EFFECT OF WOOD SPECIES ON WATER SORPTION AND DURABILITY OF WOOD–PLASTIC COMPOSITES

Jae-Woo Kim
Postdoctoral Research Associate

David P. Harper
Assistant Professor

*Adam M. Taylor**†
Assistant Professor
Tennessee Forest Products Center
Department of Forestry, Wildlife and Fisheries
University of Tennessee
Knoxville, TN 37996

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Abstract. Wood–plastic composites (WPCs) were made from isotactic polypropylene and 10 wood species (8 hardwoods and 2 softwoods). Water sorption and durability of the composites were evaluated. WPCs made with eastern redcedar and Osage orange had low moisture sorption characteristics, lower levels of fungal decay, and increased resistance to mold compared with composites made from other species. The color of the composites was initially quite different, reflecting the differences in color of the various wood species, but after outdoor exposure, the samples were similar in appearance. Metals in contact with WPCs corroded during accelerated exposure and the corrosion of galvanized steel was greatest when in contact with WPCs made from southern pine and black walnut. WPCs made from hickory, sweet gum, black cherry, and red oak corroded ordinary steel more than composites containing other species. These results demonstrate that the inherent characteristics of the wood filler can affect the properties of WPCs. The use of durable wood species in WPCs could result in products with improved durability performance.

Keywords: Wood–plastic composites, water sorption, fungal durability, mold susceptibility, color change, metal corrosion.

INTRODUCTION

Wood–plastic composites (WPCs) combine the low cost and light weight of a wood filler with the processability of a thermoplastic polymer matrix. Since their appearance in the market, WPCs have been increasingly used in exterior applications, including decking, fencing, railing, and landscape timbers. The market share of WPC decking has grown rapidly from 2% in 1997 to 18% in 2005 (Smith and Wolcott 2006). The demand for WPC in the US is expected to continue to grow to an estimated $5.4 billion by 2011 (Anon 2007).

WPCs used in decking and railing applications are exposed to outdoor environments in which mold and decay fungi, and abiotic agents such as moisture, sunlight, and temperature extremes can deteriorate them. WPCs have a reputation for low maintenance and high durability compared with pressure-treated wood. However, studies have demonstrated that WPCs can be attacked by fungi, suffer degradation of mechanical properties, and experience color change after exposure to the outdoor environment (Morris and Cooper 1998; Rangaraj and Smith 2000; Lundin 2001; Silva et al 2001; Verhey et al

* Corresponding author: adamtaylor@utk.edu
† SWST member

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2001; Pendleton et al 2002; Dawson-Andoh et al 2004; Schirp and Wolcott 2005; Morrell et al 2006; Manning and Ascherl 2007).

In addition to biological degradation, WPCs are susceptible to color change and weathering resulting from UV radiation and moisture (Rowell et al 2000; Stark and Matuana 2002). The amount of color fade depends on manufacturing methods, exposure type, and the addition of photostabilization agents (Falk et al 2001; Matuana and Kamdem 2002; Stark et al 2004; George et al 2005; Stark and Matuana 2007).

Research indicates that moisture plays a key role in the fungal degradation and weathering of WPCs (Clemons and Ibach 2003, 2004; Gnatowski 2005; Ibach et al 2003; Stark et al 2003; Stark and Matuana 2006). This suggests that improved moisture resistance would increase the durability of WPCs. Current practices to improve the moisture resistance of WPCs include changing the morphology of the composite, chemical modification of the wood component, and the incorporation of coupling agents such as maleated polyolefins (Ichazo et al 2001; Ibach et al 2007; Karimi et al 2007; Segerholm et al 2007; Stark and Matuana 2007). Manufacturing processes can also influence the moisture resistance and weathering characteristics of WPCs (Stark et al 2004; Yeh and Gupta 2007), and biocides can be added to WPCs to increase fungal durability (Verhey et al 2001; Manning and Ascherl 2007; Simonsen et al 2004; Woods 2008). Although research has indicated that WPCs are susceptible to biological degradation, the results are often inconsistent, because of a wide variety of fibers, plastics, and additives used as well as differences in processing and evaluation methods (Clemons and Ibach 2004).

Wood is inherently biodegradable. However, the heartwood of some wood species has more resistance to biological degradation than that of other species, which is mainly attributed to the presence of heartwood extractives (Wang and Hart 1983; Schultz et al 1995; Schultz and Nicholas 2000; Taylor et al 2002, 2006). Moreover, extractives are known to affect moisture sorption of wood (Choong and Achmadi 1991; Nzokou and Kamdem 2004). One option for increasing the durability of WPCs may be to use naturally durable wood. The objective of this study was to evaluate the water uptake, biological durability, and weathering resistance of WPCs made with various wood species, including those known to have natural durability.

MATERIALS AND METHODS

Preparation of Wood Flour

Dry yellow poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), sweet gum (*Liquidambar styraciflua*), eastern redcedar (*Juniperus viginiana*), hickory (*Carya* spp.), and black walnut (*Juglans nigra*) wood were purchased from local sources. Fresh-cut Osage orange (*Maclura pomifera*) was harvested from a small tree, transported to the laboratory, and air-dried. All of the wood used was combined sapwood and heartwood. Wood of each species was ground using a hammer mill and Wiley mill followed by sieving with 70 and 120 US standard sieves (0.210- and 0.125-mm square opening per side, respectively). The wood flour passing the 70 sieve but remaining on the 120 sieve was used in the subsequent manufacture of WPCs. Southern pine (*Pinus* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.) wood flour was obtained from American Wood Fibers (Schofield, WI). These flours were particles that passed 60 US standard sieve, but they were further sieved using the same mesh sizes described previously to get a similar wood particle size distribution. All wood flour was oven-dried at 105°C for 24 h before compounding with polypropylene. Virgin isotactic polypropylene (PP) homopolymer (generic brand; Performance Polymers, Leominster, MA) with a melt flow index of 35 g/10 min at 230°C was used. Density at room temperature was 910 kg/m^3.

Compounding and Sample Preparation

Each wood species was compounded with PP at 50% by mass in a 27-mm corotating twin-screw

extruder (Leistritz MICRO 27, American Leistritz Extruder Corp., Somerville, NJ) with a length-to-diameter ratio of 40:1. The barrel temperature of the extruder ranged between 180 and 195°C, and the screw rotation rate was 30 rpm. The compounded material was immediately cooled down in a water bath and pelletized. The pellets were used to make injection-molded tensile test ("dog bone") specimens in accordance with ASTM D638 Type IV (ASTM 2007). The barrel and mold temperatures of the pneumatic injection molder were 191 and 135°C, respectively. For the metal corrosion and color change tests, WPC pellets were compression-molded in a disc type aluminum mold at 191°C and 1.1 MPa for 5 min.

Water Sorption and Thickness Swelling

The injection-molded tensile specimens were cut and machined to specimen dimensions of 25.0 × 21.0 × 2.5 mm. The surface of the specimens was ground off using 100-grit sandpaper to expose wood fibers that were encapsulated in the plastic matrix. The sample mass and thickness were measured and the sample was soaked in distilled water at room temperature. The samples were periodically removed to measure mass gain and thickness swelling. For each wood species, five replicates were made for the water sorption test, and three different spots on each specimen were measured for the thickness swelling test. After 2650 h (110 da) of immersion in water, the samples were oven-dried at 105°C for 48 h and weighed to calculate the water sorption and thickness swelling. Percentage moisture gain (MC) and thickness swelling (TS) were calculated based on the following equations:

$$\mathrm{MC}(\%) = \frac{(W_t - W_o)}{W_o} \times 100 \qquad (1)$$

$$\mathrm{TS}(\%) = \frac{(T_t - T_i)}{T_i} \times 100 \qquad (2)$$

where W_o is the oven-dry mass and W_t is mass at time t, whereas T_i is initial thickness and T_t is thickness measured at time t. The water sorption data were used to calculate apparent diffusion coefficient D_A using initial slope from moisture content vs square root of time and Fick's diffusion equation:

$$D_A = \frac{\pi}{16}\left(\frac{h}{MC_{\max}}\right)^2\left(\frac{\partial MC}{\partial\sqrt{t}}\right)^2 \qquad (3)$$

where $MC_{\max}$ is the maximum moisture content measured at the end of the test, $\partial MC/\partial\sqrt{t}$ is the slope taken from the moisture content vs the square root of time relation, and h is thickness of the sample (Steckel et al 2007). Because Eq 3 is one-dimensional, diffusion through the sample edges was accounted for using a geometric edge correction factor (ECF) that is given by:

$$\mathrm{ECF} = \left(1 + \frac{h}{L} + \frac{h}{w}\right)^2 \qquad (4)$$

where h, w, and L are the sample thickness, width, and length, respectively (Shen and Springer 1976). Therefore, the corrected diffusion coefficient, D, is calculated as:

$$D = \frac{D_A}{\mathrm{ECF}} \qquad (5)$$

Thickness swelling rate was further analyzed using the following equation (Shi and Gardner 2006):

$$TS(t) = \left(\frac{T_\infty}{T_0 + (T_\infty - T_0)e^{-Ksrt}} - 1\right) \times 100 \qquad (6)$$

where $TS(t)$ is the thickness swelling at time t, T_O and T_∞ are the initial and equilibrium sample thickness, respectively, and K_{sr} is an initial (or intrinsic) relative swelling rate.

Mold Susceptibility

The mold susceptibility of the WPCs made with various wood species was evaluated following the method described in American Wood Preservers' Association (AWPA) E24-06 standard (AWPA 2007a) with a modification to the sample size. The injection-molded tensile specimens were placed in a controlled-environment mold

growth chamber, which maintains 25°C and near 100% RH. The chamber consisted of a rectangular polyethylene tank (610 × 460 × 460 mm) with a pitched-roof cover made of clear acrylic plates. The tank contained approximately 80 mm of water at the bottom. Heat was supplied by an immersion heater that was connected to a temperature controller to maintain 25°C within the chamber. A water-circulating aquarium pump was used to ensure even distribution of heat. Approximately 30 mm above the water, stainless steel wire mesh covered with plastic mesh held an 80-mm-thick layer of potting soil that had been inoculated with various mold fungi. A 100-mm-diameter fan was placed in the chamber to circulate air within the chamber over the surface of the soil to facilitate the distribution of spores. The samples were suspended from stainless steel rods spanning the width of the tank. Five replicates were made for each wood species. The temperature of the room that housed the test chamber was 20°C.

The artificial inoculum contained four organisms: *Alternaria tenuissima*, *Aspergillus niger*, *Aureobasidium pullulans*, and *Penicillium citrinum*. The fungi were first incubated on 1.5% malt extract agar in petri plates for 2 wk. Spores and mycelium from the surface of the plates were scraped and blended with water and evenly distributed over the soil surfaces in the chamber. The chambers were then held at the test conditions for 2 wk to establish the fungi. Inoculation suspension was also sprayed on the samples (including solid pine controls) when they were installed in the chamber. After 2, 4, 6, and 8 wk of exposure within the chamber, the samples were rated for the extent and intensity of mold growth based on the 0 to 5 scale indicating mold covering 0, 5–10, 10–30, 30–70, greater than 70, and 100% of the sample, respectively.

Fungal Decay

The fungal decay durability of the WPCs was evaluated using AWPA E10-06 (AWPA 2007b) with a modification of the sample size and sample placement. Two fungi were used: a white-rot, *Trametes versicolor,* and a brown-rot, *Postia placenta*. The fungi were first grown on malt extract agar. Plugs of agar covered with mycelium were placed in the sterilized soil bottles touching the feeder strips. *P. placenta* was inoculated on the pine feeder strip, whereas *T. versicolor* was inoculated on the yellow poplar feeder strips. The soil bottles were incubated for 2 wk at 28°C until the feeder strips were covered with mycelium.

The injection-molded tensile specimens were cut and machined to specimen dimensions of 25.0 × 21.0 × 2.5 mm. A total of 12 samples per species (6 per each fungus type) were prepared. Sets of 10 randomly selected cubes (12 mm) cut from southern pine sapwood and yellow poplar were used as controls to ensure sufficient fungal activity in the test. Then the surfaces of the WPC samples were sanded with 100-grit sandpaper to expose wood fibers. All the samples were then oven-dried at 100°C for 24 h and weighed to the nearest 1 mg. The WPC samples were soaked in the water at room temperature for 1 wk and then under vacuum for 2 h. WPC and wood block (control) samples were wrapped with aluminum foil and sterilized in an autoclave at 121°C for 45 min. Decay chambers were prepared in 450-mL glass jars filled with 250 g of pot soil and 80 g of water with either southern pine or yellow poplar feeder strips on top of the soil. The prepared jars were steam-sterilized in an autoclave for 45 min at 121°C.

Three sterilized samples were placed in each soil bottle. The WPC samples were inserted halfway (lengthwise) into the soil adjacent to the feeder strip. The soil bottles were incubated at 28°C. After 17 wk of exposure, the samples were removed, brushed to remove mycelium, dried for 24 h at 105°C, and weighed for moisture content determination. The percentage mass loss (on a dry wood basis) resulting from fungal decay was calculated.

Color Change

Color change was evaluated by exposing compression-molded samples (38.0 × 38.0 × 2.5

mm) outdoors at Knoxville, TN (35°49′ N, 83°59′ W). Five replicates were made for each species. The samples were held in a rack with one face exposed on a 45° angle facing south. The samples were exposed for a total of 91 da (from 19 October 2007 to 17 January 2008). The surface color of each sample over time was measured according to ISO 2470 (ISO 1999) using a Hunter Lab® Mini Scan XE Plus colorimeter (Model 45/0-L, Reston, VA). The changes on sample surface color were monitored by assessing the parameters from the CIEL*a*b* color space system. Three parameters, L*, a*, and b*, measure lightness (L*) and the color coordinates (a* and b*). L* varies from 0 (black) to 100 (white), a* and b* varies from −150 to +150, and are defined as red–green and blue–yellow coordinates, respectively. L*, a*, and b* values for each samples were measured before and after outdoor exposure and used to calculate ΔE* as a function of outdoor exposure time and species used

$$\Delta L^* = L_f^* - L_i^* \quad (7a)$$

$$\Delta a^* = a_f^* - a_i^* \quad (7b)$$

$$\Delta b^* = b_f^* - b_i^* \quad (7c)$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (8)$$

where ΔL*, Δa*, and Δb* are the changes between initial values (L_i*, a_i*, and b_i*) and values measured after outdoor exposure (L_f*, a_f*, and b_f*).

Metal Corrosion Test

Wood decking treated with alkaline copper preservative formulations can be very corrosive to unprotected metal fasteners. Extractives from wood can also react with metal, creating discolorations and corrosion. For these reasons, the corrosion of metal in contact with the experimental WPCs was tested following AWPA E12-94 (AWPA 2007c) with a modification of the sample size. Five types of metal coupons measuring 12.5 × 25.0 × 1.5 mm were used: SAE 1010 steel, hot-dipped galvanized steel 2024-T3 aluminum, 85-15 red brass, and copper. The metal coupons were cleaned with fine garnet sandpaper and washed with an alcohol–acetone mixture to remove oil and grease. After washing and drying, the metal coupons were weighed to the nearest 1 mg. Compression-molded WPC samples were cut into 19.0- × 38.0-mm strips and the surface of each strip was sanded with 100-grit sandpaper to expose wood fibers. They were dried overnight in an oven at 105°C. Each metal coupon was placed between two WPC samples and the assembly was clamped with a paper clip. For each species, five replicates were made for each metal type. The assemblies were exposed in a chamber maintained at 49°C and 90% RH for 366 h. The assemblies were then dismantled and the metal strips thoroughly washed under running water and brushed lightly to remove loose corrosion products. The remaining corrosion products were removed by immersion in the following reagents as described in AWPA E12-94 and ASTM G 1-03 (ASTM 2003): 10% ammonium citrate solution (steel), 10% ammonium persulfate (galvanized steel), 10 water: 1 nitric acid (aluminum), 3 water: 1 hydrochloric acid (brass), and 2 water: 1 hydrochloric acid (copper). The samples were then rinsed with water, dried, and reweighed to the nearest 1 mg. The corrosion rate was calculated based on the mass loss using the following equation:

$$\text{Corrosion rate } (\mu\text{m/yr}) = (8.76 \times 10^7)(W)/(A \times t \times d) \quad (9)$$

where

W = mass loss (kg)
A = area (m^2)
t = time (h)
d = density (kg/m^3).

RESULTS AND DISCUSSION

Water Sorption and Thickness Swelling

Water uptake in the WPCs was slow (Fig 1). A minimum of 500 h of immersion for the 2.5-mm-thick WPC samples was needed to reach equilibrium (Fig 1). The rate and extent of water uptake varied with species; the composites made

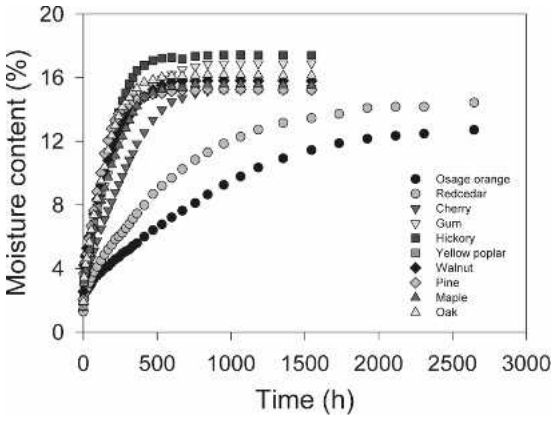

Figure 1. Water sorption of wood–plastic composites made with different wood species.

with Osage orange, redcedar, and cherry flour were slower to absorb water. However, at the end of the test, the moisture content (MC_{max}) of all WPC samples reached average levels (>25%, expressed on an oven-dry wood basis) that are sufficient to support fungal activity (Sherwood and Stroh 1989; Zabel and Morrell 1992; Cassens et al 1995; Carll and Highley 1999; Rapp et al 2000) (Table 1). The moisture sorption behavior was further characterized by Fick's law using Eqs 3, 4, and 5. The diffusion coefficient (D) and other water sorption and thickness swelling data are presented in Table 1. The diffusion coefficients of redcedar and Osage orange WPCs were 0.9 to 1.0 × 10^{-13} m^2/s and significantly lower (one-way ANOVA followed by Tukey's multiple comparison test at $p < 0.05$) than that of WPCs made with other species, which ranged from 2.5 to 4.9 × 10^{-13} m^2/s (Table 2). Composites made with cherry and walnut displayed intermediate D values. These values are similar to those found in previous research (Marcovich et al 1999; Mohd. Ishak et al 2000; Chowdhury and Wolcott 2007; Steckel et al 2007). Statistical analysis results from this test, and the other tests are shown in Table 2.

The thickness swell of the samples showed a pattern similar to the water uptake data (Fig 2). Thickness of the redcedar and Osage orange WPCs increased more slowly than all the other species and the maximum thickness swelling was lower than in other samples. Swelling in cherry WPCs appeared to be intermediate. Maximum thickness swelling (TS_{max}) at the end of the test was from 4–6% for most species; the redcedar and Osage orange swelled only approximately 3% (Table 1). The thickness swelling rate parameter (K_{sr}) was calculated following Eq 6 and the values for each species are presented in Table 1. The K_{sr} values of composites made with Osage orange and redcedar were 1.86 and 1.61 × 10^{-3}/h, respectively, which were significantly lower than for composites made with any other species except cherry (Table 2).

The low moisture sorption and thickness swelling of WPCs made with redcedar and Osage orange may be the result of the low water sorption and volumetric swelling of the wood component. The hygroscopicity of wood can be affected by variations in the type and proportion of the basic chemical components (cellulose, hemi-

Table 1. *Average (standard deviation) maximum moisture content, diffusion coefficient, maximum thickness swelling, and thickness swelling rate of wood–plastic composite samples after 2650 h of water sorption.*[a]

Species	MC_{max} (%)	Diffusion coefficient (10^{-13} m^2/s)	TS_{max} (%)	Thickness swelling rate (10^{-3}/h)
Osage orange	25.4 (1.8)	0.90 (0.08)	2.8 (0.4)	1.86 (0.41)
Redcedar	29.0 (2.5)	1.03 (0.25)	3.0 (0.3)	1.61 (0.62)
Cherry	30.6 (2.9)	2.53 (0.31)	3.9 (0.4)	4.64 (1.21)
Gum	33.8 (3.1)	3.54 (0.77)	4.2 (0.4)	5.86 (1.78)
Hickory	34.8 (0.9)	4.31 (0.37)	5.1 (0.3)	8.17 (0.89)
Yellow poplar	30.6 (2.7)	4.93 (0.59)	4.5 (0.4)	8.17 (2.27)
Walnut	31.6 (1.8)	2.93 (0.30)	3.6 (0.8)	5.87 (1.02)
Pine	30.5 (1.8)	4.68 (0.25)	4.5 (0.7)	9.39 (2.10)
Maple	31.1 (1.1)	4.13 (0.12)	4.6 (0.4)	5.71 (0.71)
Oak	32.4 (1.6)	4.10 (0.25)	4.1 (0.6)	7.10 (0.10)

[a] MC_{max} values are based on dry wood weight.

Table 2. *One-way analysis of variance followed by Tukey's multiple comparison test results.*[a]

	Moisture sorption and thickness swelling				Mold susceptibility	Fungal durability				Color change	Metal corrosion	
Species	MC_{max} (%)	Diffusion coefficient (10^{-13} m^2/s)	TS_{max} (%)	Thickness swelling rate (10^{-3}/h)	Mold rating after 8 wk	MC of BR (%)	WL to BR (%)	MC of WR (%)	WL to WR (%)	Δ E*	Galvanized steel	Steel
Osage orange	B	F	E	DE	C	CD	D	BCD	C	G	ABC	DE
Redcedar	B	F	E	E	C	D	D	D	C	B	ABC	E
Cherry	AB	E	CD	CD	BC	ABC	CD	BCD	C	FG	C	ABC
Gum	A	CD	BCD	BC	BC	AB	BC	ABC	A	DE	ABC	AB
Hickory	A	ABC	A	AB	C	A	AB	A	ABC	D	C	A
Yellow poplar	AB	A	BC	AB	ABC	BCD	AB	AB	BC	A	C	CDE
Walnut	AB	DE	D	BC	ABC	ABC	CD	A	ABC	C	AB	E
Pine	AB	AB	B	A	BC	CD	A	CD	ABC	FG	A	BCDE
Maple	AB	ABC	AB	BC	ABC	ABC	A	ABC	BC	FG	BC	DE
Oak	AB	BC	BCD	ABC	AB	ABCD	BC	ABC	AB	EF	ABC	ABCD
Control	—	—	—	—	A	—	—	—	—	—	—	—

[a] Different letters within a column indicate a statistically significant difference ($p < 0.05$) among wood–plastic composite types.

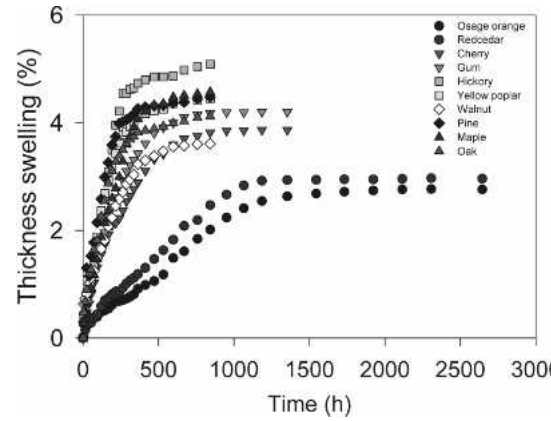

Figure 2. Thickness swelling during moisture sorption of wood–plastic composites made with different wood species.

celluloses, and lignin). Other factors such as the extractives, anatomical structure, and moisture content history can also affect hygroscopicity (Skaar 1988). In addition, reduced hygroscopicity of wood resulting from processing at elevated temperatures and mechanical restraint imposed by the PP matrix also could influence the moisture sorption of WPCs (Nakano and Miyazaki 2003). Swelling of wood varies with species, structure, density, and drying conditions (Mantanis et al 1994). Some species such as eastern redcedar are known to have relatively low volumetric swelling and shrinkage (Simpson and TenWolde 1999; Suchsland 2004). In addition, swelling of the wood component in WPCs affects the composite's microstructure, expanding cracks, debonding wood–plastic interfaces, and thus providing more pathways for water penetration (Steckel et al 2007). The low moisture sorption and thickness swelling characteristics of WPCs made with cedar and Osage orange are likely caused by the low water sorption and volumetric swelling of the wood component. However, further research is necessary to better understand the factors affecting moisture sorption and thickness swelling of WPCs.

Mold Susceptibility

All of the WPCs tested were more resistant to mold than the solid wood controls (Fig 3). Daw-

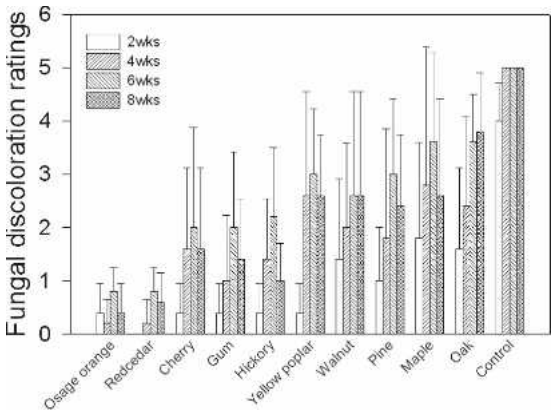

Figure 3. Mold ratings of wood–plastic composites made with various wood species.

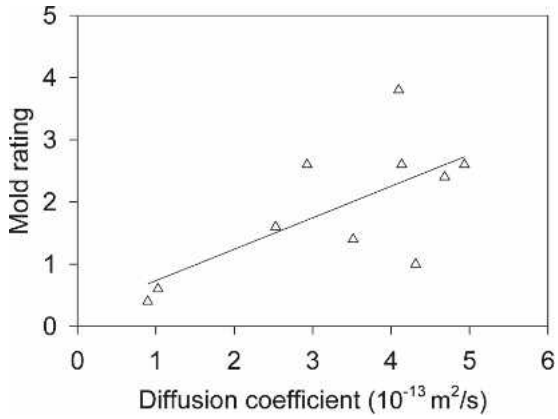

Figure 4. Average diffusion coefficient vs average mold ratings at 8 wk of wood–plastic composites made with different wood species.

son-Andoh and coworkers (2004) reported that solid wood lumber (pine and maple) was more susceptible to microbial growth than PVC/wood flour composites. The mold susceptibility of the redcedar and Osage orange WPCs was lower than for WPCs made with oak and the control. In fact, except for oak WPC and the control, there were no statistically significant differences between WPCs in mold rating after 8 wk (Table 2). The WPCs that had reduced moisture uptake (redcedar and Osage orange) were also those least susceptible to mold fungi. Average diffusion coefficient (D) values of the WPCs were positively correlated with the mold ratings ($R^2 = 0.46$) (Fig 4). These results suggest that moisture sorption is related to the mold susceptibility of WPCs. Redcedar and Osage orange are also known to be resistant to fungal decay, mainly as a result of the extractives (Wang and Hart 1983; Schultz et al 1995). These extractives may also inhibit the mold fungi in WPCs made with these species.

Fungal Decay

Despite efforts to wet the WPCs before exposure to the fungi, the wood in the samples was dry (16–22% for the whole sample) relative to the moisture content usually seen in decay testing of wood, even after 17 wk in the moist soil (Fig 5). The mass loss of the WPCs resulting from fungal attack was low overall (Figs 6 and 7), ranging approximately 1–9% for *P. placenta* (brown rot) and 0.5–7% for *T. versicolor* (white rot). The average mass loss of the solid wood controls was 50% for the brown rot on pine and 27% for the white rot on yellow poplar, indicating that the test conditions were sufficient for decay. As with the water uptake and thickness swell data, the decay levels resulting from brown rot in the samples made with Osage orange and redcedar were low relative to the samples made with other species except walnut and pine WPC. The statistical analysis indicated that there was no significant difference in brown rot durability

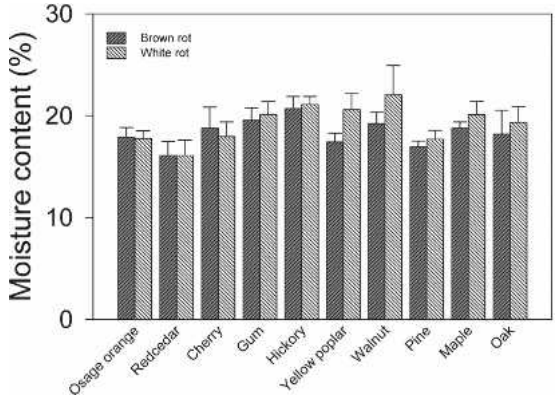

Figure 5. Moisture content of wood–plastic composites made with various wood species after 17 wk of exposure in modified soil-block test (based on wood weight).

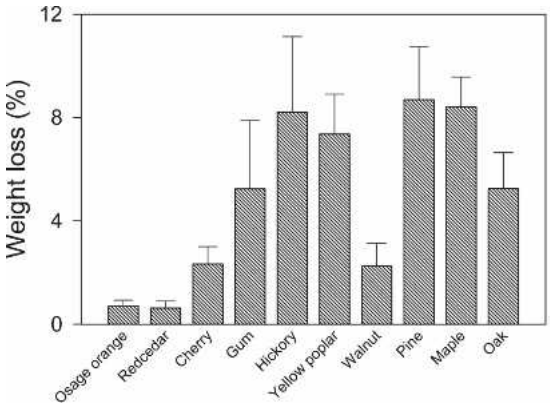

Figure 6. Weight loss of wood–plastic composites exposed to a brown rot fungus (*Postia placenta*) in a soil-block test (based on wood weight).

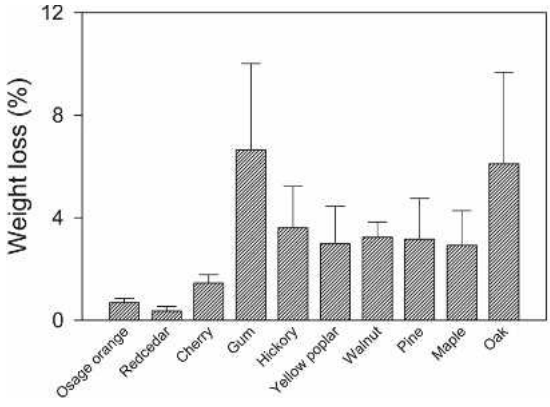

Figure 7. Weight loss of wood–plastic composites exposed to a white rot fungus (*Trametes versicolor*) in a soil-block test (based on wood weight).

among composites made with redcedar, Osage orange, cherry, and walnut, whereas for white rot, only gum and oak were significantly less durable than all other species (Table 2). The high level of positive linear correlation (R^2 = 0.87) between average D values and mass loss resulting from the brown rot fungus suggests that the moisture diffusion characteristics affect the fungal durability of WPCs (Fig 8). However, the correlation was weak between D and mass loss as a result of the white rot fungus exposure (R^2 = 0.39). As mentioned before, redcedar and Osage orange are known to have natural durability. Therefore, low fungal decay of WPCs made with redcedar and Osage orange could be

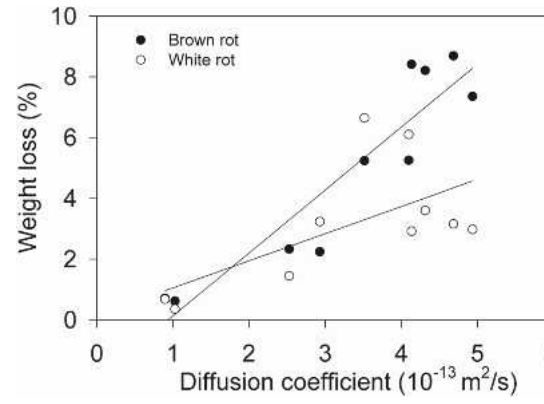

Figure 8. Average diffusion coefficients vs average weight loss resulting from brown and white rot fungi.

attributable to their low moisture sorption behavior and/or to the natural durability of the wood.

Color and Color Change after Exposure

Figure 9 is a photograph of examples of each type of WPC before and after exposure. Although the color of WPCs before exposure was different between species, the color of WPCs after exposure was quite similar. Before the color change test, WPCs made of pine had the lightest (close to white, highest L_i* value), whereas that of cedar had the darkest (close to black, lowest L_i* value) (Table 3). As expected, outdoor exposure changed the color of all the WPC samples. The changes in L*, a*, and b*

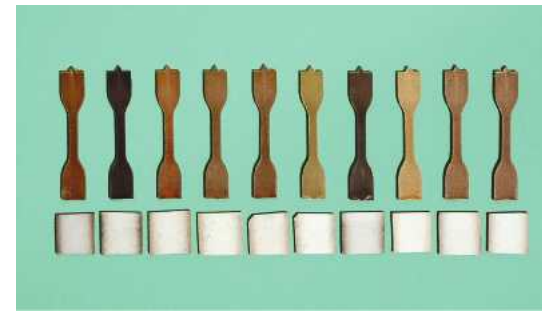

Figure 9. Examples of wood–plastic composites before (top) and after (bottom) 91 da outdoor exposure. Left to right: Osage orange, redcedar, cherry, gum, hickory, yellow poplar, walnut, pine, maple, and oak.

Table 3. *Average (standard deviation) color change before and after 91 da of outdoor exposure of WPCs made with different species.*

	Before exposure			After 91 da of exposure			
Species	L^*_i	a^*_i	b^*_i	L^*_f	a^*_f	b^*_f	ΔE^*
Osage orange	34.4 (0.7)	12.1 (0.3)	20.2 (0.7)	55.9 (1.6)	2.7 (0.2)	5.1 (0.3)	27.9 (2.1)
Redcedar	23.7 (0.3)	6.9 (0.2)	5.8 (0.4)	68.0 (1.8)	1.3 (0.1)	4.7 (0.4)	44.6 (1.7)
Cherry	40.5 (0.6)	12.3 (0.2)	17.1 (0.3)	68.6 (1.2)	3.3 (0.1)	7.5 (0.4)	31.1 (1.4)
Gum	41.8 (0.6)	7.8 (0.1)	15.9 (0.2)	75.2 (0.5)	1.8 (0.1)	8.6 (0.5)	34.7 (1.1)
Hickory	37.7 (0.6)	9.3 (0.2)	16.4 (0.6)	71.7 (1.8)	3.0 (0.1)	9.5 (0.5)	35.3 (1.7)
Yellow poplar	46.1 (1.1)	5.1 (0.3)	22.0 (0.5)	76.4 (0.6)	1.5 (0.1)	6.2 (0.4)	34.4 (0.8)
Walnut	31.5 (1.2)	5.6 (0.3)	11.0 (0.9)	70.9 (0.8)	1.9 (0.2)	5.7 (0.4)	39.9 (1.0)
Pine	52.4 (1.5)	10.1 (0.7)	26.4 (0.3)	75.3 (2.6)	2.8 (0.2)	10.0 (0.6)	29.1 (2.8)
Maple	44.7 (0.5)	8.7 (0.1)	16.9 (0.3)	73.4 (0.8)	2.3 (0.1)	7.1 (0.2)	31.0 (0.9)
Oak	43.9 (0.6)	8.6 (0.2)	16.3 (0.4)	73.5 (0.9)	2.3 (0.2)	7.1 (0.6)	31.6 (1.2)

values indicated simultaneous lightening and color change. For all WPCs tested, L* was increased, whereas a* and b* decreased. An increase in the L* value implies increase in lightness and decrease in a* and b* indicates color change from red toward green and from yellow toward blue, respectively.

These data demonstrate that just as (solid) wood species have different colors, the inclusion of various wood flours in WPCs will affect the color and color change properties of the composite.

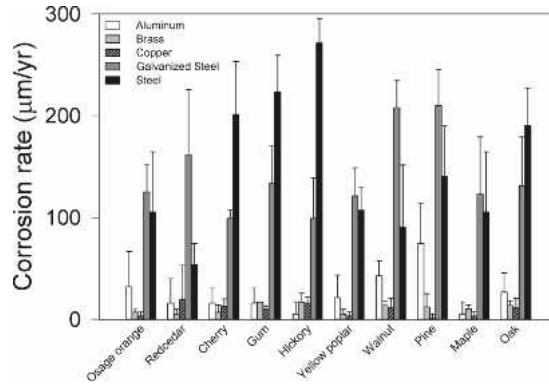

Figure 10. Corrosion of different types of metals in contact with wood–plastic composites made with different wood species.

Metal Corrosion

Corrosion of metals in contact with WPCs was observed for all species and all metals used. The corrosion of aluminum, copper, and brass was significantly lower than that of the steel and galvanized steel (Fig 10). Hendrix (2006) reported similar results using wood blocks. There were no significant differences among species in corrosion of aluminum, brass, and copper. However, the corrosion of galvanized steel was greater when in contact with WPCs made with pine and walnut than when in contact with yellow poplar, cherry, and hickory WPCs. For plain steel, contact with hickory, gum, cherry, and oak WPCs resulted in significantly more corrosion than walnut and cedar WPCs (Table 2). The corrosion of steel in contact with WPCs made from redcedar was low compared with other species but, when in contact with galvanized steel, corrosion rates were slightly higher than that of other species, except for walnut and pine. The corrosion of metal in contact with wood is basically an electrochemical process and is affected by wood species, acidity, metal chelators, inorganic components in wood, and moisture content of wood (Hendrix 2006). The correlation between average D values and metal corrosion was low ($R^2 < 0.2$) suggesting that the moisture sorption characteristics of WPCs had little influence on the corrosion of the metals with which they were in contact. Further research is necessary to clarify the effect of wood species on metal corrosion in contact with WPCs. However, the overall rate of corrosion of metals in contact with WPCs was low relative to that reported for wood treated with alkaline copper wood preservatives (Hendrix 2006).

CONCLUSIONS

The effect of wood species on water sorption and durability of WPCs was studied. Ten wood species native to the southeastern US (8 hardwoods and 2 softwoods) and polypropylene were used to make WPCs. The rates of water sorption for WPCs made with eastern redcedar and Osage orange were significantly lower than for composites made with other species. In addition, the final moisture contents of eastern redcedar and Osage orange WPCs after 2600 h of water soaking were lower than for gum and hickory WPCs. The rates and extent of thickness swelling of WPCs made with eastern redcedar and Osage orange were also lower than for composites made with other species.

Mold susceptibility and fungal decay rates of WPCs made with Osage orange and eastern redcedar were lower than for samples made with other species. The presence of fungus-inhibiting extractives in redcedar and Osage orange, together with low moisture sorption rates and resulting thickness swell, may be reasons for the durability.

WPCs made with different species varied in color. When they were exposed outside, all the WPCs became lighter and more similar in color. Corrosion of metals in contact with WPCs was generally low for all species and all metal types used.

The wood species used in WPCs influences the properties of the composite. Although more research is required to fully understand this relationship, it is possible that more durable WPCs can be made by taking advantage of the inherent properties of the wood filler.

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