RESISTANCE OF FLAT-PRESSED WOOD–PLASTIC COMPOSITES TO FUNGAL DECAY: EFFECTS OF WOOD FLOUR CONTENT, DENSITY, AND MANUFACTURING TECHNOLOGY

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(Received April 2012)

Abstract. Use of wood-based materials in exterior application is inherently at risk of degradation caused by fungal decay. This risk also holds for wood–plastic composites (WPCs), whether they are extruded into rod-shaped elements or flat-pressed to large-dimensioned panels. In this study, to show the potential of WPC panels in exterior applications, fungal decay was studied by investigating mass loss in an agar-block test using *Gloeophyllum trabeum* (Gt), *Coniophora puteana* (Cp), and *Pleurotus ostreatus* (Po) as test fungi. Characterization of WPC panel durability was performed in comparison with solid wood samples by calculating the decay susceptibility index (DSI). Moreover, durability of WPC panels from laboratory (single-daylight press) and industrial (continuous double-belt press) manufacturing were compared with commercial extruded WPC decking planks. Experiments showed that the wood particles in flat-pressed panels were well protected against fungal decay by the polymeric matrix. The fungal-induced mass loss depended on panel density and wood flour content. Using DSI as an evaluation tool, WPC panels were found to be more durable than wood samples used as reference materials (DSI < 100).

Keywords: Wood–plastic composites, WPC panel, flat-pressing technology, fungal decay, mass loss, wood-degrading basidiomycetes, density, wood flour content.

INTRODUCTION

Wood-based materials used in outdoor applications are typically at risk of degradation by microorganisms if moisture content exceeds approximately 20% (approximately fiber saturation range)

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(Huckfeldt and Schmidt 2006). In principle, this also holds for wood–plastic composites (WPCs) (Morris and Cooper 1998). Demand for low-maintenance construction materials for exterior application is satisfied with either durable wood species (inter alia from tropical forests), chemically treated timber, or other resources, such as concrete, metal, or solid plastics. Because of the combination of the good workability and positive environmental image of wood and the high durability of polymers such as polyethylene and polypropylene, WPCs have been introduced successfully to the European market during the last decade. Because of encapsulation of the wood particles in a hydrophobic matrix, vulnerability to fungal decay is decreased without impregnation with chemical wood preservatives and without use of wood from tropical forests.

WPCs are typically produced by extrusion or injection molding. However, material dimensions of WPC products are limited when applying these manufacturing technologies. Alternatively, a flat-pressing technology can be used to produce panels with WPC characteristics (Benthien and Thoemen 2012). Applications for such non-structural building panels include roofline products, windowsills, flooring material for trucks, standard containers, playground equipment, and partition walls in animal husbandry.

Because of the dominance of extrusion technology in WPC manufacturing, the majority of studies on resistance to biological degradation use samples from extruded profiles. A detailed overview of knowledge and literature in the field of biological degradation and resistance to biological decay is given by Schirp et al (2008). To evaluate the comparability of durability tests done on differently processed WPC materials, Clemons and Ibach (2004) investigated extruded, injection-molded, and compression-molded samples. They found that the shaping equipment used (extruder, injection molding machine, compression molding machine) had an influence on thickness of the polymer-rich surface layer, on damaging done to wood particles, and on material density. Irrespective of a potential effect of material preparation before specimen shaping (extruder compounding before injection molding, thermokinetic mixing before compression molding, and direct profile extrusion without pretreatment), these results showed that manufacturing technology may influence WPC durability. Examples of fungal decay tests on flat-pressed or compression-molded WPC samples are given by Khavkine et al (2000), Verhey et al (2001), and Verhey and Laks (2002).

The objectives of this study were to determine fungal degradation of flat-pressed WPC panels and to compare these results with data obtained for extruded WPC decking planks. Another factor examined was the influence of different press devices on durability. Within this study, results on fungal decay resistance of industrial-scale flat-pressed WPC were presented first.

MATERIALS AND METHODS

Raw Material

Test panels were made using WPC granulate with wood contents of 50, 60, and 70% by weight. The WPC granulates were prepared using Palltrusion technology. The Palltruder (Maschinenfabrik GmbH & Co. KG, Zweibrücken, Germany) was fed with polypropylene (PP) HC 205 TF from *Borealis Polyolefine GmbH* (Schwechat, Austria) and wood flour (WF) CB 15 E from *LA.SO.LE* (Percoto, Italy). The PP had a melt flow rate of 4 g/10 min (230°C/2.16 kg), and the main fraction of WF was found to range from 0.3-0.8 mm determined by sieve analysis.

Panel Manufacturing

Manufactured WPC test panels were 420 mm long and 380 mm wide with a target thickness of 10 mm. Lateral flow of the WPC granulate during the pressing process was inhibited for panels with target density of 0.8 g/cm^3 by using a polyurethane (PU) foam frame placed on an aluminum caul plate. An identical plate was laid on top of the PU frame. The aluminum caul plates were covered with siliconized paper to prevent adherence between the WPC panel and plates. The assembly was heated inside a computer-controlled laboratory hot press. This equipment

is typically used for manufacturing thermoset-bonded wood-based panels. The press was operated in the plate position control mode with pressure limited to a maximum of 47 N/cm^2. After hot-pressing (500 s), the panels were transferred to a second press and passively cooled down under moderate pressure to room temperature while panel thickness was kept constant. A more detailed description of the panel manufacturing process can be found in Benthien and Thoemen (2012). For those samples with a higher target density (1.2 g/cm^3), an aluminium frame was used, press parameters were changed (pressure limit of 47 N/cm^2 for the first 900 s and 1200 N/cm^2 for the following 200 s), and panel cooling was done in-line without moving the panel from a hot to a cool press. The press temperature during heating was 210°C for both densities.

In addition to manufacturing panels on a laboratory press, some panels were produced using an automatically working mat former and an industrial scale continuous double-belt press (DBP) (TPS TechnoPartner Samtronic GmbH, Göppingen, Germany), which is described in detail by Dominik (2006).

Fungal Decay Test

Based on the technical specification CEN/TS 15534:2007, the fungal decay tests were carried out according to ENV 12038:2002, whereby specific modifications for the testing of WPC are given in Annex D of CEN/TS 15534.

Before testing, the WPC and reference samples made of solid wood (50 × 50 mm) were sanded on both faces to a consistent thickness of 8.5 mm and conditioned to constant mass in an environmental chamber maintained at 20°C and 65% RH for 6 wk. Conditioned specimens were weighed, and dimensions were measured. Initial dry weight of each sample was estimated based on moisture content values measured on material samples from each panel type. Moisture content was determined after drying the samples in an oven at 103°C for 48 h.

Two brown-rots, *Gloeophyllum trabeum* (Gt) and *Coniophora puteana* (Cp), and one white-rot, *Pleurotus ostreatus* (Po), were used. Virulence control and size control specimens were made on sapwood from pine (Gt and Cp) and beech (Po). Six replications were made. Additionally, blank tests without fungi were carried out on four repetitions.

Experimental vessels were prepared with culture medium, sterilized, and inoculated with a plug of Gt, Cp, or Po, respectively. Approximately 2 wk later when the agar in the experimental glasses was completely covered with fungal mycelium, the sterilized specimens were placed on the agar. Sterilization of the test specimens was carried out according to ENV 12038, Annex D.2 (steam method).

The test series with test fungi Gt and Cp were arranged in two variations prior to sterilization for each panel type. One series was conditioned at 20°C and 65% RH (untreated samples), whereas the other was vacuum-treated using an autoclave and afterward leached by immersing in water for 14 d as specified in prEN 84:1996 (pretreated samples). This facultative pretreatment was performed to ensure optimal growth conditions and to investigate if initial moisture influenced fungal decay. When Po was applied as the test fungus, such a pretreatment was unnecessary because specimens had to be embedded into water-impregnated vermiculite, ensuring optimal growth conditions.

After 16 wk of incubation time, the specimens were taken out of the experimental vessels and the surface mycelium was removed. The cleaned specimens were weighed to calculate final moisture content and were dried afterward in an oven to determine final dry mass. The mass loss of each sample was calculated by subtracting its final mass and the mass loss of the blank test from its initial dry mass. The loss in mass was based on WF content.

Assessment of Results

According to Annex D of CEN/TS 15534, samples with a final moisture content lower than 25% and a mass loss lower than 3% have to be

excluded from the determination of resistance against fungal decay because their high water resistance character provided protection against fungal infestation itself. Values of such samples were marked within the relevant tables.

According to ENV 12038, the tested material can be designated as fully resistant against wood-degrading fungi if the mean mass loss is <3% and not more than one specimen of each series tested has suffered a loss in mass >3% but <5%. For all other specimens, the decay susceptibility index (DSI) was calculated relative to durability of solid wood using the following equation:

$$DSI\ (\%) = \frac{T}{S} \times 100$$

where T = loss in mass of an individual test specimen (%) and S = loss in mass of the appropriate set of size control specimens (%).

Proceeding in this way, the durability of each WPC sample was expressed as a percentage in relation to the durability of the size control specimen durability. Consequently, a DSI of 100% meant that durability of the sample corresponded to durability of solid wood.

Experimental Design

To identify the parameters influencing fungal decay of WPC panels, the following levels were investigated:

- Target density: 0.8 and 1.2 g/cm^3
- Wood flour content: 50, 60, and 70% by weight
- Press technology: single-daylight press (laboratory scale), continuous DBP (industrial scale)
- Pretreatment: accelerated by leaching procedure (EN 84) and untreated samples
- Test fungi: Gt, Cp, and Po

For each formulation, six replications were tested.

RESULTS AND DISCUSSION

The tests in this study were planned with specimens at two density levels because of the strong influence of density on panel properties (Sellers et al 2000; Benthien and Thoemen 2012). Within this study, a consistent density level within the WF content test series (50, 60, and 70%) was not achieved. For lower density panels (target density 0.8 g/cm^3) with the higher relative polymer content, thermal shrinkage of the polymer dominated panel behavior during cooling and led to higher density panels. Panels with lower polymer content were more influenced by springback in panel thickness after hot-pressing causing panels to have lower density. With higher density panels (target density 1.2 g/cm^3), contrary behavior was observed (Table 1). The higher density of panels with a high WF content may be based on a fill-out of the cell lumina with polymer or densification of the wood structure as a consequence of a more intensive compaction. Therefore, the actual density was the result of the pure solid wood substance (1.5 g/cm^3) and polymer (approximately 0.9 g/cm^3) (Geimer et al 1993).

However, to take account of the strong influence of density, mass loss and DSI values were standardized to a consistent density level of 1.0 g/cm^3

Table 1. Actual obtained densities after hot-pressing for panels with high and low target density (0.8 and 1.2 g/cm^3) and wood flour (WF) contents of 50, 60, and 70%.

Target density (g/cm^3)	WF content (%)	Actual density (g/cm^3)
0.8	50	0.98
	60	0.95
	70	0.87
1.2	50	1.00
	60	1.07
	70	1.11

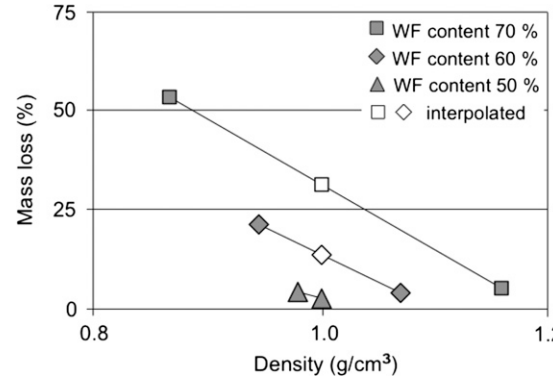

Figure 1. Exemplary standardization to a density level of 1.0 g/cm^3 by linear interpolation (*Gloeophyllum trabeum* [Gt], pretreated, wood flour content [WF] 50, 60, and 70%).

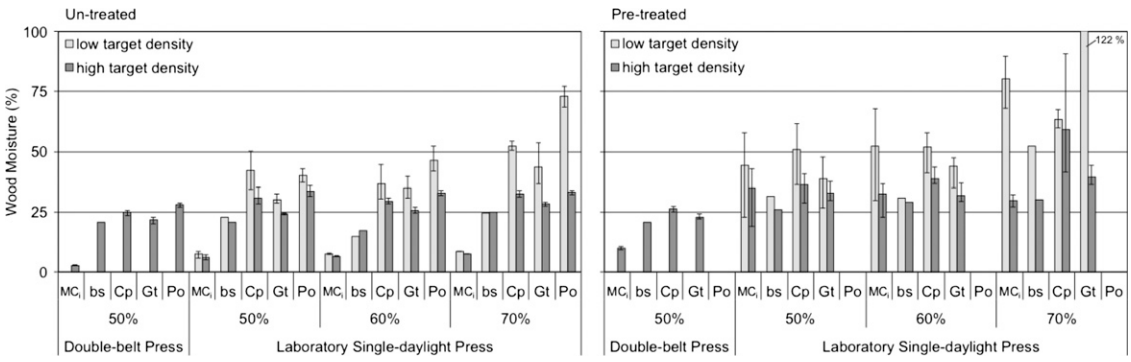

Figure 2. Moisture content (MC) for untreated and pretreated samples (wood flour content 50, 60, and 70%) before and after incubation calculated on dry wood mass. Before incubation: MC_i = initial MC; after incubation: bs = blank test sample, *Coniophora puteana* (Cp), *Gloeophyllum trabeum* (Gt), and *Pleurotus ostreatus* (Po) = test fungus.

by linear interpolation (Fig 1), like it was done for WPC panel properties (Benthien and Thoemen 2012) before. Although a linear relationship of density and mass loss was not proven here and may be debatable, such assumption can be regarded as a valuable aid to determine the influence of WF content on fungal degradation of WPC panels.

Influence of Density and Wood Flour Content

After incubation, moisture content of >90% of the samples (excluding the blank test sample and initial moisture check sample) was higher than 25% (Fig 2). Therefore, according to ENV 12038, the measured mass loss of these samples can be used to evaluate the behavior against attack by wood-degrading fungi. Invalid data are highlighted in Tables 2-4.

Influence of density and WF content on the resistance of flat-pressed WPC panels to wood-degrading basidiomycetes is shown in Table 2 (fungal-induced mass loss), whereas Table 3 lists calculated DSI (durability). It was necessary to calculate DSI for assessing durability because no

Table 2. Fungal-induced mass loss for samples with a wood flour (WF) content of 50, 60, and 70% (untreated and pretreated) made using a laboratory press as specified in ENV 12038:2002 by *Gloeophyllum trabeum* (Gt), *Coniophora puteana* (Cp), and *Pleurotus ostreatus* (Po).[a]

WF content			50%		60%		70%			
Density (g/cm^3)			0.98	1	0.95	1	1.07	0.87	1	1.16
Mass loss (%) untreated	Cp	Maximum.	+1.7	+1.7	+24.8		+0.2	+0.7		+0.3
		MW	0.9	1.9	8.1	4.9[b]	0.9	52.5	29.5[b]	2.1
		Minimum.	−0.7	−1.3	−6.0		−0.5	−0.4		−0.3
	Gt	Maximum.	+10.3	+7.7	+17.0		+0.8	+16.0		+2.3
		MW	9.8	2.2[c]	11.0	7.2[a]	2.4	22.9	15.0[b]	5.6
		Minimum.	−5.8	−1.7	−10.6		−1.1	−16.1		−3.6
	Po	Maximum.	+1.5	+1.4	+4.3		+1.3	+1.1		+0.4
		MW	4.2	5.0	9.1	6.6[b]	3.3	28.0	16.9[b]	3.6
		Minimum.	−1.9	−2.9	−2.7		−0.8	−4.1		−0.3
Mass loss (%) Pretreated	Cp	Maximum.	+1.8	+1.9	+33.3		+15.6	+12.8		+17.9
		MW	0.6	1.4	19.0	13.3[b]	6.1	50.9	42.4[b]	32.2
		Minimum.	−2.7	−1.5	−16.1		−4.4	−49.7		−28.7
	Gt	Maximum.	+26.6	+8.7	+17.8		+13.4	+5.0		+11.0
		MW	4.6	2.9	21.4	19.9[b]	4.2	53.6	31.5[b]	5.4
		Minimum.	−7.4	−2.3	−21.8		−4.2	−3.5		−2.9

[a] Mass loss based on WF; number of samples was six for each treatment.
[b] Interpolated values.
[c] Some samples had final moisture content < 25% and mass loss lower than 3%.

Table 3. Calculated decay susceptibility index (DSI) for samples with a wood flour (WF) content of 50, 60, and 70% (untreated and pretreated) made in a laboratory press.[a]

WF content		50%			60%			70%	
Density (g/cm^3)		0.98	1	0.95	1	1.07	0.87	1	1.16
DSI (%) untreated	Cp	2	3	13	8[b]	2	86	48[b]	3
	Gt	17	4[c]	11	13[b]	4	23	26[b]	10
	Po	12	14	26	18[b]	9	78	47[b]	10
DSI (%) pretreated	Cp	1	2	31	22[b]	10	83	69[b]	53
	Gt	8	5	38	24[b]	7	94	55[b]	9

[a] Used fungi were *Coniophora puteana* (Cp), *Gloeophyllum trabeum* (Gt), and *Pleurotus ostreatus* (Po).
[b] Interpolated values.
[c] Some samples had final moisture content < 25% and mass loss lower than 3%.

Table 4. Fungal-induced mass loss (mean) of flat-pressed and extruded wood-plastic composites (WPC) samples pretreated before incubation by *Coniophora puteana* (Cp), *Gloeophyllum trabeum* (Gt), and *Pleurotus ostreatus* (Po).[a]

Manufacturing technology		Flat-pressed WPC panels			Extruded decking profiles	
		Double-belt press	Laboratory press			
WF content		50%[b]	50%[c]	70%[d]	50%	70%
Mass loss (%)	Cp	0	1.4	32.2	0.5	4.1
	Gt	0[e]	2.9	5.4	0	29.0
	Po	1.9[f]	5.0[f]	3.6[f]	1.4	5.9

[a] Mass loss based on wood flour (WF); number of samples was six for each treatment.
[b] 1.05 g/cm^3.
[c] 1 g/cm^3.
[d] 1.16 g/cm^3.
[e] Final moisture content < 25% and mass loss lower than 3%.
[f] Untreated.

panel type was found to be fully resistant to attack by all tested wood-degrading fungi. For all panels, at least one test fungi induced a higher mean mass loss than 3% respectively one specimen of the six replications tested suffered a loss in mass $\geq$5%.

The influence of WF content on fungal-induced mass loss is shown in Table 2 and will be discussed separately for (1) samples with a low target density; (2) untreated samples with a high target density; and (3) pretreated samples with a high target density. It was observed for (1) that an increase in WF content led to an increase in mass loss. At high WF content, pathways for moisture and fungal hyphae were visible, indicating that the wood was easily accessible. Toward higher densities (2), samples were more protected against penetration of water and fungal hyphae because of the compactness of the material. Mass loss for high density samples was quite similar whether they had a WF content of 50 or 70%. Apparently, a high WF content did not provide any advantage for water and hyphea to enter the sample, at least not within the duration and moisture exposure of the fungal test performed here (2). For pretreated samples (3), resistance to fungal attack was inconsistent and the spread of measured values (minimum to maximum) increased. Because of the pretreatment, moisture content before incubation was about 2.6-4.6 times higher than for untreated samples. Therefore, the fungal attack was able to start immediately. With pretreated samples, mass loss was generally higher. With the wide spread range of measured mass loss for pretreated high density samples, the meaning of moisture for fungal decay was obvious. If moisture exposure was lengthy and the polymeric matrix was not absolutely faultless, wood particles were able to absorb moisture and fungal decay could take place in WPC.

In addition to the fungal-induced mass loss previously discussed, the listing of calculated DSI values in Table 3 illustrates the effect of WF

content on durability of flat-pressed WPC panels. With respect to the strong influence of density on panel properties (see Assessment of Results), the focus was on values with a consistent density level of 1.0 g/cm^3 (interpolated values for WF content 60 and 70%). Based on these values, durability decreased with increasing WF content: DSI was about 3-14% for test approaches with a WF content of 50%, about 8-24% for test approaches with a WF content of 60%, and about 26-69% for test approaches with a WF content of 70%.

Fungal-induced mass loss strongly decreased toward higher densities (Table 2). Increased compacting of the raw materials during hot-pressing for higher density panels caused a more intensive encapsulation of the wood into the polymeric matrix, which may be the reason for better protection against fungal decay. Mankowski and Morrell (2000) reported that fewer voids within the material provided fewer pathways for moisture and fungal hyphae.

The influence of density on durability will be described focusing on each level of WF content separately. For panels with a WF content of 50%, no influence of density on durability was observed because the difference between density levels was too low (0.02 g/cm^3). With a difference of 0.12 g/cm^3 for panels with a WF content of 60%, an increase in DSI from 2-10% for the high density (1.07 g/cm^3) and from 11-38% for the low density (0.95 g/cm^3) was observed. The most considerable increase in DSI (3-53% for panels with a high target density [1.16 g/cm^3] and from 23-100% for panels with a low target density [0.87 g/cm^3]) was observed for specimens with a WF content of 70%.

Influence of Manufacturing Technology

Flat-pressed laboratory WPC panels were compared with panels pressed using a continuous DBP and with commercial PP-based extruded WPC planks previously tested following the same procedure used for the flat-pressed WPC (unpublished data). As Table 4 shows, the fungal-induced mass loss was low for all WPC materials with a WF content of 50%. This indicated comparable resistance to fungal decay between extruded decking profiles and flat-pressed WPC panels. The comparable low fungal-induced mass loss of extruded samples and specimens flat-pressed on an industrial DBP promised practical suitability. Unfortunately, flat-pressed WPC panels produced on the continuous DBP cannot be declared fully resistant to fungal decay because for one test series, the required final moisture content of 25% was not reached. Regardless of using extrusion or laboratory flat-press technology, the increase of WF content from 50 to 70% resulted in increasing mass loss (except for one of the test fungi). In addition to this general trend, a considerable increase from 1.4 to 32.2% (0 to 29.0%) of mass loss was found for Cp- (Gt-) treated flat-pressed (extruded) samples. This shows the effect of high WF content WPC against fungal decay.

Decay Susceptibility Index

Calculating DSI is a useful method for estimating durability of WPC: the calculated index describes the relationship between durability of the wood particles embedded and protected by the polymeric matrix and the solid wood reference. Consequently, improvement in durability of the wood because of its encapsulation in the composites matrix can be estimated.

As a finding of this study, the solid wood reference had to harmonize with the wood species used for composite manufacturing. Since Po is specialized for hardwood degradation, it makes no sense to compare the mass loss of a softwood-based composite with a beech hardwood size control specimen. Size control specimens should be made of the wood specie on which the composite is based so that the increase of durability resulting from the embedment of wood into the polymer matrix have a more practical relevance.

CONCLUSION

In this study, experiments on the influence of density, WF content, and manufacturing process

on the resistance to wood-degrading basidiomycetes of flat-pressed WPC panels were performed by evaluating fungal-induced mass loss. WF content, a leaching procedure of storing samples in water before incubation, and panel density were established as important parameters for resistance to fungal decay. Increasing density resulted in greater resistance to fungal decay, whereas a higher WF content resulted in increasing mass loss. A leaching procedure before incubation resulted in increased mass loss.

A significant influence of the manufacturing technology was not found. Facilitating the flat-pressing technology on an industrial (continuous DBP) and laboratory scale caused a similar level of resistance to fungal decay at WF contents of 50 and 70%, respectively, as was the case for extruded decking profiles.

Using DSI as a evaluation tool showed that WPC panels were more durable than wood (DSI $\leq$ 100). It can be assumed that a compact encapsulation of the wood filler and lack of pathways for moisture and fungal hyphae caused the greater durability of WPC compared with solid wood. To assess WPC resistance to fungal decay compared with solid wood, DSI calculation has proven to be a useful method.

ACKNOWLEDGMENTS

We are grateful for the support of Priv. Doz. Dr. Habil, Gerald Koch, Johann Heinrich von Thuenen-Institute (vTI), Institute for Wood Technology and Wood Biology (HTB).

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