INFLUENCE OF FUNGAL DECAY AND MOISTURE ABSORPTION ON MECHANICAL PROPERTIES OF EXTRUDED WOOD-PLASTIC COMPOSITES

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ABSTRACT

In previous research on the effects of fungal decay on the mechanical properties of wood-plastic composites (WPC), results were inconclusive due to the influence of moisture absorption. This study was conducted to clarify the contributions of moisture and wood decay fungi to WPC damage. Changes in flexural strength (MOR), modulus (MOE), and weight of two extruded wood-polyethylene composite (WPC) formulations, yellow-poplar sapwood and redwood heartwood, were compared following 3 months of incubation with wood decay fungi. All materials were evaluated using modified agar-block tests in which the white-rot fungus *Trametes versicolor* and the brown-rot fungus *Gloeophyllum trabeum* were employed as test fungi. In addition, soil-block tests were performed with yellow-poplar, one WPC formulation, and *T. versicolor* as test fungus only. It was determined that stiffness of WPC was affected more severely by moisture absorption than by fungal colonization. Strength of WPC was not affected by decay fungi but significantly ($p = 0.0001$) reduced by moisture absorption for a formulation containing 70% wood filler. Calculation of weight loss in WPC was based on the wood fraction only. Modified agar-block and soil-block tests were equally suited for determining weight loss in WPC, but agar-block tests could be completed in a shorter time span. Weight loss of a formulation with 70% wood filler and incubated with *T. versicolor* was twice as high as that of redwood in a modified agar-block test (6% versus 3%); however, only 1% weight loss was obtained when the formulation contained 49% wood filler. These results indicate that WPC can be designed to provide high fungal durability by controlling the material composition of the formulation. Weight loss is a more sensitive indicator of fungal decay than strength and stiffness measurements in WPC as well as in redwood.

Keywords: Fungal decay, mechanical properties, moisture absorption, natural fiber thermoplastic composites, redwood, weight loss, wood-plastic composites, yellow-poplar.

INTRODUCTION

Wood–plastic composites (WPC) represent a relatively new class of hybrid materials that have been gaining rapid market share, primarily as substitute for wood decking (Wolcott and Englund 1999; Clemons 2002). Evidence for the presence of fungal decay and discoloration on WPC decking material in service was first presented by Morris and Cooper (1998). A multitude of methods are available to test for fungal degradation of wood and plastics; however,

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there is no laboratory standard available for specifically testing the fungal durability of WPC. At present, in North America, the soil-block test for wood (ASTM D2017-81; 1981) has been adopted for fungal durability tests of WPC in which weight loss serves as an indicator of decay.

Published information on the effect of wood decay fungi on strength properties of WPC has focused primarily on specimens manufactured by compression- and injection-molding (Khavkine et al. 2000; Silva et al. 2001; Verhey et al. 2001a; Ibach and Clemons 2002; Simonsen et al. 2004), methods not currently used by a majority of industrial products. An exception is research conducted by Clemons and Ibach (2004), who determined flexural strength of fungal-treated WPC produced by injection- and compression-molding as well as by extrusion.

It is well known that strength properties are the most sensitive indicators of fungal decay in solid wood (Trendelenburg 1940; Kennedy 1958; Wilcox 1978; Hardie 1980), but this concept does not necessarily apply to a composite material consisting primarily of a thermoplastic polymer matrix and wood filler. Most commercial forms of wood-plastic composites in North America utilize wood flour without the addition of coupling agents. In this form, the wood flour used in WPC does not greatly contribute to the strength of the composite. However, the wood filler tends to increase the stiffness of the composite (Wolcott 2001) and may therefore be useful as an indicator of fungal decay in WPC. It is desirable to compare potential losses in weight and stiffness in WPC formulations caused by decay fungi to determine which of the two methods is more sensitive as an indicator of fungal decay.

In summary, the principal objective of this investigation was to determine the relative contributions of wood decay fungi and moisture exposure to potential losses in flexural strength (modulus of rupture, MOR), stiffness (modulus of elasticity, MOE), and weight of extruded WPC. Fungal decay susceptibility of WPC was compared to redwood (*Sequoia sempervirens* D. Don Endl.) and yellow-poplar (*Liriodendron tulipifera* L.). In addition, the sensitivity of modified agar- and soil-block tests in WPC fungal durability testing was compared.

MATERIALS AND METHODS

Materials

Two WPC-formulations (No. 3 and No. 7), which were previously shown to be either susceptible (No. 7) or resistant (No. 3) to fungal decay (Pendleton et al. 2002), were used in this study. For each composite formulation, maple 40-mesh wood flour (American Wood Fibers 4010, Schofield, WI) was used as a filler for a high-density polyethylene (HDPE) (Equistar Chemical LB010000, Houston, TX) thermoplastic matrix material. The component weight percentages of formulation No. 3 were 49% wood filler and 45% HDPE, whereas No. 7 consisted of 70% wood filler and 24% HDPE. Process additives were maintained at 6% (by weight) in both formulations and included ethylene bis-stearamide wax (General Electric Specialty Chemicals, Parkersburg, WV), zinc stearate (Chemical Distributors Inc. DLG20, Portland, OR), phenolic resin (Plenco 12631, Sheboygan, WI), and methyl di-isocyanate resin (Bayer Mondur 541, Pittsburgh, PA). Since it was the objective of the present study to obtain fundamental information on the material characteristics of fungal-degraded WPC, zinc borate (preservative) was not included in the formulations. Yellow-poplar (*Liriodendron tulipifera*) sapwood and redwood (*Sequoia sempervirens*) heartwood specimens were included in the study to serve as references.

The components for each WPC formulation were mixed in a drum blender for 10 min and added to the feed hopper of a 55-mm counter-rotating, conical twin-screw extruder (Cincinnati Milacron, Batavia, OH). A slit die (15.24 cm by 1.27 cm) was attached to the extruder, and the extrudate was water-cooled after exiting the die. Extrusion conditions have been described previously elsewhere (Pendleton et al. 2002).

Sample preparation, fungal isolates, and culture conditions

Specimens for flexural strength and weight loss tests (nominal dimensions: 9.53-cm length, 1.27-cm width, 0.48-cm thickness) of all materials were machined by conventional techniques. When machining WPC specimens, it has to be considered that part or all of the composite surface layer may be removed, and thus wood encapsulation by the plastic may be reduced. Sets of samples and controls were randomly chosen, whereas for redwood, side-matching samples and controls were prepared. It was anticipated that side-matching of specimens would reduce variability of the test results. The largest sample dimension was coincident with the extrusion direction (for WPC) or longitudinal axis (for solid wood). After cutting, specimens were conditioned to constant weight (less than 1% change during 24 h) at 24°C and 50% relative humidity and weighed to the nearest 0.001 g. The two fungal isolates used in this study included a white-rot fungus, *Trametes versicolor* (L. ex Fr.) Pilát (USDA Forest Products Laboratory isolate No. M697), and a brown-rot fungus, *Gloeophyllum trabeum* (Pers. ex. Fr.) Murrill (USDA Forest Products Laboratory isolate No. M617) which were maintained on petri dishes containing 20 g malt extract and 15 g agar (both from Becton, Dickinson and Company, Sparks, MD) per one liter of water.

Fungal inoculation and incubation of WPC and wood samples

The conditioned and weighed WPC and wood specimens were wrapped with aluminum foil and sterilized in an autoclave for 30 min at 121°C. For agar-block tests, French Square bottles (0.24 l) were each filled with 27 ml of liquid medium (20 g/l malt extract, 15 g/l agar) and autoclaved at 121°C for 20 min with the lids of the bottles slightly opened. After autoclaving, the bottles were carefully placed in the horizontal position until the agar solidified. Each bottle was then inoculated with a plug (1-cm diameter) of either *T. versicolor* or *G. trabeum*, taken from the edge of an actively growing colony, and incubated at 25°C. When the agar in the bottles was completely covered with fungal mycelium, either a WPC or a wood sample was added on top of the mycelium in each bottle. No glass rods or plastic mesh were used to separate the test material from the agar, as is commonly done in agar-block tests, to enhance moisture uptake of WPC samples. The soil-block test was performed according to ASTM D2017-81 (1981) with the following two exceptions: larger samples and feeder-strips (made of yellow-poplar) were used for flexural strength tests, and the bottles were placed horizontally during incubation. Only formulation No. 7 and yellow-poplar were used in soil-block tests and inoculated with *T. versicolor* only. In total, 18 bottles were prepared for each fungus/test type (agar-or soil-block) combination, and 18 bottles each were prepared as controls without fungal inoculum. All bottles were incubated in an environmental chamber maintained at 75% relative humidity and 27°C for 12 weeks.

Property changes

Following incubation, the specimens were removed from the bottles, adhering mycelium was carefully removed from the samples, and specimens were weighed. Specimens were reconditioned to constant weight (less than 1% change during 24 h) at 24°C and 50% relative humidity and weighed to the nearest 0.001 g. During conditioning, heavy weights were placed on top of the WPC specimens to prevent twisting, and specimens were periodically turned over. Weight loss (WL) of each specimen, expressed in percent, was determined as the difference in weight of a specimen after initial conditioning, i.e., prior to inoculation with a fungus, and after incubation and reconditioning. For WPC, calculation of weight loss was based on the amount of wood filler present (49% or 70%), assuming that the polyethylene matrix and the additives are not degradable.

Flexural strength (MOR) and stiffness (MOE) of reconditioned WPC and wood samples were determined in a four-point bending test utilizing quarter-point loading (ASTM D790-84a, 1984, method II) on a Universal Testing Machine (In-

stron, model 4466, capacity 10 kN). Load and support span were 3.868 cm and 8.128 cm, respectively, and test speed was 0.241 cm per min. Deformation of samples was measured using a linear variable differential transformer (LVDT, Sensotec, Columbus, OH, range: +/–2.54 cm).

The specimen side contacting the fungal mycelium during incubation was located on the tension face of the beam. Load and deflection data were acquired at a collection rate of 5 Hz by computer. Calculation of MOE was based on the values for 20–40% of the maximum load in the stress-strain curves because this region represents the most linear portion in the curves, and because different treatment effects were compared. Following determination of MOR and MOE, all specimens were dried in an oven at 103°C for 12 h and weighed to determine moisture content (MC) of samples. Moisture content was calculated using the following equation:

$$MC = \frac{W_w - W_D}{W_D} \cdot 100\ (\%)$$

where W_w = wet weight of specimen (g) and W_d = dry weight of specimen (g).

For WPC, MC was calculated on a dry-weight basis of the wood content only.

Strength and stiffness measurements were also conducted on nonincubated but conditioned WPC specimens ("nonincubated controls"). These tests were done to determine if a 12-week incubation on agar or a feeder-strip *per se* caused significant losses in MOR and MOE and to evaluate if water absorption causes more damage to WPC than fungal decay. For comparison, nonincubated controls of yellow-poplar were also tested.

Statistical analysis

One-way analyses of variance (SAS Proc Mixed) were used separately for agar-block test and soil-block test to determine if there were significant differences in weight loss, MOE, and MOR between samples and incubated controls within materials and between materials within samples (SAS Institute 1999). One-way analyses of variance were used rather than two-way analyses because non-normality of the data and non-homogeneous variances required logarithmic transformation of data in some treatment and material combinations but not others. In situations when transformation of the data did not result in homogenous variances, Satterthwaite's approximation was employed to make treatment comparisons. When more than two mean values were compared (i.e., agar-block test), significant differences between material mean values or treatment mean values were followed by least significant difference tests to identify which material or treatment means were different. One-way analysis of variance was also used to compare 1) incubated and nonincubated controls and 2) agar- and soil-block tests.

RESULTS AND DISCUSSION

Weight changes

Calculation of weight loss in WPC was based on the wood filler only, since at present no conclusive evidence is contained in the literature that polyethylene can be degraded by any of the two test fungi, especially without prior abiotic oxidation (Albertsson et al. 1987; Albertsson and Karlsson 1988; Iioyshi et al. 1998; Hakkarainen et al. 2003). In general, biodegradation of high-molecular weight polyethylene proceeds very slowly but can be enhanced by, e.g., blending (for example, with starch), copolymerization, or grafting (Hakkarainen et al. 2003). Besides wood and plastic, additives in WPC are possible food sources for fungi. It is unlikely that the phenolic resin and methyl di-isocyanate in our formulations can be used as substrates by fungi, in contrast to ethylene bis-stearamide wax and zinc stearate (Brown 1946; Berk et al. 1957).

Trametes versicolor caused significant ($p < 0.0001$) weight loss in yellow-poplar, redwood, and formulation No. 7 but not in formulation No. 3 (Table 1, Fig. 1). The weight loss in yellow-poplar amounted to 56% in a modified agar-block test and to 62% in a soil-block test. *Trametes versicolor* caused a weight loss of approximately 3% in redwood and 6% in No. 7 in modified agar-block tests. This result indicates

TABLE 1. *Stiffness (MOE), flexural strength (MOR), and weight loss (based on wood fraction) of two WPC formulations, yellow-poplar and redwood, following 3 months of incubation with* T. versicolor *and* G. trabeum. *Formulation No. 3 consisted of 49% wood, 45% HDPE, and 6% additives; formulation No. 7 contained 70% wood, 24% HDPE, and 6% additives. Each value represents the average of 16 replicates, except for yellow-poplar in the soil block test (15 replicates). Figures in bold indicate significant ($p < 0.0001$) difference between samples and incubated controls.*

Material, treatment	Type of test	Density* (g/cm^3)		MOE† (MPa)		MOR (kPa)		Weight loss (%)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
#3, *T.v.*	agar	1.05	0.01	1497	212	26274	2344	1.17	1.25
#3 *G.t.*	agar	1.07	0.01	1345	94	28096	1490	–1.41	0.13
#3, incub. control	agar	1.07	0.01	1461	194	26920	2926	–1.26	0.09
#3, non-incub. control	n.a.	1.09	0.01	1979	130	26862	1101	n.a.	n.a.
#7 *T.v.*	agar	0.99	0.02	797	163	11975	2226	**6.32**	0.47
#7 *G.t.*	agar	0.98	0.01	839	109	10590	2166	0.38	0.74
#7, incub. control	agar	1.02	0.01	806	116	11171	1948	–0.46	0.21
#7, non-incub. control	n.a.	1.12	0.01	1004	216	14696	1139	n.a.	n.a.
YP, *T.v.*	agar	0.21	0.03	**2525**	479	**16355**	3500	**55.94**	5.59
YP, *G.t.*	agar	0.40	0.05	**6258**	2098	**43098**	21167	**25.21**	5.82
YP, incub. control	agar	0.48	0.02	9719	787	97598	7374	–1.19	0.70
YP, non-incub. control	n.a.	0.61	0.02	15366	623	145183	8190	n.a.	n.a.
RW, *T.v.*	agar	0.44	0.03	9380	1661	81643	14405	**3.03**	0.51
RW, *G.t.*	agar	0.45	0.01	8325	1733	68763	13596	**2.76**	1.56
RW, incub. control *T.v.*	agar	0.45	0.02	10096	1157	89621	10501	1.29	0.54
RW, incub. control *G.t.*	agar	0.47	0.03	9244	1327	91625	21824	–0.78	0.94
#7 *T.v.*	soil	0.91	0.04	**963**	164	7203	1915	**7.90**	2.97
#7, incub. control	soil	0.94	0.04	560	180	8092	2434	0.77	0.94
YP, *T.v.*	soil	0.22	0.03	**2758**	948	**13525**	4050	**61.85**	4.32
YP, incub. control	soil	0.54	0.04	13479	1518	126235	14101	2.03	0.19

T.v. = *Trametes versicolor*
G.t. = *Gloeophyllum trabeum*
YP = yellow-poplar
RW = redwood
n.a. = not applicable (equilibrated only).
* determined at time of flexural strength test.
† Calculation based on the values for 20–40% of the maximum load in the stress-strain curves.

that WPC *per se* are not less susceptible to decay by a white-rot fungus than redwood heartwood, which is classified as resistant when in ground contact (ASTM D2017-81, 1981). However, the fact that *T. versicolor* caused only 1% weight loss in formulation No. 3 demonstrates that WPC can be designed to provide high durability against fungal decay. It has previously been demonstrated that lower levels of wood filler in WPC decrease the growth substrate available for microorganisms (Mankowski and Morrell 2000; Verhey et al. 2001b; Pendleton et al. 2002; Simonsen et al. 2004).

Gloeophyllum trabeum caused 25% weight loss in yellow-poplar and approximately 3% weight loss in redwood but no weight losses in either WPC formulation. It is likely that the maple filler used in the formulations did not represent an ideal substrate for *G. trabeum*, which is usually more aggressive on softwoods than on hardwoods (Schmidt 1994).

No statistically significant difference between weight losses of No. 7 samples incubated with *T. versicolor* in agar- and soil- block tests was determined. This indicates that both test types are equally sensitive to determine fungal decay in WPC. However, modified agar-block tests are advantageous because they can be completed in a shorter time span than soil-block tests. In agar-block tests, fungi do not have to be pre-grown on a feeder-strip which takes significantly longer than growing cultures on agar.

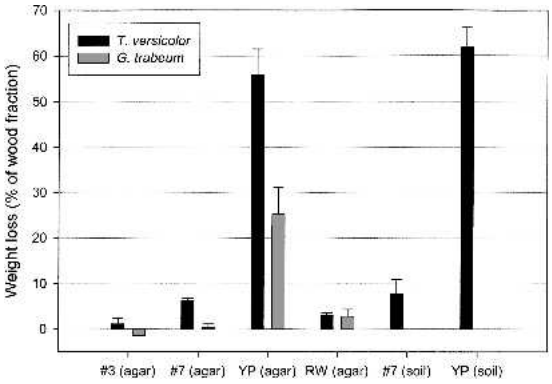

FIG. 1. Weight losses (percent of wood fraction) of formulations No. 3 (wood/HDPE/additives = 49/45/6) and No. 7 (wood/HDPE/additives = 70/24/6), yellow-poplar and redwood following 3 months of incubation with *T. versicolor* and *G. trabeum* in agar- and soil-block tests. Soil-block tests were performed with No. 7, yellow-poplar and *T. versicolor* only.

Weight loss of yellow-poplar samples incubated with *T. versicolor* in a soil-block test was significantly ($p = 0.0026$) higher than that in an agar-block test. Therefore, the soil-block test was more sensitive to detect fungal decay in yellow-poplar under the conditions of the experiments. It has to be considered that in agar-block tests with wood, specimens are usually not placed directly onto the agar but separated from it by using glass rods or a plastic mesh, thus inhibiting excessive moisture uptake.

No weight losses occurred in the incubated controls; this confirms that sterile conditions were maintained during the course of the experiments. The weight gain in some of the controls (Table 1) is due to the hysteresis effect, a common source of error in wood decay experiments (Zabel and Morrell 1992). In the soil-block test for solid wood (ASTM D2017, 1981), hysteresis is regarded as a negligible source of error because this test is primarily used to compare fungal durability of different wood species that are commonly displaying a broad range of weight losses. Since weight losses observed in WPC are generally low (less than 10%), hysteresis may negatively influence the accuracy of weight loss measurements in these composites. In addition, determination of weight loss in WPC may be affected by a lack of complete MC equilibration of specimens.

Moisture absorption

Traditional decay tests use weight loss as a means of assessing fungal decay and do not separate the effects of fungal decay and moisture absorption. In an effort to quantify moisture absorption, incubated controls were used in agar- and soil-block tests. While we recognize that this experimental design does not account for potential morphological changes that may be imparted by decay fungi on the test materials, it allows us to provide some estimate of moisture changes occurring during testing.

Moisture content of incubated controls at different stages of the experiment is presented in Table 2. Moisture content of No. 3 following

TABLE 2. *Moisture content of non-inoculated controls for WPC formulations No. 3 (wood/HDPE/additives = 49/45/6) and No. 7 (wood/HDPE/additives = 70/24/6), yellow-poplar (YP) and redwood (RW). Moisture content is calculated on a dry-weight basis of the wood content only and is presented following initial equilibration, three months of incubation, and final equilibration. Values represent the average of 16 replicates for each set (standard deviation in parentheses). Initial and final moisture equilibration occurred at 24°C and 50% relative humidity.*

Material	Type of test	Moisture content (%)		
		Initial equilibration	Incubation	Final equilibration
#3	agar	3 (1.80)	32 (9.93)	9 (1.67)
#7	agar	8 (0.55)	43 (1.96)	9 (0.30)
YP	agar	8 (0.49)	101 (29.80)	9 (0.56)
RW (control for *T. versicolor*)	agar	10 (0.67)	154 (11.33)	9 (0.36)
RW (control for *G. trabeum*)	agar	7 (0.86)	144 (10.37)	8 (0.41)
#7	soil	8 (1.20)	59 (4.61)	8 (0.37)
YP	soil	10 (0.29)	70 (10.39)	8 (0.31)

initial equilibration was lower than that of No. 7 due to the presence of less hydrophilic wood filler in No. 3; in addition, it is possible that No. 3 had not completely reached its MC equilibrium yet. At the end of incubation, MC of all formulations was 32% or higher. It is apparent that the minimal MC level for fungal decay development, 22–24% (Zabel and Morrell 1992), was surpassed in the WPC specimens. Following final equilibration, No. 3 and No. 7 converged to the same MC, likely because the accessibility of the wood filler to moisture was increased in No. 3 as a result of moisture damage during incubation. Additionally, MC equilibrium of No. 3 may not have been reached completely during the reconditioning process.

Because of adherent material properties, a direct comparison between wood and WPC regarding susceptibility to fungal decay is associated with difficulties. From a microbiological point of view, it is necessary to create conditions in a standard test that ensure optimum fungal growth conditions, including an appropriate MC level, in the test materials. Our results indicate that WPC specimens reached MC levels close to or within the optimum range for development of fungal decay (40 to 80%; Scheffer 1973) when a modified agar-block test was used. In contrast, wood controls reached MC levels in the agar-block test that were beyond the optimum for fungal decay development. This problem could be overcome in future experiments by using different incubation methods for WPC and wood specimens: the latter could be separated from agar whereas WPC could be placed directly onto the agar.

It appears that high fungal durability of WPC does not simply originate from moisture exclusion. Other factors may confer durability to WPC, such as the amount and accessibility of fungal food sources. For example, it is likely that the plastic matrix provides a physical barrier for penetration of fungal hyphae into the composite. In addition, the particular form in which wood substrate is present (flour or solid wood) and its state (uncompressed as in the case of solid wood and compressed or densified in the case of flour) may influence its susceptibility to fungal decay.

Flexural strength and stiffness measurements

No significant differences in flexural strength (MOR) of No. 7 and No. 3 samples, inoculated with either *T. versicolor* or *G. trabeum*, and their respective incubated controls in modified agar-block tests were found (Table 1, Fig. 2). There was also no significant difference in MOR between No. 7 samples incubated with *T. versicolor* and incubated controls when a soil-block test was used (no soil-block tests were conducted with No. 3).

Neither *T. versicolor* nor *G. trabeum* caused any significant decrease in stiffness (MOE) in No. 3 or No. 7 in agar-block tests. However, in the soil-block test, stiffness of incubated controls of No. 7 was significantly ($p < 0.0001$) higher than that of samples inoculated with *T. versicolor*. It may be possible that this unexpected increase in WPC stiffness is due to a reinforcing effect of the fungal hyphae present in the interfacial gaps between wood filler and polymer matrix (Schirp and Wolcott 2005); however, microscopic examination would be required to further examine the cause of the observed stiffness increase.

It is important to know if a 12-week incubation on agar or a feeder-strip *per se* caused sig-

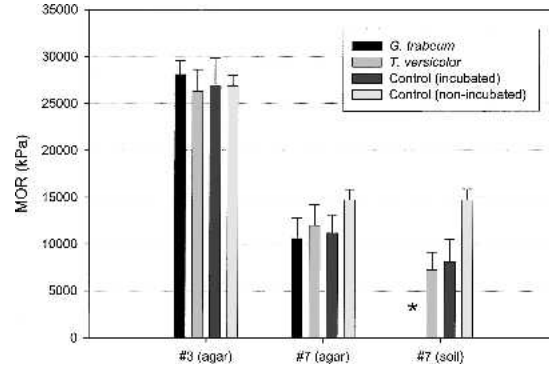

FIG. 2. Modulus of rupture (MOR) of formulations No. 3 (wood/HDPE/additives = 49/45/6) and No. 7 (wood/HDPE/additives = 70/24/6) following 3 months of incubation with *T. versicolor* and *G. trabeum*. Star (*) indicates that No. 7 was not tested with *G. trabeum* in the soil-block test. Differences between incubated and non-incubated controls were significant ($p = 0.0001$) for No. 7 in agar- and soil-block tests.

nificant losses in MOR and MOE. Stark (2001) investigated the effect of water absorption on mechanical properties of injection-molded WPC based on polypropylene. Although the results for WPC manufactured by injection-molding cannot be directly compared to extruded composites, similar tendencies with regard to the moisture uptake and mechanical performance of the materials can be expected. A decrease in flexural strength was determined for a WPC with 40% wood filler when the material had been soaked in water or exposed to 90% relative humidity (Stark 2001). None of the previously conducted research attempted to fully separate the effects of moisture absorption and fungal decay in WPC (Khavkine et al. 2000; Verhey et al. 2001a; Silva 2001; Ibach and Clemons 2002), with the exception of research by Clemons and Ibach (2004). However, Clemons and Ibach (2004) worked with preconditioned, i.e., water-soaked or boiled, WPC samples, and the total number of tested replicates in their experiments was not reported. In our experiments, MOR of No. 7 was significantly ($p = 0.0001$) higher for nonincubated than for incubated controls in agar- and soil-block tests (Fig. 2). There was no significant difference in MOR of incubated and nonincubated controls for No. 3 in the agar-block test. For both formulations, MOE of nonincubated controls was significantly higher than for incubated controls ($p = 0.0001$ for No. 3 in agar-block test and No. 7 in soil-block test; $p = 0.00029$ for No. 7 in agar-block test). These results indicate that stiffness of WPC is affected more severely by moisture absorption than by fungal attack. WPC strength was affected by water absorption only for the formulation with the higher wood filler content (No. 7).

Flexural strength and stiffness of yellow-poplar were reduced by 83% and 74% after 3 months of incubation with *T. versicolor* in an agar-block test (Fig. 4, Fig. 5). Strength and stiffness reductions were 5–6% higher in a soil-block test (Table 1). *Gloeophyllum trabeum* decreased flexural strength of yellow-poplar by 44% and stiffness by 36% during 3 months of incubation in an agar-block test. The strength

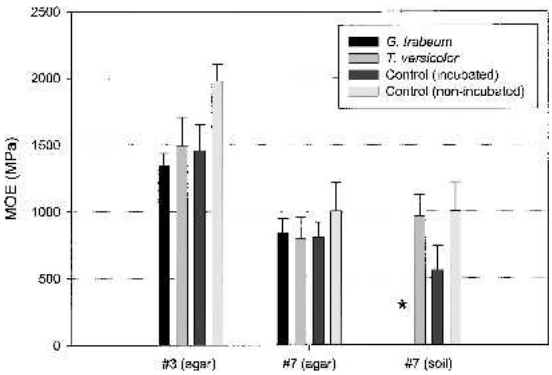

FIG. 3. Modulus of elasticity (MOE) of WPC No. 3 (wood/HDPE/additives = 49/45/6) and No. 7 (wood/HDPE/additives = 70/24/6) following 3 months of incubation with *T. versicolor* and *G. trabeum*. Star (*) indicates that No. 7 was not tested with *G. trabeum* in the soil-block test. Differences between incubated and non-incubated controls were significant for No. 3 ($p = 0.0001$) and No. 7 ($p = 0.00029$ for agar-block test and $p = 0.0001$ for soil-block test). In addition, for No. 7 in the soil-block test, MOE of samples incubated with *T. versicolor* was significantly ($p = 0.0001$) higher than MOE of incubated controls.

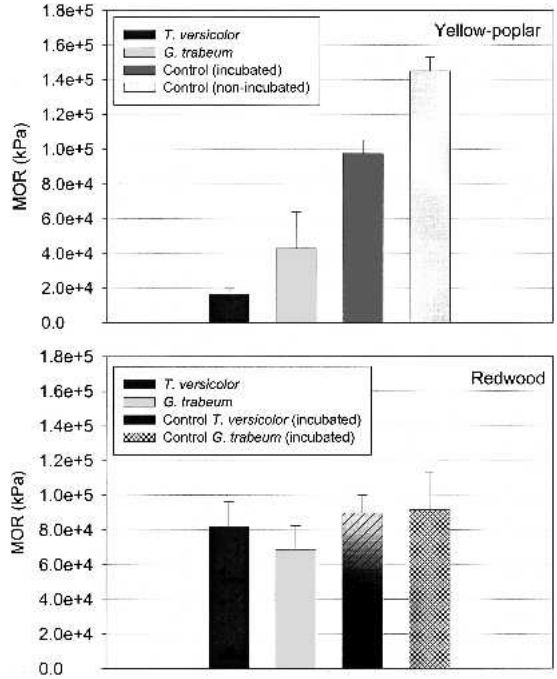

FIG. 4. Modulus of rupture (MOR) of yellow-poplar and redwood following 3 months of incubation with *T. versicolor* and *G. trabeum* in agar-block tests.

and stiffness losses of a non-durable wood species such as yellow-poplar can be expected after 3 months of incubation. Wilcox (1978) reports that modulus of rupture and modulus of elasticity in static bending tests can be reduced by 60–70% at weight losses of only 5–10%. Our results confirm that strength and stiffness measurements are the most sensitive indicators of fungal decay in a non-durable wood species (Wilcox 1978; Hardie 1980). In contrast, in the present study, neither of the two test fungi caused significant reductions in strength and stiffness of redwood heartwood, despite the occurrence of statistically significant, albeit low, weight losses.

Incubated and nonincubated controls were also included in the experiments with yellow-poplar. When comparing these two types of controls, it is apparent that moisture alone greatly reduces the strength and stiffness of wood (Table 1, Figs. 4 and 5); this effect has long been known (Kollmann and Côté 1968). In addition, differences in wood density have to be taken into account when comparing results for both types of controls. However, the reductions in MOR and MOE due to fungal decay in wood usually outweigh the effects of moisture (see Figs. 4 and 5 for yellow-poplar).

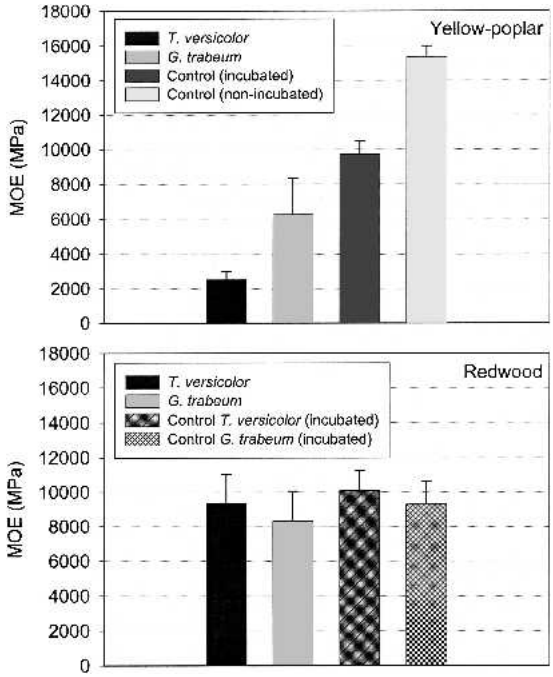

FIG. 5. Modulus of elasticity (MOE) of yellow-poplar and redwood following 3 months of incubation with *T. versicolor* and *G. trabeum* in agar-block tests.

CONCLUSIONS

The results of this study indicate that weight loss is a more sensitive indicator of fungal decay than strength and stiffness measurements in WPC and in redwood but not in yellow-poplar. Stiffness of WPC was reduced due to moisture absorption but not following 3 months of incubation with decay fungi. Wood-plastic composites *per se* are not less susceptible to fungal decay than redwood, a wood species that is resistant to fungal decay when in ground contact (ASTM D2017, 1981); however, WPC can be designed to provide high fungal durability by controlling the formulation composition. Further research is required to characterize the fungal decay mechanism in WPC and to determine the susceptibility of different polymer matrices and additives to decay fungi and other microorganisms. This will eventually lead to the development of suitable laboratory test methods for evaluation of biodeterioration in WPC and to the production of formulations providing high durability against microorganisms.

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