterization of the degree of material oxidation. At least three spectra were taken for each WPC surface of interest and analyzed, including measurement of the height of the absorption bands mentioned above. For measurement of oxidation, the carbonyl indexes were calculated from Equation (1) (Stark and Matuana 2004).

$$\text{Carbonyl Index} = \frac{I_{1715}}{I_{2912}}(100), \quad (1)$$

where I_{1715} is the height of absorbance band at 1715 cm^{-1} and I_{2912} is the height of absorbance band at 2912 cm^{-1}.

Carbonyl indexes were evaluated for statistically significant differences using a two tail *t*-test at 95% confidence level.

2.3. Color measurement

Color measurement was conducted according to American Society for Testing and Materials (ASTM) standard D2244 using a ColorEye XTH spectrophotometer (Gretag Macbeth, New Windsor, NY) (ASTM International 2014b). Five color measurements were made on three randomly selected specimens from each group of exposed samples. Five measurements were also made in randomly selected areas of the reference sample.

2.4. Fungal identification

Initial identifications were made from inspection photographs and from fungal fruiting bodies collected from WPC at exposure sites in Hilo. To aid in identification and ensure that the attached fruiting bodies were representative of the fungi causing decay within the boards, fungal isolations were taken from the collected fruiting bodies, grown in culture on 1% malt agar and compared anatomically and genetically to isolations taken from interior areas of the WPC boards. Genetic comparisons were made by extracting, amplifying and sequencing the nuc rDNA internal transcribed spacer (ITS) 1-5.8S-ITS2 region (Haight *et al*. 2016) and comparing the resulting sequences to each other and to reference sequences found in GenBank (Benson *et al*. 2005). These comparisons confirmed colonization of the interior of the WPC boards by the fungi present on the surface in this study and in earlier work (Sun *et al*. 2014, 2015, Ibach *et al*. 2016).

2.5. WPC deck board characterization

The reference board was characterized for density, WA, wood content, and polymer matrix resin composition. Details of the test methods used for such characterization are described in earlier publications (Gnatowski *et al*. 2014, Ibach *et al*. 2016). As such, only a summary of the procedures is provided.

The WA, wood MC and density of the reference WPC board were measured according to ASTM standards D7032 and D1037 (ASTM International 2014a, 2014c). WA is defined in this publication as the total water content in a WPC sample calculated based on the dry composite weight. MC is defined as the water content in the wood of the composite calculated based on the dry wood content in the specific sample. In addition, MC and WA were calculated for each specimen during flexural testing based on the weight difference at completion of the test and after drying to constant weight in oven at 50°C. For density measurements, six samples were obtained across the width of the board, with nominal dimensions $4 \times 15 \times 86$ mm^3. Also, free water detected by MRI in decayed boards was reported (Ibach *et al*. 2016). The density of each specimen was calculated from the known weight and dimensions as per ASTM D1037-12 (ASTM International, 2014a). Historical data for field-exposed samples can be found in earlier publications (Sun *et al*. 2014, 2015, Ibach *et al*. 2016).

Wood content of the WPC board was analyzed by dissolving about a 1 g sample of the oven-dried composite in decahydronaphthalene and calculating the weight of recovered wood particles. Recovered wood flour particles were further characterized with respect to their aspect ratio, size, and size distribution. Additionally, about 1g of the WPC sample was ashed at both 675°C and 900°C to find the quantity of inorganic components present, mainly pigments and fillers.

Resins used in manufacturing of the composite were characterized by FTIR spectra and Differential Scanning Calorimetry (DSC) thermograms (Prasad 1998, ASTM International 2011).

2.6. Laboratory exposure by soil block culture testing

Soil block culture testing was conducted on the reference board according to AWPA E10 (2013). Specimens ($4 \times 15 \times 86$ mm^3) were cut parallel to the length of the board and extrusion direction. A set of seven specimens was obtained from the board cross section. Each specimen was individually marked based on its location within the board. Thirty sets, each containing seven specimens cut from the board's cross-section, were used for testing. Since fruiting bodies of several species of white and brown rot fungi were found on the exterior exposed boards, soil block tests were run using both brown rot (*Gloeophyllum trabeum*) and white rot (*Trametes versicolor*) fungi. Before exposure to fungi, the specimens were conditioned by water immersion at 70°C for 5 days and/or steam sterilized at 100°C for 20 minutes, where applicable, and then inserted into soil bottles. Samples were divided into six groups and specimens belonging to each group were exposed inside the bottles to test environments with and without fungi for 12 weeks at the following conditions:

(1) No conditioning, no fungal exposure
(2) No conditioning, brown rot fungal exposure
(3) No conditioning, white rot fungal exposure
(4) Conditioning by water immersion at 70°C for 5 days, no fungal exposure
(5) Conditioning by water immersion at 70°C for 5 days, brown rot fungal exposure
(6) Conditioning by water immersion at 70°C for 5 days, white rot fungal exposure

Twenty-eight specimens cut from four blocks were exposed under each condition listed above. After 12 weeks of exposure, the specimens were cleaned of fungal mycelium, dried at 50°C, and weighed to 0.0001 g. Final dimensions were measured using a digital caliper to 0.01 mm. Specimens were then tested for flexural properties as described below.

2.7. Void volume calculations

The void volume content of reference and decayed WPC samples was calculated based on the measured density of the WPC and the theoretical densities of its components, polyethylene blend and wood. Equation (2) shown below was used for void volume calculation (Sun *et al.* 2015).

$$V_V = \frac{M_{\mathrm{WPC}}}{D_{\mathrm{WPC}}} - \frac{M_{\mathrm{WPC}}\, C_{\mathrm{W}}}{D_{\mathrm{W}}} - \frac{M_{\mathrm{WPC}}\,(1 - C_{\mathrm{W}})}{D_{\mathrm{P}}}, \qquad (2)$$

where M_{WPC} and D_{WPC} are the mass and density of the WPC, respectively; C_{W} is the mass fraction of the wood components in the sample, which was determined by extracting the plastic; while D_{W} is the theoretical density of solid wood without any voids (~1.4 g/cm^3) and D_{P} is the density of the plastic (0.92 g/cm^3) (Dow Chemical Company 1991–1992). The small amount of pigments and lubricants present were omitted in this calculation for simplification.

The relationship between the WPC calculated void volume and the void volume measured using microCT and SEM has been previously reported by Sun *et al.* (2015).

2.8. Flexural properties

Flexural properties, including modulus of rupture (MOR) and modulus of elasticity (MOE) were tested using a model 4400 Universal Testing Machine (Instron, Canton, MA) equipped with tensile/compression load cell and an environmental chamber model 3119-005 (Instron, Canton, MA).

Field-exposed samples were sawn in the same manner from randomly selected areas on the boards while keeping a record of each individual specimen's location. Seven specimens were sawn from the board cross-section with No. 1 being cut at the upper board's surface and No. 7 on the opposite side of the board. Specimens No. 2–No. 7 are referred to as "core" in this publication. Both laboratory- and field-exposed specimens for flexural evaluation were separated into two subgroups, for Dry and Wet testing, respectively. The group "Dry" was dried at 50°C to constant weight prior to flexural testing. These Dry specimens were taken from the oven in small batches and sealed in polyethylene bags prior to testing. The group "Wet" was sealed in polyethylene bags and stored in a refrigerator at about 5°C for several days before testing. For both groups, each specimen was weighed and measured immediately before and after testing at both the above mentioned temperatures. All samples were then dried at 50°C to constant weight and weight loss reported for each sample.

Flexural testing was conducted following ASTM D7032 and ASTM D790 (ASTM International 2014c, 2015). The crosshead speed was 2 mm/min and the support span 70 mm. The temperatures selected were 23°C and 52°C. The number of sample replicates used in the statistical evaluation of results varied from 5 to 30. Flexural strength was measured as stress at 3% flexural strain. Flexural modulus was measured between 10% and 40% maximum load from the stress-strain curve. Flexural results were statistically evaluated using a two tail *t*-test at 95% confidence level. Also, linear regression was performed on groups of data containing flexural strength and void volume for both laboratory and field-exposed samples. The slope, intercept and coefficient of determination (R^2), are presented on corresponding plots. The null hypothesis that the same linear regression can be used to model the behavior of various groups of samples, that is, field and laboratory samples exposed to different conditions, was tested at a .05 significance level using *p*-values generated by the linear model (lm) routine in the *R* statistical computing environment (R Core Team 2013).

3. Results and discussion

3.1. Field inspection, sample collection and fungal identification

After 28 months of field exposure (in 2007), none of the shadow and sun boards showed any obvious signs of fungal growth, but the appearance of symptoms characteristic of UV surface degradation of polymeric materials in the form of resin crazing and discoloration, as well as the initiation of WPC cracking, were observed in a limited number of boards. The development of such cracks in extruded WPC boards is known but not fully understood. One of the potential causes could be the presence of excessive internal stresses associated with manufacturing and exposure. Periodic field inspections after 40 months showed a single fruiting body of a decay fungus growing from one board at the sun location, together with progressive cracking and typical surface weathering. Further inspection a year later showed a few fruiting bodies on other boards exposed in both sun and shadow locations. Additional fungal fruiting bodies were observed with increasing exposure time, particularly after more than five years of shadow exposure.

Different degrees of board cracking were recorded, from minor fractures to total disintegration. Of the 27 composites exposed, there were 6 with decay fungal fruiting bodies and 7 with different forms of cracks present. It could be expected that cracking of WPC boards would promote water entry and the development of severe decay. Interestingly, these two features – cracking and the presence of decay fungal fruiting bodies – did not seem to be strongly connected. It is not expected that the cracking observed would affect the flexural properties described in this publication as, during the selection of boards for this study, care was taken to avoid testing of boards that showed signs of cracking.

Both cracking and decay were specific to the materials exposed. Similar products that only seemed to differ in color performed differently during exposure. A summary of the final inspection with respect to decay and cracking of exposed WPC boards is shown in Table 1.

No signs of termite activity were found at the exposure sites. Discoloration, combined with mold growth, was found

Table 1. Summary of features observed in WPC boards during field inspection after 9.5 years of exposure.

		Polyethylene		Sun			Shadow		
				Number of boards			Number of boards		
Manufacturer	Wood content	Mp (°C)	Resin type	Total exposed	Decay	Cracks	Total exposed	Decay	Cracks
A	53	112, 125	LLDPE/LDPE	6	3	1	6	3	1
B	49	132	HDPE	5	2	4	5	1	5
C	43	131	HDPE	2	–	–	2	–	–
D	48	133	HDPE	4	–	–	4	–	–
E	N/A[a]	133	HDPE	4	–	1	4	–	1
F	51	109, 124	LLDPE[b], LDPE	2	–	1	2	1	–
G	52	133	HDPE	4	–	1	4	1	1

[a]Mixture of wood and mineral filler (N/A = not applicable).
[b]LLDPE resin or mixture of LLDPE and LDPE.

on many of the exposed boards and was not altered by cleaning during this study. Biological growth, including fungal fruiting bodies, moss and lichens, was particularly distinct in the Shadow exposure. Figure 1(a–d) shows an example of some fruiting bodies of decay fungi and cracked boards that were found during this inspection.

Based on fruiting body morphology, these decay fungi were tentatively identified as including the white rot fungi *Perenniporia tephropora* and *Pycnoporus sanguineus*, as well as the brown rot fungus *Dacryopinax spathularia*. Several other fruiting bodies were sterile and could not be identified using morphological techniques. In addition, cultures grown from fruiting body tissue and wood particles were identified by DNA analysis (Table 2) and indicated that the same decay fungi were found on multiple boards in the exposure site and that fungi found on the surface, represented by fruiting bodies, were also colonizing the interiors of the boards.

Some fungi were also present in the wood but were not represented by obvious fruiting bodies and, if not for the DNA analyses, would have gone unrecorded. While some of the identified fungi are known to cause decay, the effect of the other fungi recovered in the isolations is unknown at present. *Epicoccum nigrum* is a common airborne "mold" fungus often associated with air quality issues and also is a soft rot fungus (Wang 1990). *Pestalotiopsis vismiae* is a plant pathogen that causes a leaf spot of *Leucospermum* sp. in Hawaii (Jeeson *et al*. 2004). It is unlikely that either of these fungi are causing severe degradation of the WPCs. They were probably cultured from airborne spores deposited on the exterior of the WPC samples or from saprotrophic growth on the surface of the substrate.

Laboratory evaluation of color change in sun- and shadow-exposed boards are shown in Table 3. The data indicate that relatively low surface color change, despite lengthy exposure, was observed for the boards regardless

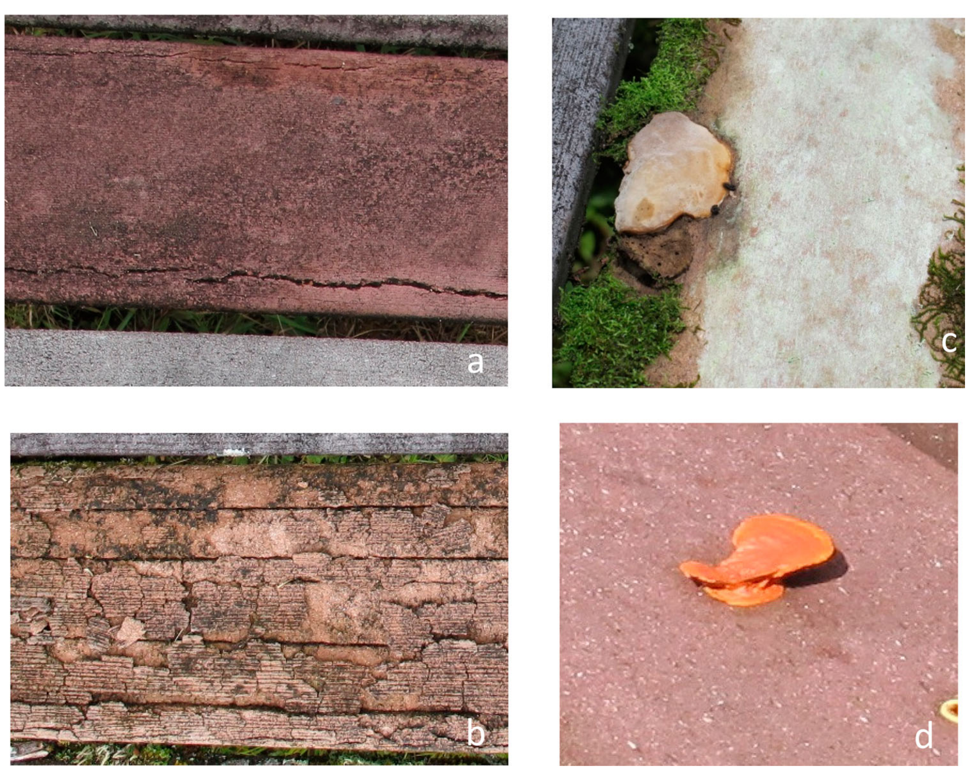

Figure 1. Examples of features developed during weathering of WPC boards near Hilo, Hawaii, for 9.5 years. (a,b) show cracks, and (c,d) show decay fungi (*Perenniporia tephropora* and *Pycnoporus sanguineus*, respectively).

Table 2. Cultures isolated from WPC decking boards exposed near Hilo, Hawaii, and identified using DNA analysis of the ITS sequence.

Taxon name	Culture number[a]	Isolated from	Manufacturer	Exposure location
Pycnoporus sanguineus	JEH-155	Interior	A[c]	*Sun*
Pycnoporus sanguineus	JEH-156	Fruiting body	A[c]	*Sun*
Perenniporia tephropora	JEH-157	Interior	A[c]	*Sun*
Perenniporia tephropora	JEH-158	Interior	A[c]	*Sun*
Stereum sp.[b]	JEH-159	Interior	A[c]	*Sun*
Unknown ascomycete[b]	JEH-160	Interior	A[c]	*Sun*
Unknown ascomycete[b]	JEH-161	Surface	A[c]	*Sun*
Unknown ascomycete[b]	JEH-162	Surface	A[c]	*Sun*
Pestalotiopsis vismiae	JEH-178	Interior	A	*Shadow*
Pycnoporus sanguineus	JEH-180	Fruiting body	A	*Shadow*
Pycnoporus sanguineus	JEH-181	Fruiting body	A	*Shadow*
Pestalotiopsis vismiae	JEH-182	Interior	A	*Shadow*
Pestalotiopsis vismiae	JEH-183	Interior	A	*Shadow*
Dacryopinax spathularia	JEH-189	Fruiting body	B	*Sun*
Epicoccum nigrum	JEH-192	Interior	A	*Sun*
Pycnoporus sanguineus	JEH-197	Interior	A	*Shadow*
Perenniporia tephropora	None	Fruiting body	F	*Shadow*
Perenniporia tephropora	None	Fruiting body	A	*Shadow*
Pycnoporus sanguineus	None	Fruiting body	A	*Sun*
Pycnoporus sanguineus	None	Fruiting body	A	*Sun*
Pycnoporus sanguineus	None	Fruiting body	A	*Shadow*

Note: Cultures are on deposit in the CFMR culture collection (http://www.fpl.fs.fed.us/search/mycology_request.php).
[a]None = DNA was isolated directly from the fruiting body.
[b]Board of interest.
[c]A closer comparison was not available in GenBank.

of exposure site. An inspection of the exposed WPC boards showed little if any signs of obvious weathering, including cracking and decay.

3.2. Characterization of the WPC boards

The unexposed reference board showed WA of 0.93% after 24-hour water immersion. Drying of the board to constant weight showed that the board lost 2.5% of its weight. This indicated 1.5% WA during storage. Increase in MC was calculated as 1.8% and 2.9%, during water immersion and storage, respectively. This indicates that wood within this board did not reach moisture equilibrium, regardless of board storage for over 8 years. After storage in a heated warehouse, the MC of most wood would be in the range of 6–8%. The average density of the WPC board was 0.922 g/cm^3. Additional data related to the MC, WA and density of the reference board can be found in earlier publications (Sun *et al.* 2014, 2015, Ibach *et al.* 2016).

Wood content analysis indicated that the WPC board collected for flexural testing contained 52.9% wood flour (Table 1). The wood flour particles had an average particle surface area of 0.046 mm^2. The average aspect ratio of the wood flour particles was measured as 3.39, which was consistent with data from literature (Klyosov 2007). The ash content of the board was 1.9% at both 675°C and 900°C, which was likely associated with small quantities of wood inorganic compounds and pigment added by the manufacturer. Due to the small quantities of inorganic content detected, they were omitted from subsequent void content calculations. Other boards decayed during exposure were made with wood content of 49% to 53% as shown in Table 1.

Analysis of FTIR spectrum showed that the thermoplastic resin used as the polymer matrix in the board was identified as polyethylene. The DSC thermogram showed resin melting temperature (Mp) peaks of 112°C and 125°C (Table 1). This is consistent with a blend of low density and linear low density polyethylene resins. These types of resins have an average density in the range 0.916–0.925 g/cm^3 (Dow Chemical Company 1991, Klyosov 2007). Based on this, a density of 0.920 g/cm^3 was used for the polyethylene blend in the void volume calculations. This calculated void volume was found to be 17.2% for the unexposed reference board.

Specimens with different geometry cut from the same WPC reference board material and tested with and without conditioning showed different weight losses after 12 weeks of fungal exposure (Figure 2). The relative weight loss of the specimen and its related wood weight loss were significantly larger for flexural test bars (4 × 15 × 86 mm^3) in comparison to earlier tested specimens that were cut to the standard size of 19 × 19 × 19 mm^3 (Sun *et al.* 2015) as required by the AWPA E10 standard (2013). Comparison of wood weight loss

Table 3. Color measurements for unexposed reference boards and boards exposed in the field for 9.5 years.

		L		*a*		*b*		*ΔE*	
Description	Surface	Avg	SD	Avg	SD	Avg	SD	Avg	SD
Reference	N/A	**36.74**	N/A	**7.97**	N/A	**8.46**	N/A	**N/A**	N/A
Sun	Top	**32.69**	1.67	**7.80**	0.16	**6.42**	0.08	**3.55**	0.48
	Bottom	**37.28**	1.42	**7.89**	0.10	**8.66**	0.15	**0.80**	0.17
Shadow	Top	**31.34**	0.95	**8.12**	0.18	**6.34**	0.27	**4.30**	0.36
	Bottom	**40.21**	0.86	**7.43**	0.08	**8.64**	0.35	**2.13**	0.64

Note: N/A = not applicable.

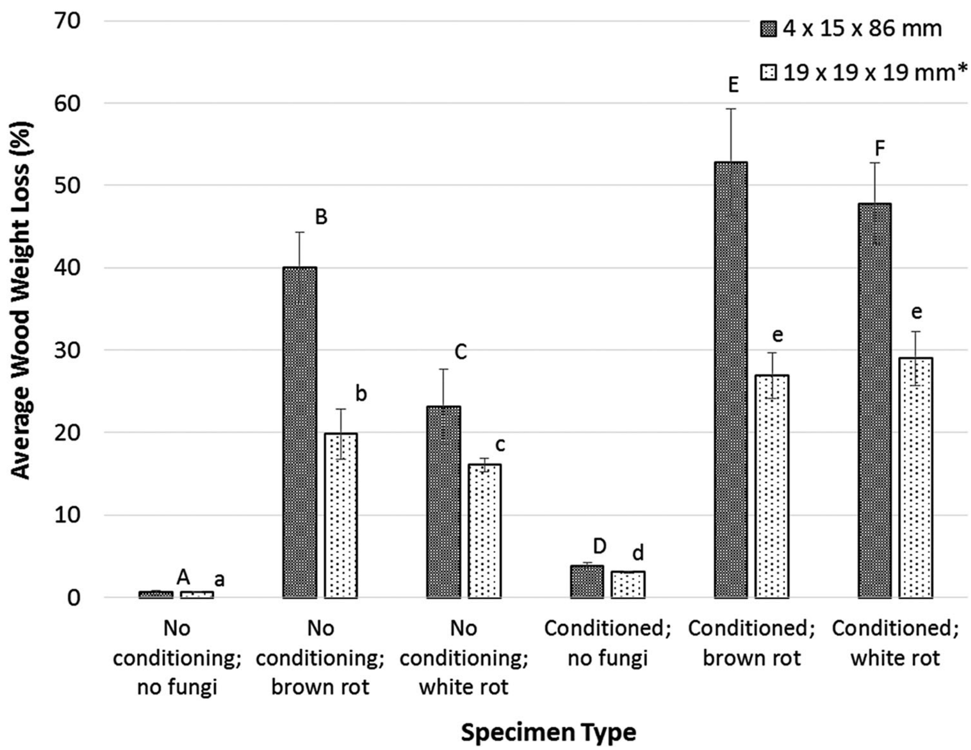

Figure 2. Wood weight loss – effect of conditioning, fungi species, specimen size and geometry; bars with the same letters (case-sensitive) are statistically similar based on a *t*-test at 95% confidence. *All data for $19 \times 19 \times 19$ mm^3 specimens are from previously published research (Sun *et al.* 2015).

between these groups of samples indicated that small weight losses (under 4%) similar for both groups were observed for unconditioned and conditioned specimens placed in bottles without the inoculation of fungi. This weight loss could be attributed to extractive leaching. The introduction of decay fungi resulted in significant weight loss in the tested samples, which is exclusively associated with wood weight loss as polyethylene seems to be resistant to brown or white fungi attack (Schirp *et al.* 2008). Standard, cube shaped samples that were exposed to fungi without conditioning showed a total weight loss of 8.5% and 10.5% for white and brown rot fungi, respectively, corresponding to an average of 16.1% and 19.9% wood weight loss (Sun *et al.* 2014). These results can be compared to the weight loss in the longer flexural bar specimens, which showed a notably larger total weight loss of 12.3% and 21.2% for white and brown rot fungi, corresponding to 23.1% and 40.0% wood weight loss; much higher than the cubes. Even larger weight losses were observed for conditioned flexural bar samples, where the total weight loss was as high as 28% and wood weight loss exceeded 50% when exposed to a brown rot fungus. A comparison of the results of soil block culture tests conducted at different times and using different geometries should be conducted with caution, but the observed differences are very obvious. These differences are expected because of the higher surface to volume ratio and geometry of the flexural bars, which may enhance WA, creating a favorable environment for fungal growth.

Wood weight losses for conditioned laboratory flexural bar samples that were exposed to decay fungi were in the range of 47% to 52% (Table 4). In comparison, the wood weight loss of field-exposed samples is shown in Tables 5–7. Overall wood weight loss was larger in the core than in the surface layers for both shadow and sun exposures (Table 5).

Significant variability between field samples was observed, particularly when sun-exposed surface specimens were compared. Some of the individual surface specimens cut from the sun-exposed board that were tested at the Dry conditions (23° C) had a lower average wood weight loss of only 23.7% with individual specimens varying between 14.0% to 39.6% (Table 7). The core of sun-exposed samples showed higher wood weight loss averages, ranging from 36.8% to 63.8%, depending on the location within the board and associated test conditions (Table 6). It was also found that the highest wood losses occurred on the side of the board opposite to the sun-exposed surface.

Wood weight loss analysis indicated that the severity of decay for conditioned laboratory flexural bar specimens and those cut from the core of field-exposed boards were of the same magnitude, while unconditioned laboratory flexural bar samples exposed to fungi showed significantly lower wood weight loss in the range of 23–40.0%, depending on the type of fungi used.

3.3. Flexural properties of laboratory samples

The MOR and MOE for laboratory samples are shown in Table 8. The linear regression analysis showed that MOE had a linear correlation to the MOR for the field and laboratory non-decayed and decayed samples tested. The regression line (not shown in publication) had an R^2 value of .94. For this reason, only the MOR data are analyzed in this publication, but conclusions drawn also apply to MOE. It could be expected that three factors contributed to flexural

Table 4. Composite properties of laboratory samples.

Sample type	Description	Number of samples	Wood weight loss (%)		Final dry density (g/cm^3)		Void volume (%)		MC after soil block test (%)	
			Average	*SD*	Average	*SD*	Average	*SD*	Average	*SD*
Reference[a]	Unconditioned	14	**0.00**	*0.00*	**0.931**	0.009	**17.2**	*0.8*	N/A	
	Conditioned	28	**3.16**	*0.58*	**0.883**	0.016	**20.9**	*1.4*		
Soil block tested[b]	Unconditioned; no fungi	28	**0.62**	*0.22*	**0.905**	0.014	**19.4**	*1.2*	**28.32**	*6.21*
	Unconditioned; brown rot	28	**40.02**	*4.29*	**0.742**	0.028	**28.1**	*1.3*	**37.02**	*10.87*
	Unconditioned; white rot	28	**23.14**	*4.55*	**0.811**	0.811	**24.2**	*2.1*	**42.77**	*7.05*
	Conditioned; no fungi	28	**3.87**	*0.38*	**0.848**	0.015	**23.9**	*0.4*	**32.93**	*8.97*
	Conditioned; brown rot	28	**52.81**	*6.47*	**0.642**	0.037	**36.2**	*2.1*	**51.67**	*19.13*
	Conditioned; white rot	28	**47.77**	*4.91*	**0.644**	0.029	**36.6**	*0.9*	**59.41**	*11.27*

[a]These reference laboratory samples were not inserted in soil block bottles.
[b]These samples were inserted into soil block bottles, with and without the inoculation of fungi, as specified in the description.

properties in WPC degraded by fungi: the presence of moisture, creation of micro-voids in the plastic matrix (due to stresses from wood expanded by moisture), and wood decay. In fact, the collected data confirmed a significant decrease in the composite's flexural properties just due to contact with moisture in the soil block test bottles. The flexural strength decreased for the reference as well for unconditioned, non-inoculated controls from 12.6 (for reference) to 9.8 and 8.2 MPa for Dry and Wet room temperature (RT) test conditions, respectively. This revealed the impact of moisture from the soil block test likely associated with wood plasticization and destruction by water of the bonds between wood and plastic. Also, the development of some new microvoids under these conditions was observed with an increase in void volume from 17.2% to 19.4% as shown in Table 4.

Exposure of the polyethylene matrix to long term stresses between expanding wood particles may create microvoids, in the form of microcracks in the plastic matrix. This process of slow crack growth (SCG) in polyethylene resins has been analyzed extensively (Brown 2007, Riemslag 1997). Sample conditioning conducted at elevated (70°C) water temperature greatly accelerated SCG. This acceleration also occurred in the field, where a sunlight absorbing surface could exceed 70°C. Such SCG cracks were most likely responsible for the observed induction time in decay development during of WPC field exposure (Ibach *et al*. 2013).

A similar exposure study using 19 mm cubes rather than flexural bars (Sun *et al*. 2015), reported an increase in void content of only 17.7%, a difference emphasizing the important effect of WA dynamics and their influence on WPC properties. WPC flexural bars in 70°C water for 5 days further reduced the flexural strength to 8.0 and 6.7 MPa for Dry and Wet RT test conditions, respectively. After insertion of conditioned samples in soil test bottles without fungi for 12 weeks, the flexural strengths of the bars tested at RT in Dry (6.8 MPa) and Wet (6.4 MPa) conditions were not statistically different. These results were similar to the conditioned only (no bottle insertion) samples tested at conditions discussed earlier. A study on void creation in WPC during exposure to moisture from conditioning and soil block testing was previously published (Sun *et al*. 2015). The calculated void volume for the tested samples is shown in Table 4.

Table 5. Overall wood weight loss of field samples (core and surface).

Description	Location of samples	Number of samples	Overall wood weight loss (%)	
			Average	SD
Shadow	Surface	8	31.74	16.65
	Core	48	50.85	11.05
Sun	Surface	8	19.37	11.25
	Core	48	57.26	19.54

Elevated temperature (52°C) testing showed a further decrease in the flexural properties of conditioned and unconditioned WPC samples. Reference unconditioned samples had a flexural strength of 7.7 MPa. Conditioned samples inserted into soil test bottles without fungal inoculation showed a flexural strength of 3.9 MPa regardless of testing in Dry or Wet conditions at 52°C.

Linear regression analysis was used to study the relationship between flexural strength and void volume change in the WPC samples when subject to different exposure conditions without the presence of fungi. In Figure 3, four linear regression lines applied to data are distinct on the graph; each line is associated with a particular flexural testing condition. For three of these lines, R^2 values were in the range of .92–.99. For the regression line representing Wet samples tested at RT (23°C), the R^2 was lower at .73, due to slightly larger data distribution. Regression lines (1) and (2) represent test points for samples tested dry at different temperatures and these lines are relatively parallel. Similarly, the two other regression lines (3) and (4) both representing samples tested wet at RT and 52°C also appear to be parallel. Another interesting observation is that lines (1) and (3) and lines (2) and (4), with each pair representing different testing temperatures, meet together at a similar void volume content of about 24%. It may be possible that 24% is the highest void volume content that can be reached for tested WPCs subject to the applied exposure conditions without decay fungi activity, and a wet/dry cycle does not introduce a significant amount of new microcracks during the experiment.

Exposure to fungi further decreased the flexural properties of samples containing moisture introduced during conditioning as shown in Table 8. Samples exposed to brown rot fungi exhibited a greater decrease than those exposed to white rot fungi. For example, the flexural strength measured Dry at 23°C for unconditioned samples was at 5.5 and 8.5 MPa for brown and white rot samples, respectively. For corresponding conditioned samples, the flexural strength was found to be 3.3 and 4.1 MPa, respectively. For conditioned samples tested Wet at RT, similar flexural strengths were achieved for both brown and white rot, at 3.3 and 3.2 MPa, respectively.

Table 6. Field samples (core) – composite properties based on samples #2–7 only.

			Wood weight loss (%)		Final dry density (g/cm^3)		Void volume (%)	
Description	Test condition	Number of samples	Average	SD	Average	SD	Average	SD
Shadow	Dry RT	30	**50.83**	*10.79*	**0.673**	*0.053*	**33.52**	*3.76*
	Dry 52°C	6	**57.00**	*6.02*	**0.643**	*0.029*	**35.63**	*2.18*
	Wet RT	6	**47.97**	*14.78*	**0.687**	*0.072*	**32.59**	*5.10*
	Wet 52°C	6	**47.57**	*9.61*	**0.688**	*0.047*	**32.36**	*3.32*
Sun	Dry RT	30	**63.84**	*11.64*	**0.614**	*0.06*	**37.90**	*4.28*
	Dry 52°C	6	**62.23**	*21.89*	**0.617**	*0.107*	**37.90**	*7.61*
	Wet RT	6	**36.82**	*25.27*	**0.741**	*0.123*	**29.22**	*8.17*
	Wet 52°C	6	**44.46**	*26.62*	**0.704**	*0.130*	**31.79**	*8.62*

Elevated temperature tests conducted at 52°C showed a further decrease in the flexural properties of WPC bars exposed to decay. For example, conditioned brown rot samples had flexural strengths of only 2.1 and 1.3 MPa when tested in Dry and Wet conditions. For these samples, the flexural modulus was found to be 112 and 57 MPa, respectively.

To determine if a single linear regression is sufficient to model the behavior for conditioned or unconditioned WPC samples, regardless of exposure to either fungal species or no fungi, linear regression analysis was performed on the data relating flexural properties to void volume content. Previous research determined that WPC exposed to different fungal species would develop different void volumes and sizes (Sun *et al*. 2014, 2015). All of the applicable 42 individual test data belonging to the six test groups with unconditioned and conditioned samples exposed to white- and brown-rot under Dry conditions at RT were used to construct the graph in Figure 4. The individual test results for each group are averaged and presented in Table 8. There were two regression lines constructed with R^2 values of .87 (line No. 1) for unconditioned specimens and $R^2 = .92$ (line No. 2) for conditioned specimens to fit these data. These regression lines seem to be characteristic for the composite tested.

To confirm the proposed approach to data analysis, the other tested sets of samples were analyzed with respect to the dependence of flexural strength on void volume. Figure 5 contains corresponding regression lines of WPC samples that were conditioned and unconditioned and tested Dry at RT and 52°C. For clarity, individual data points were not shown in the graphs. The fit of the points is represented by the coefficients of determination for the regression lines that are shown together with line equations on the graph.

In Figure 5, the regression lines for unconditioned samples showed larger slopes and usually ended in contact with lines constructed based on data for conditioned specimens. Also, it appears that if regression lines for conditioned samples were to be extended to intersect the x-axis, it would occur at a point where the void volume is about 50%, which happens when the wood content is 0% (data not shown). If the observed relationship between flexural strength and void volume is still valid in the region of 50% void volume, then mechanical disintegration of the composite before testing may be expected when all wood becomes completely digested by fungi.

3.4. Flexural properties of field samples

Flexural strength and modulus for field-exposed samples are shown in Tables 9 and 10 and in Figures 6(a,b) and 7. A comparison of flexural properties of unexposed (Reference) WPC board and decayed boards exposed in sun and shadow both showed a decrease compared to the Reference. The average MOR and MOE for the unexposed board tested dry at RT was 12.6 and 854 MPa (Table 8) vs. 3.5 and 170 MPa, respectively, for the sun-exposed board and 4.8 MPa and 255 MPa for the Shadow-exposed boards. The reductions in the performance of the exposed boards could be explained by the average of about 60% wood loss due to decay for the core samples that were exposed in the sun location and about 50% for those exposed in Shadow. Testing temperature, as would be expected, influenced the flexural properties of WPC decayed. For sun exposure, flexural strength decreased from about 3.5 MPa to 2.4 MPa and flexural modulus from 170 to 138 MPa with temperature increase to 52°C. The presence of moisture during testing did not affect

Table 7. Field sample (surface) properties measured at Dry RT conditions for sample #1 only.

		Wood weight loss (%)		Final dry density (g/cm^3)		Void volume (%)	
Description	Number of samples	Average	SD	Average	SD	Average	SD
Shadow-1	1	**42.64**	*N/A*	**0.712**	*N/A*	**30.61**	*N/A*
Shadow-7	1	**22.83**	*N/A*	**0.809**	*N/A*	**24.38**	*N/A*
Shadow-8	1	**21.49**	*N/A*	**0.815**	*N/A*	**23.99**	*N/A*
Shadow-9	1	**27.07**	*N/A*	**0.788**	*N/A*	**25.65**	*N/A*
Shadow-10	1	**30.10**	*N/A*	**0.773**	*N/A*	**26.58**	*N/A*
Shadow-average	5	**28.85**	*8.48*	**0.780**	*0.041*	**26.25**	*2.66*
Sun-1	1	**39.56**	*N/A*	**0.727**	*N/A*	**29.60**	*N/A*
Sun-7	1	**22.83**	*N/A*	**0.809**	*N/A*	**24.38**	*N/A*
Sun-8	1	**14.03**	*N/A*	**0.852**	*N/A*	**21.86**	*N/A*
Sun-9	1	**22.60**	*N/A*	**0.810**	*N/A*	**24.32**	*N/A*
Sun-10	1	**19.48**	*N/A*	**0.825**	*N/A*	**23.40**	*N/A*
Sun-average	5	**23.70**	*9.55*	**0.805**	*0.046*	**24.71**	*2.91*

Table 8. Laboratory samples – flexural properties.

Sample type	Description	Test condition	WA during flexural testing (%)		MC during flexural testing (%)		Strength, MOR (MPa)		Modulus, MOE (MPa)	
			Average	SD	Average	SD	Average	SD	Average	SD
Reference[a]	Unconditioned	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**12.6**	*1.0*	**854**	*122*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**7.7**	0.8	**483**	71
	Conditioned	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**8.0**	*0.6*	**346**	*67*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**4.6**	0.4	**206**	20
		Wet RT	**39.46**	*1.93*	**76.74**	*3.74*	**6.7**	*0.3*	**353**	*22*
		Wet 52°C	**32.78**	*0.44*	**63.57**	*0.70*	**4.4**	0.4	**302**	56
Soil block tested[b]	Unconditioned; no fungi	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**9.8**	*0.6*	**637**	*45*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**6.1**	*1.1*	**358**	*85*
		Wet RT	**17.78**	*1.15*	**33.85**	*2.23*	**8.2**	*1.0*	**423**	*157*
		Wet 52°C	**15.90**	*0.63*	**30.23**	*1.21*	**4.7**	*0.5*	**305**	*40*
	Unconditioned; brown rot	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**5.5**	*0.6*	**306**	*44*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**3.7**	*0.9*	**203**	*53*
		Wet RT	**14.88**	*0.84*	**46.85**	*3.65*	**4.4**	*0.7*	**248**	*42*
		Wet 52°C	**12.59**	*1.02*	**39.37**	*4.73*	**2.3**	*0.2*	**117**	*12*
	Unconditioned; white rot	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**8.5**	*1.1*	**541**	*80*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**5.2**	*0.9*	**314**	*66*
		Wet RT	**18.96**	*1.66*	**46.79**	*3.24*	**6.1**	*1.2*	**356**	*90*
		Wet 52°C	**16.90**	*1.75*	**42.65**	*2.10*	**3.4**	*0.3*	**196**	*26*
	Conditioned; no fungi	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**6.8**	*0.6*	**361**	*45*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**3.9**	*0.8*	**185**	*46*
		Wet RT	**20.69**	*0.40*	**40.77**	*0.69*	**6.4**	*0.7*	**444**	*59*
		Wet 52°C	**18.83**	*0.68*	**37.07**	*1.29*	**3.9**	*0.5*	**256**	*40*
	Conditioned; brown rot	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**3.3**	*0.7*	**160**	*38*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**2.1**	*0.5*	**112**	*30*
		Wet RT	**17.77**	*2.51*	**63.99**	*6.56*	**3.3**	*0.3*	**175**	*18*
		Wet 52°C	**14.77**	*3.06*	**63.00**	*13.91*	**1.3**	*0.3*	**57**	*22*
	Conditioned; white rot	Dry RT	**<0.5**	*<0.1*	**<1**	*<0.15*	**4.1**	*0.6*	**230**	*37*
		Dry 52°C	**<0.5**	*<0.1*	**<1**	*<0.15*	**2.5**	*0.4*	**131**	*22*
		Wet RT	**17.66**	*1.32*	**63.18**	*6.27*	**3.2**	*0.5*	**156**	*31*
		Wet 52°C	**16.03**	*0.89*	**58.37**	*2.87*	**2.1**	*0.1*	**100**	*13*

[a]These reference laboratory samples were not inserted in soil block bottles.
[b]These samples were inserted into soil block bottles, with and without the inoculation of fungi, as specified in the description.

the flexural properties of the field decayed WPC, which is similar to what was seen in the conditioned laboratory samples for the composites with similar wood content. This was confirmed by a comparison of Shadow-exposed samples tested Wet and Dry at RT where flexural strength and modulus were statistically similar, 4.8 vs 4.7 MPa and

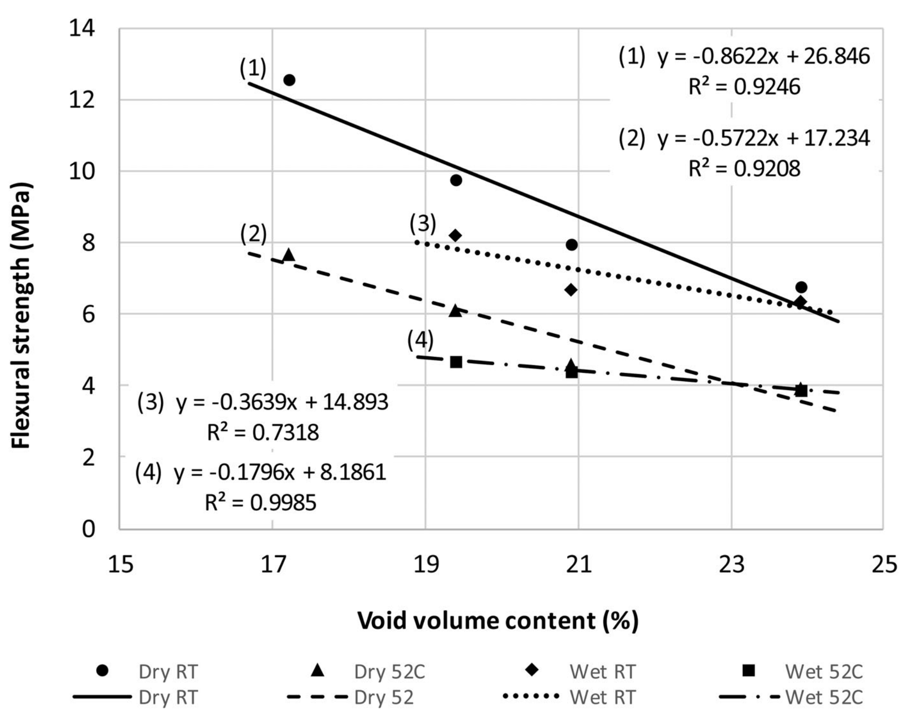

Figure 3. The relationship between flexural strength and void volume content for unconditioned and conditioned laboratory samples with and without insertion into soil block bottles, tested at four different conditions. No decay fungi were present in the tests.

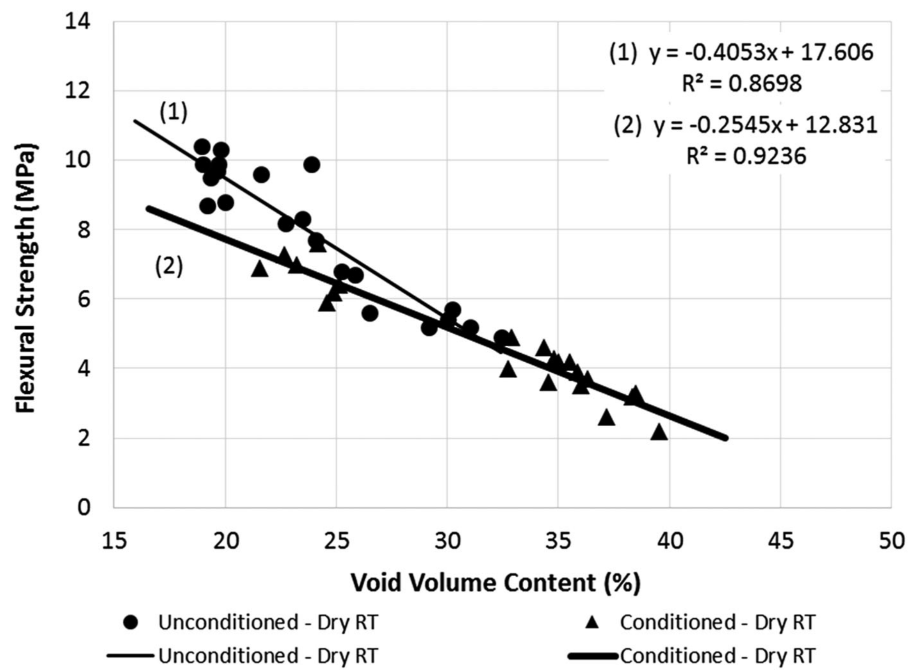

Figure 4. Laboratory samples conditioned and unconditioned and exposed to decay fungi – flexural strength versus void volume content – linear regression analysis with experimental data.

255 vs 269 MPa for Dry (MC < 1.5%) and Wet samples (MC ~28%), respectively.

Wood loss and the decrease in flexural properties were not uniform through the thickness of the exposed board. A decrease in flexural properties observed in both sun and shadow-exposed boards was significant with increased distance from the board's upper (sun-exposed) surface, with maximum strength near the upper surface and minimum flexural strength and modulus on the opposite side. For example, the sun-exposed set of specimens cut from the board upper surface (#1 group) showed an average MOR 5.5 MPa (tested Dry at RT) vs. only about 2.8 MPa for #5, #6 and #7 groups of specimens from the opposite side of the board (Figure 6 (a)). A similar trend was also observed for the shadow-

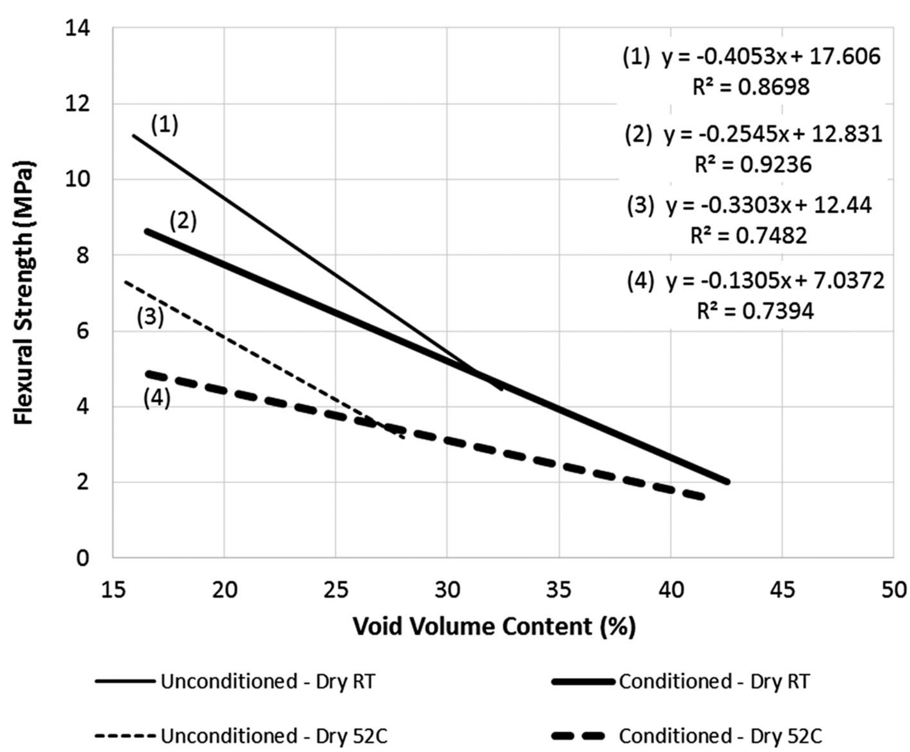

Figure 5. Laboratory samples conditioned and unconditioned and exposed to decay fungi – linear regression analysis for flexural strength versus void volume content – samples tested dry at RT and 52°C.

Table 9. Field samples (core) – flexural properties based on samples #2–7 only.

			WA during flexural testing (%)		MC during flexural testing (%)		Strength, MOR (MPa)		Modulus, MOE (MPa)	
Description	Test condition	Number of samples	Average	SD	Average	SD	Average	SD	Average	SD
Shadow	Dry RT	30	**0.31**	*0.12*	**1.28**	*0.58*	**4.8**	*1.0*	**255**	*66*
	Dry 52°C	6	**−0.01**	*0.01*	**−0.05**	*0.03*	**2.1**	*0.3*	**115**	*25*
	Wet RT	6	**7.68**	*2.27*	**28.02**	*3.00*	**4.7**	*1.2*	**269**	*79*
	Wet 52°C	6	**6.63**	*0.61*	**24.48**	*4.39*	**4.7**	*1.2*	**146**	*39*
Sun	Dry RT	24–30[a]	**0.32**	*0.12*	**1.79**	*0.85*	**3.5**	*1.0*	**170**	*65*
	Dry 52°C	6	**N/A**	*N/A*	**N/A**	*N/A*	**2.4**	*1.3*	**138**	*92*
	Wet RT	6	**11.64**	*1.31*	**40.63**	*17.50*	**5.3**	*2.7*	**317**	*166*
	Wet 52°C	6	**9.64**	*2.89*	**36.80**	*14.53*	**3.1**	*1.4*	**169**	*95*

[a]WA and MC are based on 24 samples while flexural strength and modulus values are based on 30 samples.

Table 10. Field samples (surface) tested at Dry RT conditions – flexural properties based on sample #1 only.

		WA (%)		MC (%)		Strength, MOR (MPa)		Modulus, MOE (MPa)	
Description	Number of samples	Average	SD	Average	SD	Average	SD	Average	SD
Shadow-1	1	0.45	*N/A*	1.48	*N/A*	4.3	*N/A*	219	*N/A*
Shadow-7	1	0.24	*N/A*	0.59	*N/A*	6.2	*N/A*	313	*N/A*
Shadow-8	1	0.18	*N/A*	0.44	*N/A*	5.1	*N/A*	221	*N/A*
Shadow-9	1	0.19	*N/A*	0.50	*N/A*	5.1	*N/A*	254	*N/A*
Shadow-10	1	0.19	*N/A*	0.52	*N/A*	4.8	*N/A*	217	*N/A*
Shadow-average	5	0.25	*0.11*	0.71	*0.44*	5.1	*0.7*	245	*41*
Sun-1[a]	1	N/A	*N/A*	N/A	*N/A*	3.1[a]	*N/A*	134[a]	*N/A*
Sun-7	1	0.24	*N/A*	0.58	*N/A*	6.1	*N/A*	298	*N/A*
Sun-8	1	0.20	*N/A*	0.45	*N/A*	6.8	*N/A*	377	*N/A*
Sun-9	1	0.20	*N/A*	0.50	*N/A*	6.0	*N/A*	311	*N/A*
Sun-10	1	0.22	*N/A*	0.51	*N/A*	5.7	*N/A*	289	*N/A*
Sun-average	4	0.22	*0.02*	0.51	*0.05*	6.2	*0.5*	319	*40*

[a]Sample excluded due to defect.

exposed board. The results were surprising because there is an expectation that the upper board surface would be more susceptible to decay due to its much more severe exposure to atmospheric moisture in the form of rain and dew. This may be explained by the less favorable conditions for fungal growth near the upper board surface due to more rapid cyclic moisture variability and a higher than optimal temperature. These results may bring into question the expectation that the application of a co-extruded cap covering the upper side of some deck boards would not only help with maintaining appearance, but also eliminate the risk of WPC decay in field exposure.

Linear regression analysis was conducted for the flexural strength results obtained for all (sun and shadow) field decayed WPC samples tested Dry at RT. For this analysis, the data for samples sawn from the board surface exposed to sun radiation were excluded due to the potential photo-degradation. Also, 2 samples out of 60 were excluded as outliers after examination due to material defects. Figure 7 shows the relationship between void content and flexural strength of field decayed WPC. The first regression line represents all field analyzed samples from both sun and shadow exposures. The second line was obtained by analysis of data associated with laboratory tested samples shown earlier in Figure 4. The R^2 value calculated for field decayed samples (.77) was lower in comparison to the R^2 value for laboratory conditioned and decayed samples (.92), indicating more variability in the data related to field specimens. Despite this difference in variability, the equations of the regression lines are similar indicating that the flexural properties of the laboratory conditioned and decayed samples may be used to predict the flexural properties of field-exposed and aged as well as decayed composite, regardless of the difference in fungi species colonizing the WPC. On the other hand, the regression analysis of data related to the laboratory samples exposed to decay fungi without conditioning (not shown on the graph) was not a good fit for the data of field-exposed samples. Also, this regression line ended at much lower void volume than that observed in the field samples.

3.5. UV-induced photo-degradation

The data obtained during testing of the field-exposed WPC samples allowed the effect of UV induced photo-degradation on flexural properties of the composite to be evaluated. The impact of photo-degradation is shown in Figure 8 where the data representing sun-exposed surface specimens are shown together with the linear regression analysis applied to data representing flexural strength and void volume of sun (core) exposed samples. Data from the flexural bars cut from the sun-exposed board surface fits well in the regression line constructed for the core samples. This indicated that UV photo-degradation had a relatively small impact (if any) on the flexural properties of the surface specimens. An even lower impact would be expected if a full size deck board would be tested, as the UV degraded zone would represent an even smaller portion of the whole board cross-section. To explain this limited effect of UV radiation on flexural properties of WPC, further testing was conducted. A randomly selected board surface region that had been exposed to sun radiation was analyzed for carbonyl index using FTIR spectroscopy. The measured carbonyl index values with the

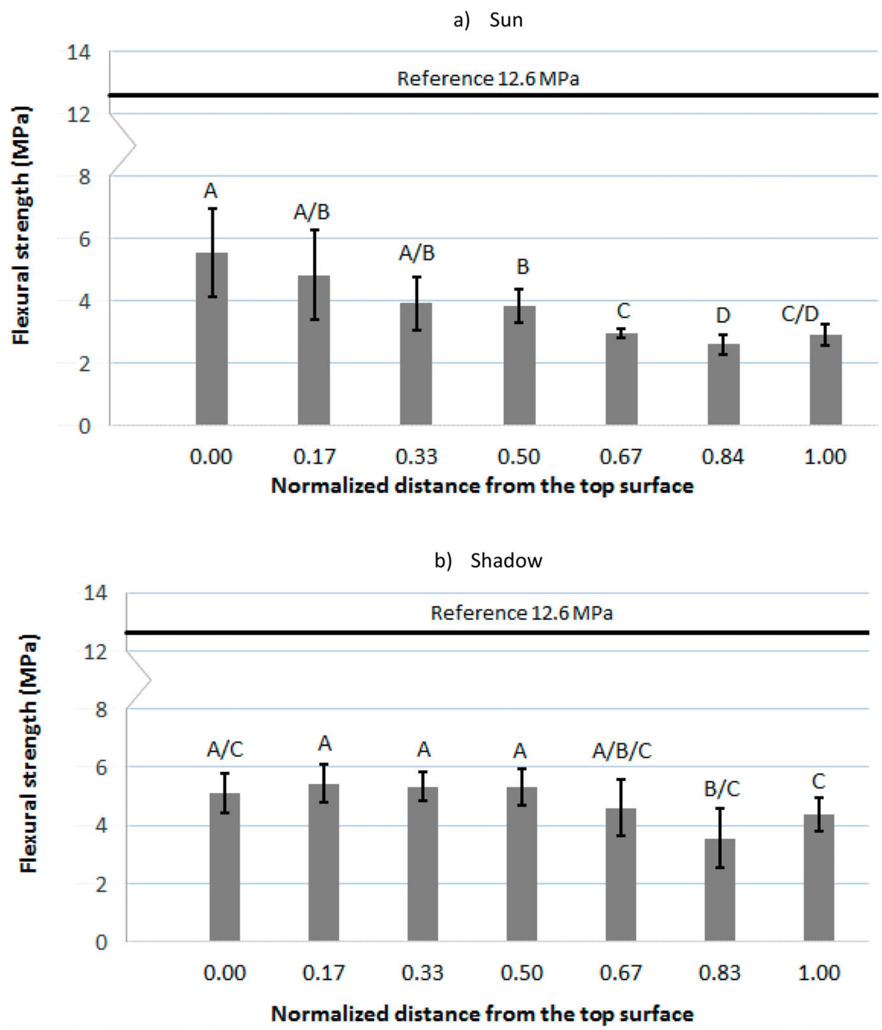

Figure 6. Sun and shadow samples tested dry at RT – flexural strength versus normalized distance from the top surface; bars with the same letters are statistically similar based on a *t*-test at 95% confidence.

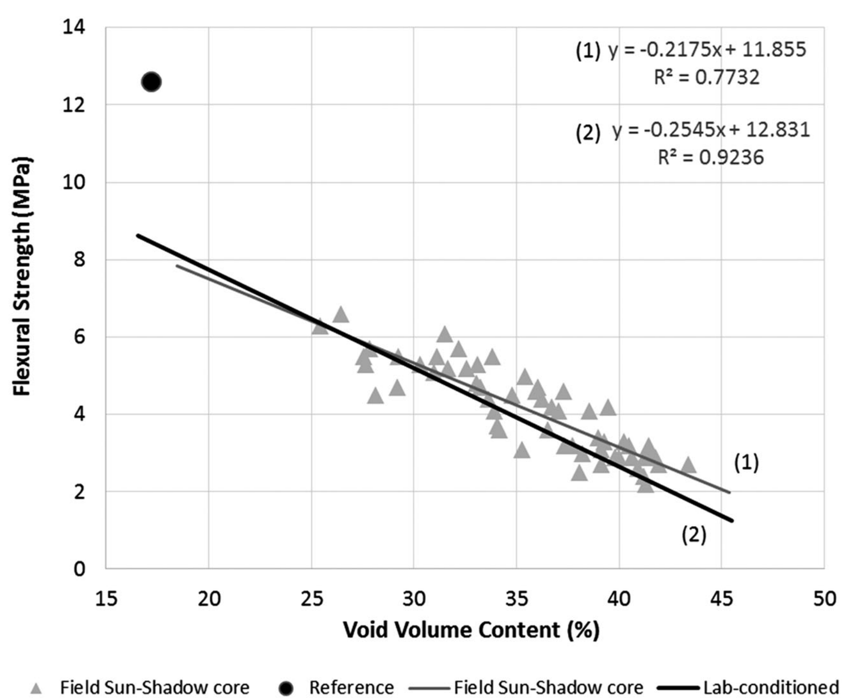

Figure 7. Field samples (core) tested dry at RT – flexural strength versus void volume content, shown with regression line for conditioned laboratory samples (black) and test points with regression line for sun and shadow field samples (gray). The flexural strength for the reference unconditioned sample is also shown.

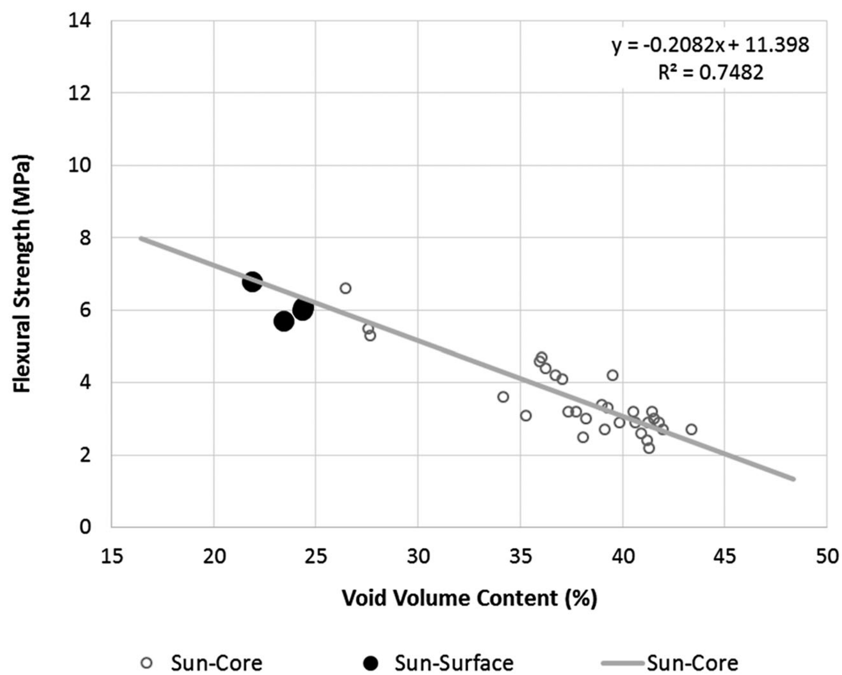

Figure 8. Sun samples tested dry at RT – flexural strength versus void volume, comparison of surface and core specimens.

distance from the board surface are shown in Figure 9. At the surface, the carbonyl index measured 21.2. At a distance of 0.10 mm from the surface, it was reduced by almost half to 14.2 and at a distance of 0.73 mm, it was only 3.0. This was close to the threshold of the carbonyl index, which was measured as 2.9 in the center of the board. A statistical evaluation of the carbonyl index data indicated that photo-oxidation in WPC was similar for samples taken at 0.73 mm below the board surface and deeper. As can be seen, the carbonyl index decreased quickly with the increasing distance from the surface, regardless of almost 10 years exposure of the tested samples in tropical conditions. Similar results, with very shallow UV induced degradation, have been reported in the past where photo-oxidation in the board cross-section in the vicinity of the surface of the laboratory weathered WPC sample, made without UV absorbing pigments and stabilizers, was tested using Raman spectroscopy (Gnatowski *et al*. 2007). However, UV radiation from the sun may have a significant effect on the exposed surface appearance related to material discoloration (Ebe and Sekino 2015)

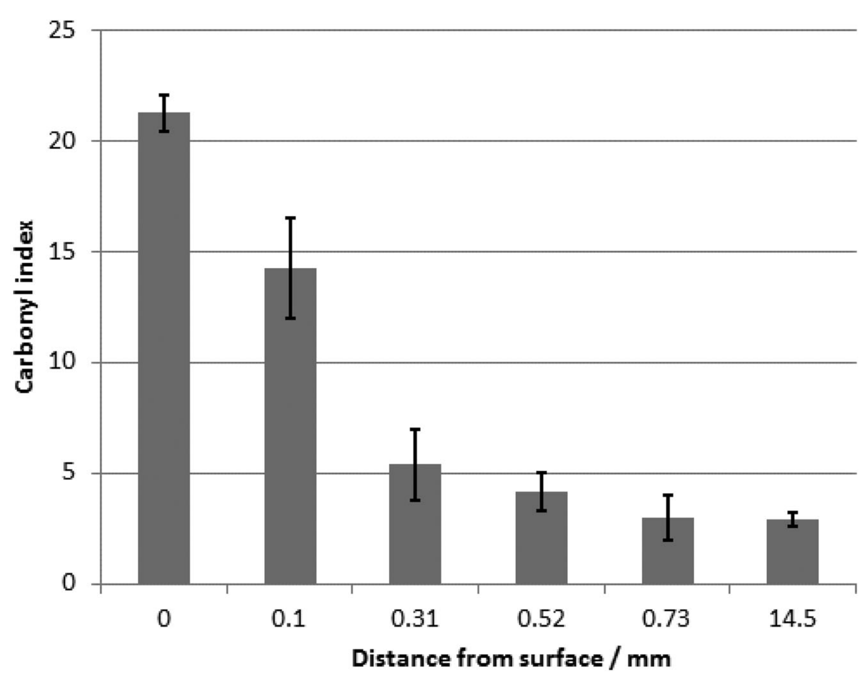

Figure 9. Carbonyl index versus distance from the sun board surface.

or when the WPC surface is exposed simultaneously to UV and wear (Gnatowski *et al*. 2007).

4. Conclusions

The major factors degrading the mechanical properties of the tested composite under field exposure conditions detected were elevated temperature and moisture exposure followed by fungal wood decay; UV radiation from the sun had a low impact, if any, on the flexural properties of a WPC board exposed for almost 10 years. Flexural strength versus void content for laboratory samples without fungal exposure and samples exposed to different species of fungi followed similar regression lines. In contrast, statistically different regressions were obtained between samples that were not conditioned and those that were conditioned in hot water prior to exposure to fungi. Regression analysis of combined data from field-exposed core samples (sun and shadow) and combined data from laboratory conditioned samples (no fungi, white and brown rot exposure) showed that the data could be represented by the same regression line, regardless of any difference in the species of wood decaying fungi colonizing the field and laboratory samples. However, the data obtained for field and laboratory aged samples without conditioning followed statistically different regression lines.

The mechanism of the aging process on colonization of WPC by fungi was examined and is consistent with the development of SCG in the polyethylene matrix combined with wood decay by fungi. These results question the efficiency of accelerated aging procedures conducted without conditioning or conditioning by the immersion of full size WPC deck boards in RT water, which is not sufficient for the SCG process to develop. This study demonstrated that, in order to simulate the long-term field impact (including SCG and decay) on WPC flexural properties in the laboratory, conditioning of specimens in hot water for an extended period of time is required. Conditioning used for $4 \times 15 \times 86\ mm^3$ specimens that were exposed to water at 70°C for 5 days was adequate to simulate long-term composite exposure in Hawaii.

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Disclosure statement

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