Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Forest Products Laboratory | General Technical Report FPL–GTR–303 | July 2024

Fungal and Moisture Durability of Wood–Plastic Composites

Summarizing 20 Years of Forest Products Laboratory Research

Rebecca E. Ibach
Craig M. Clemons

Abstract

After wood–plastic composites (WPCs) began to be used in exterior applications, early failures were noticed, which created considerable uncertainty about how resistant these materials were to environmental factors such as fungal attack. To address these concerns, we began a research program to develop a knowledge base on the fungal durability of WPCs. This report summarizes approximately 20 years of Forest Products Laboratory research on this subject. Improved evaluation protocols along with the application of new instrumental techniques were used to better understand and assess the fungal degradation of WPCs and identify key contributing factors. It appears that after an initial period of outdoor exposure, stresses resulting from moisture-induced expansion of wood particles create microcracks in the plastic matrix, ultimately providing decay fungi access to the wood component of WPCs. Approaches for improving fungal durability of WPCs using antimicrobials, additives, chemical treatments, and chemical modification of the wood component were explored during this research program.

Keywords: Wood–plastic composites, fungal decay, durability, moisture, soil block, field testing

Contents

July 2024

Ibach, R.E.; Clemons, C.M. 2024. Fungal and moisture durability of wood–plastic composites: summarizing 20 years of Forest Products Laboratory research. General Technical Report FPL-GTR-303. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 13 p. https://doi.org/10.2737/FPL-GTR-303

USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI, USA 53726
(608) 231-9200
SM.FS.MailroomFPL@usda.gov

This and many other Forest Service research publications are available for download through TreeSearch at https://research.fs.usda.gov/treesearch/.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Fungal and Moisture Durability of Wood–Plastic Composites

Summarizing 20 Years of Forest Products Laboratory Research

Rebecca E. Ibach, Research Chemist, retired
Craig M. Clemons, Research Materials Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Introduction

Shortly after wood–plastic composites (WPCs) came into use in exterior applications such as decking and fencing, consumers began to notice that these materials were experiencing early failures, which caused considerable uncertainty as to how resistant these materials were to environmental factors such as fungal attack. Contributing to the uncertainty was the lack of consistency in processing methods and formulations and also the use of different (and sometimes inappropriate) evaluation protocols. Other factors that needed exploration were the properties and interactions of WPC constituent materials and the complexity of WPC degradation mechanisms caused by simultaneous exposure to environmental factors such as fungi, moisture, and ultraviolet (UV) radiation, which vary by time and location.

To address the uncertainty surrounding the performance of WPCs, we began a research program to develop a knowledge base on the fungal durability of WPCs. This report summarizes approximately 20 years of Forest Products Laboratory (FPL) research on WPC fungal durability. The work focused on three areas: (1) developing appropriate protocols for evaluating the fungal durability of WPCs, (2) understanding how WPCs degrade and identifying the important contributing factors, and (3) demonstrating how this understanding can lead to new approaches for improving durability. In this summary, we provide a broad perspective on the fungal durability of WPCs, summarize protocols, and highlight key results. More specific details of individual investigations can be found in the publications cited. Tables 1 and 2 provide grading criteria for field tests on WPCs, Table 3 details the isolated fungal cultures, and the Appendix provides some helpful supplemental data.

Summary of Forest Products Laboratory Research Program on Wood–Plastic Composites

Wood–plastic composites typically contain 50% to 60% of wood by weight in the form of a particulate or wood flour. Also, they usually contain 40% or more of a thermoplastic polymer, which is most often a polyethylene, polypropylene, or polyvinyl chloride. However, wood and thermoplastic are not the only components in WPCs. They also contain additional materials (“additives”) that are added in small amounts to improve processing and performance. Although specific formulations are highly proprietary, additives such as antioxidants, lubricants, colorants, light stabilizers, fungicides, and coupling agents have all been used to some extent in WPCs.

The components in WPCs interact in a variety of ways. For example, the thermoplastic matrix can at least partially encapsulate the wood particles, slowing moisture sorption and improving durability. However, the slow moisture sorption of WPCs must also be considered when evaluating the durability of such composites because exposure times are much longer in service than during laboratory investigations. Not all material interactions are positive. Wood shrinks and swells considerably with changes in moisture but very little with temperature. The opposite is true with most thermoplastics used as matrices for WPCs. Consequently, matrix cracking can be a problem if significant moisture is absorbed (especially at elevated temperature) or the thermoplastic matrix is brittle. Additives can further complicate material performance. For example, they can migrate to interfaces between components or surfaces, block UV radiation, scavenge free radicals, improve the adhesion between wood and plastic, or slow moisture sorption.

Manufacturing processes can also influence WPC performance, including moisture sorption and fungal durability. For example, the pressures developed by different processes affect how much the wood particles are compacted and the amount of thermoplastic present at the surface of the composite, which can affect the rate of moisture sorption and fungal decay. Understanding the many influences on the material behavior is critical in predicting fungal durability of WPCs.

In most of our investigations, we prepared our own composites to control material and process variables rather than investigating commercial WPCs of unknown composition and process history. To reduce the number of material variables, investigations were typically performed

Table 1—Grading system to evaluate both in-ground and aboveground wood–plastic composites and untreated wood controls for decay and termites

Grade number	Description of condition	
	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 or stain for aboveground wood–plastic composites and solid-wood controls for cracks or checking, color change, and mold or stain

Grade number	Description of condition		
	Cracks or checking	Color change	Mold or stain
10	Sound	No change in color	No stain
9	Slight checking	Slight change (such as loss of green in CCA treated, slight gray)	Slight stain
8	More checking	More change (such as brown to gray)	More stain
7	Severe checking	Still more change (such as untreated, yellow to gray)	Blotched on whole stake
0	Failure due to checking	Failure (such as gray to white or all black stain)	Black

on composites made from 50% to 60% wood flour by weight in a high-density polyethylene (HDPE) matrix, a typical wood flour content and matrix used in exterior WPCs such as deck boards. Additives were used as necessary (for example, lubricant needed for extrusion) or were included as a material variable in the investigations and were noted. Full-size, commercial WPC deck boards were used in several investigations for comparison (Ibach and others 2016, 2018a; Sun and others 2014, 2017).

Fungal Evaluation Protocols

Laboratory-Scale Fungal Testing

Laboratory-scale fungal testing offers the advantages of small-scale evaluation in a carefully controlled environment. However, because of differences in material behavior, fungal testing protocols historically used for solid wood needed to be revised to evaluate WPCs more appropriately and explore degradation mechanisms in more depth. Consequently, much of our initial laboratory work on WPCs

Table 3—Cultures isolated from wood–plastic composite decking boards exposed outdoors in Hilo, Hawaii, and identified using DNA analysis of the ITS[a] sequence[b]

Taxonomic name[c]	Culture number[d]	Isolation site	Exposure location
Pycnoporus sanguineus	JEH-155	Interior	Sun
Pycnoporus sanguineus	JEH-156	Fruiting body	Sun
Perenniporia tephropora	JEH-157	Interior	Sun
Perenniporia tephropora	JEH-158	Interior	Sun
Stereum sp.	JEH-159	Interior	Sun
Unknown ascomycete	JEH-160	Interior	Sun
Unknown ascomycete	JEH-161	Surface	Sun
Unknown ascomycete	JEH-162	Surface	Sun
Pestalotiopsis vismiae	JEH-178	Interior	Shade
Pycnoporus sanguineus	JEH-180	Fruiting body	Shade
Pycnoporus sanguineus	JEH-181	Fruiting body	Shade
Pestalotiopsis vismiae	JEH-182	Interior	Shade
Pestalotiopsis vismiae	JEH-183	Interior	Shade
Dacryopinax spathularia	JEH-189	Fruiting body	Sun
Epicoccum nigrum	JEH-192	Interior	Sun
Pycnoporus sanguineus	JEH-197	Interior	Shade
Perenniporia tephropora	None	Fruiting body	Shade
Perenniporia tephropora	None	Fruiting body	Shade
Pycnoporus sanguineus	None	Fruiting body	Sun
Pycnoporus sanguineus	None	Fruiting body	Sun
Pycnoporus sanguineus	None	Fruiting body	Shade

[a]ITS, internal transcribed spacer.
[b]Ibach and others (2018a).
[c]Cultures are on deposit in the Center for Mycology Research culture collection https://www.nrs.fs.usda.gov/tools/mycology/
[d]None indicates that DNA was isolated directly from the fruiting body.

(Clemons and Ibach 2002, 2004) explored modifications to the standard soil bottle fungal tests for solid wood (ASTM D1413, ASTM D2017, and AWPA E10) (ASTM 1990a, 2005; AWPA 2012).

For example, additional soil bottles were prepared for the purpose of evaluating samples at intermediate times to better understand the progression of material behavior during the course of the test. Also, because mechanical properties are often important performance criteria for WPCs, the specimen shape was changed from a cube to long, thin specimens, which is required by flexural testing protocols (ASTM D790-84) (ASTM 1990b).

Two major moisture-related issues also needed to be addressed in the fungal test protocols: (1) the very slow moisture sorption rate of the WPCs relative to the limited duration of the test and (2) the need to separate the damage caused by fungal attack from that caused by moisture alone.

The modification of the specimen dimensions to accommodate flexural testing also increased surface area, which accelerated moisture sorption. Additionally, we investigated conditioning methods (for example, water soaking, cyclic boiling and drying, weathering) to further accelerate moisture sorption and to simulate exposures that WPCs might experience in service. In addition to weight and flexural performance, moisture content (MC) was determined before and after preconditioning and periodically during the soil-block tests. Finally, to help separate the effects of moisture sorption from fungal attack, the inoculated bottles were compared with a second set of soil bottles prepared using the same protocols except that the bottles were not inoculated (“no-fungus controls”). Figure 1 shows an uninoculated (left) and inoculated (right) modified soil bottle after a 12-week test. Unless otherwise specified, the brown-rot fungus, *Gloeophyllum trabeum*, was used in the modified soil bottle tests and the wood flour was western pine.

After being established, the modified soil-block tests were used to better understand the mechanisms of degradation as well as the effects of processing method (Clemons and Ibach 2002, 2004), additives (Ibach and Clemons 2006; Ibach and others 2003, 2007), fungicides (Ibach and others 2003), chemical modifications/treatments (Ibach and Clemons 2002, 2006; Ibach and others 2007, 2014), and different types or combinations of exposures (for example water, humidity, UV light) (Ibach and Clemons 2006; Ibach and others 2003, 2007).

Field Testing

Laboratory decay testing can be helpful in predicting long-term durability, but field studies are also needed to further understand degradation mechanisms, validate laboratory protocols, and assess overall performance. Field exposure can encompass deterioration caused by moisture, fungi, UV radiation, wind, temperature, freeze–thaw cycling, wet–dry cycling, termites, and mold.

Field tests were conducted on aboveground and in-ground stakes at the Valley View test site in Madison, Wisconsin, and in the Harrison Experimental Forest in Saucier, Mississippi. Field evaluations of full-size deck boards of select compositions were also evaluated at the Wisconsin and Mississippi test sites and in Vancouver, British Columbia, and Hilo, Hawaii. Figures 2 and 3 show in-ground stakes and aboveground full-size boards, respectively, at the Mississippi test site.

Figure 1—Modified soil bottles after a 12-week test: uninoculated (left) and inoculated (right).

Figure 2—In-ground stakes at the Mississippi test site.

Figure 3—Aboveground full-size boards at the Mississippi test site.

As with laboratory testing, traditional protocols for field testing of solid wood (ASTM D1758 or AWPA E7) (ASTM 2006, AWPA 2021) were modified. Solid wood is only visually rated for fungal attack and termites (when present). However, for aboveground WPCs, we also rated for checking/cracking, color change, and mold/stain. Grading criteria for the field tests on WPCs are given in Tables 1 and 2. There were challenges in evaluating the WPCs in the field, causing the need for accommodations and solutions. For example, WPCs do not soften with fungal attack as solid wood does, making decay ratings more difficult. Although not unique to WPCs, major events such as hurricanes and falling trees can complicate analyses.

Mechanisms of Fungal Degradation and Key Factors Affecting Them

Effects of Moisture Sorption Alone

Fungi have four basic requirements: food, moisture, temperature, and oxygen. Encapsulating wood in plastic can reduce fungal access and moisture intrusion. Unfortunately, wood is not completely encapsulated when preparing WPCs by conventional processing methods at the wood flour levels commonly used (50% to 60% by weight). This allows the intrusion of water, damaging the composite and eventually providing access to the wood for fungal hyphae. Consequently, much early research focused on understanding and accelerating moisture sorption to simulate moisture sorption of WPCs in the field.

Figure 4 shows the slow initial water sorption by WPCs processed by different methods. Specimens formed with higher pressure processes (for example, injection molding) have plastic-rich surfaces and tend to absorb less moisture and do so more slowly (Ibach 2010).

This moisture sorption also depends on the nature of exposure to water (for example, time, temperature, and number of exposure cycles). Not surprisingly, more extreme exposures result in greater moisture penetration and more damage accumulation.

For example, Figure 5 shows the damage caused by cyclic boiling. The swelling and shrinking of the wood particles damaged the interface between the wood and plastic matrix and could eventually lead to matrix cracking. This damage can reduce mechanical properties and provide fungal hyphae with access to the interior of the composite. How the WPCs are exposed to water determines the type and extent of damage (Clemons and Ibach 2004).

Conditioning Prior to Laboratory Fungal Testing

Different approaches to moisture exposure protocols prior to laboratory fungal testing were investigated. Cyclic boiling led to more damage than did 2 weeks of water soaking at room temperature (Clemons and Ibach 2004). Ibach and Clemons (2006) and Ibach and others (2003) demonstrated that WPCs conditioned by weathering (cyclic water spray and UV radiation exposure) and then water soaking gave weight losses greater than did conditioning by just water soaking. Also, a 5-day water soak at elevated temperature (70 °C) was found to be more aggressive than a 2-week water soak at room temperature in later work (Ibach and others 2013).

Not surprisingly, more aggressive moisture conditioning procedures also led to greater moisture sorption during fungal tests. For example, Figure 6 compares the effects of room temperature water soaking and cyclic boiling protocols on moisture sorption during the modified soil-block tests. Little differences in MC were found except for extruded WPCs near the end of the test (Clemons and Ibach 2004).

Weight loss correlated well with MC, as shown in Figure 7, which shows the MC–weight correlation for the specimens from Figure 6. A consistent trend in the laboratory tests was that significant weight losses were typically found after the composite MC reached roughly 12% to 15% (Clemons and Ibach 2004). Because the WPCs contained 50% wood, this

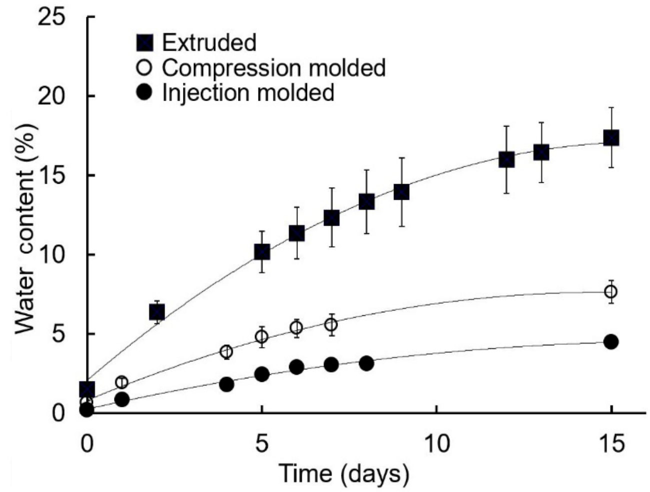

Figure 4—Effect of processing method on the moisture sorption of wood–plastic composites containing 50% pine wood flour during water soaking.

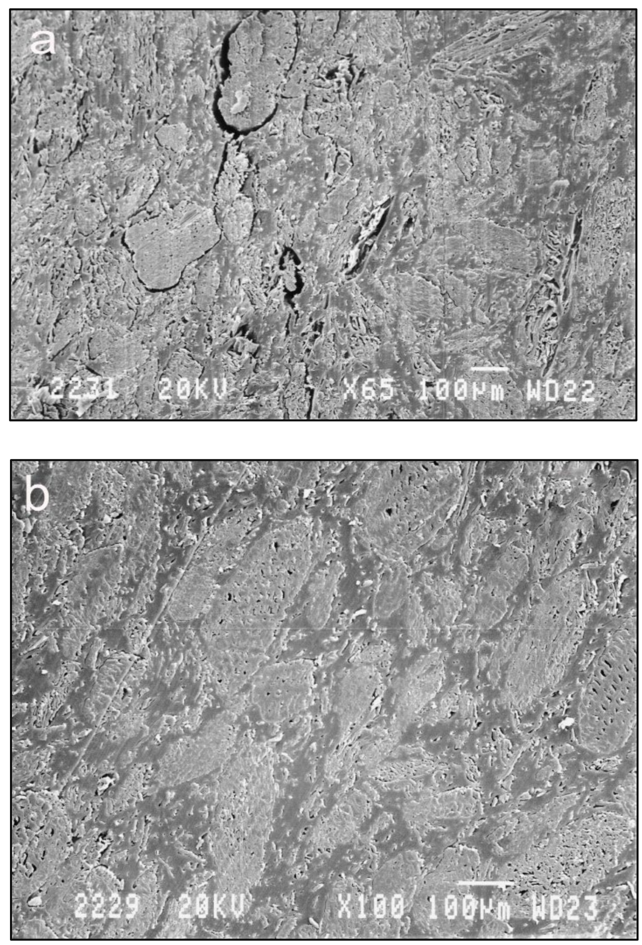

Figure 5—Effect of cyclic water sorption on composite microstructure (five cycles of 2 h of boiling followed by 22 h of oven-drying): (a) microtomed surface of composite after cyclic boiling, (b) control sample.

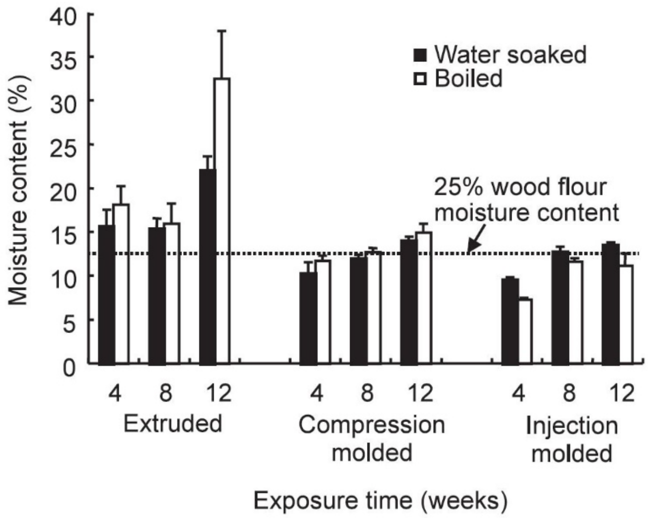

Figure 6—Effects of processing and preconditioning method on moisture sorption of wood–plastic composites during soil-block test. Error bars are one standard deviation.

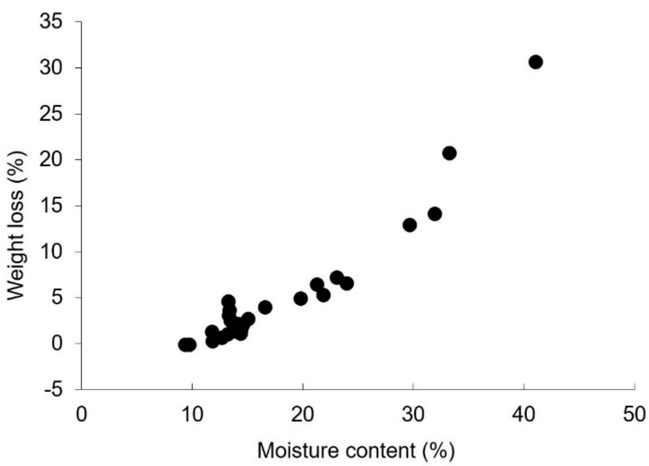

Figure 7—Correlation between weight loss (dry basis) and moisture content in soil-block test of wood–plastic composites.

corresponds to an average wood flour MC of about 24% to 30%, which is near the threshold for the onset of fungal attack. The HDPE matrix is very hydrophobic and does not absorb water.

Because WPCs are often used as semistructural applications such as deck boards, mechanical performance is an important material property. Consequently, flexural tests were performed on specimens that had been dried after fungal testing. To separate the effects of fungal attack from damage cause by water only, the specimens from inoculated soil bottles were compared with those from uninoculated soil bottles. Results for the extruded WPCs are shown in Figure 8. Water soaking and especially cyclic boiling conditioning procedures reduced flexural strength, but there

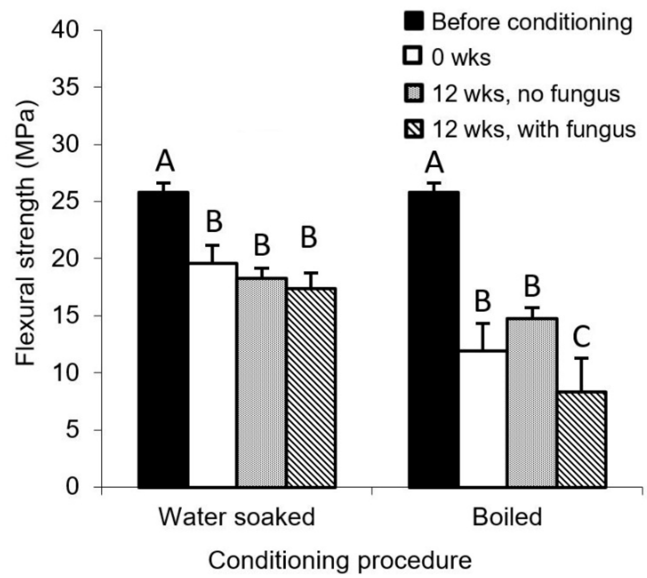

Figure 8—Flexural tests on extruded composites. Bars with the same letter are statistically equivalent at 95% confidence.

were no statistically significant differences in flexural strengths between inoculated and uninoculated WPCs after fungal testing for specimens conditioned by water soaking. However, with the more heavily damaged boiled specimens, fungal attack further reduced flexural strength (Clemons and Ibach 2004).

Field Testing

Short-term laboratory testing on small specimens in controlled environments led to an initial understanding of some key factors and mechanisms of moisture intrusion and fungal attack. However, long-term field testing on larger specimens was necessary to understand moisture sorption and fungal attack in a less-controlled, multi-exposure environment closer to what would be experienced in use.

Aboveground and In-Ground Field Stakes

Aboveground and in-ground tests were installed at the Wisconsin and Mississippi test sites. Performance depended on specific formulation and exposure conditions, the details of which are not fully described here. However, several general trends are discussed in the following paragraphs.

Not surprisingly, differences in location and type of exposures (for example, shade or sun) affected performance (Ibach and Clemons 2017; Ibach and others 2007, 2018b, 2020). All ratings for aboveground specimens were lower for Wisconsin than for Mississippi, probably because of greater bioaccumulation. However, in-ground decay ratings tended to be lower in Mississippi. Also, termites were present at the Mississippi site but not at the Wisconsin site.

Surface properties such as the growth of mold/stain fungi or color changes began in the first year, but the onset of macroscopic cracking, decay, and termite attack appeared to occur between 1 and 10 years after exposure, depending on geographic location and exposure conditions. However, this delay in macroscopic evidence does not necessarily mean that fungal attack and moisture intrusion had not yet begun. Damage may simply have been insufficient to be detected visually.

The relationship between moisture sorption and fungal attack was of particular interest not only in the laboratory tests but also in the field tests. However, MC itself is difficult to measure in the field, and most of the moisture distribution investigations were performed on full-size deck boards installed above ground (these investigations are summarized in the next section). Nevertheless, the effects of moisture sorption beyond just fungal decay (for example, cracking and swelling of specimens) were monitored during field testing, and inferences regarding mechanisms and performance could be made from the findings. Select results on cracking are subsequently discussed, and those on swelling are discussed in the Chemical Modification and Treatments section.

Figure 9 summarizes results for stakes installed in 2002 in the shade at the Wisconsin test site. These results demonstrate how moisture-induced macroscopic crack development relates to fungal decay in aboveground stake tests. No decay or macroscopic cracks were detected for the first 6 years (decay and checks/cracks all rated as 10). Interestingly, after this initial 6-year period, decay was visually detected prior to the onset of macroscopic cracking (that is decay ratings decreased but the checks/cracks rating remained at 10). Small cracks may have existed but were not detected or fungal hyphae may have helped generate the cracks by transporting water into the stakes (Ibach and others 2018a). After 2010, there was a clear correlation between the decay and crack development based on the fact that the composite was increasingly damaged.

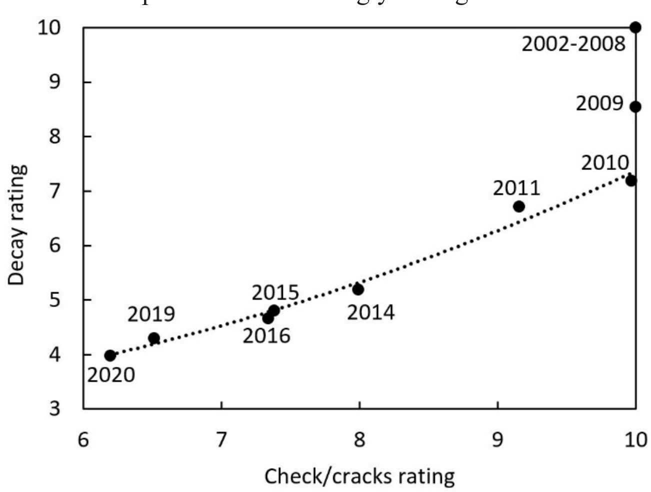

Figure 9—Correlation between decay and checks/cracks ratings for aboveground stakes of several formulations. Wisconsin test site for an 18-year period. Data from Table A1 in the Appendix.

Full-Size Deck Boards

Multiple methods were used to investigate moisture distribution through the thickness of the full-size deck boards and its effect on fungal decay.

In one method, boards were frozen, carefully sectioned, and weighed before and after drying to determine the MC of each section (Ibach and others 2013). Figure 10 shows how the moisture distribution changed with time in WPCs installed above ground in a sunny location in Hilo, Hawaii. Although short-term variability existed because of variability in precipitation, sunlight, temperature, and other weather conditions, two overall trends emerged: (1) the MC tended to be higher near the surface and (2) MC of the board interior increased with time. In less than a year, most of the board had an MC exceeding that required for the onset of fungal degradation. Similar trends but lower MCs were found in shaded locations.

In a series of investigations, magnetic resonance imaging (MRI) (Sun and others 2014, 2017; Ibach and others 2016), scanning electron microscopy (SEM) (Sun and others 2014), and micro X-ray computed tomography (CT) (Sun and others 2014) were used to provide additional insight into the fungal decay process of full-size deck boards. The detection of free water by MRI correlated well with the sectioning method of determining moisture distribution (Fig. 11) (Sun and others 2014). Although void analysis from CT scans showed a higher average percentage volume of voids after field exposure, no apparent relationship was established between the presence of free water detected by MRI and the average volume of voids detected by CT. As with stake field testing, fungal decay appeared to be a self-propagating process requiring an initiation period where no obvious decay damage was observed. However, after 8 years, many different decay fungi species had colonized and damaged the WPCs (Fig. 12; Table 3) (Sun and others 2014).

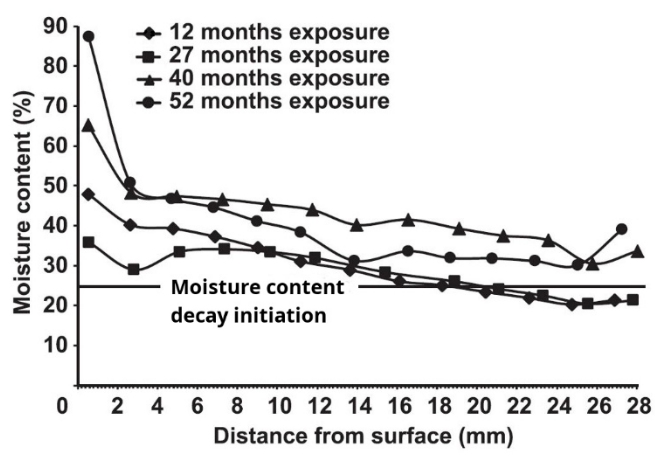

Figure 10—Wood moisture content distribution in wood–plastic composite deck boards as measured from the upper board surface in boards exposed in a sunny location in Hilo, Hawaii.

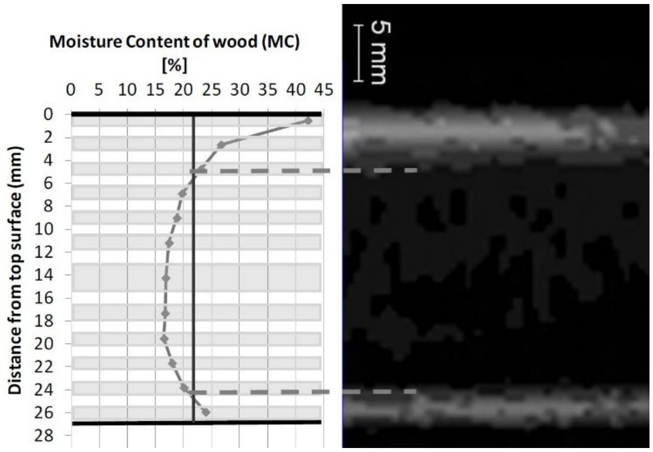

Figure 11—Distribution of moisture through the thickness of a wood–plastic composite board by the sectioning method (left) and MRI image (right). Light areas in the MRI image show free water (used with permission from International Research Group for Wood Protection and the authors of Sun and others (2014)).

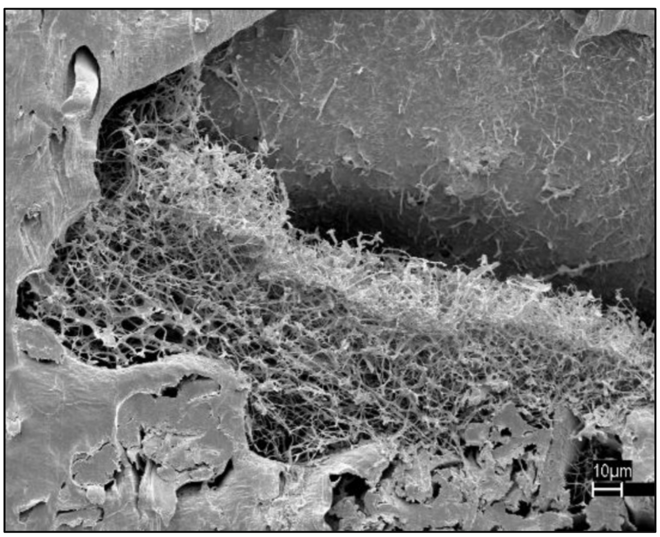

Figure 12—High-magnification scanning electron microscopy image of a mycelial mass of wood decay fungi.

In later work, Ibach and others (2018a) further refined the understanding of the mechanism of mechanical property reduction in full-size, commercial WPC deck boards. Most of the mechanical property reduction occurred on the underside of the deck boards, and UV radiation had little effect on the flexural properties even after 10 years. However, long-term stresses between expanding wood particles created microcracks in the plastic matrix, and this moisture-induced slow crack growth provided decay fungi access to the wood component of WPCs. Another key finding was that simulating slow crack growth in laboratory specimens required soaking of specimens in hot (rather than room temperature) water for an extended period because both heat and moisture are required for slow crack growth, which is the mechanism for matrix failure in the field. Specific temperatures and water soaking times necessary to simulate field exposure depended on the environmental conditions at a particular test site. For example, soaking specimens in water at 70 °C for 5 days was necessary to simulate long-term composite exposure at the test site in Hilo, Hawaii.

Improving Fungal Durability

Methods of reducing moisture sorption and fungal decay were also explored. These can be divided into two main categories: (1) additives and (2) chemical modification/treatment.

Additives

One of the most obvious ways to protect WPCs from decay is by the addition of biocides or antimicrobials. In both our laboratory and field tests, the most effective antimicrobial investigated was zinc borate (ZnB) added at 1% by weight (the highest level investigated) (Ibach and others 2003, 2020). Besides efficacy, ZnB has the advantages of low cost, low toxicity for both humans and the environment, low water solubility, which leads to leach resistance, and the ability to withstand typical processing temperatures (Ibach 2010). Figure 13 summarizes ratings for in-ground field stakes in both Mississippi and Wisconsin that contained several antimicrobials at different levels in WPCs with and without a commercial colorant. Despite some data scatter, ratings for WPCs containing 1% ZnB are the highest of any of the formulations investigated whether a colorant was used or not. Zinc borate also showed good efficacy in laboratory testing, greatly reducing weight losses even in specimens with high MCs (Ibach and others 2003).

In the investigation summarized in Figure 13, the colorant was added to improve UV radiation resistance in aboveground stakes but was also added to the in-ground stakes for consistency. The fact that the colorant had a major influence on the decay resistance of in-ground samples was unexpected. Notably, the colorant was supplied as a concentrate, which often contains other additives besides pigments, such as carrier resins, process aids, and binders. These additives help disperse the pigment, compatibilize it with the plastic matrix, and can aid in processing of the composite. They can also have similar effects on the wood flour, not just the pigment, potentially increasing wood flour encapsulation or wood–matrix bonding, which has been shown to slow moisture sorption. This demonstrates how additives can reduce moisture sorption and increase fungal resistance through mechanisms other than toxicity. However, the complexity of formulating WPCs increases quickly as the number of constituent materials increases, and additives must be carefully chosen to avoid negative interactions.

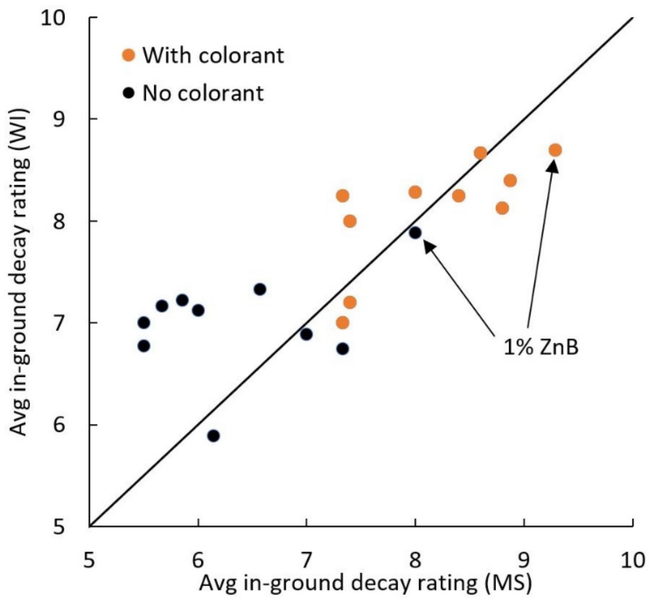

Figure 13—Effect of zinc borate (ZnB) and colorant on decay resistance. Ratings for in-ground field tests in Mississippi (MS) and Wisconsin (WI) after 17 years. Data from Table A2 in the Appendix.

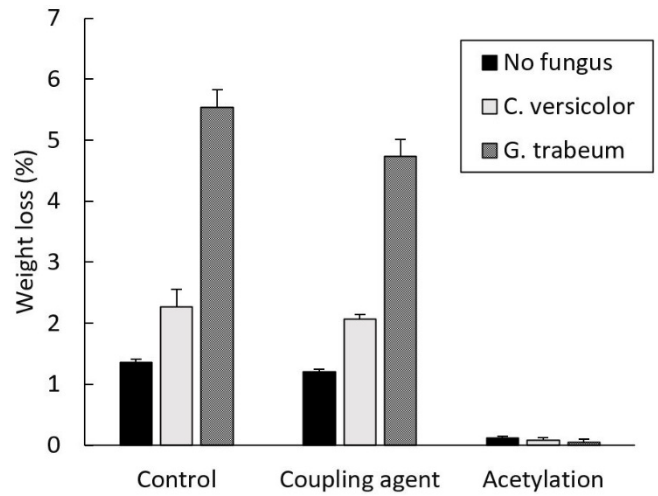

Figure 14—Weight losses of water-soaked wood–plastic composites during modified soil-block testing (*C. versicolor* is a white-rot fungus; *G. trabeum* is a brown-rot fungus).

Chemical Modifications and Treatments

Although additives can improve the fungal durability of WPCs, the most effective way to do this is by chemically modifying the wood to permanently make it more hydrophobic. This not only keeps the wood MC below the threshold for fungal attack of about 25% but also minimizes damage from the cyclic swelling and shrinking of the wood component caused by moisture sorption.

Early work investigated the chemical modification of wood flour by acetic anhydride, butylene oxide, or propylene oxide prior to the fabrication of the composites (Ibach and Clemons 2002). Acetic anhydride treatment performed the best and was used in later work in the laboratory and field comparing different approaches to improving fungal durability of WPCs (Ibach and Clemons 2006, 2017; Ibach and others 2007; Segerholm and Ibach 2013). Acetylation is particularly interesting, not only because of its efficacy but also because of its low toxicity, its low cost, and recent commercial interest in its use in related areas, including as a solid wood treatment (Ibach 2010).

Figure 14 demonstrates the large reduction in weight loss during modified soil-block tests when the wood flour in the WPCs was acetylated. A composite containing a coupling agent was also included as a comparison because coupling agents have been used in WPCs to slow moisture sorption (Ibach and others 2007).

In a complementary investigation, composites made from acetylated wood fiber and polylactic acid retained mechanical performance far better than composites with unacetylated wood fiber when exposed to multiple soil types (Segerholm and others 2012b).

In another investigation, the rates of moisture sorption of WPCs that were artificially aged by exposing them to UV radiation, moisture, and fungi were continuously tracked using a microbalance. Acetylating the wood used in the WPC composite slowed moisture sorption. Interestingly, higher moisture sorption rates were found for WPCs exposed to *Trametes versicolor*, a white-rot fungus, than for those exposed to the brown-rot fungus, *G. trabeum* (Segerholm and others 2012a).

In field tests, WPCs made from acetylated wood flour showed excellent decay resistance (Fig. 15a), cracking/checking resistance, dimensional stability, and termite attack resistance (Ibach and others 2007, 2018b). Figure 15b shows that most of the moisture-induced thickness changes for WPCs with unacetylated wood flour occurred in the first year. This was 6 years before ratings for decay began to decrease, demonstrating how degradation processes begin well before any visual signs are present.

More recently, novel cobalt(II) sulfate and organosilicate modifications of wood flour were investigated with the goal of providing nontoxic methods of wood protection not only for fungal resistance but also for UV radiation resistance (Ibach and others 2017).

Techniques such as X-ray scattering (Ibach and Plaza 2019), thermal neutron imaging (Plaza and others 2021a), and small-angle neutron scattering (SANS) (Ibach and others 2022; Plaza and others 2021b, 2022) are being used to help understand the nanostructural mechanisms behind decay and moisture resistance of chemically modified wood. Differences were found between the nanostructures of swollen wood and unmodified wood fibers. Because fungal

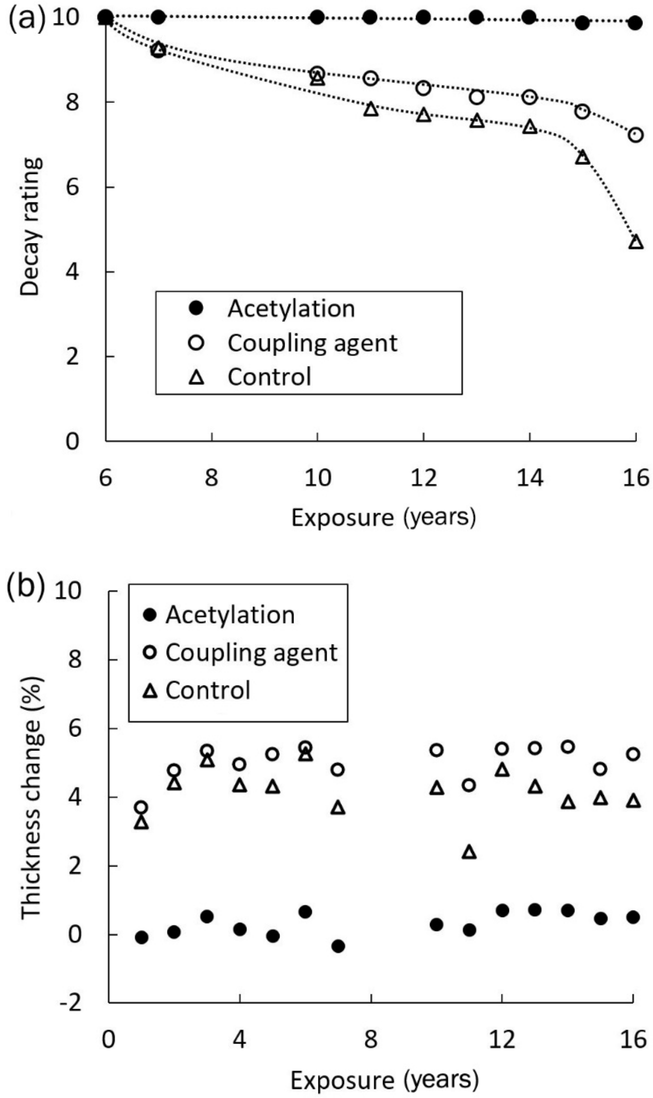

Figure 15—Wood–plastic composite stakes exposed at Wisconsin test site: (a) in-ground decay ratings (for the first 5 years, decay for all stakes was rated as 10); (b) thickness changes.

action occurs on a microscale and nanoscale, the investigation of nanostructures may lead to better strategies for preventing fungal decay. The modifications led to differences in the nanoscale features observed in samples that were exposed to brown-rot fungal attack compared with unmodified wood fibers and solid wood blocks modified with alkylene oxides.

Conclusions

Because of the large amount of wood used in WPCs, some issues related to their fungal durability have similarities to those of solid wood. However, WPCs are more complex because of other components present (such as plastic matrix and additives), their differing material behaviors, and the interactions between them. Consequently, how WPCs fail is different from how solid wood fails, and both laboratory and field test protocols needed to be modified to better understand and assess fungal resistance.

The new protocols, along with the application of new instrumental techniques, were used to better understand the mechanisms of fungal degradation of WPCs. It was initially hoped that encapsulating wood flour in a hydrophobic and durable plastic matrix would sufficiently protect it from moisture intrusion and fungal decay, but protection was not necessarily sufficient for the entire life of the composite in an exterior application. An initiation period where the composite remains relatively undamaged typically lasts about 1 to 7 years, depending on formulation and exposure conditions. However, over the long term, stresses resulting from moisture-induced expansion of wood particles create microcracks in the plastic matrix. This moisture-induced slow crack growth ultimately provides decay fungi access to the wood component of WPCs.

Various approaches for improving fungal durability were explored, and acetylation of the wood flour prior to composite fabrication was found to be the most effective. Such an approach keeps the MC from reaching the threshold for the onset of fungal attack and also helps prevent stress-induced slow crack growth, which can lead to moisture intrusion and provide access to wood flour for fungal hyphae.

Ultimately, this work has led to important modifications in standards such as AWPA E10 on soil-block testing and ASTM D7032 (ASTM 2017) on the evaluation of WPC deck boards and guardrails. With the current trend toward biobased materials, investigations such as those summarized here will only become more important as wood, or components of wood, are increasingly used in combination with other materials.

Acknowledgments

Such a large and long-term investigation does not happen without many contributors. The coauthors acknowledge the many collaborators and coauthors of the referenced literature, especially Marek Gnatowski, Grace Sun, and Mathew Leung at the Polymer Engineering Company and fellow Forest Service employees, including those at the Forest Products Laboratory and the Harrison Experimental Forest.

Literature Cited

ASTM. 1990a. D1413. Standard test method for wood preservatives by laboratory soil-block cultures. In: Annual Book of ASTM Standards, Vol. 4. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 1990b. D790-84. Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. In: Annual Book of ASTM Standards, Vol. 8. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2005. D2017. Standard test method of accelerated laboratory test of natural decay resistance of woods. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2006. D1758. Standard test method of evaluating wood preservatives by field tests with stakes. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2017. D7032. Standard specification for establishing performance ratings for wood–plastic composite and plastic lumber deck boards, stair treads, guards, and handrails. West Conshohocken, PA: ASTM International. https://www.icc-nta.org/services/testing/astm-d7032/

AWPA. 2012. E10. Standard method of testing wood preservatives by laboratory soil-block cultures. Birmingham, AL: American Wood Protection Association.

AWPA. 2021. E7-21. Standard field test for evaluation of wood preservatives to be used in ground contact (UC4A, UC4B, UC4C); stake test. Birmingham, AL: American Wood Protection Association.

Clemons, C.M.; Ibach, R.E. 2002. Laboratory tests on fungal resistance of wood filled polyethylene composites. In: ANTEC 2002, Proceedings, Annual Technical Conference, Society of Plastics Engineers, Volume 2, Materials, S.I., May 5–9, 2002, San Francisco, CA. Danbury, CT: Society of Plastics Engineers: 2219–2222. https://www.fs.usda.gov/research/treesearch/8740

Clemons, C.M.; Ibach, R.E. 2004. The effects of processing method and moisture history on the laboratory fungal resistance of wood–HDPE composites. Forest Products Journal. 54: 50–57. https://www.fs.usda.gov/research/treesearch/6355

Ibach, R.E. 2010. Durability of wood–plastic composite lumber. In: McGraw-Hill Yearbook of Science & Technology. New York: McGraw-Hill: 113–116. https://www.fs.usda.gov/research/treesearch/36662

Ibach, R.E.; Clemons, C.M. 2002. Biological resistance of polyethylene composites made with chemically modified fiber or flour. In: Proceedings, the 6th Pacific rim bio-based composites symposium & workshop on the chemical modification of cellulosics, Portland, OR. Corvallis, OR: Wood Science and Engineering Department, Oregon State University: 574–584. https://www.fs.usda.gov/research/treesearch/22139

Ibach, R.E.; Clemons, C.M. 2006. The effect of acetylated wood flour or coupling agent on the moisture, UV, and biological resistance of extruded woodfiber–plastic composites. In: Proceedings, wood protection 2006 conference, March 21–26, 2003, New Orleans, LA. Madison, WI: Forest Products Society: 139–147. https://www.fs.usda.gov/research/treesearch/28817

Ibach, R.E.; Clemons, C.M. 2017. Long term durability of wood–plastic composites made with chemically modified wood. In: Proceedings, advancements in fiber-polymer composites conference, May 16–18, 2017, Madison, WI. Peachtree Corners, GA: Forest Products Society. 17 p. https://www.fs.usda.gov/research/treesearch/55003

Ibach, R.E.; Plaza, N.Z. 2019. Using x-ray scattering to elucidate the mechanisms behind the moisture and fungal decay resistance of epoxybutene modified wood. In: Proceedings, 50th annual meeting of the International Research Group on Wood Protection; Quebec City, Canada. Stockholm, Sweden: International Research Group on Wood Protection: 15 p. https://www.fs.usda.gov/research/treesearch/58478

Ibach, R.E.; Clemons, C.M.; Stark, N.M. 2003. Combined ultraviolet and water exposure as a preconditioning method in laboratory fungal durability testing. In: Proceedings, 7th international conference on woodfiber–plastic composites, May 19–20, 2003. Madison, WI. Madison, WI: Forest Products Society: 61–67. https://www.fs.usda.gov/research/treesearch/7436

Ibach, R.E.; Clemons, C.M.; Schumann, R.L. 2007. Wood–plastic composites with reduced moisture: effects of chemical modification on durability in the laboratory and field. In: Stark, N.M., ed. Proceedings, 9th international conference on wood & biofiber plastic composites, May 21–23, 2007. Madison, WI. Madison, WI: Forest Products Society: 259–266. https://www.fs.usda.gov/research/treesearch/31174

Ibach, R.E.; Gnatowski, M.; Sun, G. 2013. Field and laboratory decay evaluations of wood–plastic composites. Forest Products Journal. 63: 76–87. https://doi.org/10.13073/fpj-d-12-00115

Ibach, R.E.; Chen, Y.; Stark, N.M.; Tshabalala, M.A.; Fan, Y.; Gao, J. 2014. Decay resistance of wood–plastic composites reinforced with extracted or delignified wood flour. IRG/WP 14-40655. In: Proceedings, 45th annual meeting of the International Research Group on Wood Protection, section 4, processes and properties, May 11–15, 2014, St. George, UT. Stockholm, Sweden: International Research Group on Wood Protection. 9 p. https://www.fs.usda.gov/research/treesearch/46173

Ibach, R.E.; Sun, G.; Gnatowski, M.; Glaeser, J.; Leung, M.; Haight, J. 2016. Exterior decay of wood–plastic composite boards: characterization and magnetic resonance imaging. Forest Products Journal. 66: 4–17. https://doi.org/10.13073/fpj-d-15-00011

Ibach, R.E.; Clemons, C.M.; Chen, G.C. 2017. The use of new, aqueous chemical wood modifications to improve the durability of wood–plastic composites. IRG/WP 17-40787. In: Proceedings, 48th annual meeting of the International Research Group on Wood Protection, June 4–8, 2017, Ghent, Belgium. Stockholm, Sweden: International Research Group on Wood Protection. 9 p. https://www.fs.usda.gov/research/treesearch/54437

Ibach, R.E.; Gnatowski, M.; Sun, G.; Glaeser, J.; Leung, M.; Haight, J. 2018a. Laboratory and environmental decay of wood–plastic composite boards: flexural properties. Wood Material Science & Engineering.13: 81–96. https://doi.org/10.1080/17480272.2017.1313311

Ibach, R.E.; Hadi, Y.S.; Clemons, C.M.; Sulaeman, Y. 2018b. Termite resistance of wood–plastic composites made with acetylated wood flour, coupling agent or zinc borate. IRG/WP 18-10917. In: Proceedings, 49th annual meeting of the International Research Group on Wood Protection, section 1, biology, April 29-May 3, 2018, Johannesburg, South Africa. Stockholm, Sweden: International Research Group on Wood Protection. 11 p. https://www.fs.usda.gov/research/treesearch/56529

Ibach, R.E.; Clemons, C.; Stark, N. 2020. Long-term field exposure of wood–plastic composites processed on a commercial-size extruder. IRG/WP 20-40894. In: Proceedings, 51st annual meeting of the International Research Group on Wood Protection, section 4, processes and properties, June 10–11, 2020. Stockholm, Sweden: International Research Group on Wood Protection. 11 p. https://www.fs.usda.gov/research/treesearch/60575

Ibach, R.E.; Plaza, N.Z.; Pingali, S.V. 2022. Small angle neutron scattering reveals wood nanostructural features in decay resistant chemically modified wood. Frontiers in Forests and Global Change. 4: 814086. https://doi.org/10.3389/ffgc.2021.814086

Plaza, N.Z.; Ibach, R.E.; Hasburgh, L.E.; Taylor, M. 2021a. Using thermal neutron imaging in forest products research. Environmental Sciences Proceedings. 3(1): 92–98. https://doi.org/10.3390/IECF2020-08082

Plaza, N.Z.; Ibach, R.E.; Pingali, S.V. 2021b. Probing the nanostructural mechanisms behind decay resistance of chemically modified wood using small angle neutron scattering. In: Proceedings, Forest Products Society Virtual International Conference, June 15–17, 2021. LaGrange, GA: Forest Products Society: 159–163. https://www.fs.usda.gov/research/treesearch/63127

Plaza, N.Z.; Pingali, S.V.; Ibach, R.E. 2022. Nanostructural changes correlated to decay resistance of chemically modified wood fibers. Fibers. 10(5): 40. https://doi.org/10.3390/fib10050040

Segerholm, B.K.; Ibach, R.E. 2013. Moisture and fungal durability of wood–plastic composites made with chemically modified and treated wood flour. IRG/WP 13-40648. In: Proceedings, 44th annual meeting of the International Research Group on Wood Protection, section 4, processes and properties, June 16–20, 2013, Stockholm, Sweden. Stockholm, Sweden: International Research Group on Wood Protection. 8 p. https://www.fpl.fs.usda.gov/documnts/pdf2013/fpl_2013_segerholm001.pdf

Segerholm, B.K.; Ibach, R.E.; Wålinder, M.E.P. 2012a. Moisture sorption in artificially aged wood–plastic composites. BioResources. 7(1): 1283–1293. https://doi.org/10.15376/biores.7.1.1283-1293

Segerholm, B.K.; Ibach, R.E.; Westin, M. 2012b. Moisture sorption, biological durability, and mechanical performance of WPC containing modified wood and polylactates. BioResources. 7(4): 4575–4585. https://doi.org/10.15376/biores.7.4.4575-4585

Sun, G.; Ibach, R.E.; Gnatowski, M.; Glaeser, J.; Leung, M.; Haight, J. 2014. Modern instrumental methods to investigate the mechanism of biological decay in wood plastic composites. IRG/WP 14-40674. In: Proceedings, 45th annual meeting of the International Research Group on Wood Protection, section 4, processes and properties, May 11–15, 2014, St. George, UT. Stockholm, Sweden: International Research Group on Wood Protection. 20 p. https://www.fs.usda.gov/research/treesearch/46176

Sun, G.; Ibach, R.E.; Faillace, M.; Gnatowski, M.; Glaeser, J.A.; Haight, J. 2017. Laboratory and exterior decay of wood–plastic composite boards: voids analysis and computed tomography. Wood Material Science & Engineering. 12(5): 263–278. https://doi.org/10.1080/17480272.2016.1164755

Appendix—Supplemental Data

The following details are from WPCs prepared at the Forest Products Laboratory. Western pine wood flour (grade 4020) was obtained from American Wood Fibers, Inc. (Columbia, Maryland, USA). A high-density polyethylene (HDPE) was used as the matrix (Fortiflex A60-70-162 from Solvay Polymers, Inc. (Neder-Over-Heembeek, Brussels, Belgium)). When added, the colorant used was Holcobatch Yellow L25153, Holland Colours Americas, Inc. (Richmond, Indiana, USA). Three biocides were investigated:

- OBPA: 10,10-oxybisphenoxarsine in an ethylene acrylic acid carrier (Vinyzene SB-11 EAA, Rohm and Haas, LLC, Philadelphia, Pennsylvania, USA)
- DCOIT: 4,5-dichloro-2-N-ocytyl-4-isothiazolin-3-one in polyethylene-vinyl acetate-carbon monoxide terpolymer carrier (Vinyzene SB-27 ELV, Rohm and Haas, LCC)
- ZB: zinc borate (2 ZnO, 3 B_2O_2, 3.5 H_2O, from U.S. Borax, Boron, California, USA)

Field test stakes were prepared by profile extrusion on a reconfigured 32-mm twin-screw compounding extruder (D-Tex, Davis-Standard, LLC, Pawcatuck, Connecticut, USA). All components were fed into the main feed throat, and the HDPE and lubricant were melted and then blended with the wood flour (50 wt% by weight), colorant (0 or 1 wt%), and biocide (0, 0.25, 0.50, or 1.0 wt%) in the extruder. The material was then forced through a die into 19- by 19-mm specimens, cooled in water, and then cut to 0.46-m lengths. To prevent tearing of the material as it exited the die, 5% of a lubricant (TR251 from Struktol Company of America, Cuyahoga Falls, Ohio, USA) was also used in the formulation. In half of the specimens, 1% of the colorant was added.

Ten identical stakes of each formulation were installed in ground and above ground at both the Valley View (Madison, Wisconsin) and the Harrison Experimental Forest (Saucier, Mississippi) test sites. Stakes were periodically visually graded according to the criteria listed in Tables 1 and 2. Select data are summarized in Tables A1 and A2.

Table A1—Average aboveground ratings[a] for wood–plastic composites stakes with and without colorant at the Valley View test plot (Madison, Wisconsin), 2002–2020

	Cracks or checking		Color change		Decay		Mold or stain	
Year	Without colorant	With colorant	Without colorant	With colorant	Without colorant	With colorant	Without colorant	With colorant
2002	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
2003	10.0	10.0	7.0	8.0	10.0	10.0	9.4	8.2
2004	10.0	10.0	7.0	7.0	10.0	10.0	9.2	8.7
2005	10.0	10.0	7.0	7.0	10.0	10.0	9.0	8.5
2006	10.0	10.0	0.1	0.0	10.0	10.0	8.7	8.1
2007	10.0	10.0	0.0	0.0	10.0	10.0	7.8	6.4
2008	10.0	10.0	0.0	0.0	10.0	10.0	6.4	5.8
2009	10.0	10.0	0.0	0.0	8.4	8.7	6.0	6.4
2010	9.9	10.0	0.0	4.7	7.1	7.3	5.1	5.5
2011	8.8	9.5	0.1	4.6	6.5	6.9	4.6	5.1
2014	7.3	8.7	0.0	2.3	5.0	5.4	1.1	1.7
2015	7.0	7.8	0.0	0.3	4.7	5.0	0.9	1.3
2016	7.0	7.7	0.0	0.3	4.5	4.8	0.9	1.3
2019	5.9	7.1	0.0	0.0	4.2	4.4	0.0	0.1
2020	5.5	6.9	0.0	0.0	3.6	4.3	0.0	0.1

[a]See Tables 1 and 2 for descriptions of grading numbers.

Table A2—Average in-ground field test ratings[a] after 17 years for wood–plastic composite stakes at Harrison Experimental Forest (Saucier, Mississippi) and Valley View (Madison, Wisconsin) test sites

				Decay, Wisconsin		Mississippi			
						Decay		Termites	
Biocide type[b]	Biocide level (%)	Colorant level (%)	Blend No.	Mean	SD[c]	Mean	SD	Mean	SD
None	NA	0	1	6.1	1.5	7.4	1.3	5.9	1.4
OBPA	0.25	0	2	5.5	1.2	8.2	1.5	7.0	0.8
OBPA	0.50	0	3	5.7	1.5	9.7	0.6	7.2	0.8
OBPA	1.00	0	4	6.0	1.4	8.5	1.3	7.1	1.0
DCOIT	0.25	0	5	5.9	1.3	8.1	1.5	7.2	1.2
DCOIT	0.50	0	6	5.5	1.0	7.9	1.2	6.8	1.7
DCOIT	1.00	0	7	6.6	1.4	7.6	1.1	7.3	1.1
ZB	0.25	0	8	7.0	0.6	7.8	1.3	6.9	1.4
ZB	0.50	0	9	7.3	0.6	9.3	0.6	6.8	1.3
ZB	1.00	0	10	8.0	1.2	9.4	0.5	7.9	0.8
None	NA	1	11	7.5	0.6	8.5	1.7	8.0	1.7
OBPA	0.25	1	12	7.3	0.5	8.3	2.4	7.0	1.5
OBPA	0.50	1	13	7.4	1.1	7.6	1.8	7.2	1.3
OBPA	1.00	1	14	8.0	0.8	6.8	2.1	8.3	1.6
DCOIT	0.25	1	15	8.8	1.4	9.0	0.9	8.4	1.3
DCOIT	0.50	1	16	8.4	0.5	8.0	1.2	8.3	0.7
DCOIT	1.00	1	17	7.3	1.2	6.7	3.1	8.3	0.9
ZB	0.25	1	18	8.8	0.4	6.4	2.5	8.1	0.8
ZB	0.50	1	19	8.6	0.9	8.8	1.3	8.7	1.1
ZB	1.00	1	20	9.3	0.5	8.4	1.1	8.7	1.1

[a]See Table 1 for descriptions of rating numbers.
[b]OBPA, 10,10-oxybisphenoxarsine; DCOIT, 4,5-dichloro-2-N-ocytyl-4-isothiazolin-3-one; ZB, zinc borate.
[c]SD, standard deviation.