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Section 4 **Processes and Properties**

Long-term field exposure of wood-plastic composites processed on a commercial-size extruder

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Long-term field exposure of wood-plastic composites processed on a commercial-size extruder

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ABSTRACT

Wood-plastic composites (WPC) contain wood fiber (or flour), thermoplastics and additives and are exposed to UV light, moisture, and biological deterioration in outdoor installations. Accelerated laboratory tests can help to predict the durability of WPCs, but long term evaluations are needed to validate these results. Field exposed above-ground WPC deck boards (30.5 x 139.7 x 609.6 mm) and in-ground (19 x 19 x 457 mm) stakes were visually evaluated near Saucier, Mississippi and Madison, Wisconsin over 17 years. Four blends were extruded on commercial-scale equipment containing additives including colorant, light stabilizers, lubricant, and the fungicide zinc borate (ZnB). There are some difficulties evaluating the WPC materials compared to solid wood: in-ground stakes snap quite easily when removing them for inspection and decay is more difficult to determine because the WPC does not become soft. Differences in deterioration were seen between each test site: the in-ground deterioration was more severe in Mississippi and the above-ground deterioration was more severe in Wisconsin. The ZnB fungicide provided some decay protection in-ground even at the low level of 1%, and the UV stabilizer package (including colorant) slowed the color change compared to the WPC control above-ground. The blend including both ZnB and UV package provided both decay and UV protection, but mold and stain are still an issue for above-ground. The in-ground results are analogous to the short-term accelerated laboratory evaluations.

Keywords: wood-plastic composites, moisture, decay, above-ground exposure, in-ground exposure, WPC durability, deck boards

1. INTRODUCTION

The wood plastic composite (WPC) market is growing globally and is expected to increase about 13.2% to approximately $9.7 billion by 2025 (Cole 2017). Consumers expect high durability, low maintenance, and enhanced appearance in this WPC market, but some of these improvements may not meet consumer satisfaction. WPCs may also be used in more difficult environments such as in-ground contact applications where moisture and decay may pose a challenge.

The mixing of plastic and wood together was initially thought to result in complete encapsulation of the wood component, thereby preventing moisture sorption and fungal decay. Early research by Morris and Cooper (1998) found evidence of fungal decay and discoloration on WPC decking in service. Subsequently, many research investigations on the durability of WPCs followed. WPCs have slower moisture sorption than wood (Rowell *et al.* 2002, Wang and Morrell 2004), but water affects the mechanical properties and then can promote the fungal decay of the composite (Clemons and Ibach 2002, Clemons and Ibach 2004, Shirp and Wolcott 2005, Ibach and Clemons 2007, Ibach *et al.* 2017, Mankowski and Morrell 2000). A review of the literature on the biological degradation of WPCs and ways to improve the resistance were addressed by Shirp et al. (2007). These strategies ranged from the addition of toxic chemicals (i.e. ZnB) to chemically modifying the wood flour component (i.e. acetylation).

When WPCs are used in outdoor conditions, they are exposed to not only biological degradation and moisture, but also UV, thermal, chemical, and mechanical degradations. New laboratory testing protocols were investigated to assist in understanding the interaction of some of these combined exposures (Ibach *et al*. 2004). WPC specimens were preconditioned by ultraviolet (UV)/water spray and water soaking before laboratory fungal decay evaluations. This allowed an accelerated protocol which combined moisture, UV, and fungal exposures in the laboratory (Ibach *et al.* 2004). To verify the accelerated laboratory results, long-term field tests which include multiple types of exposures, were needed to provide a useful comparison. With regards to biodeterioration and termite attack of WPCs, the ASTM Standards reference the wood standards (ASTM 2017, ASTM 2019). When this research was started, we had no idea how these WPC materials would perform and even look like throughout outdoor exposures. Wood is hygroscopic so it is prone to moisture followed by decay and weathering. At the time this research was started, WPCs were only for nonstructural use, but we included in-ground exposure because of the expanding application of WPCs, some of which could include ground contact (e.g., landscape timber).

Accelerated laboratory tests can help to predict the durability of WPCs, but long-term evaluations are needed to confirm these results. We screened various fungicides and weathering packages in the laboratory and picked the top performing fungicide and the top performing UV stabilizer package. The objective of this research was to perform field evaluations of above-ground deck boards and in-ground stakes of 4 WPC blends containing additives to improve the durability including colorant, light stabilizers, and fungicide. The goal was to determine the efficacy of the additives and their interactions of the WPCs that were produced on commercial-scale equipment.

2. EXPERIMENTAL: MATERIALS AND METHODS

2.1 Materials

The following materials/chemicals were used to produce the WPC deck boards.

- Plastic (HDPE): High-density polyethylene (BP Solvay Polyethylene, grade A60-70-162; melt flow index (MFI) approximately 0.72).
- Wood flour (WF): Mostly ponderosa pine flour, nominally -40, +80 mesh (i.e. most particles pass through a screen with 40 mesh (0.420mm) openings but not an 80 mesh (0.177mm) openings); (American Wood Fibers grade 4020).
- Lubricant (Lub): 7.8 to 8.4 percent of a blend of calcium stearate, ethylene bistearamide, and a proprietary amide (Struktol Company of America, Struktol TR 016).
- Fungicide (ZnB): 1 percent zinc borate (U.S. Borax, Boragard ZB).
- Light stabilizer package (UV): 0.5 percent of a hydroxyphenylbenzotriazole light absorber (Ciba Specialty Chemicals, Tinuvin 328) and 1 percent of a zinc ferrite colorant (Holland Colors Americas, Holcobatch Yellow L25153)

A simple 2^2 factorial design was used to investigate the effects of several additives on fungal, termite, and UV resistance. All blends used HDPE as the matrix material and contained 50 percent

WF and 8 percent lubricant. Additionally, three of the four blends contained additives. All percentages are on a weight basis. The blends are as follows:

1. No additives
2. ZnB only
3. UV stabilizer package only
4. ZnB and UV stabilizer package

Untreated southern pine solid sapwood stakes (19 x 19 x 457 mm) were included for the in-ground plots to determine fungal and termite activity at each test site.

2.2 Processing

Commercial-scale extrusion trials were run at the University of Maine's Advanced Engineered Wood Composite Center, Orono, ME. Processing parameters were determined and 30 by 140 mm (1.2 by 5.5 in.) radius edge deck boards were produced using an in-line twin-screw extruder profiling system on a 94-mm profiling extruder (Davis-Standard, Woodtruder, Pawcatuck, CT). Because the ZnB and UV absorber were in powder form, concentrates containing 10 percent by weight active ingredient in HDPE were compounded at the USDA Forest Products Laboratory on a 32-mm compounding extruder (Davis-Standard, D-TEX, Pawcatuck, CT) to facilitate feeding of the additives during the trials.

2.3 Field Installation

Installations (in-ground and above-ground) were made at the Harrison Experimental Forest (Saucier, Mississippi) in October of 2002 and at the Valley View test site (Madison, Wisconsin) in November 2002.

2.3.1 In-ground installations and evaluations

WPC stakes (19 x 19 x 457 mm) were cut from the deck boards and installed in-ground according to AWPA E7 (AWPA 2001). The stakes were installed in both plots by a randomized method and were set in the ground in an upright position with about half their length (229 mm or about 9 in.) in the ground. Ten replicates of each blend, along with untreated southern pine sapwood stakes were installed at each site. The Wisconsin site has a clay loam soil with an average annual rainfall of 787 mm (31 in.) The Mississippi site has a sandy loam soil with an average annual rainfall of 1575 mm (62 in.) In-ground stakes were visually rated annually with respect to decay (both sites) and termite attack (only at Mississippi) and Table 1 describes the rating system (AWPA 2001).

2.3.2 Above-ground installations and evaluations

Above-ground deck boards (30.5 x 139.7 x 609.6 mm) were installed 1 m above-ground horizontally on a CCA-treated wooden rack and visually evaluated and rated annually with respect to cracks/checking, color change, decay, mold/stain, and termites (only at Mississippi).Tables 1 and 2 describe the rating system. Ten replicates of each blend were installed above-ground in full sun.

Table 1: Grading system to evaluate wood-plastic composite stakes and above ground deck boards and untreated wood controls for decay and termites.

	Description of Condition	
Grade Number	**Decay**	**Termite**
10	Sound, Suspicion of decay permitted	Sound. 1 to 2 small nibbles permitted
9	Trace decay to 3% of cross section	Slight evidence of feeding to 3% of cross section
8	Decay from 3 to 10% of cross section	Attack from 3 to 10% of cross section
7	Decay from 10 to 30% of cross section	Attack from 10 to 30% of cross section
6	Decay from 30 to 50% of cross section	Attack from 30 to 50% of cross section
4	Decay from 50 to 75% of cross section	Attack from 50 to 75% of cross section
0	Failure	Failure

Table 2: Grading system to evaluate checking, color change and mold/stain for wood-plastic composite and untreated wood control above ground deck boards.

		Description of Condition	
Grade Number	**Cracks/Checking**	**Color change**	**Mold/Stain**
10	Sound.	No change in color	No stain
9	Slight checking	Slight change (e.g. loss of green in CCA treated, slight grey)	Slight stain
8	More checking	More change (e.g. brown to grey)	More stain
7	Severe checking	Still more change (e.g. untreated, yellow to grey)	Blotched on whole stake
0	Failure due to checking	Failure (e.g. grey to white or all black stain)	Black

3. RESULTS AND DISCUSSION

3.1 Processing

The actual weight percentage of the composition of the deck boards made at the University of Maine are in Table 3. During commercial-scale extrusion trials, it is difficult to weigh precise amounts of materials. Therefore, the wood flour varies from 48.2 percent in blend 2 to 51.9 percent with blend 3.

Table 3. Chemical composition (weight percentages) of deck boards extruded on a commercial scale extruder at the University of Maine.

Blend Number	1	2	3	4
Wood flour	48.9	48.2	51.9	50.5
HDPE	43.1	43.0	38.3	39.0
Lubricant	8.0	7.8	8.4	8.2
ZnB	-----	1.1	-----	0.9
Light absorber	-----	-----	0.5	0.5
Colorant	-----	-----	0.9	0.9

3.2 Field Results

3.2.1 In-ground stakes

Untreated southern pine solid wood stakes were included and evaluated to verify the fungal viability of the field plots at each test site and the presence of termites at the site in Mississippi. The untreated solid wood controls had an average life of 5.7 and 2.1 years in Wisconsin and

Mississippi, respectively (Table 4). This demonstrates the more severe exposure in Mississippi, which was expected for in-ground stakes, due to greater biodeterioration hazard from fungal decay as well as the presence of termites (AWPA 2019).

Subterranean termites are present in Mississippi, but not at the Wisconsin site. Tables 4 and 5 show the results of in-ground field exposure of the WPC stakes after 17 years. The first termite attack of the WPCs was seen in 2009 (7 years exposure), whereas the untreated solid wood was attacked at 1 year and failed completely after 2 years exposure. After 17 years, the remaining stakes show termite ratings from 9.6 to 8 (Table 5), which corresponds from a trace to 3 to 10% of the cross section. All the blends performed well against termites and none of the stakes failed just from termites, but blend 1, 3, and 4 had failures by a combination of decay and termites in Mississippi (Table 4).

One of the difficulties with in-ground testing of WPCs is that they can easily snap while taking them out of the ground. This happened early in the field tests and is noted in Table 4 by the column "Snapped-Mechanical." The breaking can be from the clearing of the plot, not pulling the stake straight up out of the ground, or from just moisture, since we have found in the lab that moisture alone can affect the mechanical properties (Ibach and Clemons 2002, Clemons and Ibach 2004).

The fungal decay ratings and condition of the remaining WPC stakes after 17 years are in Table 4 and 5. Wisconsin has lower ratings for blends 2-4, but more stakes have failed in Mississippi, and blend 3 only has 1 stake remaining in Mississippi due to breakage/moisture and decay. Blend 1 (with no additives) has the lowest rating of 2.8 ± 3.3 in Mississippi. Blend 2 and 4 that contain ZnB which gave some protection, but a higher level than 1% or a more powerful fungicide is needed for improved effectiveness. These results are similar to our short term accelerated laboratory evaluations (Ibach *et al.* 2004) as well as Mankowski et al. (2005). The failures in Wisconsin are from just mechanical and moisture/decay, compared to Mississippi that has mechanical, moisture/decay, termites, and a combination of termites and decay.

The WPCs have a slower moisture sorption compared to solid wood which results in a lag time before the wood component reaches the equilibrium moisture content where decay will occur. Initiation of in-ground decay of the WPCs was different for each site location. In Mississippi, decay was first detected after 2 years of outdoor exposure, while in Wisconsin it was 12 years. Fig. 1 shows some of the in-ground WPC remaining stakes at the test sites after 17 years exposure near: a.) Madison, Wisconsin and b.) Saucier, Mississippi.

a.) b.)

Figure 1. In-ground WPC stakes after 17 years exposure near: a.) Madison, Wisconsin and b.) Saucier, Mississippi.

Table 4. Condition of in-ground wood-plastic composite stakes and Southern Pine untreated control stakes (19 x 19 x 457 mm) after 17 years in test. Stakes placed in test on both the Harrison Experimental Forest, Saucier, Mississippi, October, 2002 and Valley View Test site, Madison Wisconsin, November 2002.

			--Type of attack on remaining---			---------------Reason for removal------------------					
Blend Number[1]	**Number in test**	**Total remaining**	**Fungal decay only**	**Termite only**	**Decay & Termite**	**Total removed**	**Snapped-Mechanical**	**Fungal decay only**	**Termite attack only**	**Decay & Termite**	**Average life (year)**
Mississippi											
1	10	3	1	0	2	7	3	1	0	3	---[2]
2	10	5	3	0	2	5	5	0	0	0	---[2]
3	10	1	0	0	1	9	5	3	0	1	---[2]
4	10	5	0	1	4	5	3	1	0	1	---[2]
Untreated solid wood	10	0	0	0	0	10	0	0	0	10	2.1
Wisconsin											
1	10	8	8	---[3]	---[3]	2	1	1	---[3]	---[3]	---[2]
2	10	9	9	---[3]	---[3]	1	1	0	---[3]	---[3]	---[2]
3	10	7	7	---[3]	---[3]	3	1	2	---[3]	---[3]	---[2]
4	10	7	7	---[3]	---[3]	3	2	1	---[3]	---[3]	---[2]
Untreated solid wood	10	0	0	---[3]	---[3]	10	0	10	---[3]	---[3]	5.7

[1]Blends = 1. No additives; 2. ZnB only; 3. UV stabilizer package only; 4. ZnB and UV stabilizer package.
[2]Average life cannot be calculated since not all stakes have failed.
[3] No termites were present at Wisconsin site.

Table 5. Decay and termite ratings of remaining WPC stakes after 17 years in-ground exposure near Saucier, Mississippi and Madison, Wisconsin.

Blend Number[1]	Decay	Termite	Number of stakes remaining and included in rating
Mississippi			
1	2.8 ± 3.3	8.0 ± 1.7	6
2	8.4 ± 0.5	9.6 ± 0.5	5
3	9.0	9.0	1
4	9.2 ± 0.4	8.0 ± 0.7	5
Wisconsin			
1	6.8 ±0.7	---[2]	8
2	8.0 ± 0.5	---[2]	9
3	7.0 ± 0.6	---[2]	7
4	8.3 ± 1.1	---[2]	7

[1]Blends = 1. No additives; 2. ZnB only; 3. UV stabilizer package only; 4. ZnB and UV stabilizer package
[2] No termites were present at Wisconsin site.

3.2.2 Above-ground deck boards

Above-ground deck boards (30.5 x 139.7 x 609.6 mm) were mounted on racks horizontally and visually rated (Table 1 and 2) for each of 5 criteria: 1) cracking and checking, 2) color change, 3) decay, 4) mold and stain, and 5) termite attack (Mississippi only). In addition to the number ratings, visual observations were noted at each inspection. Unlike the in-ground stakes, all of the above-ground deck boards are still remaining in test at each test site.

Table 6 shows the rating results, with standard deviations, of field exposed above-ground deck boards in the fall of 2019, after 17 years. The cracks/checking ratings range from 7.0 to 8.5 with no failures and results were similar at both test sites. Blends 1 and 2 (without UV package) had more severe checking/rough surfaces than blends 3 and 4 (with the UV package). The color change ratings range from 0 for blends 1 and 2 (without UV package) to 7 for blends 3 and 4 (with UV package) at both test plots. The color change ratings were made by visually comparing the exposed boards to unexposed specimens (Fig.2). The UV package has a colorant included which faded over time, but was still present after 17 years.

There were no termites present on any of the above-ground deck boards in Mississippi, with ratings of all 10's (Table 6.) The rack was made of CCA and no termites/tunnels were found on the rack. Wisconsin does not have termites at the Valley View test site, but it was included to calculate the "Overall Rating."

The deck boards in Mississippi had higher decay and mold/stain ratings than those in Wisconsin for all blends (Table 6.) In Mississippi, blends 2 and 4 (with ZnB) had decay ratings of all 10's compared to 9 and 9.5 for blends 1 and 2, respectively. This trend was not seen in Wisconsin, with the decay ratings from 4 to 5.6. The mold/stain ratings ranged from 4.0 to 6.9 for Mississippi and all 0's for Wisconsin. None of the blends were better than another regarding mold and stain. It was unexpected that the above-ground deck boards performed worse in Wisconsin with respect to decay and mold since the biodeterioration hazard is worse in Mississippi with more rainfall and higher temperatures. A possible explanation is that Wisconsin has lower temperatures such that when the boards get wet, they do not dry out as fast, therefore having more conducive conditions for bioaccumulation. Another factor may be the snow cover on the boards in Wisconsin which can maintain an overall higher moisture content. Fig. 2 compares the above-ground deck boards from a.) Wisconsin versus b.) Mississippi after 17 years outdoor exposure.

Table 6: Visual ratings (average ± standard deviations) of above ground wood-plastic deck boards after 17 years in test. Stakes placed in test on both the Harrison Experimental Forest, Saucier, Mississippi, October, 2002 and Valley View Test site, Madison Wisconsin, November 2002. No termites at the Wisconsin test site, but added 10 ratings to compare overall rating to Mississippi.

	Above Ground Ratings after 17 years exposure (2019)					
Blend Number*	**Cracks/ Checking**	**Color Change**	**Decay**	**Mold/ Stain**	**Termite**	**Overall Rating**
Mississippi						
1	7.0 ±0.0	0.0	9.0 ±0.0	6.9 ±0.3	10.0 ±0.0	32.9 ±0.3
2	7.3 ±0.5	0.0	10.0 ±0.0	4.6 ±1.0	10.0 ±0.0	31.9 ±0.9
3	8.5 ±0.5	7.0 ±0.0	9.5 ±0.5	4.0 ±0.0	10.0 ±0.0	39.0 ±0.7
4	8.4 ±0.5	7.0 ±0.0	10.0 ±0.0	4.2 ±0.6	10.0 ±0.0	39.6 ±0.7
Wisconsin						
1	7.0 ±0.0	0.0	4.0 ±0.0	0.0	10.0 ±0.0	20.8 ±0.4
2	7.0 ±0.0	0.0	5.6 ±1.2	0.0	10.0 ±0.0	23.0 ±1.8
3	8.0 ±0.0	7.0 ±0.0	4.4 ±0.8	0.0	10.0 ±0.0	29.0 ±1.2
4	8.0 ±0.0	7.0 ±0.0	4.7 ±1.2	0.0	10.0 ±0.0	29.7 ±2.4

*Blends = 1. No additives; 2. ZnB only; 3. UV stabilizer package only; 4. ZnB and UV stabilizer package

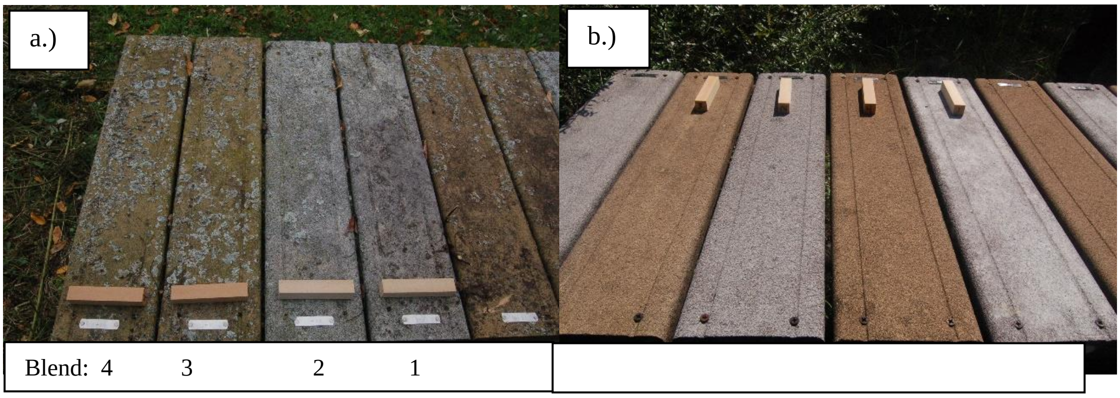

Figure 2. Above ground deck boards exposed for 17 years near: a.) Madison, Wisconsin and b.) Saucier, Mississippi. (Blends = 1. No additives; 2. ZnB only; 3. UV stabilizer package only; 4. ZnB and UV stabilizer package)

4. CONCLUSIONS

Field decay results were similar to laboratory fungal decay tests (not shown), both of which demonstrated that ZnB can improve WPC decay performance. ZnB at 1% gave some protection from decay in-ground, but higher levels or a more potent fungicide are needed for longer protection. The UV package helped with the color change in above-ground deck board exposure. The combined ZnB and UV package blend provided protection from decay and weathering, but mold/stain are still an issue for aesthetics and cleaning is needed. Field observations and measurements help to improve both accelerated laboratory test methodology as well as the understanding of the long term durability of WPCs.

Multiple exposure site locations with different climatic conditions are needed to evaluate WPC materials. There is a higher decay hazard in Mississippi, but moisture is still an issue in Wisconsin along with freeze/thaw cycles and a greater bioaccumulation on above-ground boards. There is less precipitation in Wisconsin, but the lower temperatures may provide more favorable conditions for fungal growth on the above-ground boards. There were different initiation periods before in-ground decay occurred at each location (12 years Wisconsin vs. 2 years Mississippi). Although it takes a longer time for in-ground decay in Wisconsin, the above ground stakes showed more bioaccumulation than in Mississippi.

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