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Durability of High Wood-Content WPCs

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Abstract

One increasing market segment of building materials is so-called biocomposites, or wood-thermoplastic composites (WPCs). Chiefly, these products are partly made from renewable resources such as wood residuals or agro fibres, functioning as reinforcement, and partly from recyclable thermoplastics or biopolymers, functioning as matrix. In general, WPC products are marketed as a low maintenance building material with a high outdoor durability. The intrinsic high moisture sensitivity of the wood component in combination with a low compatibility between the hydrophilic wood and hydrophobic thermoplastic may, however, result in poor long-term performance and outdoor durability. The objective of this paper is to recapitulate some of our research group's observations and experience during recent years with respect to both field and laboratory tests related to the durability of WPCs. Of particular interest is one type of extruded WPCs with a comparable high wood content, i.e. ca 70 weight-%, prepared with either a heat treated, acetylated, or unmodified wood component. Observations from outdoor field trials, laboratory fungal decay tests, moisture sorption properties and effects on micromorphology, show that the use of a modified wood component in these WPCs considerably increases their long-term outdoor durability. One reason for this is related to the reduction of the moisture sensitivity of the wood component. Such durable biocomposite-type of building materials with a high wood-content level have the potential to fulfill the criteria for being eco-efficient, that is being both a sustainable and a cost-efficient "green" material.

Key words: wood-plastic composite, WPC, modified wood, durability, moisture properties

Introduction

Wood plastic composites (WPCs) have gained continuous increasing market shares during the last 15 years for the use in outdoor applications such as decking, sidings and window frames (Eastin et al. 2005). It has been estimated that these composites have reached a market share of ca 23,5% of the total decking market in US, where pressure treated wood have ca 50 % and other wood (redwood, western red cedar, tropical hardwoods etc.) have ca 20 % of the market (Eastin et al. 2005). A significant market share increase can also be found in e.g. Germany, France, England, Japan and China. WPCs are in general composed of a reinforcing wood component combined with an olefin thermoplastic matrix. The former usually consists of wood residuals from the saw mill and wood working industry, e.g. sawdust and shavings, and the latter of recyclable plastics, e.g. polyethylene (PE), polyvinyl chloride (PVC) and polypropylene (PP). These components are usually "thermo-formed" through extrusion into continues profiles or injection moulded into final three-dimensional shapes, see example in Figure 1 (Left) of an extruded WPC profile.

It is obvious that an increase of the wood content in the composite, and thus using less amount of olefin based matrix, would be beneficial in a eco-efficiency perspective, i.e. being more efficient in both a ecological and economical viewpoint - the plastics used are several times more expensive than the wood component. In this work we elaborate on using wood contents of up to 70 dry weight-% in the WPC. An important question that arise when applying such high wood-content levels in WPCs is, of course, how this influence their in-service behaviour in out-door use, in particular their water sorption properties and related dimensional stability as well as their resistance to mould growth and fungal decay? The WPC processing temperatures, around 180–200°C, means not only a risk for thermal degradation of the wood component but also that in principal all of its natural moisture will be vented out from the extruder creating a, close to, completely dry composite material. We argue therefore here that one of the most critical in-service issues for the use of WPCs in out-door applications is the high moisture sensitivity of such an absolute dry wood component, even though it is embedded in a hydrophobic thermoplastic. The general observation, however, is that moisture uptake is slow in conventional WPCs compared with solid wood, even when immersed in water, but continues over a long period of time. Wang and Morrell (2004) have shown that moisture will not penetrate deep into the material, but the moisture levels close to the surface may be very high. A moist environment will swell the wood particles close to the surface, and the particles will shrink upon drying. This will cause stresses within the material and create microcracks, especially in the form of interfacial cracks between the wood and plastic components (Segerholm 2007), which may create new pathways for water intrusion deeper into the material. An accelerated moisture uptake may therefore take place after some years.

One means to reduce the moisture sensitivity of the wood fraction in WPCs is to use a modified wood component instead of conventional untreated wood residuals. For cost efficiency reasons, the main concept here is to use residuals from the production of heat treated and acetylated solid wood boards which means that the wood raw material cost can be held to a minimum. And furthermore, if this concept makes possible a 20–25 % higher wood content in the composites than otherwise possible, the increased wood raw material costs will most likely be out ruled by the fact that the thermoplastics used are even more costly than such modified wood residuals.

Similar to solid wood, the macroscopic performance and behaviour of WPCs are strongly related to their microscopic structure. Some important microstructural features, in this case, are related to distribution, dispersion, orientation, form, and damage of the wood component embedded in the plastic matrix (Segerholm 2007, Segerholm et al. 2007), see the example of a WPC´s micromorphology in Figure 1 (Right). As can be seen, in this case a good dispersion exists between the wood component and the polypropylene matrix, i.e. a matrix filled wood lumen and a very low over-all porosity (ca 2-5%) of the WPC.

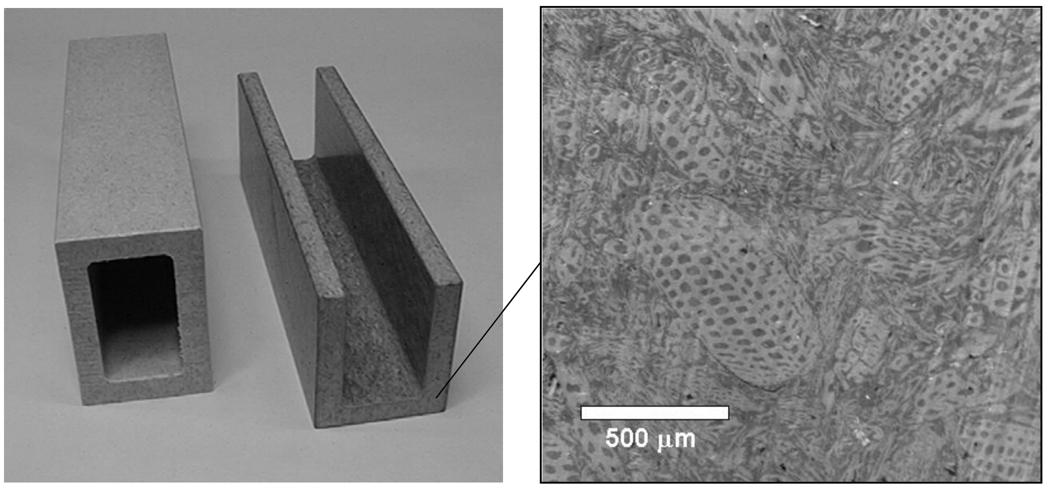

Figure 1. *Left: Examples of extruded WPCs with approximately 70 weight-% wood, 25 weight-% polypropylene and 5 weight-% additives (coupling agent, lubricant and UV inhibitors). Right: Micrograph exposing the micromorphology of the composite cross section (lighter parts represent the wood component and the darker parts the polypropylene matrix*

It is also important to point out another important factor that influence the final WPC performance, namely wood-thermoplastic adhesion or compatibility, i.e. the problematic contrast between the inherent hydrophilic wood substance and the hydrophobic nature of olefin thermoplastics. However, this topic is not dealt with in this paper; see other studies by e.g. Bryne and Wålinder (2010).

The objective of this paper is to recapitulate our research group's observations and experience during recent years with respect to both field and laboratory tests related to the durability of WPCs. Of particular interest is one type of extruded WPCs with a comparable high wood content, i.e. ca 70 weight-%, prepared with either a heat treated, acetylated, furfurylated or unmodified wood component.

Materials and methods

The wood raw material used in this study was prepared from acetylated and unmodified boards of Scots pine (Pinus sylvestris L.) sapwood and from heat treated Norway spruce (Picea abies L.). The acetylation was performed according to Rowell et al. (1986) in a pilot plant with a microwave heated reaction vessel of 0.67 m^3. The degree of acetylation was about 20% expressed as wood acetyl content. The heat treatment was performed by Stora Enso according to the ThermoWood® D procedure which has a peak temperature of 212 °C (Anonymous 2003). All boards where ground into particles in a two step process. First 190 mm long blocks were fed into a disk flaker (Bezner) and processed into thin veneer strands. In the second step the veneer strands were fed into a dry grinding knife-mill (Condux) and chopped into fine particles. The particles where characterized by standard sieve analysis. The thermoplastic matrix used was polypropylene (PP, Moplen HF 500N). The unmodified and modified wood components were dried to a moisture content (MC) of less than 1% and mixed with the PP and compounded into pellets on a counter rotating twin screw extruder at OFK Plast AB in Karlskoga, Sweden. The wood/thermoplastic/additives ratio was 70/25/5 based on dry weight. The pellets were then fed into a conical extruder located at Conenor Oy in Tampere, Finland, and extruded into rectangular-shaped hollow profiles as shown in Figure 1. (Left), i.e. three different WPC samples were produced: a) a control with an unmodified wood component; b) an acetylated wood component; and c) a heat treated wood component. The cross-section of the profiles measured 60 x 40 mm^2, with a wall thickness of ca 8 mm.

The assessment of microbiological durability properties of the WPCs in this case, included laboratory-scale soil box tests of wood-based materials (extended ENV 807), in-ground (EN 252) and above ground field tests (Horizontal double layer test, hazard class 3). The principles of the test setups and pictures from the field tests are shown in Figures 2–3.

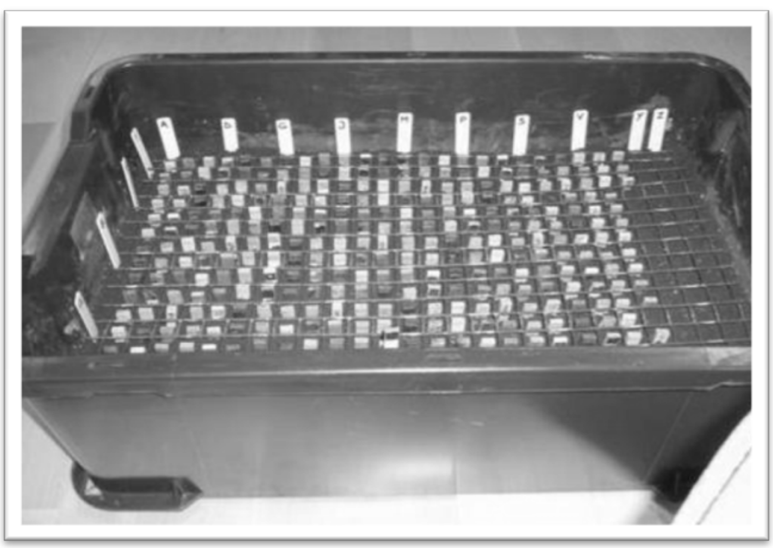

Figure 2. *Laboratory TMC test set-up of WPCs according to an extended version of ENV 807*

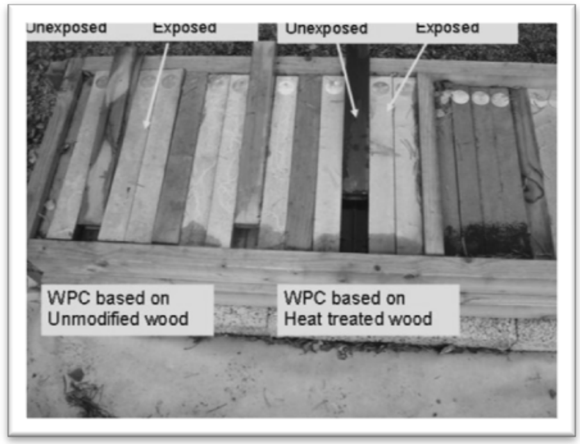

Figure 3. *In ground field testing of WPCs according to EN 252 (left picture) and example of WPC test samples of unmodified and heat treated wood exposed above ground for 2 years in a so-called "Horizontal double layer test" (right picture).*

Unsteady state water vapour sorption assessment of the WPCs were also performed according to the following procedures: Two replicates of each WPC profile were cut into specimens with the dimensions 25 x 10 x 2 mm^3 leaving one (25 x 10 mm^2) original outer surface of the extruded specimen unaltered. All the other surfaces were then sealed with aluminum tape and dried in a desiccator with silica gel for 4 weeks prior to the test. The water vapor sorption test was carried out by placing the specimens in an enclosed chamber above a saturated ammonium chloride solution, giving the ambient air a relative humidity of approximately 80% at 22 ˚C. The specimens were weighed at certain time intervals until the equilibrium moisture content (EMC) was reached, and the climate was recorded by a temperature and humidity logger placed inside the chamber. After the test when the specimens have reached EMC they were oven-dried at 105 ˚C overnight in order to determine the initial and final MC.

A low-vacuum scanning electron microscope (LV-SEM) was used to study the micro structure of the materials before and after being subjected to a moisture saturation (by immersion in liquid water) and drying cycle. In order to avoid the formation of mechanically induced microdefects, a UV-laser irradiation technique was applied as a surface preparation method for the microscopy analysis.

Results

The results indicated that the biological resistance of WPCs with untreated wood is not sufficient for outdoor exposure conditions. Especially this is valid for WPC samples with high wood content, see Figure 4 showing examples of the results from the laboratory TMC tests in three different soils.

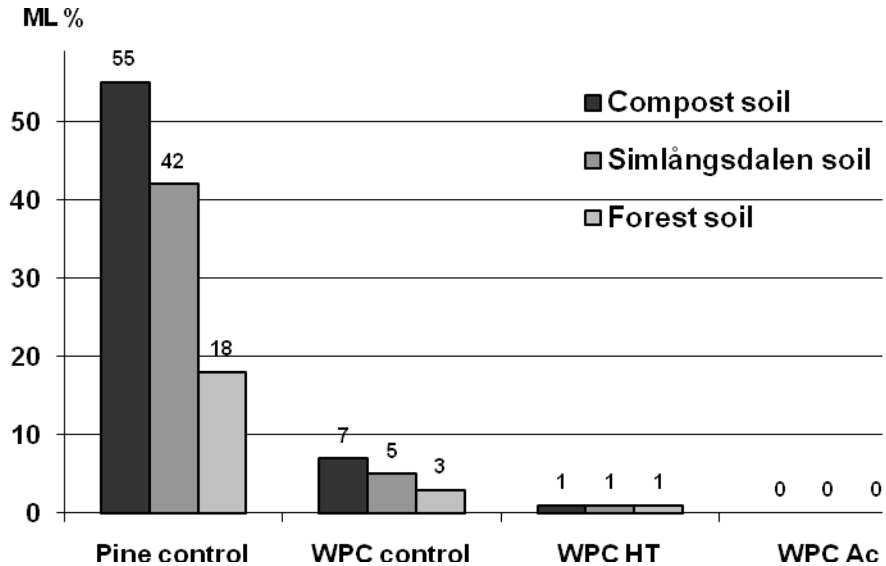

Figure 4. *Results from laboratory TMC soil box tests according to an extended version of ENV 807 of WPCs (70% wood, 25 % PP, 3% lubricants and 2% coupling agent) presented as mass loss in three different types of unsterilized soils after 32 weeks exposure.*

In the samples exposed for five years in the in ground field tests, initial decay was detected in all untreated samples, see example of some exposed test samples in Figure 5. Also unacceptable swelling and distortion could be observed in the untreated samples exposed in the above ground Horizontal double layer test after two years, see Figure 5. The biological resistance of WPC materials against fungal damages (losses in mass and strength) can be improved by using a chemically modified wood component. Rather promising results have been obtained with for the WPCs containing heat treated and acetylated wood. In the WPC samples with these modified wood components no indication of decay could be detected in any test specimens. Also the swelling and distortion of the specimens with modified wood was minimal, see Figure 6.

Figure 5. *WPCs from in ground field tests showing white rot fungi attacked on samples with untreated wood after five years exposure while the heat treated and acetylated samples showed no signs of fungal attack.*

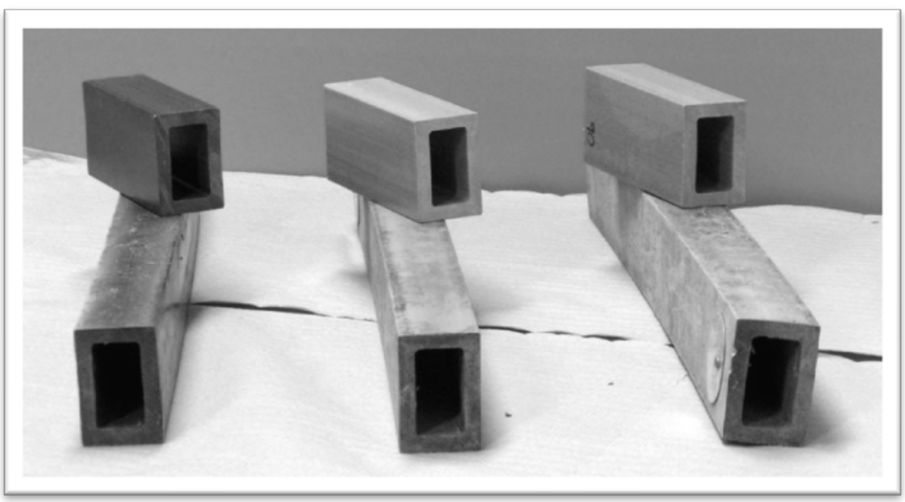

Figure 6. *Dimensional changes in the extruded WPC profiles after exposure two years in the Horizontal Double layer test. From left to right, pictures show samples with heat treated wood, acetylated wood and unmodified wood respectively, the upper samples are unexposed and the lower samples are exposed. Note the severe distortion of the unmodified sample.*

Figure 7 shows the moisture content of the different WPC samples versus exposure time. Results showed that, the WPCs with the heat treated and acetylated wood components had significantly better moisture resistance compared with controls containing an untreated wood component.

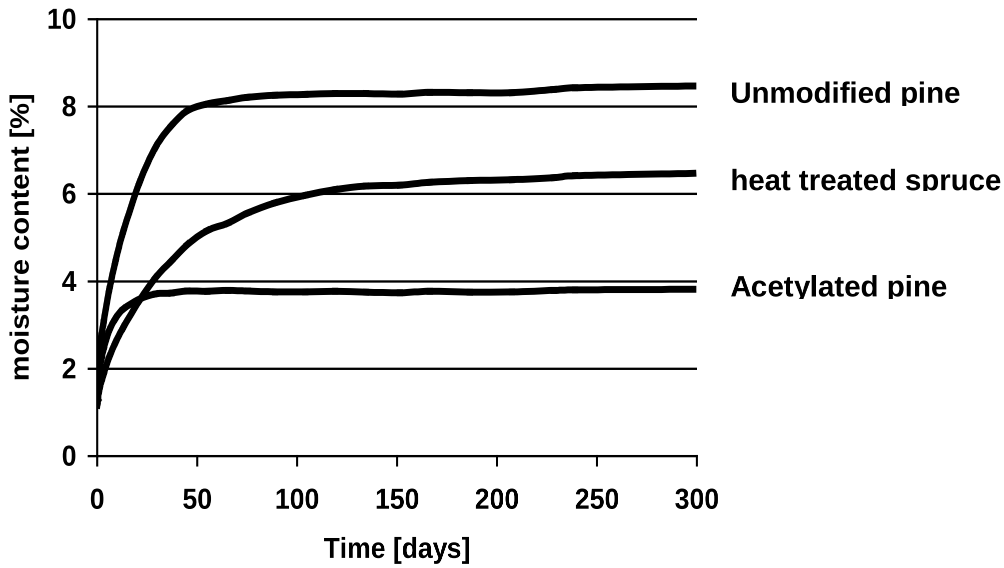

Figure 7. *Moisture content (MC) versus exposure time in a climate of 80% relative humidity and 22°C for thin veneers of a high wood-content WPC prepared with unmodified, heat treated and acetylated unmodified wood. Initial MC of the WPCs was approximately 1–2 %.*

Figure 8 shows a micrograph of a WPC with an unmodified wood component after subjected to a moisture saturation and drying cycle. Results showed that, due to this moisture stress cycle a severe damage occurred within these composites with frequent interfacial cracks between the wood components and the polypropylene matrix, whereas the composites based on modified wood (heat treated or acetylated) were only slightly affected or not affected at all by the moisture stress.

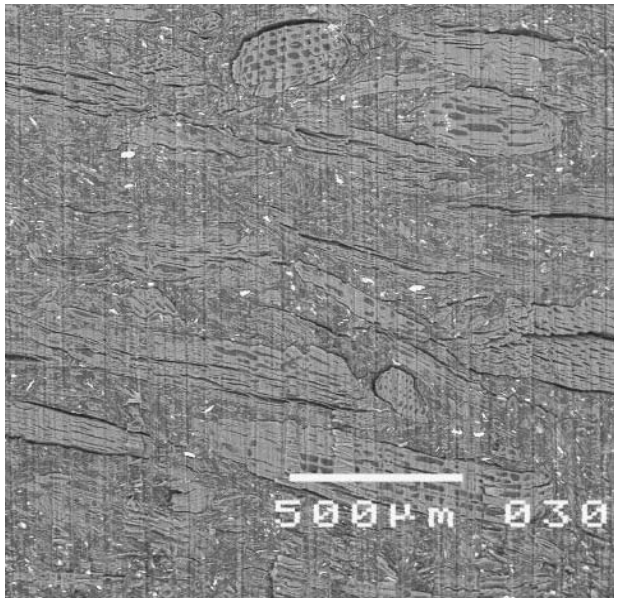

***Figure 8**. Micrograph of the micromorphology of a wood polypropylene composite with an unmodified wood component after subjected to a moisture saturation and drying cycle. Note the frequent interfacial cracks between the wood particles and the polymer matrix. The surface of the sample was initially prepared using a UV laser ablation technique.*

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