# Durability of Wood and Polyethylene Composite Lumber

## Final Report

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This report covers the work supported by the Partnership for Advanced Technologies in Housing. It provides an overview of the research program, including the results. Part of this research has been incorporated into several presentations and papers.

The following presentations were given that included research from Phase I investigations:

- "Laboratory tests on fungal resistance of wood-filled polyethylene composites", Clemons, C.M. and Ibach, R.E., *Society of Plastics Engineers Annual Technical Conference (ANTEC),* May 5-9, 2002, San Francisco.
- "Photostabilization of Wood Flour Filled HDPE composites", Stark, N.M. and Matuana, L.M., *Society of Plastics Engineers Annual Technical Conference (ANTEC)*, May 5-9, 2002, San Francisco.
- "Fungal Exposure of Wood-Filled Polyethylene Composites", Clemons, C.M. and Ibach, R.E., at the *Progress in Woodfibre-Plastic Composites Conference*, Toronto, Ontario, May 23-24, 2002

Additionally, some of the results from the Phase I research have been incorporated into several published manuscripts. The following references can be found on the website hosted by the Forest Products Laboratory, http://www.fpl.fs.fed.us.

- "Laboratory Tests on Fungal Resistance of Wood-Filled Polyethylene Composites", Clemons, C.M. and Ibach, R.E., *Society of Plastics Engineers Annual Technical Conference (ANTEC),* May 5-9, 2002, San Francisco, **2**: 2219-2222.
- "Photostabilization of Wood Flour Filled HDPE composites", Stark, N.M. and Matuana, L.M., *Society of Plastics Engineers Annual Technical Conference (ANTEC)*, May 5-9, 2002, San Francisco, **2**: 2209-2213.
- "The Effects of Processing Method and Moisture History on the Laboratory Fungal Resistance of Wood-HDPE Composites", Clemons, C.M. and Ibach, R.E., *Forest Products Journal,* **54**(4): 50-57, 2004
- "Ultraviolet Weathering of Photostabilized HDPE/Wood Flour Composites", Stark, N.M. and Matuana, L.M., *Journal of Applied Polymer Science*, **90**(10): 2609-2617, 2003.

The field tests will take years and sufficient data has not yet been collected to report results. Information from the field tests will be reported periodically at conferences and in technical journals as appropriate.

# Acknowledgements

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# Abstract

The introduction of wood-plastic composites into an outdoor environment has led to concerns about durability and some failures have been found in the field [1]. The actual lifetime of wood–plastic lumber is still uncertain.

The objective of this investigation was to determine the durability of wood-plastic composites for use in exterior building applications were structural requirements are not great. This study focuses on two areas of concern for wood-plastic lumber materials, fungal decay and UV stability. This research was broken into two phases: 1) laboratory evaluation of several additives to improved fungal resistance and UV stability and 2) commercial-scale extrusion trials using the best formulations for the laboratory evaluation to produce sufficient composite decking from outdoor exposure tests.

As part of the phase I research, a standard method for determining the durability of structural wood was modified for testing the fungal resistance of the composites. Moisture content, mechanical properties, and weight loss were measured over 12 weeks exposure to brown- and white-rot fungi. The modified procedure yielded considerably more information on the moisture sorption and mechanical property changes of the specimens throughout the duration of the fungal exposure than the unmodified procedure. The modified soil block method was then used to screen several fungicides for their use in wood-plastic composites.

Due to increased moisture sorption, greater weight losses were found for extruded composites compared to injection molded ones. Greatest weight losses were found when the composites were subjected to a boil/drying cycle rather than a 2-week water soak prior to testing. Several commercially available biocide concentrates had little effect at the levels added. Zinc borate proved effective in preventing fungal attack in water-soaked samples and at a concentration of 1%, weight losses were less than 2%.

Optical and flexural properties were examined for all the formulations after they had been exposed to UV in an accelerated weathering apparatus. A UV absorber and colorant proved effective in reducing color fade and strength loss; several commonly used hindered amines light stabilizers did not.

The best performing additives from the laboratory evaluation were used in commercial-scale extrusion trials in Phase II. Full-size deck boards were produced containing different combinations of zinc borate, colorant, and UV absorber. These deck boards were installed in outdoor test sites in Mississippi and Wisconsin and will be periodically evaluated.

# Table of Contents

# Introduction

Traditionally, inorganic fillers such as fiberglass, calcium carbonate, and talc have been added to plastics to improve stiffness and strength, or to reduce cost. In recent years wood and other lignocellulosic fibers have been added to plastic, leading to the development of wood-plastic composites (WPC). These fibers are inexpensive, renewable, and are lighter and less abrasive to processing equipment than are inorganic fillers.

Automotive paneling and consumer products have been identified as applications for WPC [1,2]. However, the largest and fastest growing markets are in exterior building applications [3,4]. Building products account for 70% of the total end market use of natural fibers in plastic composites [5]. The wood-plastic decking market is projected to more than double by 2005, increasing from approximately 8% of the market share in 2000 to 20% [6]. Besides decking, building products such as fencing, industrial flooring, landscape timbers, railings, and moldings are also produced. Additionally, new building products using wood-plastic composites such as roof shingles and siding have recently been commercialized or are nearing commercialization. Development of waterfront applications for the navy facilities is a also major effort [6]. It is seen as advantageous to use WPC over wood for outdoor applications because they don't split, warp, and require little maintenance. WPC are also more dimensionally stable than unfilled plastic lumber when the temperature is varied [7].

However, the introduction of WPC into an outdoor environment has led to concerns about durability and some failures have been found in the field [8]. The actual lifetime of wood–plastic lumber is currently uncertain. Most manufacturers offer a 10-year warranty but some of the companies offering this warranty have only been in business for several years. It is of utmost importance to understand the outdoor durability including fungal resistance, ultraviolet (UV) stability, moisture resistance, and fire performance of this rapidly growing area.

The objective of this study was to determine the durability of wood-plastic composites for use in building applications where the structural requirement is not great. In particular, the wood-plastic composites were evaluated for exterior use, such as lumber for decking. This study focuses on two areas of concern for lumber materials, fungal decay and UV stability.

This work is broken into two phases: 1) laboratory evaluation of several additives to improve fungal resistance and UV stability and 2) commercial-scale extrusion trials using the best formulations from the laboratory evaluation to produce sufficient composite decking for outdoor exposure tests. All fungicide research was performed in cooperation with Dr. Rebecca Ibach, Modification of Lignocellulosics Group, USDA Forest Service, Forest Products Laboratory.

# Phase I: Laboratory Testing and Analysis

In Phase I research, we screened additives to determine their effect on improving either the fungal resistance or the UV stability of wood-plastic composites using laboratory processing and accelerated test protocols. For the fungal durability research, test method development was also required. The most successful of these additives were used in Phase II.

## FUNGICIDE RESEARCH: METHOD DEVELOPMENT

Little consistent information on fungal resistance is available in the literature. Morris and Cooper [8] reported fungal growth on WPC decking in-service in Florida after 4 years. Mankowski and Morrell [9] evaluated several proprietary WPCs by laboratory soil block tests. Weight loss varied from 0.4% to 20.4% depending on the fungi used and type of composite.

Researchers have also investigated the fungal resistance of model composites, but the literature to date is far from conclusive. Khavkine et al. [10] found little weight loss caused by fungal attack for polyethylene composites containing 40% to 70% wood, despite good fungal colonization on the composite surfaces and a conditioning procedure that included oven drying at 105°C for 24 h, a 2-h boil, and a 24-h water soak. However, using a modified soil block procedure, Verhey et al [11] found significant weight loss in composites containing 60% or greater wood content. In other research, Verhey et al [12] also showed that particle size influenced fungal durability. Pendleton et al. [13] evaluated more complex formulations. Of the formulations not containing zinc borate, weight loss occurred if wood content was 53% or greater. The varied results are not surprising considering the widely varying formulations evaluated (i.e., different types and quantities of fiber, plastic, and additives), as well as different processing and test methodologies.

Because of the variability in commercial formulations and processes and since this information is usually proprietary, we chose to make our own composites. To reduce the number of material variables, we chose a single formulation of commonly used materials in decking applications. Soil block methods such as ASTM D1413 [14] are the most commonly used methods to assess the durability wood for exterior building products such as deck boards. However, wood-plastic composites perform differently than solid wood (e.g., they absorb moisture much more slowly than solid wood), which creates difficulties in using this method for fungal screening. The objectives of this first investigation were to modify ASTM D1413 and verify the suitability of the modified test for its use with wood-plastic composites.

### Experimental Methods

The plastic material was high density polyethylene (HDPE) from reprocessed milk bottles (Muehlstein and Co., Inc., Roswell, GA), with a melt flow index of approximately 0.7 g per 10 min. The wood filler was a nominal 40 mesh (420 μm) western pine wood flour from American Wood Fibers (Schofield, WI).

Wood flour was dried and then compounded with HDPE in a 32-mm compounding twin-screw extruder (Davis Standard, Pawcatuck, CT). The compounded pellets were injection molded into flexural specimens (3 by 13 by 127 mm) using a 33-ton reciprocating-screw injection molder (Cincinnati Milacron, Batavia, OH). The specimens were cut and tested for fungal resistance. For comparison, specimens cut from southern pine sapwood were also tested.

ASTM D1413 was modified to compare the behavior of solid wood and composite materials. In ASTM D1413, specimens are placed in a sterilized bottle containing moist soil and weight loss is measured after 12 weeks exposure to decay fungi [14]. To investigate fungal resistance of wood–plastic composites, ASTM D1413 was modified by 1) changing specimen size, 2) measuring weight loss after 4, 8, and 12 weeks exposure, 3) adding flexural tests, and 4) measuring moisture content.

Specimen size was changed from 19 by 19 by 19 mm to 3 by 13 by 89 mm to conform to span-to-depth requirements of ASTM D790–84 [15]. The 89-mm length allowed the specimen to fit into a standard soil bottle turned on its side. Longer feeder strips and several fungal inoculations along the specimen length were also necessary. The decrease in specimen thickness increased the surface-to-volume ratio, facilitating moisture sorption and increasing fungal exposure area.

Two conditioning procedures were investigated to accelerate the moisture sorption of the composite samples: 2 weeks of water soak using the leaching procedure in ASTM D1413 or a cyclic boiling and drying procedure, consisting of 5 cycles of a 2-h boil followed by 24 h of oven drying at 105°C. After conditioning, specimens were placed in a humidity room at 65% relative humidity and 27°C for 4 weeks.

Soil bottles were inoculated with the brown-rot fungus *Gloeophyllum trabeum* (Madison 617) or the white-rot fungus *Trametes versicolor* (Madison 697). At 4, 8, and 12 weeks of fungal exposure, specimens were removed from the bottles, and their weight loss and moisture content were determined. There were two sets of controls: the original dry specimens and specimens exposed for 4, 8, and 12 weeks without fungal inoculation.

Flexural tests were performed to determine the effect of fungal attack on mechanical properties. Four-point flexural tests were performed on oven-dried specimens according to ASTM D790–84. Maximum strength was determined before and after 4, 8, and 12 weeks exposure. In all cases, failure occurred between the load points in the center third of the specimen.

## Results and Discussion

### Moisture Content

Untreated solid wood is included in soil block tests as a check for fungal activity. It can also be used as a relative benchmark for fungal decay. However, untreated solid wood must be stained or painted before use in exposed, exterior applications. Therefore, favorable performance of a material in a soil block test relative to the performance of untreated wood should not be used to justify suitability of the material for exterior use. Comparing the performance of solid wood and wood–plastic composites in soil block tests was nonetheless useful in investigating test methodology.

Solid wood showed large increases in moisture content during fungal exposure (Figure 1). Water soaked solid wood exposed to white-rot fungi absorbed the least amount of moisture (40%) in the 12-week exposure period. Wood exposed to white-rot fungi appeared to reach equilibrium within the first 4 weeks of the test. When exposed to brown-rot fungi, solid wood continued to absorb water throughout the test, ending with moisture content in excess of 100%. Even at 4 weeks, all the solid wood samples had absorbed more than the approximately 25% to 30% moisture required for fungal attack [16].

Wood–plastic composites performed quite differently. Maximum moisture content was about 12% to 13% for both boiled and water soaked composites regardless of the fungus used. Boiled composites appeared to approach this maximum more quickly than did water soaked composites, but all the composites reached maximum moisture content levels much later than did solid wood. Whether or not 12% to 13% moisture content represents the maximum moisture exposure is uncertain since the moisture content of some specimens appeared to be increasing, albeit slowly, at the end of the tests.

Assuming that the wood flour absorbs all the moisture, the moisture content of the wood flour in the composite would be about 25%. This is close to the critical moisture content of 25% to 30% necessary for fungal decay [16]. A moisture gradient may well exist through the thickness of the sample, resulting in more moisture near the surface. Based on moisture alone, wood–plastic composites represent a borderline case for fungal attack. Even if the critical moisture content is reached, it may be reached late in the test leaving insufficient time for significant fungal attack. The long time for composites to absorb water continues to be a potential limitation of this modified test despite the use of thin specimens.

### Weight Loss

Decay caused large weight losses (12%–70%) in solid wood. Exposure to brown-rot fungi caused the greatest weight loss (Figure 2). This aggressive attack on softwood sapwood is why brown-rot fungi such as *G. trabeum* are often used in soil block tests.

Weight losses for composite samples were much smaller than those for solid wood (Figure 3). The greatest weight loss was about 3% for boiled composites exposed to the brown-rot fungus. Since decay fungi do not attack HDPE, this corresponds to about a 6% weight loss in wood flour.

### Flexural Testing

Researchers have used loss in mechanical performance of wood as a sensitive measure of incipient fungal attack [17]. Since wood flour is used as a filler in many wood–plastic composites, the sensitivity of the mechanical properties of these composites to fungal attack is probably not as great as that of solid wood. Nevertheless, loss in mechanical performance could help corroborate weight loss results.

In all cases, failure occurred between the load points in the center third of the specimen. Flexural strength of solid wood decreased more than that of composites (Figure 4 and Figure 5). When exposed to brown-rot fungi, many solid wood specimens were so degraded after 8 weeks that they could not be tested. Not surprisingly, the strength of solid wood specimens in soil bottles without fungi was similar to that of the original wood.

Composite specimens showed significant, though small, losses in flexural strength over exposure time (Figure 5). However, strength loss also occurred in specimens from soil bottles that had not been inoculated with fungus (Figure 6). Since strength comparisons were made on a dry basis, these results suggest irreversible damage due to moisture sorption. Others that have found similar mechanical property losses when exposing wood-plastic composites to moisture and have suggested interfacial damage and matrix cracking as mechanisms (18, 19). Hence, to determine the effect of fungal attack, the flexural strength of composites exposed to fungi should be compared with that of unexposed composites. This comparison assumes that the composites (with or without fungi) have similar moisture sorption histories.

Since weight loss suggested little fungal decay, it is not surprising that strength loss due to fungal attack was also low. The greatest strength loss due to fungal attack was 3% for boiled composites exposed to brown-rot fungi.

## Summary and Conclusions from Method Development Investigation

A standard method for determining the durability of structural wood was modified for testing the fungal resistance of composites made from high density polyethylene filled with 50% wood flour. Moisture content, mechanical properties, and weight loss were measured over 12 weeks exposure to brown- and white-rot fungi. Injection molded composites showed little fungal degradation when tested using the modified soil block method. Mechanical properties were decreased, but irreversible damage due to water sorption made separating this effect from that of fungal attack difficult.

The modified procedure did yield considerably more information on the moisture sorption and mechanical property changes of the specimens throughout the duration of the fungal exposure than the unmodified procedure. We decided to use the modified soil block method for the fungicide screening investigation with the following modifications: 1) extruded samples rather than injection molded ones were tested and 2) only the more aggressive of the two fungi, *G. trabeum* (a brown rot fungus) were used. WPC are more often extruded rather than injection molded. Additionally, extrusion results in composites with lower density compared with the density of injection-molded composites. Also, a polymer-rich surface layer does not form on extruded composites as it does on injection molded composites. Thus, water is often more readily absorbed in extruded composites. The higher moisture content of extruded composites may very well lead to greater fungal attack than that seen in the injection-molded composites in this study.

# INVESTIGATION 2: FUNGICIDE SCREENING

Zinc borate has been the most investigated fungicide for use in wood-plastic composites [e.g., 11,12,13,20,21] and has been found attractive due to its low cost and effectiveness. In wood and wood-based composites, leaching of zinc borate is a problem but wood-plastic composites absorb and desorb moisture much slower dramatically reducing the leaching problem. This phase of the research program investigated the use of zinc borate in addition to several other additive concentrates containing several important classes of fungicides use by the plastics industry. Lower levels of zinc borate than those than have used by other researchers were investigated to determine the efficacy at or below 1% by weight. The modified soil block method from the method development investigation was used with slight modification. The best performing additives were then to be used with the additives for UV stability in phase II.

## Experimental Methods

Three fungicides were investigated:

1) "ZB": Zinc Borate, Borogard ZB, U.S. Borax
2) "OBPA": 10,10-oxybisphenoxarsine in an ethylene acrylic acid carrier, Vinyzene SB-1 EAA, Rohm and Haas Company
3) "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.

Zinc Borate is the most common commercially used fungicide for wood-plastic composites. The other two represent several important classes of biocide concentrates used by the plastics industry. The same wood flour and HDPE were used as in Investigation 1. Solid wood samples were included in the test to check for fungal activity.

To simulate commercial processing, an extrusion profiling line was built at the Forest Products Laboratory. To build a profiling line, modifications to our existing twin-screw extrusion line were necessary. The following equipment was designed and manufactured either in-house or purchased commercially.

1) Extrusion dies for initial sizing of the composite melt.
2) Calibration dies for determining final dimensions and initial cooling of extrudate.
3) Spray tank for cooling of the extrudate.
4) Puller for consistent extrudate haul off.

Extrusion Tooling Technology Inc. (Wauconda, IL) produced a ¾" by ¾" square die for the project. Several conveyer belts used to build the puller were purchased from Plastic Processing Equipment, Inc, (Macedonia, OH). FPL employees built all other equipment. Figure 7 is a diagram of the profiling line.

Due to low melt strength, a lubricant is necessary to avoid tearing of the melt as it exits the extruder die when profiling. 5% of a commercial lubricant (TR-251, Stuktol Co. of America) was found to be sufficient to prevent this tearing for most blends. Most tearing occurred in the sharp corners of the profile. A profile with more rounded corners would reduce the amount of lubricant needed. For blends containing OBPA concentrate, it was necessary to increase the amount of lubricant with a maximum of 10% lubricant when 1% OBPA concentrate was added. This suggests that the fungicide or more likely the ethylene acrylic acid carrier resin interferes with the lubricant. Blend compositions for the fungicide screening investigation are listed in Table 1.

Samples for the fungicide screening investigation were cut from the extruded samples. The modified soil block method from the method development investigation was used with the following modifications: 1) extruded samples rather than injection molded ones were tested and 2) only the more aggressive of the two fungi, *G. trabeum* was used. For solid wood and blends containing 0 or 1% fungicide, two conditioning procedures were compared: 1) 5 cycles of two-hour boil followed by oven drying at 105°C for 22 hours and 2) a 2-week water soaking according to the leaching procedure outlined in ASTM D1413 [14]. Blends containing low levels of fungicide (0.25% or 0.50%) were also made and then water soaked prior to fungal testing. Due to space limitations, no samples with low fungicide levels were conditioned by boiling and only composites without fungicide were evaluated at 4 and 8 weeks. Table 2 lists the composites and fungal tests performed.

## Results and Discussion

The extrusion process produced composites with slightly lower density compared with the density of injection-molded composites. In addition, a polymer-rich surface layer does not form on extruded composites and water is more readily absorbed. Figure 8 shows the effect of processing on water sorption when specimens were immersed in water. Given the higher moisture contents, it is likely that the extruded composites would be more susceptible to fungal attack than the injection molded composites.

Table 2 summarizes the data from the fungicide screening investigation. High standard deviations were found for some of the results on the boiled specimens. Moisture content increased with exposure time for the extruded composites and reached about 20% for water soaked composites and about 30% or greater for boiled composites after 12 weeks (Table 2). Weight losses for composites without fungicide are given in Figure 9. As expected, the weight losses are considerably larger than the injection molded specimens in the method development investigation due to increased moisture sorption (compare boiled specimens in Figure 9 with the boiled specimens exposed to brown rot in Figure 3). Not surprisingly, the weight losses increase with exposure time with the greatest weight losses in the composites that had been subjected to severe boiling/oven-drying cycles.

Figure 10 shows the effects of the two different fungicide concentrates. Both concentrates contain an active ingredient (OBPA or DCOIT) and a carrier resin. The fungicides represent several important classes of biocides used by the plastics industry. However, the two fungicide concentrates had little effect at the levels added. Several reasons for this are possible. Only up to 10% active ingredient is used in either concentrate. Since only 1% concentrate was used in the wood-plastic composite formulations, they contain at most 0.1% of active ingredient.

However, the high price of these concentrates prevented investigation at larger additions. Other components such as the lubricant or the wood itself can greatly affect how the concentrate performs. For example, additional lubricant was needed to maintain surface appearance during profiling of the composites containing OBPA concentrate suggesting an interaction between the lubricant and OBPA concentrate. Where the active ingredient locates itself in the final composite (e.g., in the polymer matrix, near or at the wood-plastic interface) is uncertain. Many questions are left unanswered. The present work is only preliminary, and further testing and development work are necessary to ultimately determine the efficacy of these concentrates for wood-plastic composites.

The effect of adding zinc borate to wood-plastic composites that had been water soaked is shown in Figure 11. The zinc borate decreased the weight loss even at the low additions investigated with less than 2% weight loss when 1% zinc borate was added. Figure 12 shows the correlation between weight loss and moisture content for the composites after 12 weeks of fungal exposure. Soil block results from the injection molded composites in the method development investigation have also been added. Aside from several apparent outliers, the data shows a strong relationship between moisture content and weight loss. The data suggests a negligible weight loss at approximately 15% moisture content or less. If we assume that the wood absorbs all of the moisture and that no moisture gradient through the sample thickness exists, the wood moisture content is approximately 30% before significant weight loss occurs. This is about the fiber saturation point for solid wood [16].

The water soaked composites containing zinc borate had both lower weight losses and lower moisture contents than those without zinc borate. Due to the low weight losses, low zinc borate concentrations and data scatter, it is difficult to ascertain if lower moisture content or if increased toxicity is the cause of the increased fungal resistance in the water soaked composites. If there were a toxicity mechanism, lower weight losses at higher moisture contents would be expected. The boiled composites containing zinc borate lay on the same curve as the other composites. However, the zinc borate may have leached from the composite during the aggressive conditioning procedure where thin samples were subjected to boiling and drying cycles. This may be an overly aggressive conditioning procedure for these composites and points out the difficult balance between trying to reduce the time necessary for moisture sorption yet not subject the specimen to an extremely harsh leaching regimen.

## Summary and Conclusions from Fungicide Screening Investigation

The modified soil block test developed in investigation 1 was used to screen three fungicides for their use in wood-plastic composites. Due to increased moisture sorption, greater weight losses were found for extruded composites compared to injection molded ones. The greatest weight losses were found when the composites were subjected to a boil/drying cycle rather than a 2-week water soaking prior to testing. Several commercially available biocide concentrates had little effect at the levels added. Further developmental work on the concentrates is warranted to determine the efficacy of these concentrates. Zinc borate proved effective in preventing fungal attack in water soaked specimens. At a concentration of 1%, weight losses were less than 2%. In composites that had been boiled, zinc borate was not effective presumably due to leaching.  Zinc borate was chosen for the commercial-scale trials in the next phase of research.

# LIGHT STABILIZER RESEARCH

The photodegradation of WPC is a difficult problem, complicated by the fact that each component may degrade via a different mechanism. The photodegradation of polyolefins originates from excited polymer–oxygen complexes [20] and is caused mainly by the introduction of catalyst residues, hydroperoxide groups, carbonyl groups, and double bonds introduced during polymer manufacturing. Even in the absence of a significant amount of UV absorption, small amounts of these impurities can be sufficient to induce polymer degradation [21]. Degradation of polymers as a result of photooxidation has undesirable effects, such as loss of strength, stiffness, and surface quality. Slowing down or stopping the reactions that are responsible for degradation is necessary for UV stabilization.

Photostabilizers are compounds developed to protect polyolefins and combat UV degradation. They are generally classified according to the degradation mechanism they hinder. Ultraviolet absorbers (UVAs), hydroperoxide decomposers, and free radical scavengers are all important photostabilizers for polyolefins. Commercial UVAs are readily available as benzophenones and benzotriazoles [21]. A relatively new class of materials, hindered amine light stabilizers (HALS), has been extensively examined for polyolefin protection [22,23] as free radical scavengers.

Although the photodegradation of both polyethylene and wood has been extensively examined, little information is available on the photodegradation of wood-flour-filled high-density polyethylene (WF/HDPE) composites [24,25]. In addition, much of the available information on photostabilizers covers solely the photostabilization of unfilled plastics [20-23]. The objective of this portion of the research project was to evaluate the effectiveness of various light stabilizers by monitoring color changes and mechanical property losses of wood-polyethylene composites. A factorial experimental design was employed to determine the most effective combinations of additives for photostabilization.

## Experimental Methods

### Materials

The materials used in this portion of the study are presented in Table 3. Combinations of pine wood flour (WF), a UV absorber (UVA), a low molecular weight hindered amine light stabilizer (LS1), a high molecular weight hindered amine light stabilizer (LS2), and a colorant (Color) were added to HDPE. In each blend that WF was added to, the WF was maintained at 50% by weight of the composite, while the photostabilizers and HDPE constituted the remainder of the composite. The effects of each of the variables on properties, as well as their interactions, were determined using a $2^5$ factorial experimental design to study the influences of WF and the four additives.

### Processing

The wood flour was dried for 24 hours at 105 °C, and then dry-blended with the additives and HDPE at the composition required to generate each composite. Compounding was accomplished using a 32-mm Davis Standard (Pawcatuck, CT) co-rotating, intermeshing, 32:1 length to diameter ratio, twin-screw extruder to produce homogeneous composite pellets. All composite pellets were dried at 105°C for at least 24 hours prior to injection molding. Test specimens were molded in a 33-ton Cincinnati Milacron reciprocating screw injection molder (Batavia, Ohio). The American Society for Testing and Materials mold cavity used for the flexural samples is 120 x 3 x 12 mm [15].

### Testing and Analysis

Weathering. Twenty replicates of each of the 32 formulations were placed in a xenon arc-type light-exposure apparatus and operated according to ASTM D2565 [26]. Samples were mounted on a drum that rotated around the chamber at 1 rpm, in four rows. The samples were rotated vertically periodically to ensure that all samples were exposed to the same irradiance. The exposure cycle consisted of 108 minutes of light exposure and 12 minutes of simultaneous water spray and light exposure. Samples were removed after 250, 500, 1000, and 2000 hours of exposure for analysis.

Optical Properties. A Minolta CR-200 Chroma Meter was used to measure color using the CIELAB color system. Lightness (L), red-green (a) and yellow-blue (b) were measured for five replicate samples and color change, ($\Delta E_{ab}$), was determined (Eqn. 1) using the procedure outlined in ASTM D2244 [27]. In the CIELAB color system, the value L can be thought of as a lightness factor; an increase in L means the sample is whitening, positive b represents yellow, negative b represents blue, positive a represents red, and negative a represents green.

$$\Delta E_{ab} = \left(\Delta L^2 + \Delta a^2 + \Delta b^2\right)^{1/2} \qquad (1)$$

Mechanical Properties. The samples were oven-dried at 105 °C for 24 hours before testing. This ensured the same conditioning for samples before and after exposure. Flexural tests were carried out according to ASTM D790 on an Instron Universal Testing [15]. The three point loading system was utilized with a crosshead speed of 1.3 mm/min. The exposed surface was placed away from the center load to place that part of the sample in tension. Five replicate specimens were tested for each formulation before exposure. Four replicate samples were tested after exposure due to limited space in the weathering chamber. The stress at maximum load and tangent modulus of elasticity were calculated according to the standard.

## Results and Discussion

The results from the color analysis are presented in Tables 4 and 5, while Tables 6 and 7 report the mechanical property testing results. In Tables 4 through 7, columns A, B, C, and D represent the photostabilizer added to each composite blend. A plus sign "+" designates that the photostabilizer is included in the blend whereas a minus sign "-" designates the absence of the photostabilizer. The first row shows the formulation without photostabilizers. In the next four rows, the effects of the individual photostabilizers can be seen while the effect of combining two to four of the photostabilizers can be seen in rows six through sixteen. The objective of this study was to determine the effects of weathering on optical and mechanical properties; therefore the change in a property value from the unexposed sample is reported. For the mechanical property data (Tables 6-7) a value reported in gray italics represents no significant change in property from the unexposed value at α = 0.05. An attempt was made to model each property in terms of LS1, LS2, UVA, and Color after 2000 hours of exposure. The models are in terms of coded factors. The presence of a component is represented by a "+1", while the absence is represented by "–1". For the duration of the paper, the discussion is broken into two parts: 1) the performance of unfilled HDPE composites, and 2) the performance of WF/HDPE composites.

### Color Analysis

Table 4 shows $\Delta E_{ab}$ and ΔL and at different exposure times for the HDPE without WF. Generally, the HDPE samples that had the Color added showed little if any change in lightness after UV exposure regardless of the other photostabilizers added. In the absence of Color, the UVA performed the best at 2000 hours exposure time. In our analysis LS2 was not found to be a significant term, therefore equation 2 was derived to include only the significant terms. For the majority of the samples, the changes in lightness were not apparent to the naked eye.

$$\begin{aligned}\Delta L &= 1.66 + 0.12 * LS1 - 0.21 * UVA - 1.62 * Color \\ &- 0.31 * LS1 * Color + 0.23 * UVA * Color\end{aligned} \qquad (2)$$

Predicted $r^2 = 0.94$

Table 5). Examining the results for ΔL, it is evident that while all samples experience a significant increase in ΔL, the increase is less pronounced if colorant is added to the formulation. As with the unfilled HDPE formulations, at 2000 hours of exposure time the UVA performed the best in the absence of Color. The only photostabilizers to significantly lower ΔL are UVA and Color (Eqn. 3). Color fading was noticeable in the composite samples after only 250 hours, and after 2000 hours the surface of the sample appeared white.

$$\Delta L = 26.86 - 1.26 * UVA - 3.19 * Color \qquad (3)$$

Predicted $r^2 = 0.75$

### Flexural Analysis

The flexural MOE was calculated using the initial tangential slope of the load-displacement curve. The flexural strength was calculated using the maximum load the sample sustained. All of the samples failed on the tensile side.

For the unfilled HDPE samples, the flexural MOE and strength generally increased significantly upon exposure starting as early as 250 hours of exposure time (Table 6). For many of the formulations, the MOE appears to increase with increasing exposure time through 1000 hours. At this point the MOE drops off slightly but remains larger than the original value. There are no significant factors that influence the change in MOE for photostabilized HDPE at 2000 hours exposure time. The initial increase in MOE is thought to be due to cross-linking of the HDPE during initial weathering. Eventually the HDPE undergoes chain scission with the result being a loss in MOE. Further research is being conducted to verify the cross-linking versus chain scission mechanism of photodegradation.

The strength for HDPE without the addition of photostabilizers decreases after 1000 hours of exposure time (Table 6). All of the photostabilizers used negated this effect and even increased strength after UV exposure. As with the flexural MOE, the strength of the photostabilized formulations increases through 1000 hours of exposure time and then drops off slightly. None of the photostabilizers or combinations performs significantly different from one another regarding the change in strength of HDPE at 2000 hours exposure time.

The change in flexural MOE is generally insignificant for wood flour/HDPE composites until the exposure time reaches 2000 hours (Table 7). At this point there is a decrease in MOE. The change in MOE appears unaffected by the addition of photostabilizers.

Similar to the trend seen for the flexural MOE of wood flour/HDPE composites, the flexural strength generally does not change significantly until the exposure time reaches 2000 hours. At this point, there is a drop in strength that is most extreme for the unprotected wood flour/HDPE formulation. The addition of Color improves the drop in strength over the unprotected formulation. Again in the absence of Color, the UVA performed the best at 2000 hours of exposure time. Both Color and UVA significantly increase the strength (Eqn 4).

$$\Delta Str. = \begin{pmatrix} 36.45 + 9.83 * UVA + \\ 15.53 * Color \end{pmatrix}^{\frac{1}{2}} - 9.87 \qquad (4)$$

Predicted $r^2 = 0.84$

## Summary and Conclusions from Light Stabilizer Research

As wood plastic composites become increasingly used for outdoor applications, a need to understand their UV durability arises. There is little available information regarding the photostabilization of wood flour/HDPE composites. In this study, a full-factorial experimental design was used to examine the effects of photostabilizers on both unfilled HDPE and wood flour/HDPE composites. Optical and flexural properties were examined for all the formulations after they had been exposed to UV in an accelerated weathering apparatus. After analysis, the following statements can be made:

1) The change in lightness is decreased through the addition of an ultraviolet absorber and colorant for both unfilled HDPE and wood flour/HDPE.
2) The effect of hindered amine light stabilizers on lightness is not significant for any of the formulations.
3) The flexural properties of HDPE are immediately affected by UV exposure while the properties of wood flour/HDPE composites are not affected until 2000 hours of exposure.
4) Exposure of unprotected HDPE results in a drop in flexural strength, which can be reversed through the addition of any of the photostabilizers.
5) The strength of wood flour/HDPE composites decreases after 2000 hours of UV exposure, and the addition of an ultraviolet absorber and colorant both significantly decreased strength loss.

The colorant and ultraviolet absorber were chosen as components of the UV stabilization package (UVS) for the commercial trials.

# OVERALL CONCLUSIONS FROM PHASE I

The objective of this laboratory-scale research was to screen additives for increased fungal resistance and UV stability in wood-plastic composites.

A modified soil block test was developed to screen fungicides for use in wood-plastic composites. Even zinc borate concentrations as low as 1% showed some effectiveness in preventing fungal attack and reduced weight losses in a modified soil block test to less than 2% in specimens that had been water soaked for 2 weeks prior to fungal testing. Due to its efficacy and cost effectiveness, 1% zinc borate was selected for commercial-scale trials.

In investigations using a weatherometer, a UV absorber and colorant proved effective in reducing color fade and strength loss but hindered amine light stabilizers were not very effective. For commercial-scale extrusion trials, 1% of the colorant and 0.5% of the UV absorber selected as the additive package.

# Phase II: Commercial-Scale Trials and Field Test Installation

The objectives of Phase II were to process wood-filled HDPE composites containing selected additives from Phase I on a commercial-scale extruder and produce sufficient deck boards on for outdoor exposure tests.

## Experimental Methods

### Materials

- Plastic (HDPE): High density polyethylene (BP Solvay Polyethylene, grade A60-70-162; MFI approximately 0.72).
- Wood flour (WF): grade 4020 pine, (-40, +80 mesh pine flour, mostly ponderosa pine). American Wood Fibers.
- Lubricant (Lub): 8% of a blend of calcium stearate and a proprietary amide, (Struktol TR 016, Struktol Company of America)
- Fungicide (ZB): 1% Zinc Borate (Boragard ZB, U.S. Borax),
- Light stabilizer package (LS): 0.5% of a light absorber (Tinuvin 238, Ciba Specialty Chemicals) and 1% of a colorant (Holcobatch Yellow L25153, Holland Colors Americas)

### Experimental Design

A simple $2^2$ factorial design will be employed for a total of 4 formulations. The following formulation were run:

1) HDPE with 50% WF and Lub
2) HDPE with 50% WF, Lub, and ZB
3) HDPE with 50% WF, Lub, and LS
4) HDPE with 50% WF, Lub, ZB, and LS

All numbers are percentages by weight.

### Processing

Commercial-scale extrusion trials were run at University of Maine's Advanced Engineered Wood Composite Center. Processing parameters were determined and 1.2" x 5.5" radius edge deck boards were produced using an in-line twin-screw extruder profiling system on a Davis Standard 94 mm extruder (Woodtruder). Due to the low density of the ZB and UV absorber, concentrates containing 10% active ingredient were compounded on FPL's compounding extruder prior to the trials. Deck boards were produced at a rate of 380 pounds/hour. 100 feet of each of the 4 formulations were produced to provide sufficient material for field installations. Figure 13 through Figure 16 are several photos from the extrusion trials.

## Field Plot Installation

Deck boards were installed in the Harrison Experimental Forest near Saucier, Mississippi on with the cooperation with the USDA Forest Service, Southern Research Station. Stakes were also installed at our Valley View test site west of Madison, Wisconsin. This was done to provide a northern site with the freeze and thaw cycles typical of a Wisconsin winter and southern site with the warm and humid environment of Mississippi. 24” boards of all 4 formulations were horizontally mounted on a rack made from CCA treated lumber (Figure 17). Additionally, ¾” by ¾” by 18” stakes were cut from each board and installed in-ground (Figure 18) following the procedures from the American Wood Preserver’s Standard AWPA E7-93 [28T]. Deck boards and ground stakes will be visually rated at 1, 2, 3, 5, 7, and 10 years to assess overall condition as well as fungal attack and color fade.

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# Figures

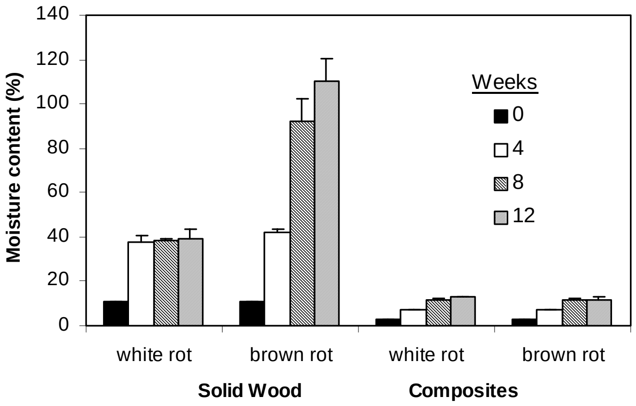

Figure 1: Water sorption of water soaked solid wood and wood–plastic composites exposed to white-rot (*T. versicolor*) and brown-rot (*G. trabeum*) fungi in soil block tests. Error bars are one standard deviation.

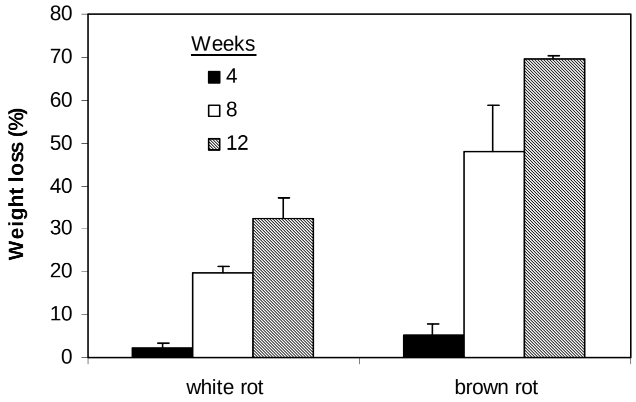

Figure 2: Weight loss of solid wood exposed to white- and brown-rot fungi in soil block tests (boiled specimens).

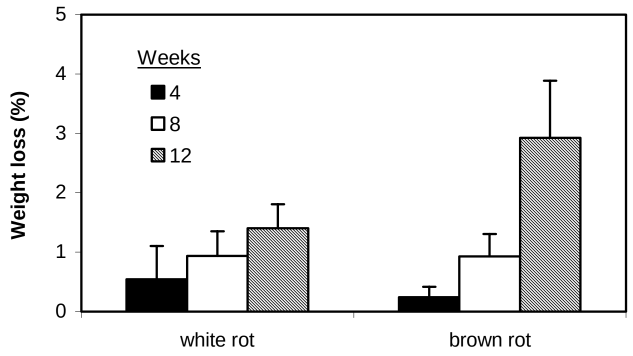

Figure 3: Weight loss of wood–plastic composites exposed to brown- and white-rot fungi in soil block tests (boiled specimens).

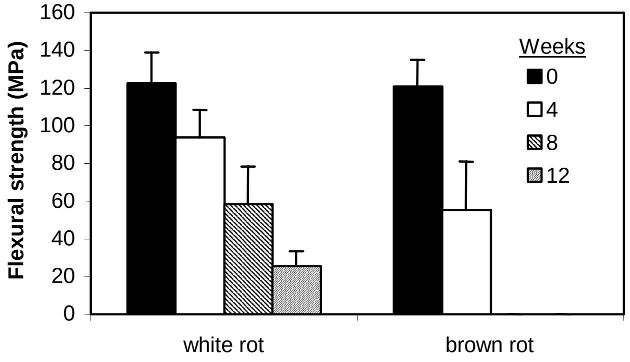

Figure 4: Strength loss for solid wood exposed to brown- and white-rot fungi during soil block tests (boiled specimens). Specimens exposed to brown-rot fungi for 8 and 12 weeks were too degraded to test.

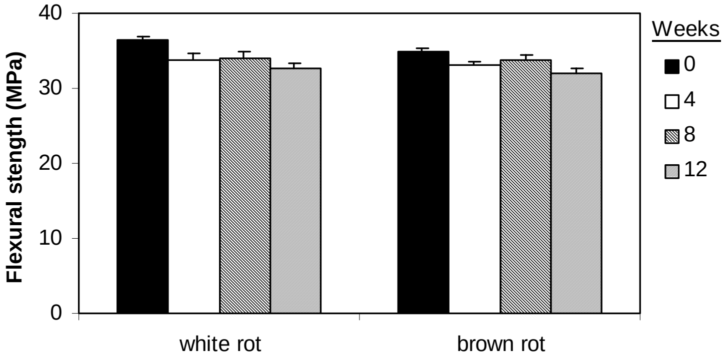

Figure 5: Strength loss for wood–plastic composites exposed to white- and brown-rot fungi during soil block tests (boiled specimens). All specimens tested dry.

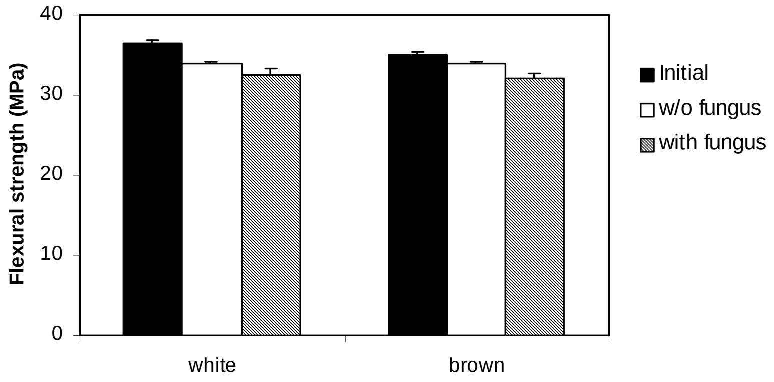

Figure 6: Strength of wood–plastic composites before and after 12-week exposure to fungi. “Initial” = water soaked specimens that were then oven dried; “w/o fungus” = water soaked specimens, that were then placed in an uninoculated soil bottle, removed after 21 weeks, and oven dried; “with fungus” = water soaked specimens that were then placed in an inoculated soil bottle, removed after 21 weeks of fungal exposure, and oven dried.

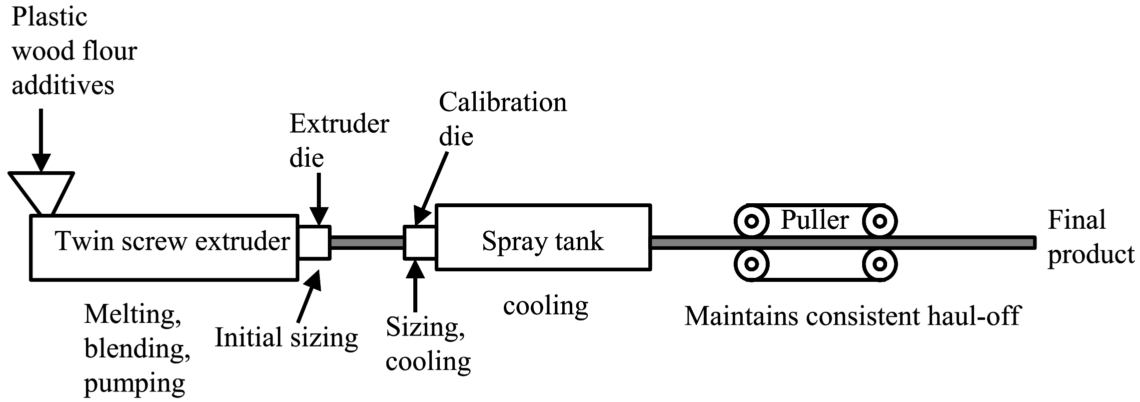

Figure 7: FPL profile extrusion line.

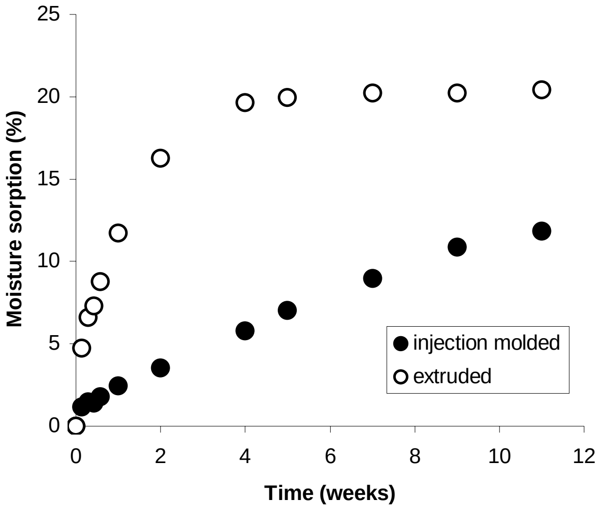

Figure 8: Water sorption of wood–plastic composites processed by different methods. Ambient water soak

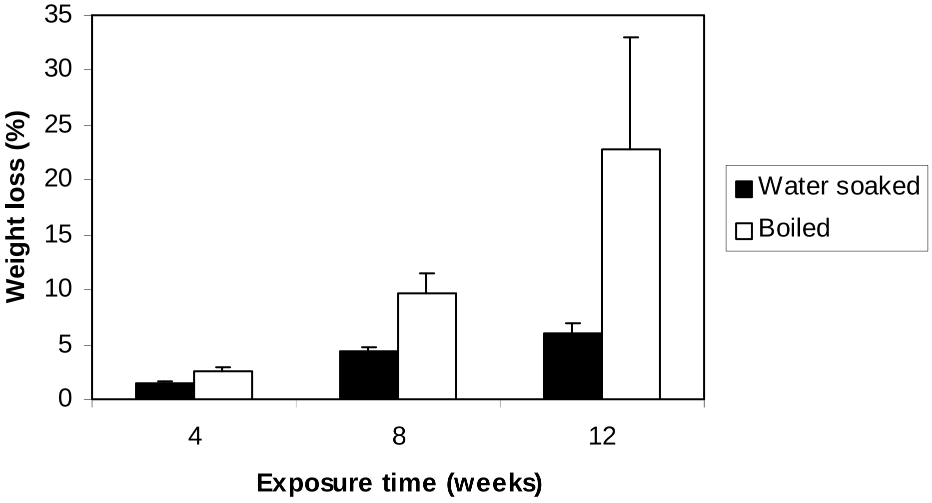

Figure 9: Weight loss for extruded wood–plastic composites that were: 1) first water soaked or boiled and then 2) exposed to brown-rot fungi in modified soil block tests.

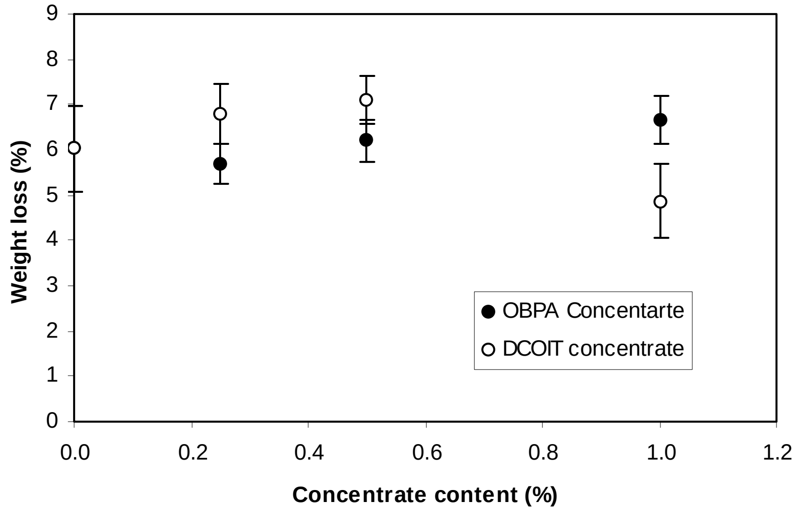

Figure 10: Weight loss for extruded wood-plastic composites containing several fungicide concentrates. Modified soil block tests containing brown-rot fungi (water soaked specimens).

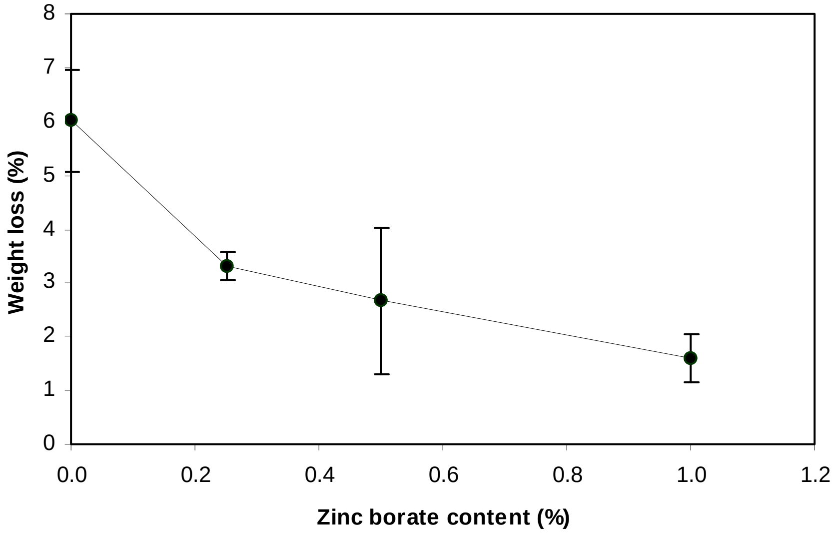

Figure 11: Weight loss for extruded wood-plastic composites containing zinc borate. Modified soil block tests containing brown-rot fungi (water soaked specimens).

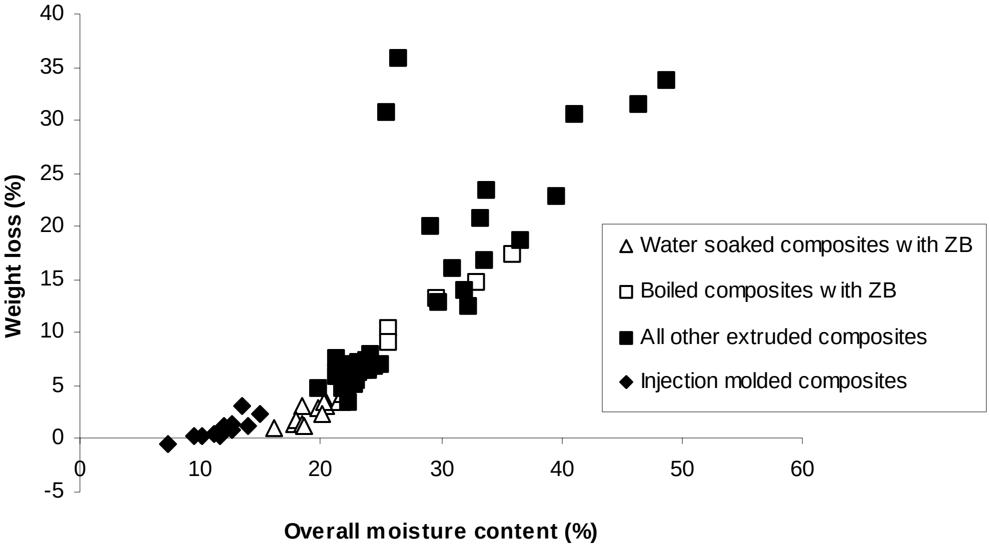

Figure 12: Correlation between weight loss and moisture content for extruded wood-plastic composites in modified soil block tests containing brown-rot fungi.

Figure 13: 94 mm profile extrusion line running formulation 1

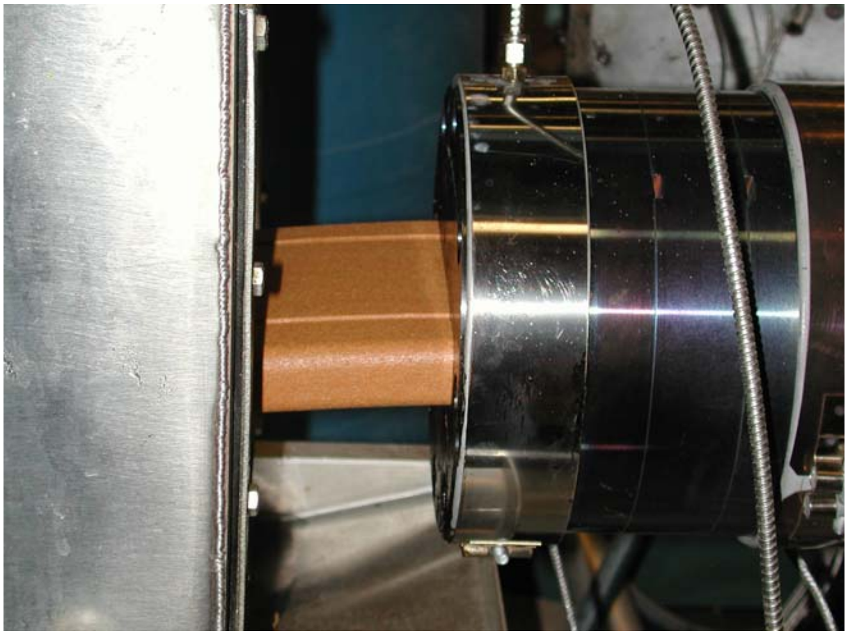

Figure 14: Wood-plastic composite (center) exiting extruder die (right) and entering cooling tank (left).

Figure 15: Wood-plastic composite exiting cut-off saw at end of profiling line.

Figure 16: Finished wood plastic composite deck boards (four formulations).

Figure 17: Deck boards installed in the Harrison Experimental Forest, Mississippi.

Figure 18: Ground stakes cut from deck boards installed in the Harrison, Experimental Forest, Mississippi.

# Tables

Table 1. Blend compositions for the fungicide screening investigation.

| Blend # | Plastic | Wood | Fungicide | Lubricant |
|---|---|---|---|---|
| 1 | HDPE | 50% WF | None | 5% Lub |
| 2 | HDPE | 50% WF | 0.25% OBPA | 7% Lub |
| 3 | HDPE | 50% WF | 0.50% OBPA | 8.5% Lub |
| 4 | HDPE | 50% WF | 1.00% OBPA | 10% Lub |
| 5 | HDPE | 50% WF | 0.25% DCOIT | 5% Lub |
| 6 | HDPE | 50% WF | 0.50% DCOIT | 5% Lub |
| 7 | HDPE | 50% WF | 1.00% DCOIT | 5% Lub |
| 8 | HDPE | 50% WF | 0.25% ZB | 5% Lub |
| 9 | HDPE | 50% WF | 0.50% ZB | 5% Lub |
| 10 | HDPE | 50% WF | 1.00% ZB | 5% Lub |

Table 2. Data summary for the fungicide screening investigation.

| Blend | Fung. type | Fung. content (%) | Condition | Time (wks) | Moisture content* | | Weight loss** | |
|---|---|---|---|---|---|---|---|---|
| | | | | | (%) | SD | (%) | SD |
| | | | | | | | | |
| 1 | None | 0.00 | Water soaked | 4 | 15.62 | 1.93 | 1.45 | 0.16 |
| 1 | None | 0.00 | Water soaked | 8 | 15.36 | 1.19 | 4.41 | 0.40 |
| 1 | None | 0.00 | Water soaked | 12 | 22.03 | 1.61 | 6.03 | 0.95 |
| | | | | | | | | |
| 1 | None | 0.00 | Boiled | 4 | 18.10 | 2.14 | 2.53 | 0.47 |
| 1 | None | 0.00 | Boiled | 8 | 15.95 | 2.30 | 9.63 | 1.88 |
| 1 | None | 0.00 | Boiled | 12 | 32.46 | 5.48 | 22.84 | 10.16 |
| | | | | | | | | |
| 2 | OBPA | 0.25 | Water soaked | 12 | 22.41 | 0.63 | 5.68 | 0.44 |
| 3 | OBPA | 0.50 | Water soaked | 12 | 22.64 | 0.82 | 6.21 | 0.46 |
| 4 | OBPA | 1.00 | Water soaked | 12 | 22.73 | 1.03 | 6.65 | 0.53 |
| 4 | OBPA | 1.00 | Boiled | 12 | 32.49 | 2.79 | 16.86 | 2.93 |
| | | | | | | | | |
| 5 | DCOIT | 0.25 | Water soaked | 12 | 22.16 | 1.11 | 6.79 | 0.67 |
| 6 | DCOIT | 0.50 | Water soaked | 12 | 24.22 | 0.52 | 7.10 | 0.52 |
| 7 | DCOIT | 1.00 | Water soaked | 12 | 22.44 | 0.45 | 4.86 | 0.82 |
| 7 | DCOIT | 1.00 | Boiled | 12 | 38.75 | 9.48 | 28.51 | 5.00 |
| | | | | | | | | |
| 8 | ZB | 0.25 | Water soaked | 12 | 20.78 | 0.77 | 3.31 | 0.27 |
| 9 | ZB | 0.50 | Water soaked | 12 | 18.87 | 2.20 | 2.66 | 1.35 |
| 10 | ZB | 1.00 | Water soaked | 12 | 18.76 | 0.77 | 1.60 | 0.44 |
| 10 | ZB | 1.00 | Boiled | 12 | 29.89 | 4.51 | 13.04 | 3.33 |
| | | | | | | | | |
| Wood | None | 0.00 | Water soaked | 4 | 36.28 | 2.39 | 2.90 | 1.06 |
| Wood | None | 0.00 | Water soaked | 8 | 21.28 | 10.25 | 25.59 | 11.40 |
| Wood | None | 0.00 | Water soaked | 12 | 128.06 | 9.03 | 65.66 | 1.50 |

* Moisture content of specimen at the end of soil block test, before oven drying.

** Weight loss from 12-week soil block test (*G. trabeum*). Oven-dry basis.

Table 3. Materials used in the Light Stabilizer Research and their content in the composite blends examined.

| Variable | | Suppliers | Tradename | Content (%) |
|---|---|---|---|---|
| Wood Flour | WF | American Wood Fibers | 4020 | 50 |
| Low MW Light Stabilizer | LS1 | Ciba Specialty Chemicals | Tinuvin 770 DF | 0.5 |
| High MW Light Stabilizer | LS2 | Ciba Specialty Chemicals | Chimassorb 944 FD | 0.5 |
| Ultraviolet Absorber | UVA | Ciba Specialty Chemicals | Tinuvin 328 | 0.5 |
| Colorant | Color | Holland Colors Americas, Inc. | Cedar TI-8536 | 1 |
| High-Density Polyethylene | HDPE | Solvay Polymers, Inc. | Fortiflex A60-70-162 | 47.5-50 |

Table 4. Change in color ($\Delta E_{ab}$) and change in lightness ($\Delta L$) at various exposure times for unfilled HDPE and photostabilizer blends after accelerated weathering.

| | | | | $\Delta E_{ab}$ | | | | $\Delta L$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | B | C | D | Exposure Time (Hours) | | | | Exposure Time (Hours) | | | |
| LS1 | LS2 | UVA | Color | 250 | 500 | 1000 | 2000 | 250 | 500 | 1000 | 2000 |
| - | - | - | - | 4.6 | 4.5 | 4.5 | 4.9 | 2.6 | 1.2 | 1.8 | 3.5 |
| + | - | - | - | 1.9 | 10.5 | 11.5 | 11.0 | 0.7 | 3.2 | 3.4 | 3.8 |
| - | + | - | - | 8.4 | 9.7 | 9.9 | 9.5 | -1.7 | 2.8 | 2.5 | 3.4 |
| - | - | + | - | 2.6 | 3.2 | 4.0 | 4.5 | 2.3 | 1.3 | 1.5 | 1.8 |
| - | - | - | + | 0.5 | 2.4 | 3.0 | 3.2 | -0.4 | 0.1 | -0.1 | 0.1 |
| + | + | - | - | 4.0 | 11.4 | 11.9 | 11.4 | -0.6 | 3.5 | 3.7 | 4.2 |
| + | - | + | - | 4.1 | 6.7 | 7.7 | 7.8 | -0.8 | 1.9 | 2.5 | 3.1 |
| - | + | + | - | 9.2 | 6.6 | 7.4 | 6.9 | -3.5 | 2.3 | 2.1 | 2.7 |
| + | - | - | + | 0.3 | 1.4 | 1.8 | 2.7 | 0.0 | -0.2 | -0.4 | -0.1 |
| - | + | - | + | 0.5 | 2.7 | 2.8 | 3.4 | 0.1 | 0.3 | 0.3 | 0.3 |
| - | - | + | + | 0.9 | 1.7 | 2.0 | 1.6 | 0.3 | 0.1 | -0.3 | 0.3 |
| + | + | + | - | 8.0 | 7.4 | 8.4 | 7.8 | -3.0 | 3.3 | 3.2 | 3.8 |
| + | + | - | + | 0.5 | 2.9 | 3.7 | 4.3 | -0.4 | -0.2 | -0.3 | -0.2 |
| + | - | + | + | 0.2 | 1.2 | 2.7 | 4.1 | 0.1 | -0.3 | -0.4 | -0.4 |
| - | + | + | + | 0.9 | 1.7 | 2.5 | 1.1 | 0.1 | -0.3 | -0.3 | 0.3 |
| + | + | + | + | 0.2 | 2.5 | 3.6 | 3.8 | -0.2 | -0.1 | -0.1 | 0.2 |

Table 5. Change in color ($\Delta E_{ab}$) and change in lightness ($\Delta L$) at various exposure times for wood flour filled HDPE and photostabilizer blends after accelerated weathering.

| | | | | $\Delta E_{ab}$ | | | | $\Delta L$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | B | C | D | Exposure Time (Hours) | | | | Exposure Time (Hours) | | | |
| LS1 | LS2 | UVA | Color | 250 | 500 | 1000 | 2000 | 250 | 500 | 1000 | 2000 |
| - | - | - | - | 4.4 | 16.7 | 25.4 | 35.8 | 4.1 | 13.1 | 20.4 | 31.0 |
| + | - | - | - | 8.6 | 20.2 | 29.3 | 37.2 | 8.0 | 17.5 | 25.2 | 33.1 |
| - | + | - | - | 9.0 | 19.6 | 28.1 | 34.7 | 8.6 | 16.4 | 23.6 | 30.5 |
| - | - | + | - | 6.7 | 17.7 | 25.6 | 32.8 | 5.7 | 13.6 | 20.1 | 27.7 |
| - | - | - | + | 6.6 | 13.1 | 20.1 | 25.4 | 6.2 | 11.4 | 18.6 | 24.3 |
| + | + | - | - | 7.9 | 19.4 | 27.6 | 34.8 | 7.7 | 17.2 | 24.2 | 31.5 |
| + | - | + | - | 7.4 | 18.2 | 27.0 | 33.8 | 7.2 | 16.3 | 23.7 | 30.5 |
| - | + | + | - | 6.9 | 16.3 | 24.7 | 30.3 | 6.6 | 13.9 | 20.8 | 26.8 |
| + | - | - | + | 7.1 | 13.3 | 18.7 | 23.6 | 6.9 | 12.6 | 17.9 | 22.7 |
| - | + | - | + | 9.6 | 16.4 | 21.6 | 26.1 | 9.4 | 15.6 | 20.8 | 25.2 |
| - | - | + | + | 5.7 | 11.1 | 16.0 | 20.8 | 5.5 | 9.8 | 14.7 | 19.7 |
| + | + | + | - | 8.3 | 18.6 | 25.9 | 32.2 | 8.1 | 16.9 | 23.1 | 29.4 |
| + | + | - | + | 11.7 | 17.8 | 23.6 | 27.5 | 11.4 | 17.1 | 22.8 | 26.7 |
| + | - | + | + | 7.8 | 13.1 | 19.2 | 23.8 | 7.7 | 12.3 | 18.3 | 22.9 |
| - | + | + | + | 10.8 | 15.0 | 20.9 | 26.0 | 10.7 | 14.4 | 20.1 | 25.2 |
| + | + | + | + | 7.1 | 14.4 | 19.6 | 23.8 | 6.9 | 13.8 | 18.8 | 22.9 |

Table 6. Flexural modulus (MOE) and strength at various exposure times for unfilled HDPE and photostabilizer blends after accelerated weathering.

| | | | | MOE (GPa) | | | | | Strength (MPa) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | B | C | D | Exposure Time (hours) | | | | | Exposure Time (hours) | | | | |
| LS1 | LS2 | UVA | Color | 0 | 250 | 500 | 1000 | 2000 | 0 | 250 | 500 | 1000 | 2000 |
| - | - | - | - | 0.84 | *0.93* | 1.16 | 1.07 | *0.77* | 22.3 | 23.0 | *23.4* | 17.1 | 17.5 |
| + | - | - | - | 0.80 | 0.90 | 0.93 | 1.10 | 0.93 | 21.6 | 24.9 | 25.3 | 27.4 | 27.2 |
| - | + | - | - | 0.89 | *0.96* | 1.00 | 1.14 | 1.03 | 22.7 | 26.1 | 26.6 | 28.9 | 28.1 |
| - | - | + | - | 0.79 | 0.90 | 0.90 | 1.05 | 1.01 | 21.5 | 24.3 | 25.8 | 27.8 | 27.3 |
| - | - | - | + | 0.81 | 1.00 | 0.98 | 1.12 | 0.97 | 21.3 | 25.1 | 25.9 | 27.4 | 25.6 |
| + | + | - | - | 0.81 | 0.98 | 0.94 | 1.12 | 1.03 | 21.5 | 24.9 | 25.7 | 28.0 | 26.7 |
| + | - | + | - | 0.78 | 0.91 | 0.91 | 1.07 | 0.88 | 20.9 | 23.9 | 24.9 | 27.4 | 26.5 |
| - | + | + | - | 0.74 | 0.95 | 0.96 | 1.08 | 1.07 | 21.2 | 24.7 | 25.4 | 27.2 | 27.5 |
| + | - | - | + | 0.81 | 0.99 | 0.96 | 1.10 | 0.99 | 21.0 | 25.2 | 25.3 | 28.0 | 25.3 |
| - | + | - | + | 0.87 | 1.01 | 1.01 | 1.16 | 1.03 | 22.3 | 25.7 | 26.3 | 28.7 | 26.8 |
| - | - | + | + | 0.80 | 0.90 | 0.96 | 1.11 | 0.98 | 22.0 | 24.8 | 25.3 | 27.7 | 25.3 |
| + | + | + | - | 0.74 | 0.92 | 0.88 | 1.07 | 0.98 | 20.3 | 24.4 | 24.3 | 27.7 | 25.9 |
| + | + | - | + | 0.78 | 0.96 | 0.92 | 1.13 | 0.92 | 20.6 | 24.8 | 25.5 | 28.4 | 25.8 |
| + | - | + | + | 0.79 | 0.94 | 0.88 | 1.07 | 0.91 | 19.6 | 24.6 | 24.2 | 27.1 | 25.1 |
| - | + | + | + | 0.85 | 0.98 | 1.03 | 1.14 | ***0.97*** | 21.8 | 25.7 | 26.7 | 28.6 | 24.6 |
| + | + | + | + | 0.72 | 0.92 | 0.90 | 1.07 | 0.96 | 19.9 | 24.0 | 24.7 | 27.4 | 25.0 |

A value reported in gray italics represents no significant change in property from the unexposed value at α = 0.05.

Table 7. Flexural modulus (MOE) and strength at various exposure times for wood flour filled HDPE and photostabilizer blends after accelerated weathering.

| | | | | MOE (GPa) | | | | | Strength (MPa) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | B | C | D | Exposure Time (hours) | | | | | Exposure Time (hours) | | | | |
| LS1 | LS2 | UVA | Color | 0 | 250 | 500 | 1000 | 2000 | 0 | 250 | 500 | 1000 | 2000 |
| - | - | - | - | 3.34 | 3.48 | *3.32* | *3.23* | 2.46 | 40.1 | *40.5* | 37.2 | 37.9 | 31.2 |
| + | - | - | - | 3.35 | *3.40* | *3.29* | *3.32* | 2.49 | 41.1 | *40.4* | *39.0* | *39.3* | 34.0 |
| - | + | - | - | 3.34 | *3.38* | *3.20* | 3.15 | 2.58 | 41.3 | *40.5* | *39.9* | 38.9 | 34.6 |
| - | - | + | - | 3.01 | 3.19 | *3.11* | 3.24 | 2.47 | 37.6 | *37.5* | *38.4* | *38.5* | 33.7 |
| - | - | - | + | 3.51 | 3.91 | *3.37* | 3.60 | 2.98 | 38.3 | *38.2* | *37.4* | *37.1* | 34.4 |
| + | + | - | - | 3.42 | *3.48* | *3.33* | *3.33* | 2.71 | 41.0 | *40.8* | *40.7* | *39.9* | 35.8 |
| + | - | + | - | 3.34 | *3.33* | *3.24* | *3.42* | 2.42 | 39.7 | *39.1* | *39.0* | *39.9* | 34.9 |
| - | + | + | - | 3.24 | *3.27* | *3.11* | *3.32* | 2.44 | 39.4 | *38.7* | *38.5* | *39.0* | 35.2 |
| + | - | - | + | 3.80 | *3.83* | *3.59* | *3.72* | 3.20 | 39.8 | *40.1* | *39.4* | *39.5* | 36.3 |
| - | + | - | + | 3.81 | *3.82* | *3.67* | *3.73* | 3.20 | 38.7 | *38.4* | *38.5* | 37.4 | 35.7 |
| - | - | + | + | 3.30 | *3.45* | *3.38* | 3.66 | *3.31* | 36.2 | *37.5* | *37.3* | *37.6* | *34.2* |
| + | + | + | - | 3.28 | *3.33* | 3.07 | *3.23* | 2.62 | 40.3 | 39.2 | *38.5* | 37.7 | 36.3 |
| + | + | - | + | 3.94 | *3.97* | *3.63* | 3.72 | 3.09 | 39.1 | *38.9* | *38.5* | *37.6* | 36.2 |
| + | - | + | + | 3.72 | *3.71* | *3.38* | *3.82* | 3.08 | 37.2 | *38.6* | *37.3* | *37.4* | 34.8 |
| - | + | + | + | 3.45 | 3.64 | *3.36* | 3.69 | 3.11 | 37.5 | *36.2* | *38.0* | *38.4* | 34.9 |
| + | + | + | + | 3.76 | 3.57 | *3.35* | *3.59* | 3.08 | 37.6 | *38.3* | *37.7* | *38.7* | 36.2 |

A value reported in gray italics represents no significant change in property from the unexposed value at α = 0.05.