Oppdragsrapport 19/2010
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ON THE USE OF FURFURYLATED WOOD FOR THE PRODUCTION OF HIGH-PERFORMANCE WINDOWS MADE OF EUROPEAN TIMBERS

Workpage 2: Evaluation and optimization of material properties

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WOODWISDOM PROJECT WINFUR

Omslagsfoto: Furfurylated wood used in buildings, Fotograf: Kebony ASA

Norsk institutt for skog og landskap, Pb 115, NO-1431 Ås

SUMMARY

Wood modification with furfuryl alcohol is an extensively investigated process and already produced commercially. Furfurylated wood is in the focus of a European project on its use for the production of high performance windows. Different wood species were treated with furfuryl alcohol and tested on water uptake, dimensional changes, leaching in water, resistance to fungal degradation, and ecotoxicity.

The results show a reduced water uptake and a reduced swelling of the furfurylated wood samples. A high resistance against fungal attack of the treated wood samples can be shown. A low amount of furfuryl alcohol was leached out and the water samples of two different leaching tests showed in general low toxicity.

Southern yellow pine showed good results in all of the tests and has potential for the production of window frames according to the tests performed.

Nøkkelord: furfurylering av tre, holdbarhet, vinduer

Key words: furfurylation of wood, durability, windows

Andre aktuelle publikasjoner fra prosjekt:

- Pilgård, A., Treu, A., Van Zeeland, A.N.T., Gosselink, R.J.A. & Westin, M. 2010. Toxic hazard and chemical analysis on leachates from furfurylated wood. Environmental Toxicology and Chemistry 29: 1918-1924.

- Treu, A., Pilgård, A., Puttmann, S., Krause, A. (2009). Material properties of furfurylated wood for window production. IRG/WP 09-40480. Proceedings of The International Research Group on Wood Preservation, Beijing, China, May 24-28, pp 1-13.

- Puttmann, S., Krause, A., Pilgård, A., Treu, A. & Militz, H. 2009. Furfurylated wood for wooden window constructions. In: Englund, F., Hill, C.A.S., Miltz, H. & Segerholm, B.K. (eds.): 4th European Conference on Wood Modification, pp. 569-576. 27-29 April, 2009, Stockholm, Sweden. ISBN 978-91-8631936-6.

- De Vetter, L., Pilgård, A., Treu, A., Westin, M. & Van Acker, J. 2009. Combined evaluation of durability and ecotoxicity: A case study on furfurylated wood. Wood Material Science and Engineering 4: 30-36.

CONTENT

1. INTRODUCTION

Currently, wood windows have an average market share of 30% in Central Europe and merely 20% in Germany. The market is dominated by plastic and aluminum; materials that are not based on sustainable resources, are not CO2-neutral and show poor eco balance. Nevertheless, plastic and aluminum windows possess technological advantages and require only little maintenance during service life in comparison to wood windows that, even when well-constructed, rely on proper and periodic maintenance in every 2-3 years. In addition, the strict requirements of the window industry for dimensional stability and durability against wood decaying fungi can hardly be fulfilled by using untreated European species. In consequence, most wood windows are constructed of appropriate tropical timbers which naturally exhibit excellent material properties and can thus meet the demands. However, most tropical species do not come from sustainably managed forests and must be shipped over long distances from South-East Asia, Africa or South America to Europe.

Against this background, the central-European wood window market has been experiencing a dramatic slump since the 1970s. In contrast, the Scandinavian window market shows a different structure. Traditionally, windows are predominantly made of pine or spruce and currently have a market share of 80-90% although they are nowadays almost exclusively combined with aluminum profiles for the exterior parts.

Though the sales situation appears comparatively good in Scandinavia, the producers are facing an increasing cost pressure by foreign manufacturers, especially from the Baltic countries, and an increasing competition of PVC window manufacturers. In addition, the growing internationalization in terms of legislation, technical development (e.g. heat insulation) and customer expectations require innovative approaches to prevent that the Scandinavian wood window industry looses market share in the future and encounters similar difficulties alike the German industry today.

A modern wooden window has to meet numerous requirements in terms of service and design. The demands towards easy-maintenance, service-life, heat-and noise insulation and design aspects have been increasing continuously. The major drawback of wooden window frames is that they require comparatively short maintenance intervals of about 2-3 years. In contrast, plastic and metal window frames only need to be maintained in every 8-10 years interval. The German scenario is that the majority of customers is not willing to do the necessary maintenance work although they prefer wooden window frames from an aesthetic and ecologic view point. The short maintenance intervals are predominantly related to the wood properties, e.g. dimensional stability and durability.

The challenge of using European species is their low dimensional stability and durability. Conventionally used wood preservatives contain biocides and are mainly considered as toxic and hazardous. Therefore, these agents are generally not available directly to the public and may require special approval to import or purchase depending on the product and the national legislation.

One of the most extensively investigated wood modification processes is furfurylation, named after the modification chemical furfuryl alcohol, which is obtained from biomass waste (corn cobs or sugar cane residuals). Due to its polarity, furfuryl alcohol can penetrate into the cell wall where it reacts with wood components and polymerizes, leading to permanently swollen wood structure because of the grafted polymer within the cell wall. At higher treatment levels, furfuryl alcohol polymer will also be found in the cell lumina which further increases the hardness.

The wood properties depend on the amount of furfuryl alcohol that is brought inside the cell wall. Thus, the degree of modification can be controlled by using either pure furfuryl alcohol or water-based solutions in different concentrations. Material properties, e.g. hardness, dimensional stability, durability against fungi and insects and resistance against chemicals, are strongly increased especially at higher loadings. The products are produced and distributed by the Norwegian company Kebony ASA, which is one of the seven project partners. Kebony will in turn supply the German and Swedish window manufacturers Menck and TanumsFönster/Bordörren who are interested in using furfurylated wood as a substitute for softwoods and tropical timbers.

This study evaluates material properties which are important for the use of high-performance windows made of European timber. The focus is therefore on water uptake and dimensional changes, resistance against wood destroying and staining fungi, resistance against attack in soil contact, water uptake and dimensional changes.

2. MATERIAL AND METHODS

2.1. Wood - water relations of furfurylated wood

2.1.1. WATER SORPTION OF FURFURYLATED WOOD

The water sorption of furfurylated wood is evaluated by calculating the sorption isotherms. The Equilibrium Moisture Content (EMC) as well as the swell rate of wood depending on relative humidity are measured concerning the method described by Krause (2006).

2.1.2. WATER SUBMERSION OF FURFURYLATED WOOD

A submersion test was performed where furfurylated ash, beech, Southern yellow pine and Radiata pine were submerged in water for 0.5, 1, 6, 24 and 48 hours and compared to the untreated wood species respectively and also to Sipo mahogany. Weight and dimension was measured.

By using the relative increase in radial and tangential dimension (swelling coefficient, S) the anti swelling-efficiency (ASE %) was calculated for both directions.

$$S = \frac{Dt - Dt_0}{Dt_0} \qquad (1)$$

S = swelling coefficient
Dt = dimension of sample in one direction after time t
Dt0 = dimension of sample in one direction after time t0

$$ASE\,[\%] = \frac{S_c - S_{FA}}{S_c} \cdot 100 \qquad (2)$$

ASE = anti swelling-efficiency
Sc = swelling coefficient of the control
SFA = swelling coefficient of the FA-treated sample

2.1.3. CAPILLARY WATER UPTAKE

The method of determining the capillary water uptake of wood has been adapted from
DIN 52617 (1987), which is used for porous materials in building industry. As wood is also a porous material and water flows through capillary force in wood, this test gives information on its water resistance coefficient. The tangential water uptake is measured.

2.1.4. WATER VAPOR DIFFUSION

The determination of the water vapor transmission properties is described in EN ISO 12572 (2001). Round wood samples are positioned on glass containers, which are filled with dried silicagel.

2.2. Resistance against wood destroying fungi

A fungi test was performed according to CEN/TC 38 (modified EN 113). Boards from ash, beech, Southern yellow pine and Radiata pine were furfurylated and samples with dimension 15 x 25 x 50 mm³ were cut out of the boards. The weight percent gain (WPG)of the boards was determined and used to classify the boards and samples into 3 different uptake classes.

Test fungi (brown rot) on soft woods:	Test fungi on hardwoods (white rot):
Coniophora puteana	*Trametes versicolor*
Gloeophyllum trabeum	*Irpex lacteus*
Postia placenta	*Gloeophyllum trabeum* (brown rot)

Figure 1: Overview over test fungi on furfurylated samples

2.3. Resistance against staining fungi

Furfurylated and untreated control samples, as described before, were tested on colonization of staining fungi using a fungi mix of 7 fungi: *Aureobasidium pullulans* ((deBary) Arnaud), *Ulocladium atrum* (Preuss), *Cladosporium cladosporioides* ((Fresenius) de Vries), *Alternaria alternata* ((Fries:Fries) von Keissler), *Aspergillus niger*, *Trichoderma koningii* and *Penicillium sp.*. The test was performed under non-sterile laboratory conditions at room temperature. The evaluation of mould growth was carried out according to the method used by Viitanen & Ritschkoff (1991). The number of spores in the applied fungi-solution per 100µl was 172640, which was calculated by aid of a Bürker Counting Chamber with a double net ruling.

The original wood samples had sizes of 10 x 40 x 110mm³ and had been cut in halves of which one surface was infected with 100µl liquid fungi suspension while the other half stayed free from fungi and was used as comparison.

The samples were placed in closable containers which were each filled with 0,5l water, afterwards a plastic-framed distance keeper with a net-surface was placed in the water and the wood samples were positioned on top. That enabled fungi spores to develop under 100% humid climate without direct water contact.

Each wood species and treatment had one container of only treated and only untreated samples and as well containers in which treated and untreated samples were put in together to see whether there was a neighbor effect such as growth-inhibition of FA-treated samples on untreated species.

The determination of fungal growth was done by the following mould fungi determination (according to Viitanen & Ritschkoff 1991):

Table 1: Classification of growth of surface fungi

- 0 - no growth
- 1- some growth detected only with microscopy (trace, some hyphae of mould fungi on the studied surface)
- 2 - moderate growth detected with microscopy (coverage of hyphae more than 10 to 25 per cent of studies surface
- 3 - some growth detected visually (coverage of molded surface below 10 per cent of studies surface (2)
- 4 - moderate growth detected visually (coverage 10 -50 per cent) (3)
- 5- abundant growth detected visually (coverage above 50 per cent) (4)
- 6- very heavy and tight growth (100 %) (5)

2.4. Test in soil contact

Furfurylated samples of the before mentioned wood species were tested in soil contact by using two different soils: a compost soil and a brown rot dominated soil from Sweden (Simlångsdalen). The two soils are representing two different decay hazards: -Compost soil with soft rot and tunneling bacterial decay type and -Simlångsdalen soil with dominating brown rot decay type. The test was performed according to ENV 807. The samples tested in compost soil were harvested after 32 weeks. The Simlångsdalen soil is not as active as predicted. The test in this soil was therefore extended.

2.5. Leaching of furfurylated wood in water

The furfurylated wood samples were submerged in demineralized water for 1 hour and 48 hours (leaching test 1) and for 24 hours and 14 days (leaching test 2). The leaching water was changed for test 1 after 0.5, 1, 6, 12 and 24 hours and for leaching test 2 according to EN84 (1997) with water changes 9 times during 14 days. The water was always changed one day before the leaching water sample was taken.

The leaching water was analyzed according to an internal standard method using an Agilent liquid chromatograph (HPLC) with auto injector. The liquid chromatograph was equipped with a diode Array detector. The system had an injection valve with a 20 μL loop. The chromatographic separations were done with Supelco LC-18-DB (250 mm×4.6 mm; 5μm particle size) and furfuryl alcohol was measured with 220 nm. To perform the isocratic elution at a flow rate of 1 ml min−1, a mixture of acetonitrile and water (5/100, v/v) was used.

2.6. Ecotoxicity

Leaching water from leaching test 1 and leaching test 2 was collected and all water samples were adjusted with NaOH (0,5mol/l) to a pH between 6 and 8. All leachates were run according to the Microtox assay (Azur Environmental 1995) using the bacterium *Vibrio fischeri* as test organism (ISO/DIS 11348-3 1996). The basic test protocol was used with 45%, 22.5%, 11%, and 5.5% dilutions of the collected leaching water. Every test was run twice and a mean value was calculated. The results were normalized and the EC50 values (concentration producing a 50% reduction in luminescence) were calculated from data collected after 30 minutes of exposure. The Toxic Unit (TU) was then calculated from the obtained EC50 values with Eq. 1 (Manusadžianas *et al*. 2003). Non-toxicity was set to a TU of 2 (De Vetter *et al*. 2008).

$$TU = \frac{1}{EC_{50}(\%)} \times 100 \qquad (3)$$

3. RESULTS

3.1. Furfurylated wood in contact with water

3.1.1. WATER SORPTION OF FURFURYLATED WOOD

The calculated sorption isotherms show clearly that the wood modification via furfuryl alcohol reduces the water sorption of wood. As shown in Table 2, the furfurylated samples of Southern yellow pine (SYP), ash and beech have a lower EMC than the untreated control samples. The furfurylated wood samples show even a lower water sorption than the samples of the tropical reference Sipo mahogany.

Table 2: mean values of EMC [%] at 20 °C and different relative humidity (RH), standard deviation in brackets

RH [%]		SYP	Beech	Ash	Sipo
30	treated	3,35 [± 0,3]	3,16 [± 3,1]	2,96 [± 0,2]	
	untreated	6,36 [± 2,0]	5,31 [± 0,1]	5,12 [± 0,4]	6,20 [± 0,5]
50	treated	4,44 [± 0,1]	4,25 [± 3,4]	4,52 [± 0,4]	
	untreated	8,06 [± 0,1]	7,24 [± 0,1]	7,24 [± 0,1]	8,22 [± 0,1]
65	treated	6,52 [± 0,2]	6,48 [± 3,5]	6,90 [± 0,6]	
	untreated	11,54 [± 0,1]	10,48 [± 0,1]	10,74 [± 0,5]	12,27 [± 1,1]
85	treated	9,05 [± 0,4]	9,36 [± 3,8]	10,21 [± 1,1]	
	untreated	16,37 [± 0,1]	16,38 [± 0,1]	16,33 [± 0,1]	16,75 [± 0,1]
90	treated	10,48 [± 0,4]	10,98 [± 3,7]	12,08 [± 1,4]	
	untreated	19,55 [± 0,1]	20,45 [± 0,1]	20,02 [± 0,1]	18,99 [± 0,1]
95	treated	11,71 [± 0,5]	12,36 [± 4,0]	13,51 [± 1,6]	
	untreated	21,68 [± 0,1]	22,22 [± 0,2]	20,64 [± 0,2]	20,36 [± 0,1]

The measured dimensions during the different conditioning steps allow a statement about the dimensional stability of furfurylated wood. The furfurylated wood samples show a reduced swelling regarding their dimensions in comparison to the untreated control samples. In Table 3 the swell rates of the samples at 20 °C and 65% respectively 85% relative humidity are shown. The dimensional stability of the modified samples is even higher than the dimensional stability of Sipo mahogany. The dimensional stability is an important property for the window construction. The stability of varnishes and the influence on crack behavior depend on it.

Table 3: mean values of swell rate [%] at 20 °C and between a relative humidity (RH) of 0-65 % and 0-85 %; standard deviation in brackets

RH [%]		SYP	Beech	Ash	Sipo
0-65	**treated**	3,16 [± 0,8]	2,29 [± 1,4]	3,02 [± 1,6]	
	untreated	6,47 [± 0,4]	5,84 [± 0,5]	5,27 [± 0,6]	5,38 [±1,6]
0-85	**treated**	4,63 [± 0,4]	4,93 [± 1,4]	5,32 [± 1,8]	
	untreated	10,10 [± 0,4]	9,80 [± 0,5]	8,89 [± 0,4]	8,26 [± 1,7]

3.1.2. WATER SUBMERSION OF FURFURYLATED WOOD

All FA-treated hardwoods showed significantly reduced water uptake both after short submersion time (1 hour) and after a long submersion time (48 hours). The FA-treated beech wood samples with high uptake of FA performed as well as Sipo mahogany. The untreated hardwoods ash and beech had a high water uptake and beech had a three times higher water uptake than ash.

The untreated softwoods showed a high water uptake within the first hour, whereas SYP-samples had even a high water uptake after 1 hour.

The water uptake of wood is an important factor when the material is used for wooden window constructions. Nevertheless, even more important is the corresponding dimensional stability of wood when used for windows. Low swelling and shrinkage of wood products is required.

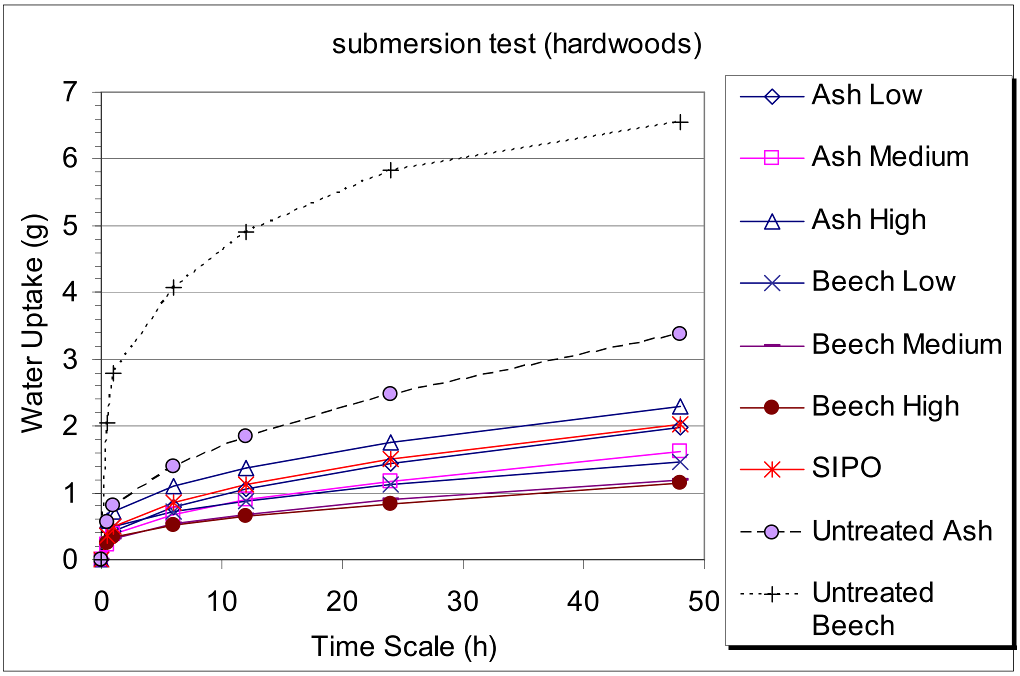

Figure 2: Water uptake during 48 hours of submersion of furfurylated hardwood samples, compared to untreated hardwood samples and sipo mahogany; the treated samples were divided by uptake classes into low, medium and high weight percent gain classes

The anti swelling efficiency (ASE) was calculated for radial and tangential direction for all FA-treated samples in the submersion test after 1 hour and 48 hours. All treated samples showed an ASE of more than 55 %, except the FA-treated ash samples with high uptake level. A high ASE value describes a high reduction in swelling.

Westin *et al*. (2004) gave ASE values for FA-treated Scots pine sapwood after storing the samples in 30% relative humidity and 90% relative humidity at 20°C. Even low weight percent gain of FA resulted in high ASE values. A weight percent gain of 15% led to an ASE of 25% and a WPG of 50% to an ASE of 75%.

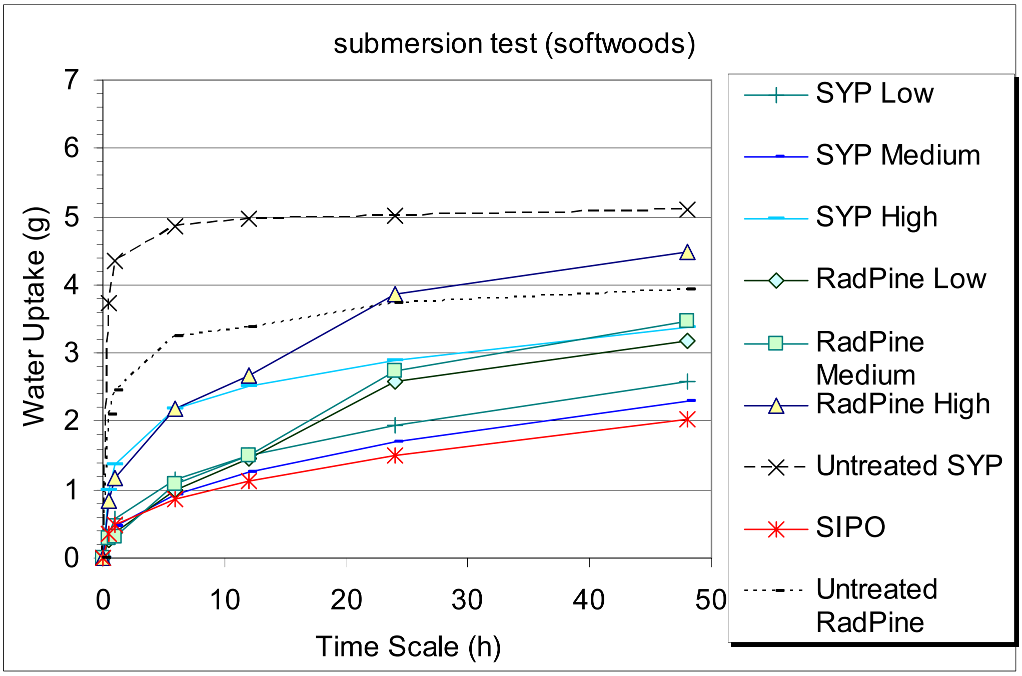

Figure 3: Water uptake during 48 hours of submersion of furfurylated softwood samples, compared to untreated hardwood samples and sipo mahogany; the treated samples were divided by uptake classes into low, medium and high weight percent gain classes

Oil-heat treatment of Scots pine samples that were conditioned at 0 and 85 % relative humidity showed ASE values of 40 % at maximum for Scots pine (Sailer *et al*. 2000).

Table 4: Average values of swelling efficiency in radial and tangential direction of furfurylated wood after 1 hour and 48 hours of water submersion

wood species	uptake level	$ASE_{rad\ 1\ hour}$	$ASE_{tang\ 1\ hour}$	$ASE_{rad\ 48\ hour}$	$ASE_{tang\ 48\ hour}$
	low	67.7	76.5	56.1	70.4
ash	medium	63.2	71.2	64.5	76.8
	high	15.5	43.8	30.7	67.6
	low	87.6	92.1	79.6	88.3
beech	medium	90.6	95.2	79.8	89.5
	high	90.8	93.9	80.2	89.6
	low	91.1	85.4	70.8	62.9
SYP	medium	91.8	90.4	72.9	65.2
	high	83.5	76.2	76.9	68.8
	low	88.8	89.7	72.3	73.2
Radiata Pine	medium	87.4	86.1	71.4	67.9
	high	71.9	67.7	65.6	65.9

However, when swelling coefficients of FA-treated wood is related to untreated wood, the amount of swelling of the untreated samples is also important in order to interpret the results. A high ASE of FA-treated beech wood takes also into account the relatively high swelling coefficient of untreated beech wood. Nevertheless, both the radial and the tangential swelling are drastically reduced by the FA treatment.

3.1.3. CAPILLARY WATER UPTAKE

The reduced tangential water uptake of the modified wood samples compared with the untreated control samples is clearly visible (Table 4). The water absorption coefficient shows the water uptake in relation to time. The modified wood comprises a low coefficient. The results are comparable to Sipo mahogany. The untreated control samples however show a high water absorption coefficient. The wood modification with furfuryl alcohol results in hydrophobic wood properties. Due to the fact that furfurylated wood is planned to be used for the window construction, the reduced water uptake is very important for the behavior in outside construction. But beside of that, the reduced water uptake gives information about glue penetration into Kebony wood. It has to be considered for the further work on use of the right glue and coating systems.

Table 5: Results of capillary water uptake (tangential wood direction) depicted by water absorption coefficient [kg/m²]; standard deviation in brackets

		Beech	Ash	SYP	Scots pine	Sipo
water absorption coefficient [kg/m²]	**treated**	0,08 [0,03]	0,082 [0,03]	0,06 [0,01]		
	untreated	0,41[0,22]	0,19 [0,08]	0,45 [0,18]	0,543 [0,09	0,10 [0,03]

3.1.4. WATER VAPOR DIFFUSION

The resistance of the furfurylated wood against water vapor diffusion is much higher than the untreated control samples (see Table 5). The furfurylated wood samples show even a higher vapor resistance than the samples of the tropical hardwood Sipo mahogany. The water vapor resistance is an important property for the window construction, because requirements concerning the insulation and the new U-value regulations of modern windows lead to high requirements regarding the frame material. The good resistance of furfurylated wood against water vapor helps to establish furfurylated wood in the window industry.

Table 6: Water vapor diffusion resistance [µ] of furfurylated and untreated control samples

Wood species	Water vapor diffusion resistance [µ]	
	treated	untreated
SYP	112 [± 40,7]	24,65 [± 3,6]
Beech	234 [± 132,6]	30,22 [± 4,7]
Ash	248 [± 124,0]	35,48 [± 16,1]
Sipo	-	41,19 [± 4,6]

3.2. Resistance against wood destroying fungi

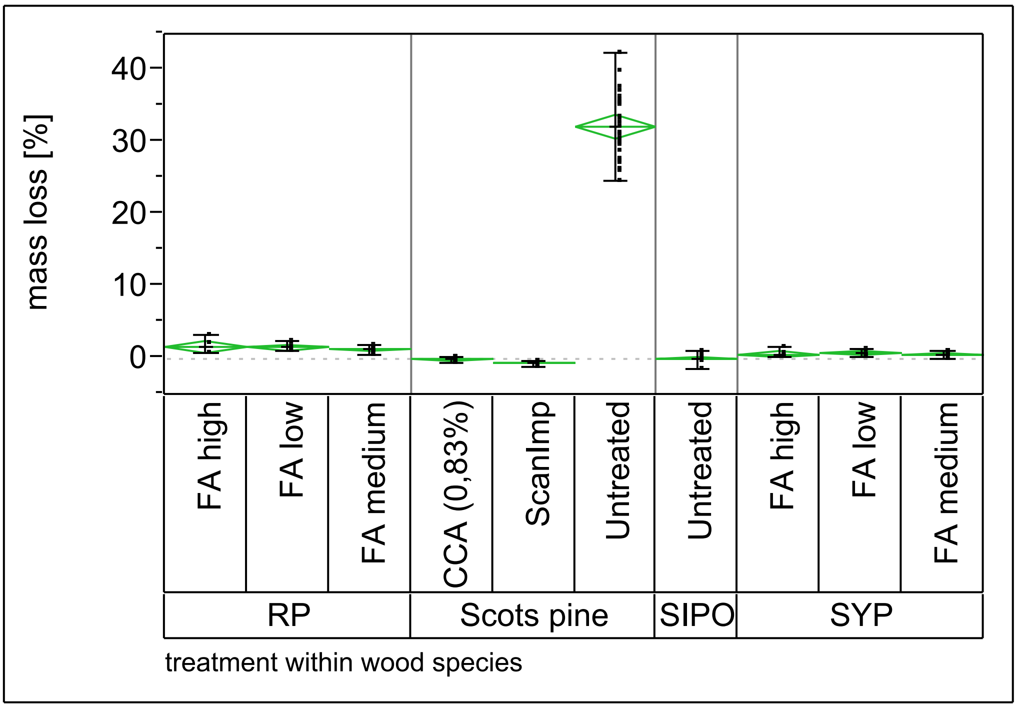

Figure 4: Mass loss of furfurylated wood samples after exposing to Coniophora puteana for 16 weeks

All furfurylated samples show significantly lower mass loss compared to untreated control samples. The different treated wood samples exposed to *Coniophora puteana* showed an average mass loss below 5% whereas untreated Scots pine had a mass loss of 30%.

The exposure to other fungi showed different results. Especially ash and beech exposed to *Trametes versicolor* and *Irpex lacteus* have higher mass loss than expected. Earlier results showed very low mass loss of furfurylated samples on different fungi. However, the performance of furfurylated samples in outside exposure has to be taken into account.

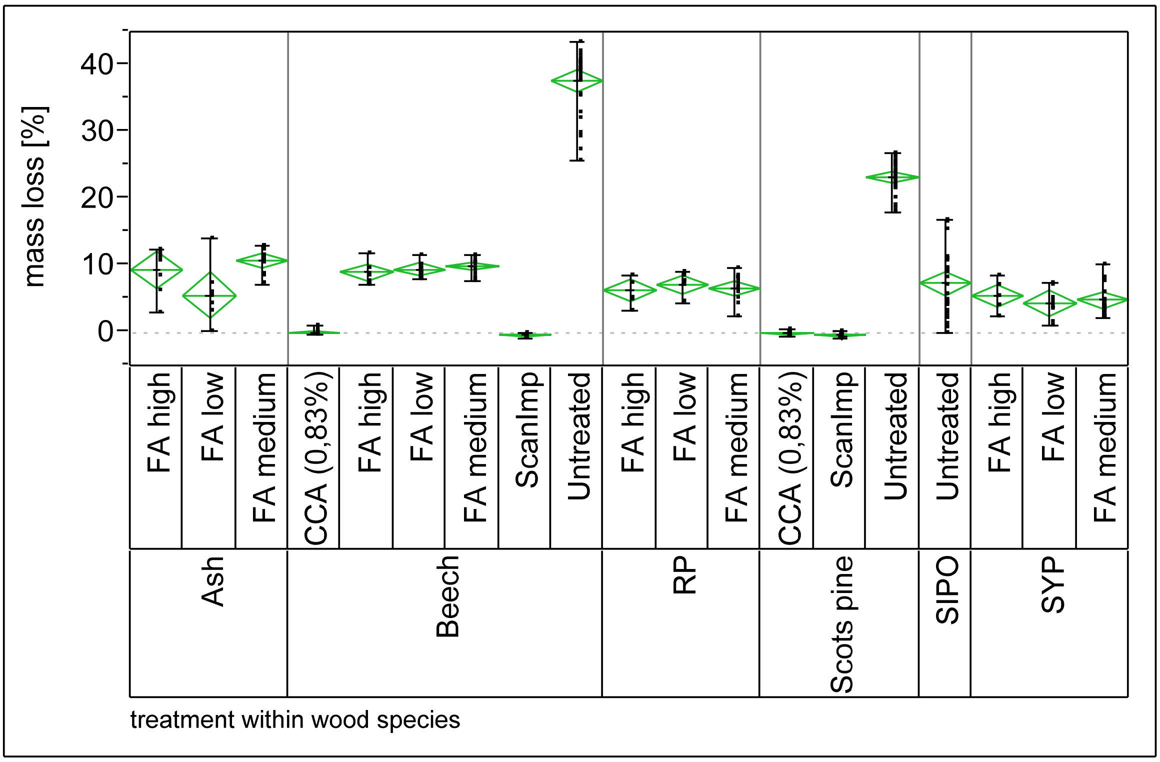

Figure 5: Mass loss of furfurylated wood samples after exposing to Gloeophyllum trabeum for 16 weeks

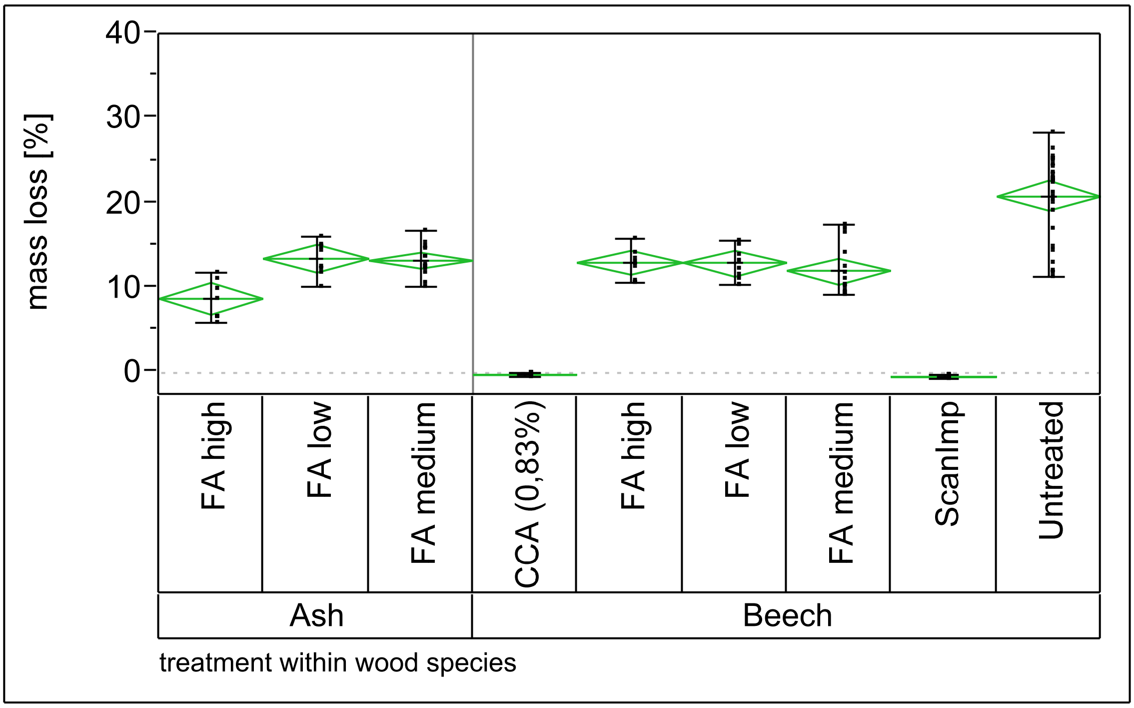

Figure 6: Mass loss of furfurylated wood samples after exposing to Irpex lacteus for 16 weeks

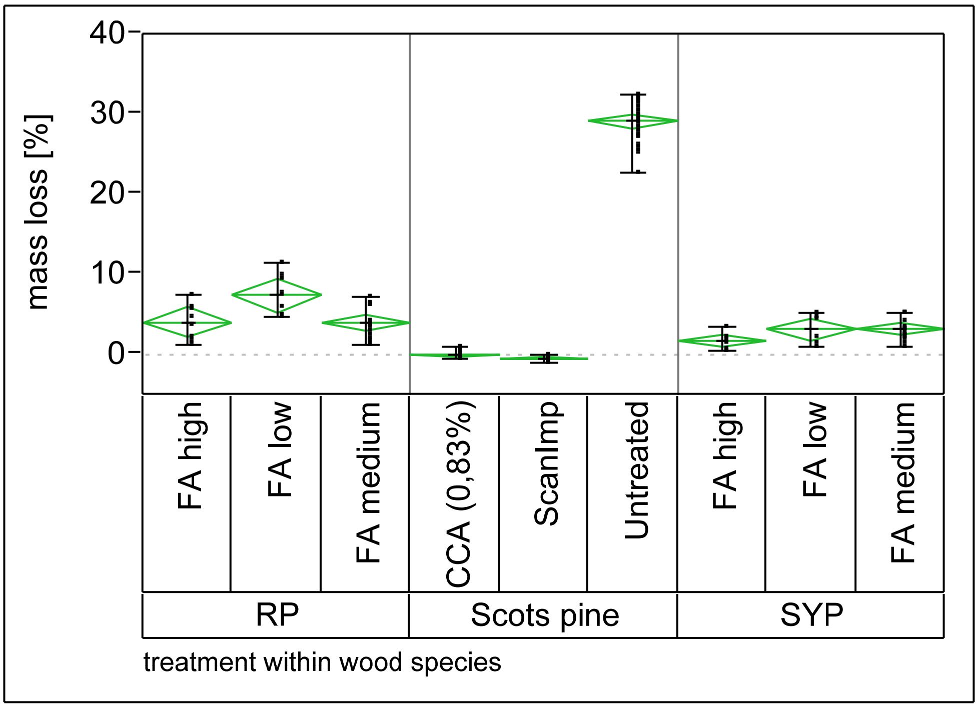

Figure 7: Mass loss of furfurylated wood samples after exposing to Postia placenta for 16 weeks

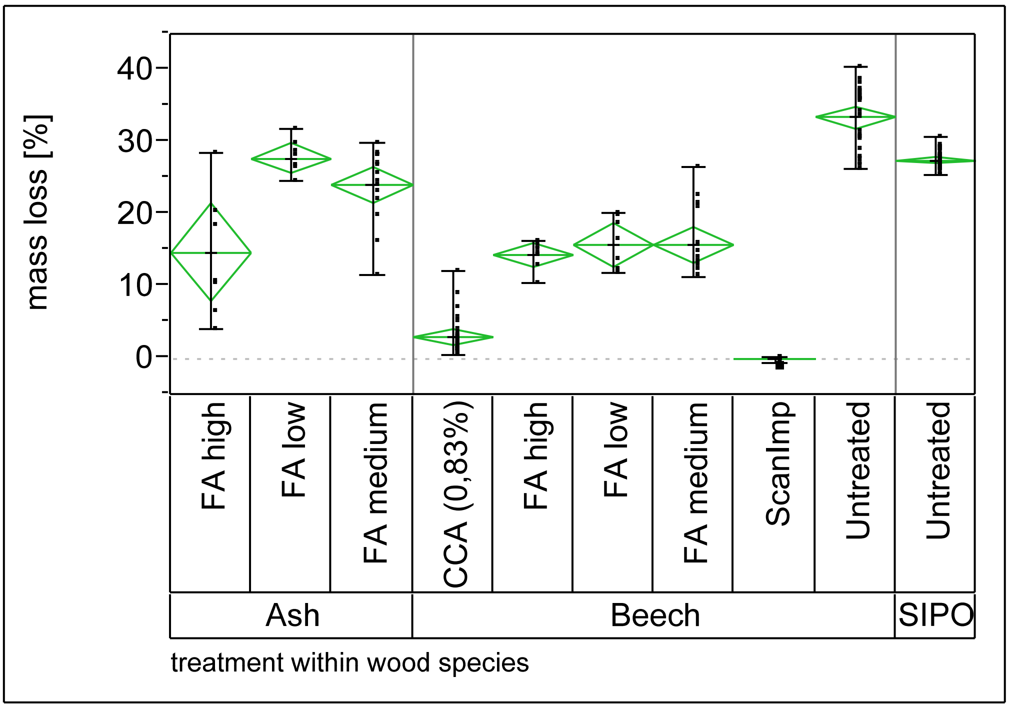

Figure 8: Mass loss of furfurylated wood samples after exposing to Trametes versicolor for 16 weeks

The classification of uptake of furfuryl alcohol into three different WPG groups doesn't explain consistently the different mass loss within one wood species. Uptake doesn't correlate to the mass loss. The uptake groups can therefore only be seen as a rough estimate.

The sample preparation prior to the fungi test has to be taken into account.

3.3. Resistance against staining fungi

The untreated and furfurylated softwood samples exposed to a fungi mix in a non-sterile test showed nearly the same classification of colonization (up to growth class 3) during the first two weeks. Untreated and furfurylated hardwood samples showed however smaller numbers of growth classes during the entire test.

After 5 weeks

11 weeks

Figure 9: Surface of untreated and furfurylated Southern Yellow pine after 5 and 11 weeks of exposure to a surface fungi mix

Fungal growth that is classified from 0 – 2 can only be detected by the microscope and is not visible for the human eye. The classification from 3 -6 is done by visual inspection without using a microscope. Due to the darker color of the furfurylated samples a visual inspection can result in favor for the furfurylated samples. However, since the cured furfuryl alcohol should not have any negative influence on the growth of surface fungi. Cured furfuryl alcohol is non-toxic and should not affect the growth of surface fungi, which preservatives do due to growth inhibiting substances.

Figure 10: Surface of untreated and furfurylated Radiata pine after 5 and 11 weeks of exposure to a surface fungi mix

Furfurylated wood samples have a good visual appearance even after 60 days of exposure to staining fungi in comparison to all untreated samples.

After 5 weeks

11 weeks

Figure 11: Surface of untreated and furfurylated ash after 5 and 11 weeks of exposure to a surface fungi mix

After 5 weeks

11 weeks

Figure 12: Surface of untreated and furfurylated beech after 5 and 11 weeks of exposure to a surface fungi mix

After 5 weeks

11 weeks

Figure 13: Surface of untreated sipo mahogany after 5 and 11 weeks of exposure to a surface fungi mix

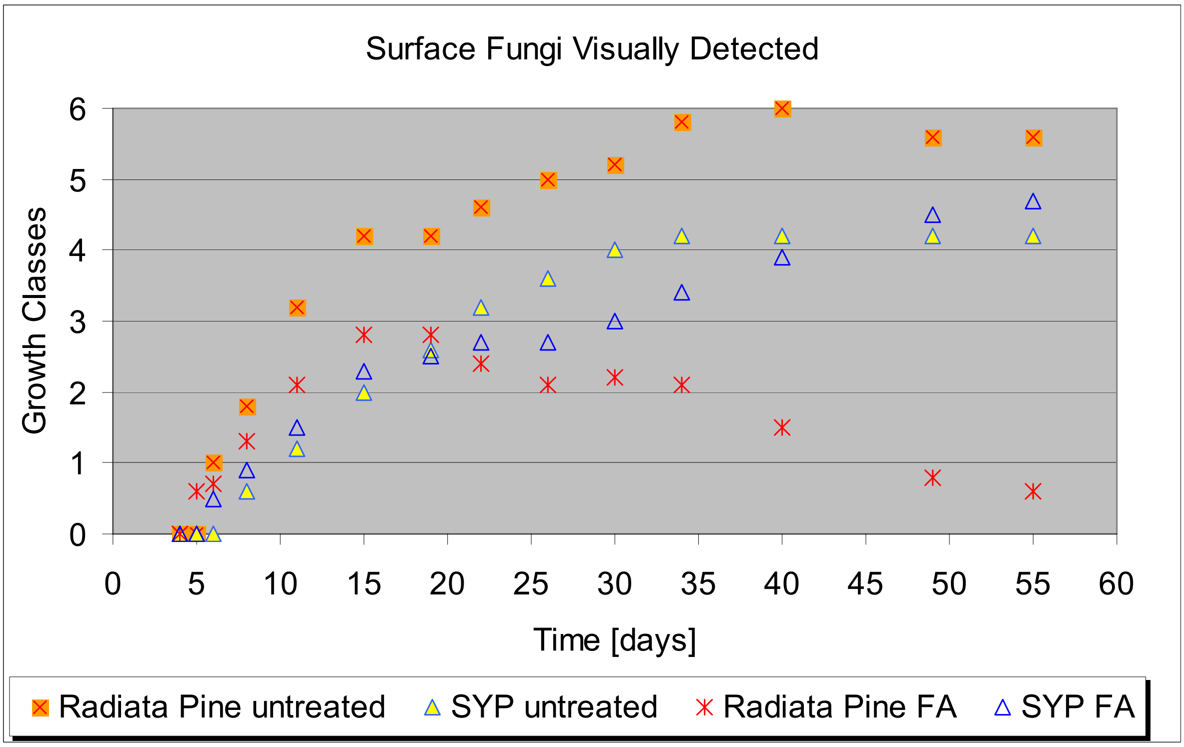

Figure 14: Classification of growth on untreated and furfurylated sofwoods during 60 days of exposure to a surface fungi mix

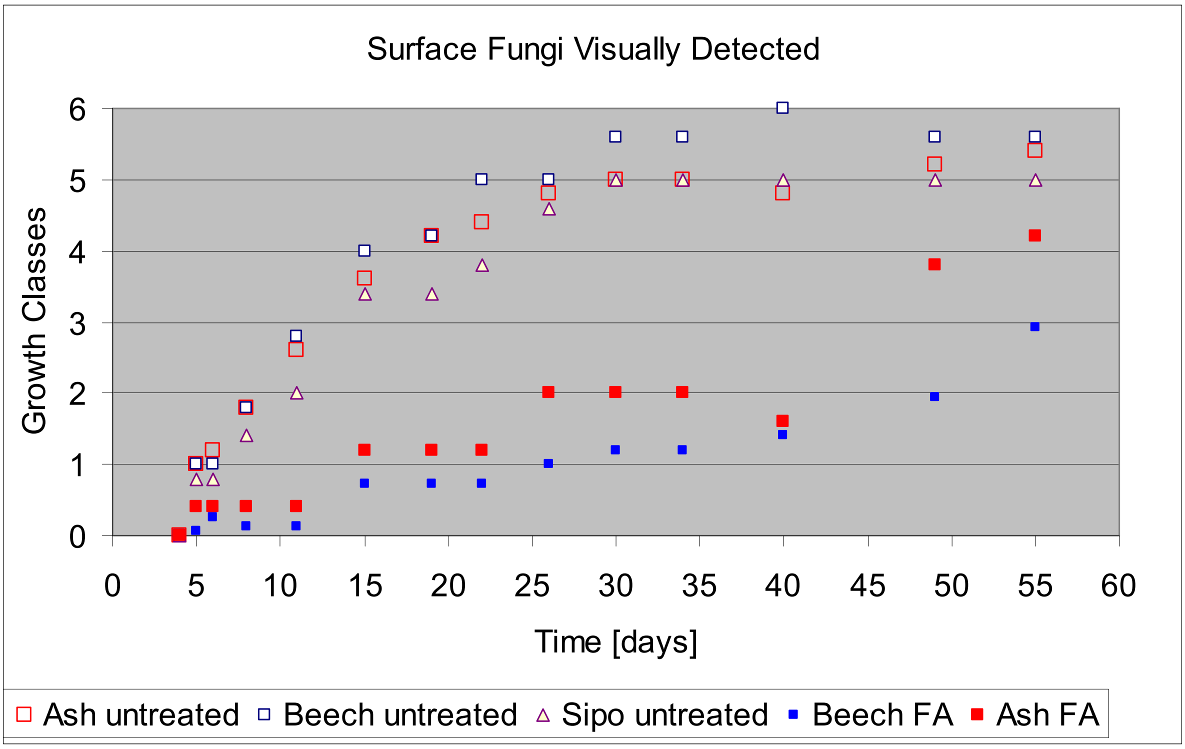

Figure 15: Classification of growth on untreated and furfurylated hardwoods during 60 days of exposure to a surface fungi mix

3.4. Test in soil contact

The untreated wood samples showed significantly higher mass loss after 32 weeks of exposure in compost soil. Furfurylated Radiata pine and Southern Yellow pine showed a low mass loss, whereas furfurylated ash and beech had a mass loss of 8-15%. This is comparable to the results from the test on basidiomycetes, where furfurylated ash and beech showed significantly higher mass loss than furfurylated Southern Yello pine and Radiata pine.

Figure 16: Test setup of ENV 807 test

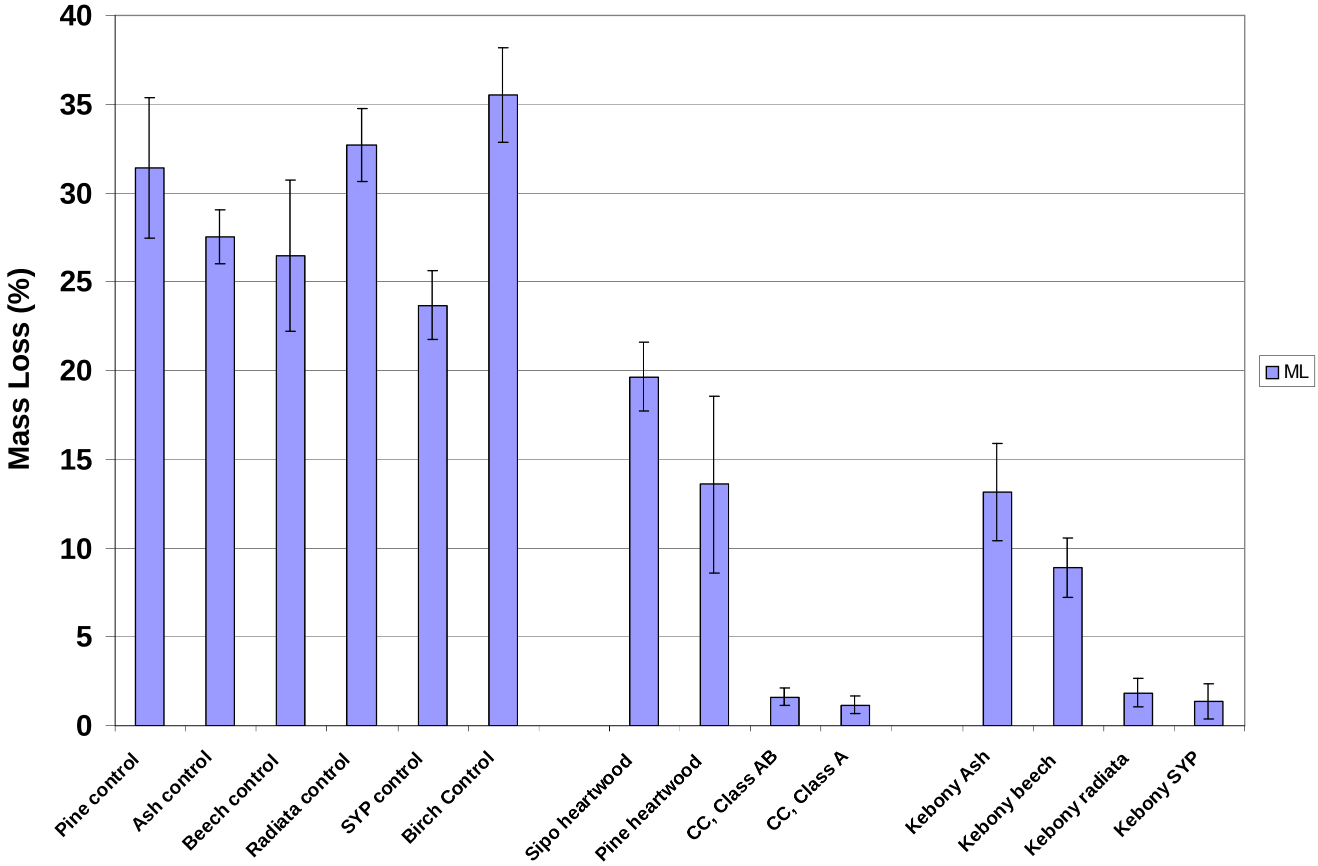

Figure 17: Mass loss of furfurylated and untreated control samples after 32 weeks in compost soil

The results on mass loss of samples exposed in the second soil in test (Simlångsdalen soil) is ongoing due to low mass loss even after 32 weeks.

3.5. Ecotoxicity and leaching of furfuryl alcohol

3.5.1. LEACHING TEST 1

The ecotoxicity of the leachates from leaching test 1 show that all the furfurylated samples, except from ash, beech low and medium and Radiata pine low had no toxicity (TU below 2) (Fig. 3). Ash furfurylated at a high level had the highest toxicity, TU of 10 at 48 hours, compared to all the other samples both at 1 hour and 48 hours. At 1 hour none of the samples showed any toxicity. Ash furfurylated at a low level had the second highest at 48 hours with a TU of 6. Beech furfurylated at a low level had the 3rd highest at 48 hours with a TU of 4. Beech furfurylated at a medium level had its highest value at 48 hours with a TU of 3.

In general the ecotoxicity values followed the pattern of leached furfuryl alcohol, with some minor exceptions. All the samples had a higher level of leached furfuryl alcohol after 48 hours than after 1 hour (Fig. 3). Ash high and ash medium had the highest and next highest amount of leached furfuryl alcohol compared to the other samples.

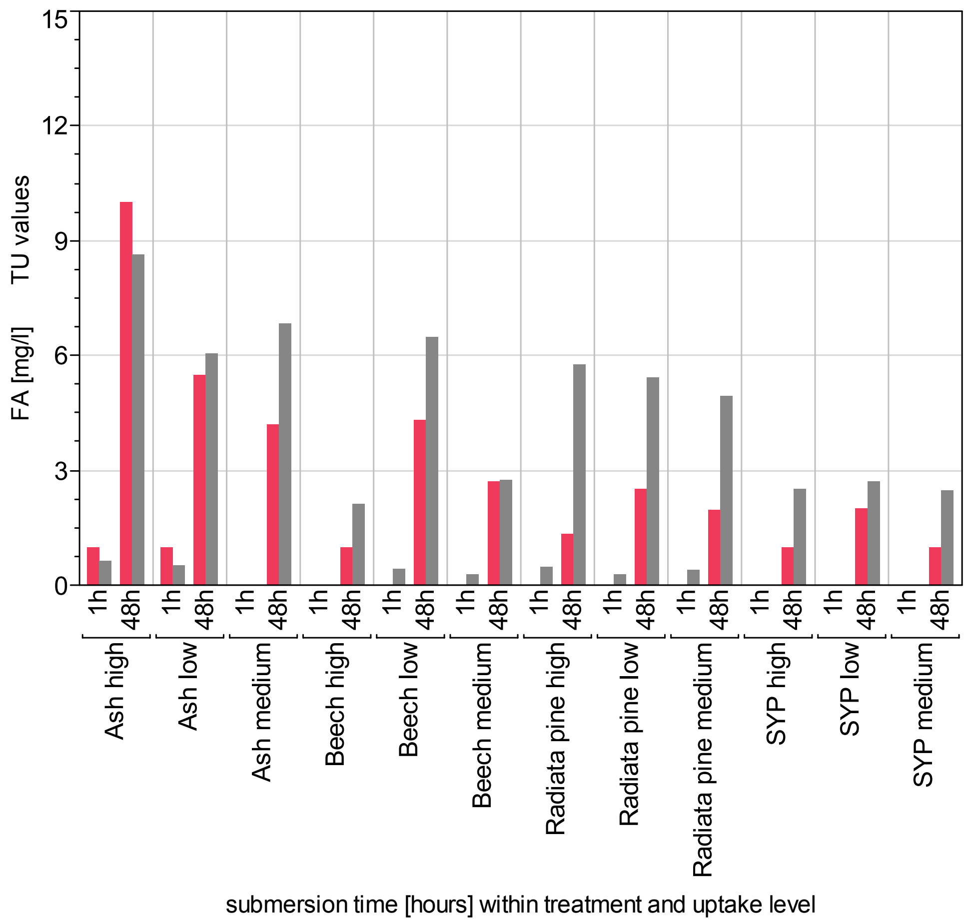

Figure 18: Ecotoxicity (toxic unit) after 30 minutes exposure time in the Microtox assay and amount of furfuryl alcohol (FA) in leaching water from Leaching Test 1. Sample taken after 1 hour and 48 hours

3.5.2. LEACHING TEST 2

The ecotoxicity of the leachates from leaching test 2 (EN84) (Fig. 4) show that all the furfurylated samples, except for ash and Radiata pine had no toxicity (TU below 2). Ash high had the highest TU of all ash samples and Radiata pine samples after 1 day with a TU of 7. For Radiata pine the highest value was after 1 day for the high treatment level with a TU of 5. All ash samples and Radiata pine samples had a lower TU after 14 days than after 1 day. Scots pine with a TU of 3 at 1 day, was the only untreated sample that had a TU above 2 during the test series.

These results can be compared to beech treated ScanImp that had a TU of 50 and CCA treated beech that had a TU of 17 after 1 day. Scots pine treated with CCA had a TU of 13 after 1 day and Scots pine treated with ScanImp had a TU of 17. After 14 days the TU had decreased and the highest TU could be found for ScanImp treated Scots pine with a TU of 14.

In general the toxicity values followed the pattern of leached furfuryl alcohol. Furfurylated ash high and low had a noticeable higher amount of FA leaching compared to the leaching water of the other samples. The highest leaching values were obtained from the leaching of furfurylated ash low (21 mg/l). Lande *et al*. (2004) found an average leaching value after a comparable leaching procedure with furfurylated Scots pine sapwood (WPG 30%) of 0.23 mg/l which is 100 times less than the highest value (furfurylated ash low, see fig. 4) in our test.

De Vetter *et al.* (2008) tested the ecotoxicity of EN 84 (1997) leachates from SYP and maple (Acer pseudoplatanus) furfurylated with monomeric furfuryl alcohol to Daphnia magna. These results showed that SYP had a lower toxicity than maple. They also showed that EN 84 (leaching test 2) leachates of CCA treated Scots pine (Pinus sylvestris) had a higher toxicity towards Daphnia magna after one day than after 14 days.

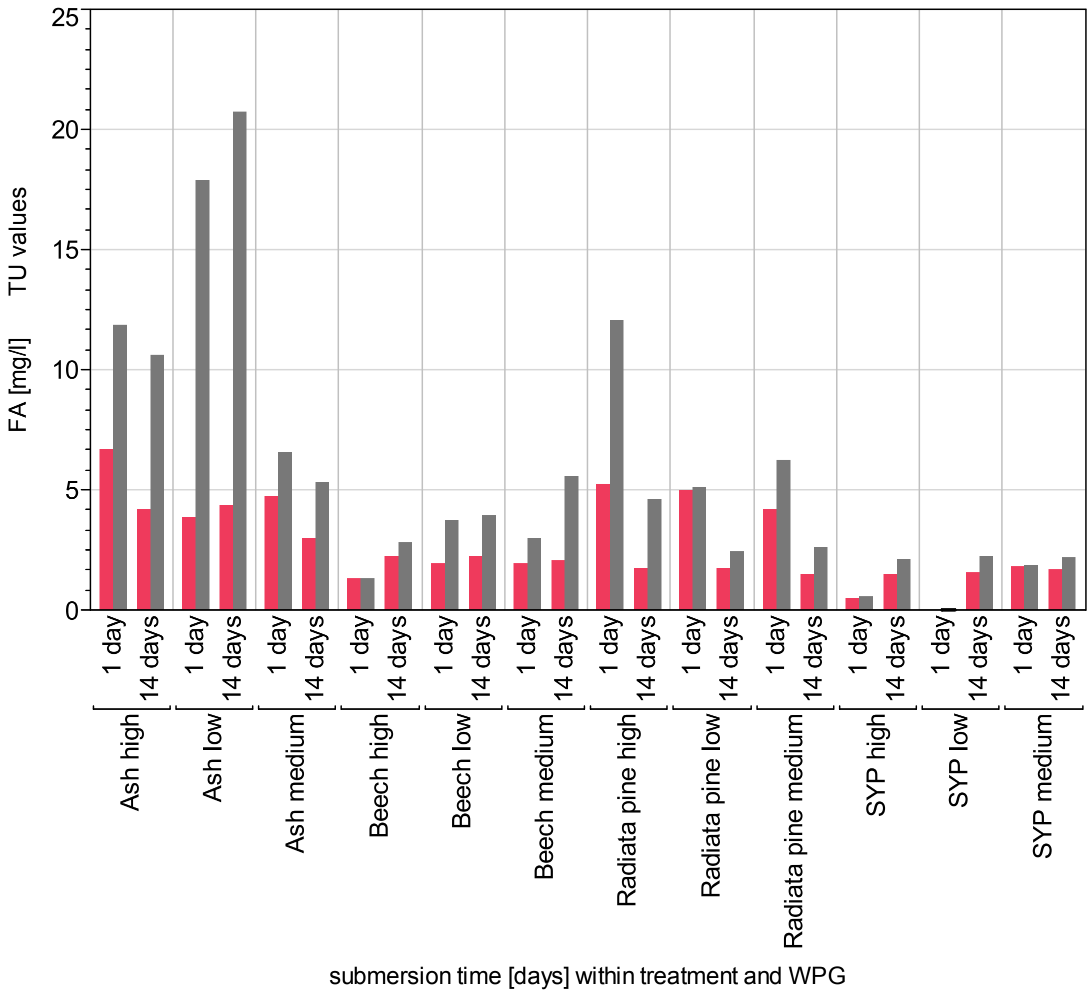

Figure 19: Ecotoxicity (toxic unit) after 30 minutes expositing time in the Microtox assay and amount of furfuryl alcohol (FA) in leaching water from leaching test 2 (EN84) taken after 1 day and 14 days

Table 7: Toxic units (TU30) after 1 and 14 days of leaching

WOOD SPECIES	TREATMENT	AFTER 1 DAY	AFTER 14 DAYS
beech	Scanimp	50	7
	CCA	17	2.3
Scots pine	Scanimp	17	14
	CCA	13	3

Furfurylated SYP had in general a lower toxicity and a lower amount of leached furfuryl alcohol than Radiata pine. Pilgård and Westin (2008) showed that there was a difference in ecotoxicity between furfurylated Radiata pine and furfurylated Scots pine and that furfurylated Scots pine had in general lower toxicity in the Microtox Assay than furfurylated Radiata pine.

In both leaching methods (leaching test 1 and 2) furfurylated SYP had in general the lowest amount of leached furfuryl alcohol compared to all the other wood species. SYP also had in general the lowest toxicity.

4. CONCLUSION

- The results of the different experiments are important to proof the basic requirements for the use in the modern window construction.
- The furfurylated wood shows a satisfactory behavior against moisture, which leads to good expectations for the coating and weathering tests
- The water uptake and the swelling of the furfurylated wood samples are reduced compared to untreated samples. This is an important material property when it comes to dimensional stable wood products.
- The high dimensional stability, reduced water uptake as well as good water vapor resistance indicate that the furfurylated wood has great potential for the production of wooden windows.
- The toxicity of leachate of furfurylated wood is low compared to CCA and ScanImp treated wood in the ecotox test.
- The gathered water samples showed in low toxicity for both different leaching tests. The toxicity values correlated well to the amount of leached furfuryl alcohol for both leaching methods. In both leaching methods (leaching test 1 and 2) furfurylated SYP had in general the lowest amount of leached furfuryl alcohol compared to all the other wood species. SYP also had in general the lowest toxicity.
- The durability test showed that the mass losses for furfurylated SYP, beech and Scots pine were low for all tested fungi.
- Southern yellow pine showed good results in all of the tests and has potential for the production of window frames according to the tests performed.

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