Moisture behaviour and biological durability of Wood-Polymer Composites

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ABSTRACT

In recent years wood-polymer composites appears at the European market more frequently, mainly in decking applications as an alternative for durable tropical hardwood decking. This study focuses on extruded decking products based on polypropylene (PP), polyethylene (PE) or polyvinylchloride (PVC) and wood flour. All products are commercially available on the Belgian market. Initially WPC's were said to be resistant for biological degradation as the wood particles should be encapsulated by the polymer, but over the years several cases of fungal decay of WPC have been reported. Therefore the moisture behaviour of the different WPC decking materials was first assessed by various moistening methods to determine if the moisture content can reach levels that initiate fungal growth. Concerning this, WPC shows better results than the traditional wood composites like particle board, MDF or OSB, but clearly absorbs sufficient moisture to be critical if sorption time is long enough. Therefore, when biological durability is tested, an adequate standard, more specific for WPC products, is needed in stead of just copying the standards designed for wooden panel products. For WPC materials a moistening pre-treatment is needed prior to the proper fungal test to include moistening time as a critical factor for assessing biological durability of these materials. Furthermore placing the products in a fungal control unit that evaluates the susceptibility for airborne surface stains revealed different results and showed that fungi grew earlier and faster on weathered samples. Concluding, in spite of the different composition of the tested products, no product was significantly better or worse than the other concerning the moisture behaviour. Furthermore only a few products were to a small extent covered by moulds in the fungal control unit.

INTRODUCTION

WPCs (Wood-Polymer Composites or Wood-Plastic Composites) are defined as any combination of wood and thermoset or thermoplastic polymers (Ellis, 2000; Clemons, 2002). Bringing those two materials together moderates their weaknesses. Compared to wood, the WPC products are less susceptible for moisture sorption, easier to design and they need less maintenance, while compared to plastic the material becomes stiffer by incorporation of wood, cheaper, lighter and show lower thermal deformation. By mixing both materials, new frailties are introduced in the resulting material. Compared to wood WPCs have a lower E-modulus, a higher density and are more expensive. Finally a WPC component is an anisotropic material that is more brittle than plastic, susceptible to colour change and moisture uptake.

Today a large amount of WPC material is used as decking and the reasons why people prefer WPC to wood are the relatively stable colour, they need no treatment against microbial attack or attack by termites, they are easy to clean (stains are easier removed), the lack of splinters, the easy nailing and screwing and the quick installation (Mankowski et al., 2005; Manning et al., 2006). Moreover Mankowski et al. (2005) and Manning et al. (2006) mentioned that warranties given typically range from 10 to 25 years and some up to 'limited lifetime'. Prices in America are different than in Europe which can be explained by the perception of WPC-products. In America WPC products are considered as a cheap material made of recycled plastic and recycled wood and intended to replace preservative treated wood. In Europe WPC products are introduced to replace tropical hardwood as a high technological product of renewable, but mostly virgin, resources for specific applications. Prices vary from 0,5 to 1,5 times the prices for the best tropical hardwood deckings.

When WPC-production was introduced, wooden particles were thought to be entirely encapsulated and therefore inaccessible for water and fungi. Meanwhile these assumptions are rejected (Morris & Cooper, 1998; Mankowski & Morrell, 2000; Mankowski et al., 2005; Manning et al., 2006) and certainly wrong if high amounts of ligno-cellulose fibre are used and if the surfaces of the decking boards are brushed to make it look less like plastic and to increase slip resistance.

Fungal growth is inextricably connected to the moisture content in the wood particles. Generally wood decaying fungi are said to be able to grow on wood when it has a moisture content above the fibre saturation point (20-25%). Therefore this research first verifies if this limit is exceeded in WPC and if the moisture behaviour (amount and rate of absorption) is similar to that of wooden panel products. If the latter is correct, standards for wooden panel products can be adopted without adjustments to test the biological durability of WPC, but when there is a significant difference in the moisture behaviour, the use of the standards for wooden panel products is not justified and a specific standard for these composite materials must be formulated.

As a first indication for the susceptibility to fungal growth, virgin and artificially weathered specimens are put in a 'fungal control unit' (FCU), which makes it possible to assess if airborne fungal spores can settle and develop on WPC-material.

MATERIAL

Although a lot of researchers develop their own WPCs and report their properties in literature, this composite material is commercialized for several decades as decking, sliding, cladding, benches,… Therefore this research focuses on nine commercialized decking products, available on the Belgian market and produced by six different companies. The products, coded from A to I, vary in board type (solid or hollow profile), polymer (PVC, PE or PP) and wood content (50 to 70%) (Table 1). Product B and C are produced by the same producer, but differ in colour. F and G should be the same product, but commercialised with another profile.

Table 1: General product properties of the tested materials, as provided by the producers

Code	Board type	Polymer	Wood content [%]
A	Hollow	PVC	50 (softwood)
B	Solid	PE	50-60 (recycled wood)
C	Solid	PE	50-60 (recycled wood)
D	Hollow	PP	70 (softwood)
E	Hollow	PE	65 (softwood)
F	Hollow	PE	60-70
G	Hollow	PE	60-70
H	Solid	PE	70
I	Hollow	PVC	50

The dimensions of the test specimens, their original location in the board and the number of replicates are shown in Table 2. This table also shows that for half of the specimens the surface is planed to eliminate the influence of the surface design. In UV artificial weathering device with spray option (UVCON machine) and the FCU only products A, B, D, E, F and H were tested; this is one material per producer. Due to a deficit of material I, no steam treatment and immersion in an ultrasonic bath was performed (see Methods).

Table 2: Dimensions, location in the board and number of replicates for every test method

Test method	Length [cm]	Width [cm]	Thickness [cm]	Location + surface	Replicates
DVS	0.5	0.5	0.5*	Central	1
Other sorption tests (see Methods)	5	5	0.5*	• Top, original surface	3
				• Top, planed	3
				• Bottom, original surface	3
				• Bottom, planed	3
UVCON and/or FCU	32	7	0.5*	• Top, original surface	3
				• Top, planed	3

* In case of material A 0.5 cm thickness was not possible; a thickness of 0.35 cm is used

To assess how to position WPC materials in the construction related wood based panels, common chipboard, plywood, oriented strand board (OSB) and medium density fibreboard (MDF) specimens of the same size, but with the original board thickness were added to the tests.

METHODS

Wood particle size

Not all product properties are (accurately) published and some are moreover hard to determine. For example a simple method to measure the wood or polymer content of WPC products is not available. Also, detailed information about additives like UV stabilizers, plasticizers, pigments, anti-oxidants, lubricants,… is not apparent, but can have an influence on certain properties. Furthermore the wood particle size can only be estimated, but can have a significant influence on the moisture behaviour and fungal growth. Measuring the particle size automatically by means of CT-scans was hard and hence it was decided to measure manually only the ten largest particles since the goal was not to have an exact size distribution, but just to determine a general particle size in an objective way.

Moisture behaviour

The moisture behaviour was determined by several moistening methods, which vary in duration (20 min to three weeks), temperature (20 to 120°C) and the way moisture is provided (vapour/steam, water). The methods simulate potential situations and sometimes cause an accelerated moisture sorption. In every test thickness swell and mass change were calculated based on the measured mass and thickness of the whole specimen. Finally the coefficient of dimensional change (%) was calculated as:

$$\frac{final\ thickness\ swell}{final\ mass\ change}$$

Air humidity impact

With a dynamic vapour sorption (DVS) device it is possible to measure very accurately mass changes caused by (de)sorption of samples in varying humidity conditions. The specimens went through a cycle of three stages while the temperature was fixed at 25°C. In the first stage, the relative humidity (RH) is 0% until the mass decreases less than 0.002 g/s or maximum during 4 hours. Subsequently the RH is raised with 10% every hour up to 90% and then lowered using the same steps. In the last stage the RH is fixed again at 0% for 4 hours. Every minute during this cycle, mass change is registered.

Steam treatment

Specimens were steam treated in an autoclave at 120 °C and 1 bar for 20 minutes. Then they were put in inert receivers on a stainless steel grid at approximately 2 cm height to prevent any contact with occasionally present liquid water. Every two specimens were separated by two stainless steel grids. Before and after this treatment the thickness and mass were measured.

Contact with a humid material in damp environment (‘contact test’)

To combine a warm and moist environment and contact with a wet object, specimens were wrapped in a wet bath towel and put in a closed plastic bag. The bag was put in an oven at 70 °C for two weeks, while water was added to keep the material wet. Again thickness and mass of the samples were measured before and after the treatment.

Immersion in water at ambient temperature and in warm water (‘cold/warm bath’)

Specimens, separated from each other and the bottom of the container by stainless steel grids, were submersed with demineralised water at room temperature. The thickness and mass was measured after 1, 2, 3, 7, 14 and 21 days to get a sorption curve for each material. A parallel, closed container was put in an oven at 70 °C and evaluated similarly.

Immersion in an ultrasonic warm water bath

Ultrasonic baths create little shock waves that have a brushing effect on the immersed object and are known as cleaning devices for laboratory material. For evaluating this effect on WPC, specimens were put randomly and separated from each other with stainless steel grids in an ultrasonic cleaning device filled with demineralised water. A frequency of 40 kHz was used in two stages. In the first stage during 90 minutes the water temperature was raised to 90 °C and in the second stage the temperature stayed at 90 °C for 90 minutes. Samples were then removed, cooled down and thickness and mass were determined.

Biological durability

Half of the specimens were weathered in an UVCON weathering device for six weeks. In the FCU a fog passes over a compartment, where a spore suspension of moulds and blue stain is poured over the soil, and then condenses against the specimens. In an environmentally open system fog can also contain other airborne fungal spores. On regular moments the percentage of the surface that is coloured by growing fungi is estimated by the naked eye or by using a light microscope. After 40 days exposure some fungi were harvested and identified at genus level.

RESULTS AND DISCUSSION

Wood particle size

The averages, standard deviation, minimum, median and maximum cross sectional area of the ten largest wood particles are shown in Table 3. For some products standard deviation in terms of percentage is up to 90%. As can be seen macroscopically there is a significant difference in the size of the particles that were used in the WPC products: the largest particles vary from 0.05 mm^2 to 0.47 mm^2. Material D has significant larger particles than all other products, while I has the smallest particles. The fact that the PP material, with the highest wood content, has the largest particles and the PVC materials, with the lowest wood content, have the smallest, imply that sorption results can not be linked to only one of the factors being polymer, wood content or particle size. Materials B, C and F are not significantly different from each other and this is also the case for materials C and H, G and H, E and G. Although products F and G should be the same product according the producer, material G has smaller particles than material F, which of course can affect the properties.

Table 3: Average, standard deviation, minimum, median and maximum cross sectional area of the ten largest wood particles (mm^2)

Product	Average	Standard deviation	Minimum	Median	Maximum	*
D	0.47	0.26	0.08	0.47	1.16	D
F	0.24	0.20	0.06	0.18	0.94	F
B	0.23	0.21	0.07	0.16	0.95	B
C	0.19	0.12	0.07	0.15	0.59	C
H	0.14	0.06	0.05	0.14	0.38	H
G	0.10	0.03	0.05	0.11	0.15	G
E	0.10	0.04	0.04	0.08	0.24	E
A	0.06	0.02	0.02	0.05	0.14	A
I	0.05	0.03	0.02	0.05	0.12	I

* Lines connect materials that are not significantly different from each other (confidence level 95%)

Moisture behaviour

At first it can be noticed that the standard deviation of the thickness swell is larger than of the mass change because. This is because it was not feasible to measure the thickness each time on exactly the same spot. Differences between the top and bottom of the boards and between original surface and planed specimens were in most cases minimal and therefore they are not discussed here.

In Figure 1 the maximum mass change and thickness swell caused by the different moistening methods are shown. Figure 2 gives the moisture content during the varying RH-cycle at DVS-analysis and in Figure 3 the sorption curves of the immersion tests shows the sorption rate and thickness swell during the immersion period.

The results prove that the complete encapsulation of the wood particles is an illusion. Klyosov (2007) considers WPC to be a porous material. The porosity can be caused by a poor adhesion between wood and polymer, but also the polymer itself can be porous when ligno-cellulose fibres and other additives are added at high temperature. According the author plastic undergoes a rather noticeable degradation or depolymerisation, which leads to release of volatile organic compounds. These VOC's, eventually together with steam originating from the heating of residual moisture in the ligno-cellulosic fibres can make the material foam and hence result in a porosity that is poorly controllable. This porosity and the defective encapsulation result in small channels, acting as pathways for moisture, even to the core of the material.

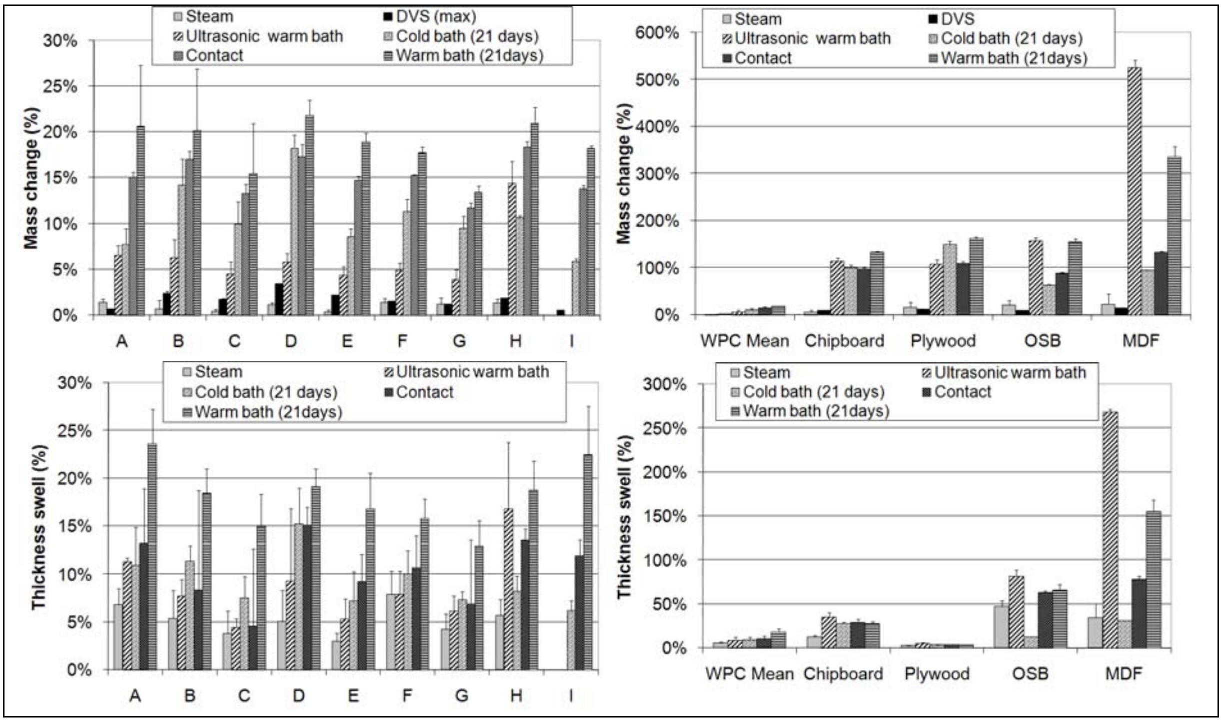

Figure 1: Mass change and thickness swell caused by sorption through different moistening methods (no values for steam treatment and ultrasonic warm bath treatment of material I)

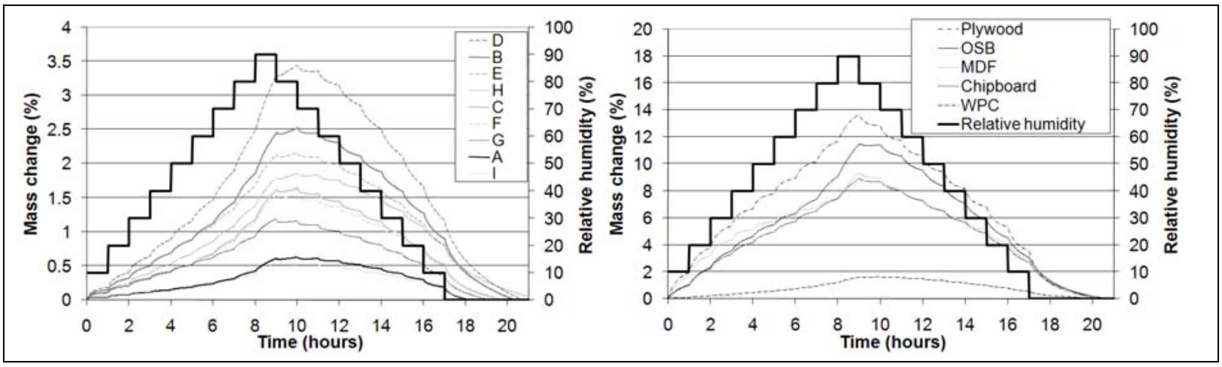

Figure 2: Sorption curves of WPC and reference materials during DVS-analysis

Obviously the sorption level depends on the moistening method used. In literature most data concern immersion of WPC in water at room temperature. Klyosov (2007) explains that WPC materials typically absorb 0.7 to 2% after 24h, 1-5% after a week and up to 18 – 22% after several moths, but the results in this study indicate higher sorption after a day and a week. The duration of the sorption is an important factor. On average a quarter of the final mass change of WPC took place in the first 24h and in that same period the thickness swell was already 32% of the value attained at 21 days. In warm water the sorption and thickness swell goes faster: after one day 46% and after two days two thirds of the final mass change was observed. After one, resp. two days in warm water 51 and 73% of the final thickness swell was reached.

Moreover, after 21 days in warm water, the specimens seemed to approach their equilibrium moisture content.

The sorption rate depends also on the shape of the samples, more precisely the surface to volume ratio (Mankowski et al., 2005; Morrell, 2007). Wang & Morrell (2004) found that after 190 days of immersion of Trex, an American WPC product, only 1% moisture was present in the inner part of the boards (15-18 mm depth), while in the outer 5 mm the moisture content raised up to 25%. Therefore this study is not based on the full product cross sections, like in the above mentioned research of Klyosov (2007), but 5 mm thick specimens were cut out of the boards. In addition by using similar specimens, they all have the same surface to volume ratio.

Except for product D, all materials absorb most moisture by immersion in warm water and in the contact test. The maximum moisture content, reached in the warm water bath, is on average 18 ± 3% for WPC, which is 11 times lower than for the reference materials.

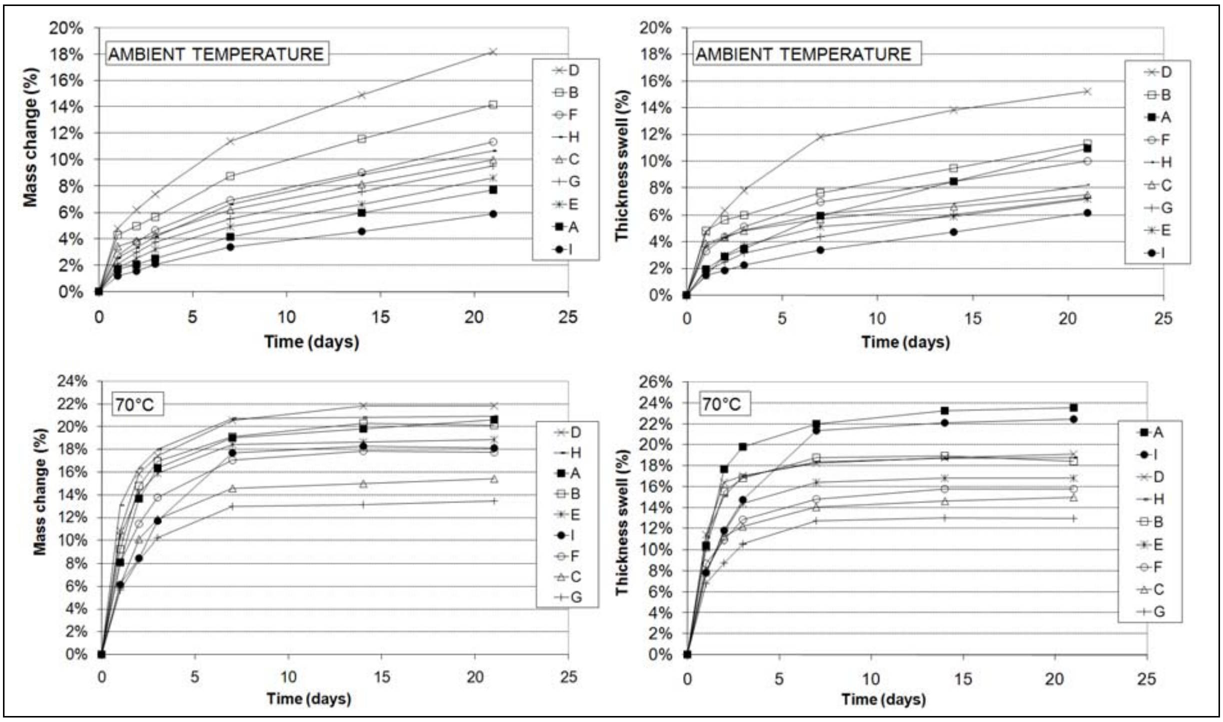

Figure 3: Sorption and thickness swell curves caused by immersing WPC in water at ambient temperature and at 70°C

The thickness swell as well is depending on the moistening method that is used and the largest swell occurred when the specimens were immersed in warm water. In the latter case, WPC swells on average 18 ± 3% or three to nine times less than the reference materials, with the exception of plywood that has also a very small swell (2.5 to 5%).

In general the mean coefficient of dimensional change of plywood is 33 times smaller than the mean value of WPC material, which is three times the mean coefficient of the other reference materials (Figure 4). The mean coefficient of dimensional change of wood (within a range of moisture content of 6-14%) fluctuates around 0.15 (Forest Products Laboratory, 1999). Although the moistening method to assess this value is not mentioned, it should be noticed that this coefficient is considerably smaller (5 to 10 times depending on the moistening method) than that of WPC-materials. The coefficients of materials based on PVC are, with exception for the steam treatment, always larger than those of other materials. As PVC becomes weaker at high temperatures, the swell of the wood particles it not moderated. The high coefficient for the steam treated specimens can be based on moisture, present in the samples, that is converted into steam and leads to swelling by its pressure while it escapes. In case of all other treatments the thickness swell is rather caused by external moisture.

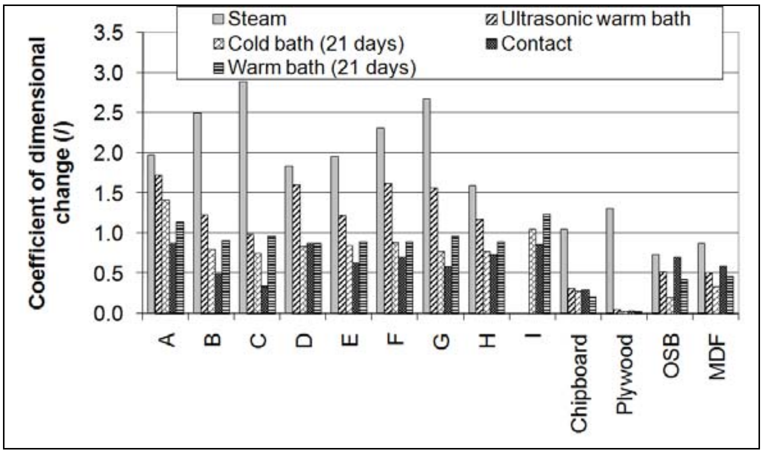

Figure 4: Coefficients of dimensional change through different moistening methods

The comparison of the WPC materials leads to different rankings depending on the moistening method that is concerned. For example material A has nearly the lowest mass change in the DVS-analysis and during the immersion in water at ambient temperature, but with al the other tests it belongs to the materials with the highest sorption. Because the latter methods include elevated temperatures, this could be the factor that influences the sorption of this PVC material. Concerning the PVC containing materials, product A absorbs and swells more than product I and as they both contain about 50% wood, the origin for this can only be linked to the larger particles of material A compared to I. Material D is always one of the most absorbing materials when the moistening time is longer than a few hours.

Although, according to the producer, materials B and C only differ in their colour, they have significantly different moisture behaviour. This is also the case for products F and G, which should have different profiles. Concerning the three materials made of PE and with about 70% wood, i.e. F, H and G, the latter absorbs the least moisture. This can be explained by its particle size, although the difference with material H is not significant.

Even though it is known that a higher wood content and larger particles result in more sorption and thickness swell (Ibach et al., 2001, Verhey & Laks, 2002), there is only a small difference for these materials and not one material is significant better or worse than the other. Apparently these materials can have a similar moisture behaviour, in spite of their composition differences.

On one hand most of these tests can be seen as a worst case scenario of realistic in service situations. If WPC decking is installed with little or no ventilation under the construction, a moist environment can be created which is simulated with the DVS device. In this case a small increase in mass is expected, but this will normally cause no serious problems. Bad design can cause water traps on the deck and lead to immersion of parts of the boards. If this wetting lasts a few weeks a considerable mass change (5 to over 20%) and a thickness swell of at least 5% is possible. Furthermore leaving a wet fabric, for example a doormat, on a WPC deck or using WPC for ground contact applications can cause moisture problems. The higher temperatures in the test methods are perhaps unrealistic, but were applied to accelerate the absorption.

Besides distortions, swelling and buckling is initiated by water sorption, fungal growth can be initiated. The moisture level that is reached in the WPC material, as well as the time of wetness

(Van Den Bulcke & Van Acker, 2008) determines the occurrence of this biological degradation. Concerning the first condition, wood is said to be susceptible to fungal growth if it has a moisture content above fibre saturation point. Because polymers are considered to absorb no or only negligibly small amounts of water (Manning et al., 2006), composite materials with respectively 50 to 70% wood should exceed a moisture content of 10% to 14% to initiate fungal growth. According to the performed tests those levels of moisture content can be reached in immersed specimens, surely in the top layers of the products. However, immersion in water at ambient temperature should last several weeks, while immersion in water at 70°C makes that the moisture content reaches the limit for fungal growth after less than a week.

The moistening tests presented can be used for the development of standards to assess the susceptibility of these materials for fungi. Till now standards recommend tests which are borrowed from the wood or plastic sector (Mankowski et al., 2005; CEN/TS 15534-1, 2006) and an appropriate test methodology specifically for this composite materials is not developed. This research shows that WPC-materials have distinct different moisture behaviour than wood-based panel products. Because, when existing standards are used, specimens absorb not enough moisture through the short duration of the tests, Clemons & Ibach (2004) plead for a pre-treatment that can bring the moisture content close to fibre saturation point. This research shows that just immersing the materials in warm water for at least one weeks seems to be the most effective and simple way to moisten samples as pre-treatment for fungal tests. Mixing wood particles with a polymer makes WPC a durable material because the moisture absorption of the wood is difficult and slow. The time needed to absorb enough moisture for initiation of fungal growth, is a very important factor in the assessment of the durability and service life of WPC (Van Acker, 2006).

Biological durability

Most of the WPC-materials have stains, caused by moulds, which increase after 40 days up to 50% of the surface area (Figure 5).

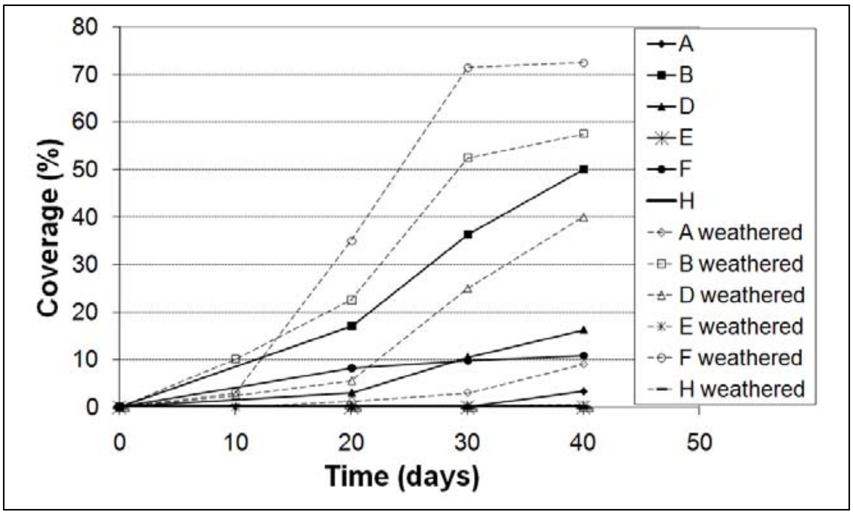

Figure 5: Percentage covered by fungi on original and weathered surfaces put in the FCU

The estimated coverage shows a significant difference between original and weathered specimens. Fungal growth was earlier present on weathered specimens and the coverage increased faster. There was no clear distinction between original surface and planed specimens. On some materials more fungal growth is determined if they were planed, perhaps because more wood particles were accessible. On the other hand, other materials showed more fungal growth on original surface specimens, maybe because fungal spores could settle easier between the grooves thanks to the rough surface. Unfortunately the coverage can not be linked to the results of the moisture behaviour. Although product H has a relatively high absorption, no fungal growth could be detected with the naked eye or under a microscope. Taking samples with a piece of tape and study this with a microscope did reveal some spores and hyphae. Only on material E no fungal structures were discovered. The identified fungal genera detected on the products are shown in (Table 4).

Table 4: Identified fungal genera detected on the materials without weathering

	A	B	D	E	F	H
Chaetomium	X		X		X	
Penicillium	X	X	X		X	
Trichoderma	X	X			X	X
Aureobasidium	X	X				
Aspergillus	X					

CONCLUSION

WPC is a porous material that absorbs in this research on average 18% moisture and swells on average 18% when the most severe moistening method was applied. Although the composition (polymer, wood content, particle size) differs in the products, the moisture behaviour is similar. WPC can absorb enough moisture to initiate fungal growth. For the assessment of the biological durability, the use of standards for wood and wood based panels is not justified because the moisture uptake is slower and the duration of those tests is too short to reach the moisture limit that allows fungal growth. The time needed to absorb sufficient moisture and the time of wetness are very important factors for the assessment of the durability and service life of WPC and need to be incorporated in the standards. At least one week immersing in water at 70°C could be an appropriate pre-treatment.

In the FCU several fungi were able to grown on the specimens and this occurred earlier and faster when the specimens were weathered. Although producers say that they avoid using fungicides in these materials because of the eco-friendly image, fungi could not or nearly not settle on some of the tested products.

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