Proceedings IRG Annual Meeting (ISSN 2000-8953)

IRG/WP 16-20576

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 2 **Test Methodology and Assessment**

On the effect of climate and exposure conditions on durability indicators and their potential for service life prediction of wood-based products

Alfredsen, G.[1], Brischke, C.[2], Flæte, P.-O.[3], Humar, M.[4], Meyer-Veltrup, L.[2]

[1]Norwegian Institute of Bioeconomy Research, Box 115, NO-1431 Ås, Norway

[2]Leibniz University Hannover, Faculty of Architecture and Landscape Sciences,
Institute of Vocational Sciences in the Building Trade, Herrenhäuser Str. 8, DE-30419 Hannover, Germany

[3]Norwegian Institute of Wood Technology, Box 113 Blindern, NO-0314 Oslo, Norway

[4]University of Ljubljana, Biotechnical Faculty, Dept. of Wood Science and Technology
Jamnikarjeva 101, SI-1000 Ljubljana, Slovenia

Paper prepared for the 47th IRG Annual Meeting
Lisbon, Portugal
15-19 May 2016

IRG SECRETARIAT
Box 5609
SE-114 86 Stockholm
Sweden
www.irg-wp.com

On the effect of climate and exposure conditions on durability indicators and their potential for service life prediction of wood-based products

Alfredsen, G.[1], Brischke, C.[2], Flæte, P.-O.[3], Humar, M.[4], Meyer-Veltrup, L.[2]

[1]Norwegian Institute of Bioeconomy Research, Box 115, NO-1431 Ås, Norway, gry.alfredsen@nibio.no

[2]Leibniz University Hannover, Faculty of Architecture and Landscape Sciences, Institute of Vocational Sciences in the Building Trade, Herrenhäuser Str. 8, DE-30419 Hannover, Germany brischke@ibw.uni-hannover.de; meyer@ibw.uni-hannover.de

[3]Norwegian Institute of Wood Technology, Box 113 Blindern, NO-0314 Oslo, Norway, per.otto.flate@treteknisk.no

[4]University of Ljubljana, Biotechnical Faculty, Dept. of Wood Science and Technology

Jamnikarjeva 101, SI-1000 Ljubljana, Slovenia

Miha.Humar@bf.uni-lj.si

ABSTRACT

In order to encourage increased use of wood, different user groups need to be better informed regarding the variation in performance between different wood materials and the effect of different use classes. It is also important to provide good empirical data on the service life of wood products as input to for example life cycle assessment studies. In the current study the effect of temperature and moisture on the performance of different wood materials in laboratory decay trials was evaluated by different approaches and compared with field exposure data. The same materials were used throughout the different tests in order to reduce variation. The durability class allocation varied, as expected, between test fungi, climates, exposure times, and decay tests. This confirms that the durability classification of a material, and the ranking between materials, is not a fixed value that can be based on one single test. Interestingly, for the most durable materials and for Scots pine sapwood (low durability) the variation in durability classification seemed to be somewhat lower than for the materials with intermediate durability. A regression model approach was used in order to predict field performance from laboratory data. However, this approach was not successful and confirms that more sophisticated models are needed in order to make good predictions of service life.

Keywords: material resistance, moisture performance, natural durability, wood modification

1. INTRODUCTION

The Nordic countries have a long tradition with utilizing wood, mainly softwoods, as construction material despite that they are not considered very durable. In Norway softwoods, especially Norway spruce, have traditionally been used as exterior cladding. Now there is a growing interest to use untreated wood from other native wood species as cladding material. This is due to an increased interest for wood among architects and increased awareness of the beneficial properties wood as a building material can provide. But architects, developers and engineers lean on documentation of reliable service life data. This cause some challenges because: 1) wood is a heterogenic material, there are variations in durability within one species, 2) there are variations between wood protection systems, 3) there is no universal service life for a given treatment, the performance relies on the climatic conditions and the deteriorating organisms at a given location, 4) if a mistake is made during construction, leading to a moisture trap, the service life of the component will drastically be reduced compared to the service life expected from a well-designed and well-built construction.

A number of definitions are available regarding durability of wood and some of them are listed in Brischke *et al.* (2006). Not all define durability as a material property. In order to avoid confusion in terminology Brischke *et al.* (2006) suggest using the following definition: 'the durability of wood is its resistance to wood-destroying organisms under the influence of its environment'. The natural durability of wood can be improved by a number of techniques, e.g. utilize the heartwood or use a wood protection system. Constructive protection serves the purpose of reducing the moisture load on construction details and thereby reduces the risk of decay and increases the service life. Brischke *et al.* (2006) list the following factors as important for the durability of wood materials: 1) material temperature and wood moisture content, 2) design and execution of detail, 3) conditions of use, 4) dimensions of a component, 5) cracks, 6) the quality of workmanship.

It is also important to keep in mind that durability is not equal to service life (Brischke *et al.* 2006). Durability is a property that provides a given service life. Durability is affected by a range of factors during the use phase of a product. Service life is a given time period usually specified in years. The service life ends when a property reaches its critical limit of performance. It is important to be aware of that there are a number of definitions of service life. The international standard ISO 15686-1 (2011) uses the following definitions: Estimated service life (ESL) - 'service life that a building or parts of a building would be expected to have in a set of specific in-use conditions, determined from reference service life data after taking into account any differences from the reference in-use conditions'. Predicted service life (PSL) – 'service life predicted from performance recorded over time in accordance with procedure described in ISO 15686-2 (2012)'. Reference service life (RSL) – 'service life of a product, component, assembly or system which is known to be expected under a particular set, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in-use conditions'. Design life (DL) – 'service life intended by the designer'. It is important to quantify service life of wooden products in a scientific manner both, because predictability is important for the user and because reliable data are needed for analyses of environmental impact of different wooden materials. Increased service life of a wood product implies less work and lower cost for the user. It also gives a positive environmental contribution because 1) the longer a wood product stays in use the longer it will store its carbon, 2) the longer one has to wait to replace a product the better since every replacement result in an environmental impact. An often neglected fact is that 'replacement due to defective performance needs to be distinguished from obsolescence. Obsolescence arises when a facility is no longer able to be adapted to satisfy changing requirements' (ISO 15686-1, 2011). Obsolescence can be functional (function no longer required), technological (better performance available from modern alternatives and/or changing pattern of building use), and economic (fully functional but less efficient, and/or more expensive than alternatives).

Unfortunately, service life prediction of wood products has so far mainly been based on expert judgement rather than empirical studies (Brischke *et al.* 2012). Brischke and Thelandersson (2014) reviewed existing modelling approaches for outdoor performance of wood products. The first comprehensive approaches include: MacKenzie *et al.* (2007), Thelandersson *et al.* (2011), Isaksson *et al.* (2014) and Brischke *et al.* (2015). Attempts to improve prediction of service life are also carried out within the framework of IRG-WP by: 1) the establishment of the Durability Database in order to provide a platform for scientific exchange of test data, 2) publication of IRG conference papers, 3) plenary discussion sessions and special sessions at the annual IRG meetings.

The aim of the current study was to: 1) investigate the effect of temperature and moisture on wood material performance in laboratory decay trials, 2) compare different durability classification methods, and 3) compare laboratory studies with field exposure data. Therefore, in total 34 different materials including untreated hardwood and softwoods, thermally and chemically modified wood, and different preservative treated timbers were submitted to a range of different decay and moisture tests. Decay tests included both, laboratory assays and field studies with and without ground contact.

2. EXPERIMENTAL METHODS

2.1 Wood material

The wood materials and the different tests applied in this study are given in Table 1 and contain two batches of materials:

1) A set of the most typical Norwegian wood species plus references of preservative treated wood and reference wood species. The material was presented for the first time by Flæte *et al.* (2006). The following decay tests were performed:
   - Laboratory trials: 1) mini block 11 weeks, 2) mini block 20 weeks, 3) ENV 807 (CEN 2001) 13 weeks, 4) EN 113 (CEN 1996) 16 weeks.
   - Field trials: horizontal double layer (HDL) (Augusta 2007) 11 years exposure, EN 252 (CEN 1989) 12 years exposure.
2) Materials include: four types of modified wood, seven wood species (from same batch as above) and three wood preservatives. The following decay tests were performed:
   - Laboratory trials: 1) mini block 20 weeks, 2) ENV 807 (CEN 2001) 13 weeks.
   - Field trials: horizontal double layer (HDL) (Augusta 2007) six years exposure, EN 252 (CEN 1989) five years exposure.

2.2 Decay tests

2.2.1 Mini block

The sample size was according to Bravery (1979), 5 × 10 × 30 (ax.) mm^3 and the test fungus was *Postia placenta* (Fr.) M.J. Larsen & Lombard (FPRL 280). The tests were performed under three different climate conditions: 22°C/70% RH, 16°C/70% RH, or 11°C/70 % RH. All materials were leached according to EN 84 (CEN 1997) prior to exposure. Two different mini block tests were performed:

1) For the test of the different wood species agar plates with 4% malt (w/v) were used and a malt agar plug from actively growing mycelia was provided as inoculum. The exposure time was 11 weeks and the tests were run with n = 10 replicates.
2) For the treated materials and reference wood species a sterile soil medium was used containing 1/3 sandy soil and 2/3 ecological compost soil. The moisture content of the soil was adjusted to 95% of its water holding capacity according to ENV 807 (CEN 2001) and 20 g soil was used in each Petri dish. The weight of the plates was recorded at the start of the test and every third week. Sterile water was added when needed in order to keep the soil moisture content stable throughout the test. As inoculum a liquid culture containing 4% malt was used and 1 ml was applied on each sample. The exposure time was 20 weeks and the tests were run with n = 10 replicates. Initial equilibrium moisture content (EMC_{in}) at 22°C/70% RH before decay was measured for all specimens.

For the mini block decay tests it is important to keep in mind that only one strain of one brown rot causing fungus was tested and that it is a well-known copper tolerant fungus.

Table 1: Wood species and treatments tested, abbreviation, scientific name of wood species or treatment level, and types of decay tests are listed. MB = mini block (malt agar 11 weeks, sterile soil 20 weeks), HDL = horizontal double layer (Ås and Bergen test sites). The EN 252 results are from 5 years in Ås test site and 12 years in the Sørkedalen test site. In the two 11 year HDL trials and the 12 year EN 252 trial the same batch of Scots pine sapwood was used for all treated wood except ThermoWood (from a building supply store). For the laboratory trials plus the 6 year HDL trial and 5 year EN 252 trial the treated wood was from the same batch of Scots pine sapwood except the furfurylated wood (from a building supply store). NWPC AB = Nordic wood preservation council, above ground use treatment level.

Species or treatment (abbreviation)	**Scientific name or treatment level (treatment facility)**	**MB lab [weeks]**	**EN 113 lab [weeks]**	**ENV 807 lab [weeks]**	**HDL Ås [years]**	**HDL Bergen [years]**	**EN 252 Sør. /Ås$^{\phi}$ [years]**
Wood modifications							
Acetylation (Ac)	WPG 21% (Titan wood)	20		13	6		5$^{\phi}$
Furfurylation (FA)	NWPC AB (Kebony ASA)	20		13			
	FA40 (Kebony ASA)				11	11	12
	FA50 (Kebony ASA)				11	11	12
DMDHEU (D)	1.3M (Uni. Göttingen)	20		13	6		5$^{\phi}$
Thermal (TM)	ThermoWood pine (ThermoWood)				11	11	12
	Thermo D, 212°C (Scandinavian Fine Wood)	20		13	6		5$^{\phi}$
Hardwoods							
Maple (Map)	*Acer platanoides*	11	16		11	11	12
Alder (Ald)	*Alnus glutinosa/ A.incana*	11+20	16	13	11	11	12
Birch (Bir)	*Betula pendula/ B. pubescens*	11	16		11	11	12
Beech (B)	*Fagus sylvatica*	11+20	16	13	11	11	12
Ash (Ash)	*Fraxinus excelsior*	11	16		11	11	12
Aspen (Asp)	*Populus tremula*	11+20	16	13	11	11	12
Oak (Oak)	*Quercus petraea/ Q. robur*	11+20	16	13	11	11	12
Goat willow (GW)	*Salix caprea*	11	16		11	11	12
Rowan (Row)	*Sorbus aucuparia*	11	16		11	11	12
Teak (Tea)	*Tectona grandis* (Asia)	11	16		11	11	12
Lime (Lim)	*Tilia cordata*	11	16		11	11	12
Merbau (Mer)	*Intsia bijuga* (Asia)	11	16		11	11	12
Wych elm (WE)	*Ulmus glabra*	11	16		11	11	12
Softwoods							
Silver fir (SF)	*Abies alba*	11	16		11	11	12
Juniper (Jun)	*Juniperus communis*	11	16		11	11	12
European larch (EL)	*Larix decidua*	11+20	16	13	11	11	12
Siberian larch (SL)	*Larix sibirica* (Russia)	11	16		11	11	12
Norway spruce (NS)	*Picea abies*	11	16		11	11	12
Scots pine heart. (SpH)	*Pinus sylvestris*	11	16		11	11	12
Scots pine sap. (SpS)	*Pinus sylvestris*	11+20	16	13	11	11	12
Sitka spruce (SS)	*Picea sitchensis*	11	16		11	11	12
Douglas fir (DF)	*Pseudotsuga menziesii* (N-Am)	11+20	16	13	11	11	12
W. red cedar (W-A)	*Thuja plicata* (N-Am)	11	16		11	11	12
W. red cedar (W-N)	*Thuja plicata* (Norway)	11	16		11	11	12
Reference preservatives							
CCA (CCA)	NWPC AB	20		13	11/5	11	12/5$^{\phi}$
Copper HDO (Cu)	NWPC AB	20		13	11/5	11	12/5$^{\phi}$
Copper naphthenate (QN)*	0.53 kg/m^3	20		13			

*This is above the toxic threshold but below the standard retention for above ground – 0.64 kg/m^3 (AWPA U1-11, 2011)

2.2.2 EN 113

The durability of the different wood species was performed according to EN 113 (CEN 1996) using n = 5 replicates (25 × 15 × 50 (ax.) mm^3). The softwoods were challenged with the two brown rot fungi *Coniophora puteana* (Schumach.) P. Karst. (BAM Ebw. 15) and *Postia placenta* (Fr.) M.J. Larsen & Lombard (FPRL 280) and the white rot fungus *Trametes versicolor* (L.) Lloyd (CTB 863 A). For hardwoods *C. puteana* and *T. versicolor* were used. The test deviated from the standard by not performing the initial drying step by oven-drying at 103°C because the severe drying conditions might interact with essential wood properties linked to decay resistance. Instead, the samples were conditioned in a climate chamber (20°C/70% RH) and five samples for each wood species were oven-dried for 18 h at 103°C in order to calculate theoretical initial oven-dry weight.

2.2.3 ENV 807 (CEN 2001)

The test was performed according to ENV 807 (CEN 2001) using specimens of 5 × 10 × 100 (ax.) mm^3 and n = 10 replicates. Deviation from the standard was that all samples were harvested after 13 weeks and that mass loss was used directly (not recalculated according to chapter A.7 in ENV 807). All materials were leached according to EN 84 (CEN 1997). Three different climates were used: 25°C/80% RH, 25°C/60% RH or 10°C/85% RH. EMC_{in} at 22°C/70% RH before decay was measured for all specimens.

2.2.4 Soil contact tests according to EN 252 (CEN 1989)

Ten replicate stakes (25 × 50 × 500 (ax.) mm^3) were prepared from each wood type in accordance with EN 252 (CEN 1989). Two test sites were used; for the 12 years exposure data the specimens were exposed from 2003 at the Norwegian Institute of Wood Technology (Treteknisk) field test site in Sørkedalen, Oslo (DD 60.024634, 10.592854). For the 5 year exposure data the specimens were exposed from 2010 in the NIBIO test site in Ås (DD 59.667016, 10.773236). The stakes were assessed annually using a pick test according to the standard. Pooled data are given for Norway spruce (annual year ring width 1, 3 and 6 mm).

2.2.5 Horizontal double layer tests

Ten replicate stakes (25 × 50 × 500 (ax.) mm^3) were prepared from each wood type. Two test sites were used: for the 11 year exposure data the specimens were exposed from 2004 at the NIBIO test site in Ås (DD 59.667016, 10.773236) and Bergen (DD 60.259945, 5.348390). For the 6 years exposure data the specimens were exposed in 2009 at the NIBIO test field in Ås. The specimens were placed horizontally in double layers according to Augusta (2007) with the upper layer displaced laterally by 25 mm to the lower layer. Supports were 25 cm above ground and made from aluminium L-profiles. Pooled data are given for Norway spruce (annual year ring width 1, 3 and 6 mm) and Scots pine heartwood (annual year ring width 1 and 3 mm).

2.3 Moisture tests

2.3.1 Specimens

Ten replicate specimens of 5 × 10 × 100 (ax.) mm^3 were used for three different W 24 – tests and a capillary water uptake test.

2.3.2 Liquid water uptake by submersion – W 24

Specimens were oven-dried at 103°C until constant mass and weighed to the nearest 0.001 g to determine oven-dry mass. Dimensions of specimens were also measured to the nearest 0.1 mm. Specimens were submersed in a container filled with demineralised water and placed in normal climate. Specimens were separated from each other by thin spacers (cross section 1 × 1 mm^2). The specimens were weighed again after 24 h submersion. The water uptake of the specimens was determined and the resulting moisture content after submersion was calculated.

2.3.3 Water vapour uptake in water saturated atmosphere – W 24

Specimens were oven-dried at 103°C until constant mass and weighed to the nearest 0.001 g to determine oven-dry mass. Furthermore, dimensions of specimens were measured to the nearest 0.1 mm. The bottom of a miniature climate chamber (plastic container with stainless steel trays and ventilator) was filled with demineralised water. Specimens were exposed using thin spacers (cross section 1×1 mm²) above water in the well ventilated miniature climate chamber and weighed again after 24 h. The water uptake of the specimens was determined and the resulting moisture content after 24 h was calculated.

2.3.4 Desorption – W 24

Specimens were stored in 100 % RH until constant mass (approx. 2 weeks) and weighed to the nearest 0.001 g to determine mass at fibre saturation. Furthermore, dimensions of specimens were measured to the nearest 0.1 mm. The specimens were exposed directly on freshly activated silica gel and weighed again after 24 h. The water release of the specimens during 24 h was determined and expressed as percentage of mass at fibre saturation.

2.3.5 Capillary water uptake

Short term water absorption was measured according to modified EN 1609 (CEN 1997) procedure using a Krüss Processor Tensiometer K100MK2. Specimens of $5 \times 10 \times 100$ (ax.) mm³ were placed in 20°C/65% RH till constant mass. The axial specimen surfaces were positioned to be in contact with water and fixed in the Tensiometer. The specimens were subsequently weighed to the nearest 0.0001 g continuously every 2 s for 200 s. The capillary water uptake was determined over time in g/cm².

2.4 Dynamic modulus of elasticity (MOE_{dyn})

In order to quantify strength loss dynamic modulus of elasticity (MOE) was measured on non-decayed and decayed ENV 807 samples using a BING system (Beam Identification by Nondestructive Grading, Pico Technology). The velocity of a sound wave through the wood is used to calculate the mechanical stiffness and strength: the higher the velocity, the higher the stiffness and strength of the wood. Elastic supports were used to support the sample. An excitation pulse was then applied to one end of the specimen and a microphone at the other end recorded the vibrations and transmitted them via an anti-aliasing filter (lo-pass filter, LPF-30, World Prediction Instruments) to the PicoScope 4262 (Pico Technology). BING software uses the spectrum analysis capabilities of the PicoScope to interpret the information in the frequency domain and calculate the mechanical properties of the specimen. The samples were left to acclimatize at 20°C/65% RH until stable weight prior to testing. Ten replicates of each material were used.

3. RESULTS AND DISCUSSION

3.1 Laboratory decay tests

3.1.1 Mini block – 11 weeks

Treatment: Table 2 (first three columns) show the mean mass losses and the comparison of means between each wood species within each climate. The best performance was achieved by: merbau, teak and western red cedar, then followed by wych elm, juniper and European larch. The highest mass loss was found for: aspen, birch, Scots pine sapwood and Norway spruce.

Climate: After pooling all samples and comparing mass loss means between the three temperatures (Figure 1) significant differences were found between the three climates. There was a significant difference between the three temperatures for all hardwood species except: rowan, wych elm, merbau and teak (right column Table 2). The three latter were also the species with the lowest mass loss. For the softwood species there was no significant difference between 22°C and 16°C for most of the materials with high mass loss (Norway spruce, Sitka spruce, silver fir, Scots pine heartwood). Western red cedar had the lowest mass loss and no significant differences were found between the three temperatures.

Table 2: Mini block samples exposed 11 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Left columns: mean mass loss and Tukey-Kramer comparison of means *between* treatments *within* each of the three climates (separating hardwoods and softwoods). All treatments not connected by the same letter are significantly different. Mass loss categories are indicated in the following categories based on CEN/TS 15083-1 (CEN 2005) but using mean mass loss (not median); >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5. Right column: Tukey-Kramer comparison of means *between* climates *within* each treatment.

	22°C/70% RH		**16°C/70% RH**		**11°C/70% RH**		**Climate**		
	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	22°C	16°C	11°C
Aspen	A	29.84	ABC	21.88	A	11.4	A	B	C
Birch	A	29.03	A	24.57	AB	7.80	A	B	C
Lime	AB	27.32	BC	19.97	C	5.58	A	B	C
Alder	AB	26.49	BC	19.89	AB	8.71	A	B	C
Rowan	ABC	25.14	AB	22.48	BC	7.67	A	A	B
Maple	BCD	22.60	CD	17.68	BC	6.03	A	B	C
Ash	BCD	21.74	DE	14.77	C	5.11	A	B	C
Beech	CDE	20.15	E	11.66	D	1.58	A	B	C
Goat willow	DE	19.01	E	12.69	C	4.96	A	B	C
Oak	E	15.08	F	6.91	D	1.01	A	B	C
Wych elm	F	7.76	FG	4.41	D	0.25	A	AB	B
Merbau	G	0.80	G	0.63	D	0.49	A	A	A
Teak	G	0.31	G	0.46	D	0.22	AB	A	B
S. pine sap.	A	38.47	A	34.61	A	20.69	A	B	C
N. spruce	AB	33.21	A	35.26	AB	19.33	A	A	B
Sitka spruce	BC	31.17	B	30.23	BC	16.64	A	A	B
Silver fir	B	29.09	B	27.66	D	13.26	A	A	B
S. pine heart	BC	27.82	B	27.60	CD	13.96	A	A	B
S. larch	C	24.76	C	19.97	E	8.45	A	B	C
Douglas fir	D	17.08	D	12.12	E	6.34	A	A	B
Juniper	E	10.58	F	4.06	F	0.64	A	B	C
E. larch	E	10.54	E	8.15	F	3.44	A	B	C
WRC (N-Am)	F	1.05	F	1.22	F	1.03	A	A	A
WRC (N)	F	0.81	F	0.64	F	0.62	A	A	A

Durability class using CEN/TS 15083-1 (CEN 2005): In Table 3 durability class is allocated according to CEN/TS 15083-1 (CEN 2005) based on median values from mass losses. With increasing temperature the wood species tend to move to higher durability classes (less durable). As expected, the pattern is very similar to the pattern given in Table 2 based on mean mass loss.

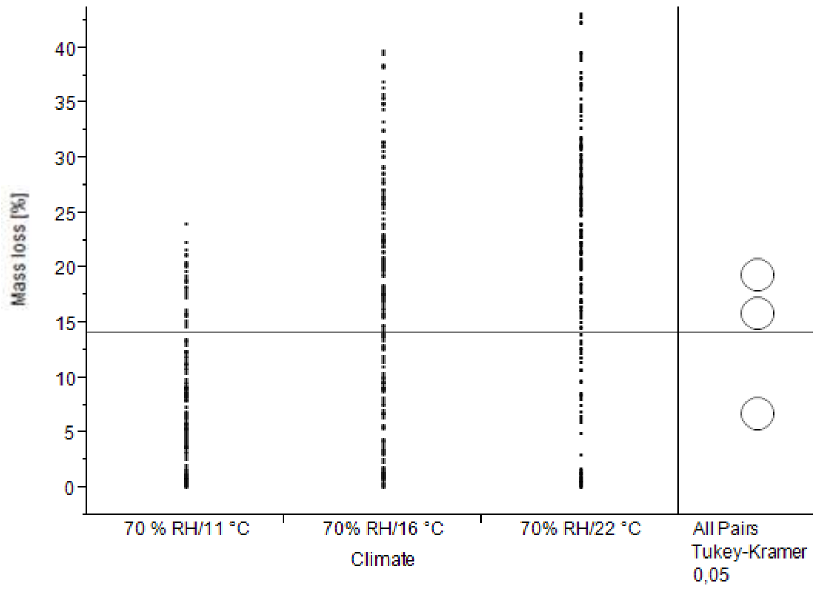


Figure 1: Mini-block samples exposed 11 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Mass losses of all samples are compared between the three climates. Statistical comparison of means using Tukey-Kramer.

Table 3: Mini block samples exposed 11 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Median mass losses (ML med.) given in percent are given together with the durability class (DC) according to CEN/TS 15083-1 (CEN 2005). Mass loss categories: >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5.

	22°C/70% RH		**16°C/70% RH**		**11°C/70% RH**	
	ML med. [%]	DC	ML med. [%]	DC	ML med. [%]	DC
Aspen	29.77	4	21.79	4	11.37	3
Birch	29.42	4	23.81	4	7.90	2
Lime	27.52	4	20.12	4	5.65	2
Alder	26.33	4	19.87	4	8.57	2
Rowan	26.50	4	22.64	4	7.15	2
Maple	23.13	4	18.77	4	5.73	2
Ash	21.93	4	14.65	3	4.95	1
Beech	20.76	4	11.99	3	1.08	1
Goat willow	19.61	4	12.18	3	4.44	1
Oak	15.40	4	6.75	2	0.89	1
Wych elm	5.42	2	3.35	1	0.29	1
Merbau	0.76	1	0.59	1	0.39	1
Teak	0.36	1	0.42	1	0.27	1
S. pine sap.	38.46	5	35.05	5	20.44	4
N. spruce	31.13	5	35.59	5	19.47	4
Sitka spruce	30.89	5	30.25	5	16.68	4
Silver fir	29.01	4	26.79	4	11.66	3
S. pine heart.	28.11	4	26.75	4	13.63	3
S. larch	24.24	4	20.01	4	8.82	2
Douglas fir	16.76	4	14.98	3	6.46	2
Juniper	10.19	3	3.46	1	0.53	1
E. larch	10.97	3	8.37	2	3.36	1
WRC (N-Am)	1.11	1	1.21	1	1.06	1
WRC (N)	0.79	1	0.75	1	0.67	1

Durability classes using CEN/TS 15083-2 (2005): Table 4 displays x values according to 15083-2 in order to allocate the wood materials to durability classes (x value = median mass loss of wood test species/median mass loss of reference test specimens). The x values using beech as reference species generally gave higher durability classes (less durable) than Scots pine as reference species. This classification approach appears to be fairly similar to the CEN/TS 15083-1 (2005) method in Table 3 for Scots pine at 22°C and 16°C, but deviated a little for Scots pine sapwood at 11°C and for beech as the reference species. It is obviously stretching the method a bit to use beech as a reference species for softwoods and Scots pine as a reference species for hardwoods species.

Table 4: Mini block samples exposed 11 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. The x value and durability class (in shades of grey) are given both Scots pine sapwood and European beech as reference species x values and durability class according to CEN/TS 15083-2 (CEN 2005) are given.

	22°C/70% RH				**16°C/70% RH**				**11°C/70% RH**			
	Scots pine sap		Beech		Scots pine sap		Beech		Scots pine sap		Beech	
	x	DC	x	DC	x	DC	x	DC	x	DC	x	DC
Aspen	0.77	4	1.43	5	0.62	4	1.82	5	0.56	4	10.53	5
Birch	0.76	4	1.42	5	0.68	4	1.99	5	0.39	3	7.31	5
Lime	0.72	4	1.33	5	0.57	4	1.68	5	0.28	3	5.23	5
Alder	0.68	4	1.27	5	0.57	4	1.66	5	0.42	3	7.94	5
Rowan	0.66	4	1.23	5	0.65	4	1.89	5	0.35	3	6.62	5
Maple	0.60	4	1.11	5	0.54	4	1.57	5	0.28	3	5.31	5
Ash	0.57	4	1.06	5	0.42	3	1.22	5	0.24	3	4.58	5
Beech	0.54	4	1.00	5	0.34	3	1.00	5	0.05	1	1.00	5
Goat willow	0.51	4	0.94	5	0.35	3	1.02	5	0.22	3	4.11	5
Oak	0.44	3	0.74	4	0.19	2	0.56	4	0.04	1	1.43	5
Wych elm	0.14	2	0.26	3	0.10	1	0.28	3	0.01	1	0.26	3
Merbau	0.02	1	0.04	1	0.02	1	0.05	1	0.02	1	0.36	3
Teak	0.01	1	0.02	1	0.01	1	0.03	1	0.01	1	0.25	3
S. pine sap.	1.00	5	1,85	5	1.00	5	2.92	5	1.00	5	18.93	5
N. spruce	0.81	5	1.50	5	1.02	5	2.97	5	0.95	5	18.03	5
Sitka spruce	0.80	4	1.49	5	0.86	5	2.52	5	0.82	5	15.45	5
Silver fir	0.75	4	1.40	5	0.76	4	2.23	5	0.57	4	10.80	5
S. pine heart.	0.73	4	1.35	5	0.76	4	2.23	5	0.67	4	12.62	5
S. larch	0.63	4	1.17	5	0.57	4	1.67	5	0.43	3	8.17	5
Douglas fir	0.44	3	0.81	5	0.43	3	1.25	5	0.32	3	5.98	5
Juniper	0.26	3	0.49	4	0.10	1	0.29	3	0.03	1	0.05	1
E. larch	0.29	3	0.53	4	0.24	3	0.70	4	0.16	2	3.11	5
WRC (N-Am)	0.03	1	0.05	1	0.03	1	0.10	1	0.05	1	0.98	5
WRC (N)	0.02	1	0.04	1	0.02	1	0.06	1	0.03	1	0.62	4

3.1.2 Mini block – 20 weeks

Treatments: Table 5 (first three columns) show the mean mass losses and the comparison of means between each material within each climate. Among the wood modifications acetylated wood performed best in all climates, thermally modified wood, furfurylated wood and DMDHEU performed at a similar level except for 22°C where DMDHEU had a significantly lower mean mass loss than thermal modification. Oak was the most durable wood species among investigated materials, the least durable wood species were aspen, alder, beech, Scots pine sapwood and Douglas fir. As expected CCA had a significantly better performance than the copper HDO and the copper naphtenate preservatives. However, one have to keep in mind that *P. placenta* is a copper tolerant fungus and this is believed to explain the rather poor performance of the copper and the copper naphtenate containing preservatives, as copper naphtenate does not contain secondary fungicides, as CCA. Also, the retention of the copper naphtenate samples treated at NIBIO was lower than the above ground retention given in the AWPA standard U1-11 (2011).

Climate: When pooling all samples and comparing mass loss means between the three temperatures (Figure 2) significant differences were found between the three climates. For the untreated materials there were significant differences between the climates (see right column in Table 5). The exception was Scots pine sapwood where no significant difference was found between 22°C and 16°C. For the preservative treated and modified wood materials only thermally modified wood showed significant differences between all three temperatures.

Table 5: Mini block samples exposed 20 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Left columns: mean mass loss and Tukey-Kramer comparison of means *between* materials *within* each of the three climates. All treatments not connected by the same letter are significantly different. Mass loss categories are indicated in the following categories based on CEN/TS 15083-1 (2005) but using mean mass loss (not median); >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5. Right column: Tukey-Kramer comparison of means *between* climates *within* each treatment.

	22°C/70% RH		**16°C/70% RH**		**11°C/70% RH**		**Climate**		
	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	22°C	16°C	11°C
Aspen	A	70.37	B	52.53	BC	36.00	A	B	C
Beech	A	66.75	AB	57.86	BC	35.80	A	B	C
S. pine sap	AB	65.47	A	64.95	A	53.44	A	A	B
Alder	AB	65.07	AB	58.56	B	38.43	A	B	C
Copper	ABC	63.34	AB	53.63	CD	26.34	A	A	B
Douglas	ABC	61.53	AB	54.00	BC	30.14	A	B	C
Cu naphtenate	BCD	53.80	C	35.16	EFG	11.55	A	B	C
E. larch	CD	51.93	C	32.75	DE	19.58	A	B	C
Thermal	DE	41.75	C	32.67	EF	13.66	A	B	C
Furfurylation	EF	32.36	C	31.70	DE	18.43	A	A	B
DMDHEU	F	28.96	CD	23.12	EFGH	9.59	A	AB	B
Oak	F	23.38	D	14.41	FGH	4.87	A	B	C
Acetylation	G	1.36	E	0.00	H	0.00	A	B	B
CCA	G	0.00	E	0.00	GH	1.26	B	B	A

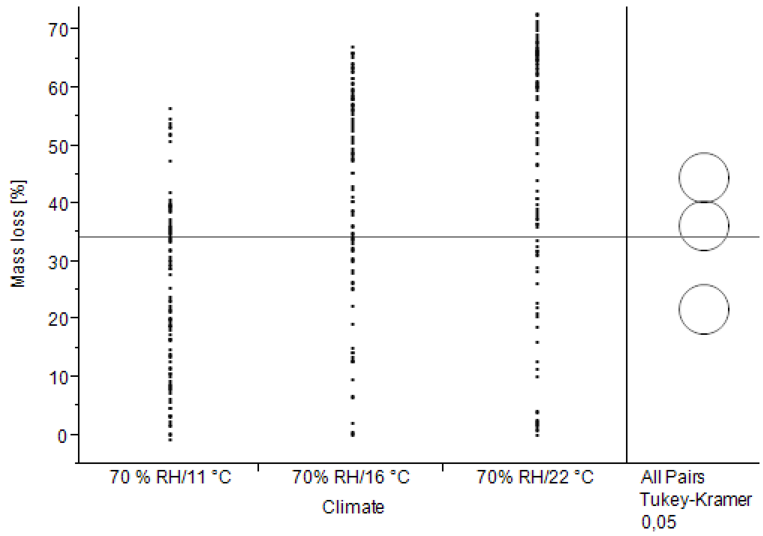


Figure 2: Mini block samples exposed 20 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Mass losses of all samples are compared between the three climates. Statistical comparison of means using Tukey-Kramer.

Durability class using CEN/TS 15083-1 (CEN 2005): In Table 6 durability classes are allocated according to CEN/TS 15083-1 (CEN 2005) based on median values from mass loss. For 22°C and 16°C the durability classes were similar except that oak was durability class 4 at 22°C and durability class 3 at 16°C. Not unexpectedly, lower temperature gave lower median mass loss and higher durability classes. The pattern is, for obvious reasons, very similar to the pattern given in Table 2 based on mean mass loss. When comparing this test with the 11 weeks mini block test above it is evident that the prolonged exposure changes the classification. Both tests also indicate that the temperature seems to influence the decay rate of some materials more than others.

Table 6: Mini block samples exposed 20 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. Median mass losses (ML med.) given in percent are given together with the durability class (DC) according to CEN/TS 15083-1. >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5.

	22°C/70% RH ML med. [%]	DC	16°C/70% RH ML med. [%]	DC	11°C/70% RH ML med. [%]	DC
Aspen	70.54	5	52.30	5	34.96	5
Beech	66.65	5	57.53	5	35.80	5
Scots pine sap.	65.67	5	65.37	5	53.18	5
Alder	65.24	5	58.48	5	38.98	5
Copper	65.58	5	57.01	5	27.37	4
Douglas fir	62.07	5	54.52	5	29.69	4
Cu naphthate	60.25	5	36.95	5	13.57	3
E. larch	51.64	5	32.47	5	19.61	4
Thermal	40.27	5	31.96	5	13.49	3
Furfurylation	31.45	5	31.28	5	22.54	4
DMDHEU	29.35	4	18.59	4	4.56	1
Oak	20.66	4	13.79	3	3.37	1
Acetylation	1.15	1	0.00	1	0.00	1
CCA	0.00	1	0.00	1	0.14	1

Durability class using CEN/TS 15083-2 (CEN 2005): Table 7 are using x values according to CEN/TS 15083-2 in order to allocate the wood materials to durability classes (x value = median mass loss for timber test species/median value of mass loss for reference test specimens). For 22°C and for 16°C the results from Scots pine *vs.* beech are nearly similar. For the lower mass losses at 11°C the difference in x values between the two reference species are larger. This method appears to differentiate more than the CEN/TS 15083-1 (CEN 2005) approach in Table 5 and 6.

Table 7: Mini block samples exposed 20 weeks to *P. placenta* at three climates: 22°C/70% RH, 16°C/70% RH and 11°C/70% RH. For the two reference species Scots pine sapwood and European beech x values and durability class (in shades of grey) according to CEN/TS 15083-2 (CEN 2005) are given.

	22°C/70% RH				**16°C/70% RH**				**11°C/70% RH**			
	Scots pine sap		Beech		Scots pine sap		Beech		Scots pine sap		Beech	
	x	DC	x	DC	x	DC	x	DC	x	DC	x	DC
Aspen	1.07	5	1.06	5	0.80	4	0.91	5	0.66	4	0.98	5
Beech	1.01	5	1.00	5	0.88	5	1.00	5	0.67	4	1.00	5
S. pine sap.	1.00	5	0.99	5	1.00	5	1.14	5	1,00	5	1.49	5
Alder	0.99	5	0.98	5	0.89	5	1.02	5	0.73	4	1.09	5
Copper	0.97	5	0.95	5	0.87	5	0.99	5	0.51	4	0.76	4
Douglas fir	0.95	5	0.93	5	0.83	5	0.95	5	0.56	4	0.83	5
Cu napht.	0.92	5	0.90	5	0.57	4	0.64	4	0.26	3	0.38	3
E. larch	0.79	4	0.77	4	0.50	4	0.56	4	0.37	3	0.55	4
Thermal	0.61	4	0.60	4	0.49	4	0.56	4	0.25	3	0.38	3
Furfurylation	0.48	4	0.47	4	0.49	4	0.54	4	0.42	3	0.63	4
DMDHEU	0.45	3	0.44	3	0.28	3	0.32	3	0.09	1	0.13	2
Oak	0.31	3	0.31	3	0.21	3	0.24	3	0.10	1	0.15	2
Acetylation	0.02	1	0.02	1	0.00	1	0.00	1	0.00	1	0.00	1
CCA	0.00	1	0.00	1	0.00	1	0.00	1	0.00	1	0.00	1

3.1.3 EN 113 (CEN 1996)

Table 8 presents the mean mass losses and the comparison of means between the different wood species for three different decay fungi. The most consistent classification was found for the most durable materials and for Scots pine sapwood. The differences in durability class ranking between the three fungi highlight the importance of including several species when durability is evaluated in laboratory experiments. When comparing with the 20°C/70% RH data in Table 2 the mean mass loss of Scots pine sapwood after *P. placenta* decay was similar (35.5 and 34.6%), but mass loss in general was lower in the EN 113 and resulted in slightly lower (more durable) durability classes compared to the mini block test after 11 weeks.

Table 8: EN 113 samples exposed 16 weeks to *Coniophora puteana* (*C.p.*), *Postia placenta* (*P.p.*) or *Trametes versicolor* (*T.v.*) at 20°C/70% RH. Left columns: Mass loss categories are indicated in the following categories based on CEN/TS 15083-1 (CEN 2005), but using mean mass loss (not median); >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5. Tukey-Kramer comparison of means for each decay fungus, separating hardwoods and soft woods. All treatments not connected by the same letter are significantly different. Right column: Tukey-Kramer comparison of mass loss means *between* fungi *within* each material.

	C. puteana		***P. placenta***		***T. versicolor***		**Mass loss**		
	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	*C.p.*	*P.p.*	*T.v.*
Birch	A	50.4	-	-	AB	39.3	B		A
Lime	AB	46.2	-	-	AB	34.9	A		B
Aspen	AB	42.4	-	-	AB	36.9	A		A
Alder	AB	40.6	-	-	AB	34.9	A		A
Maple	AB	403	-	-	AB	33.0	A		A
Rowan	AB	36.8	-	-	A	41.4	A		A
Beech	AB	32.1	-	-	B	30.1	A		A
Goat willow	B	26.4	-	-	B	31.4	A		A
Wych elm	C	2.5	-	-	AB	32.6	B		A
Ash	C	2.1	-	-	AB	32.5	B		A
Merbau	C	0.9	-	-	C	2.8	A		A
Oak	C	0.0	-	-	C	2.5	A		A
Teak	C	0.0	-	-	C	0.0	A		A
S. pine sap.	A	41.8	A	35.5	AB	33.6	A	B	B
N. spruce*	B	27.0	B	24.5	A	35.9	B	B	A
Sitka spruce	C	16.0	B	26.4	AB	31.6	B	A	A
Silver fir	BCD	15.7	BC	18.4	AB	29.9	A	A	A
S. larch	DE	3.4	B	24.7	BC	23.6	B	A	A
E. larch	DE	3.2	C	10.5	E	3.7	A	A	A
Juniper	DE	0.4	D	0.4	E	2.8	B	B	A
Douglas fir	E	0.0	CD	9.7	DE	6.0	B	A	AB
WRC (N)	E	0.0	D	0.0	DE	8.7	B	B	A
WRC (N-Am))	E	0.0	D	0.0	E	0.8	A	A	A

*The data for Norway spruce is pooled data from samples with 1 mm and 3 mm annual year rings

Table 9 shows median mass loss and durability classes according to CEN/TS 15083-1 (CEN 2005). Again, this approach gives very similar results as the mean mass loss approach in Table 8, i.e. a rather large difference in durability classification between the three test fungi, especially for the moderately durable species.

Table 9: EN 113 samples exposed 16 weeks to *Coniophora puteana*, *Postia placenta or Trametes versicolor* at 20°C/70%. Median mass losses (ML med.) given in percent are given together with the durability class (DC) according to CEN/TS 15083-1 (CEN 2005). Mass loss categories: >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5.

	C. puteana		***P. placenta***		***T. versicolor***	
	ML med. [%]	DC	ML med. [%]	DC	ML med. [%]	DC
Birch	51.79	5			39.11	5
Lime	44.12	5			34.93	5
Aspen	40.30	5			33.67	5
Alder	43.13	5			35.18	5
Maple	40.74	5			32.38	5
Rowan	40.58	5			37.57	5
Beech	33.79	5			29.75	4
Goat willow	26.44	4			29.19	4
Wych elm	0	1			32.69	5
Ash	1.51	1			33.91	5
Merbau	0.49	1			3.00	1
Oak	0	1			0.19	1
Teak	0	1			0	1
S. pine sap.	41.19	5	35.53	5	31.80	5
Norway spruce	29.52	4	23.69	4	36.45	5
Sitka spruce	14.72	3	25.52	4	29.65	4
Silver fir	15.65	4	16.69	4	26.36	4
S. larch	3.18	1	22.88	4	23.74	4
E. larch	1.94	1	8.56	3	1.99	1
Juniper	0.36	1	0.25	1	3.58	1
Douglas fir	0	1	9,79	2	3.21	1
WRC (N)	0	1	0	1	0.17	1
WRC (N-Am)	0	1	0	1	0	1

Durability classification according to CEN/TS 15083-2 (CEN 2005) is given in Table 10. This approach gave fairly similar results compared to the approaches above. Again, there is a rather large variation in the classification between the three fungi.

Table 10: EN 113 samples exposed 16 weeks to *Coniophora puteana, Postia placenta or Trametes versicolor* at 20°C/70% RH. The x value and durability class (in shades of grey) are given for both Scots pine sapwood and European beech as reference species x values and durability class according to CEN/TS 15083-2 (CEN 2005) are given.

	C. puteana				***P. placenta***		***T. versicolor***			
	Scots pine sap.		Beech		Scots pine sap.		Scots pine sap.		Beech	
	x	DC	x	DC	x	DC	x	DC	x	DC
Beech	0.82	5	1.00	5			0.94	5	1.00	5
Birch	1.26	5	1.53	5			1.23	5	1.31	5
Lime	1.07	5	1.31	5			1.10	5	1.17	5
Aspen	0.98	5	1.19	5			1.06	5	1.13	5
Alder	1.05	5	1.28	5			1.11	5	1.18	5
Maple	0.99	5	1.21	5			1.02	5	1.09	5
Rowan	0.99	5	1.20	5			1.18	5	1.26	5
Goat willow	0.64	4	0.78	4			0.92	5	0.98	5
Wych elm	0	1	0	1			1.03	5	1.10	5
Ash	0.04	1	0.04	1			1.07	5	1.14	5
Merbau	0.01	1	0.01	1			0.09	1	0.10	1
Oak	0	1	0	1			0.01	1	0.01	1
Teak	0	1	0	1			0	1	0	1
S. pine sap.	1.00	5	1.22	5	1.00	5	1.00	5	1.07	5
N. spruce	0.72	4	0.87	5	0.67	4	1.15	5	1.23	5
Sitka spruce	0.36	3	0.44	3	0.72	4	0.93	5	1.00	5
Silver fir	0.38	3	0.46	4	0.47	4	0.83	5	0.89	5
S. larch	0.08	1	0.09	1	0.64	4	0.75	4	0.80	4
E. larch	0.05	1	0.06	1	0.24	3	0.06	1	0.07	1
Juniper	0.01	1	0.01	1	0.01	1	0.11	2	0.12	2
Douglas fir	0	1	0	1	0.28	3	0.10	1	0.11	2
WRC (N)	0	1	0	1	0	1	0.17	2	0.18	2
WRC (N-Am)	0	1	0	1	0	1	0	1	0	1

3.1.4 ENV 807 (CEN 2001)

Treatment: Table 11 (first three columns) shows the mean mass losses and the comparison of means between each wood species within each climate. The least durable species were aspen, alder and beech. The most durable materials were, as expected, the treated samples. All wood modifications had less than 3% mass loss in all climates.

Climate: When pooling all samples and comparing mass loss means between the three temperatures (Figure 3) significant differences were found between the three climates. The materials with significant difference between all three climates were: alder, Scots pine sapwood and European larch (see right column in Table 11). None of the preservative treated and modified materials showed a significant difference between climates.

Table 11: ENV 807 samples exposed 13 weeks 25°C/80% RH, 25°C/60% RH and 10°C/85% RH. Left columns: mass loss and Tukey-Kramer comparison of means *between* treatments *within* each of the three climates. All treatments not connected by the same letter are significantly different. Mass loss categories: >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5. Right column: Tukey-Kramer comparison of means *between* climates *within* each treatment.

	25°C/80% RH		**25°C/60% RH**		**10°C/85% RH**		**Climate**		
	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	Tukey-Kramer	ML [%]	**25/85**	**25/65**	**10/85**
Aspen	A	45.85	A	38.78	A	16.38	A	A	B
Alder	B	35.29	B	30.76	B	14.30	A	B	C
Beech	B	32.30	B	29.78	C	12.88	A	A	B
S. pine sap.	C	12.01	C	9.20	FG	2.66	A	B	C
E. oak	CD	9.10	B	9.44	D	4.93	A	A	B
E. larch	CDE	8.10	CD	6.21	EF	3.19	A	B	C
Douglas fir	DF	3.52	DE	3.67	FGH	2.33	A	A	B
CCA	DF	3.13	DE	1.16	GHI	1.44	A	B	B
Cu napht.	DEF	4.95	CDE	4.80	DE	4.51	A	A	A
Copper	DEF	4.57	DE	1.74	HIJ	1.27	A	B	B
Furfurylation	F	2.55	DE	2.61	FGH	1.84	A	A	B
DMDHEU	F	1.09	E	1.02	GHI	1.42	A	A	A
Thermal	F	0.05	E	0.00	IJ	0.40	B	B	A
Acetylation	F	0.00	E	0.04	J	0.02	A	A	A

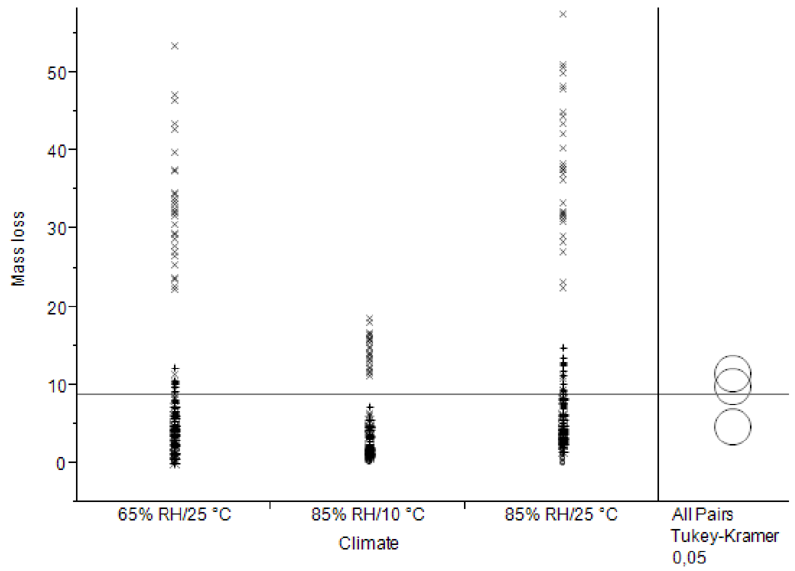


Figure 3: ENV 807 samples exposed 13 weeks 25°C/80% RH, 25°C/60% RH and 10°C/85% RH. Mass losses of all samples are compared between the three climates. Statistical comparison of means using Tukey-Kramer.

Table 12 shows median mass losses and durability classes according to CEN/TS 15083-1 (2005). Again, this approach gives very similar results as the mean mass loss approach in Table 11.

Table 12: ENV 807 samples exposed for 13 weeks at 25°C/80% RH, 25°C/60% RH and 10°C/85% RH. Median mass losses (ML med.) given in percent are given together with the durability class (DC) according to CEN/TS 15083-1 (CEN 2005). Mass loss categories: >30%, >15% to ≤30%, >10% to ≤15%, <5 to ≤10%, ≤5.

	25°C/80% RH		**25°C/60% RH**		**10°C/85% RH**	
	ML med. [%]	DC	ML med. [%]	DC	ML med. [%]	DC
Aspen	48.18	5	40.12	5	16.54	4
Alder	34.31	5	32.47	5	14.04	3
Beech	31.64	5	30.02	5	12.81	3
S. pine sap.	12.65	3	9.45	2	2.18	1
Oak	9.36	2	9.38	2	4.78	1
E. larch	7.95	2	6.04	2	3.16	1
Douglas fir	3.53	1	4.11	1	2.29	1
CCA	2.85	1	0.83	1	1.42	1
Cu naphtenate	4.55	1	4.80	1	4.61	1
Copper	4.32	1	0.61	1	1.30	1
Furfurylation	2.38	1	2.58	1	1.85	1
DMDHEU	1.25	1	1.02	1	1.19	1
Thermal	0	1	0	1	0.31	1
Acetylation	0	1	0	1	0	1

Durability classifications according to CEN/TS 15083-2 (2005) are given in Table 13. This approach gave slightly more differentiation in durability categories compared to the other two approaches above.

Table 13: ENV 807 samples exposed for 13 weeks at 25°C/80% RH, 25°C/60% RH and 10°C/85% RH. The x value and durability class (in shades of grey) are given for both Scots pine sapwood and European beech as reference species x values and durability class according to CEN/TS 15083-2 (CEN 2005).

	25°C/80% RH				**25°C/60% RH**				**10°C/85% RH**			
	Scots pine sap.		Beech		Scots pine sap.		Beech		Scots pine sap.		Beech	
	x	DC	x	DC	x	DC	x	DC	x	DC	x	DC
Aspen	3.79	5	1.52	5	4.22	5	1.34	5	7.52	5	1.29	5
Alder	2.70	5	1.09	5	3.42	5	1.08	5	6.38	5	1.10	5
S. pine sap	1.00	5	0.40	3	1.00	5	0.32	3	1.00	5	0,17	2
Beech	2.49	5	1.00	5	3.60	5	1.00	5	5.82	5	1.00	5
Oak	0.74	4	0.30	3	0.99	5	0.31	3	2.17	5	0.37	3
E. larch	0.63	4	0.25	3	0.64	4	0.20	2	1.44	5	0.25	3
Douglas fir	0.28	3	0.11	2	0.43	3	0.14	2	1.04	5	0.18	2
CCA	0.22	3	0.09	1	0.09	1	0.03	1	0.65	4	0.11	2
Cu naphtenate	0.36	3	0.14	2	0.05	1	0.16	2	2.10	5	0.36	3
Copper	0.34	3	0.14	2	0.06	1	0.02	1	0.59	4	0.10	1
Furfurylation	0.19	2	0.08	1	0.27	3	0.09	1	0.84	5	0.14	2
DMDHEU	0.10	1	0.04	1	0.11	2	0.03	1	0.54	4	0.09	1
Thermal	0	1	0	1	0	1	0	1	0.14	2	0.02	1
Acetylation	0	1	0	1	0	1	0	1	0	1	0	1

3.2 Field tests

3.2.1 Soil contact tests according to EN 252 (CEN 1989)

In Figures 4 - 7 the mean decay rating in EN 252 (CEN 1989) tests are given. Materials that failed within the 12 year evaluation period include: birch, alder, beech, lime, maple, rowan, aspen, goat willow, ash, Sitka spruce, Scots pine sapwood, silver fir, western red cedar (Norway), Norway spruce and thermally modified wood. Materials with a mean rating lower than 2 were: merbau, teak, Douglas fir, European larch, CCA and copper HDO.

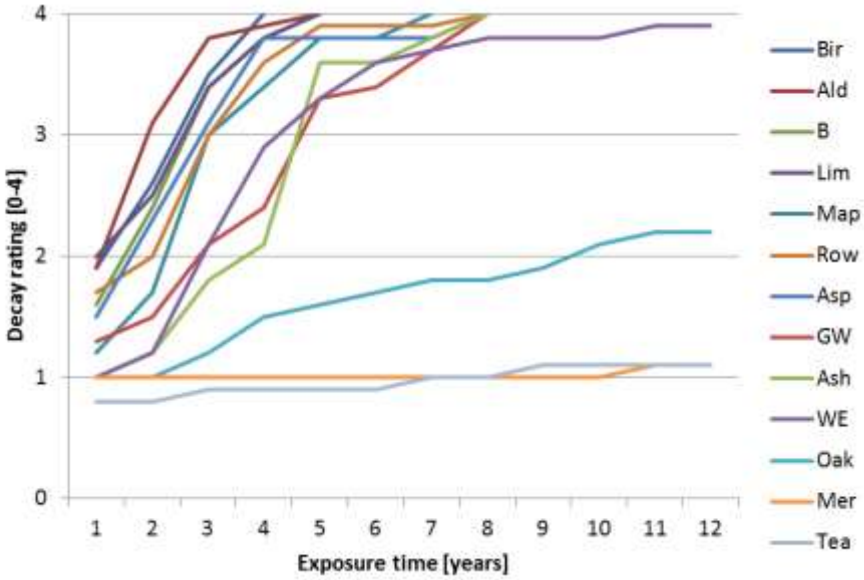


Figure 4. Mean decay rating of hardwood species in EN 252 (CEN 1989) in years – Sørkedalen test site. The material legends are listed starting with the least durable, ending with the most durable material.

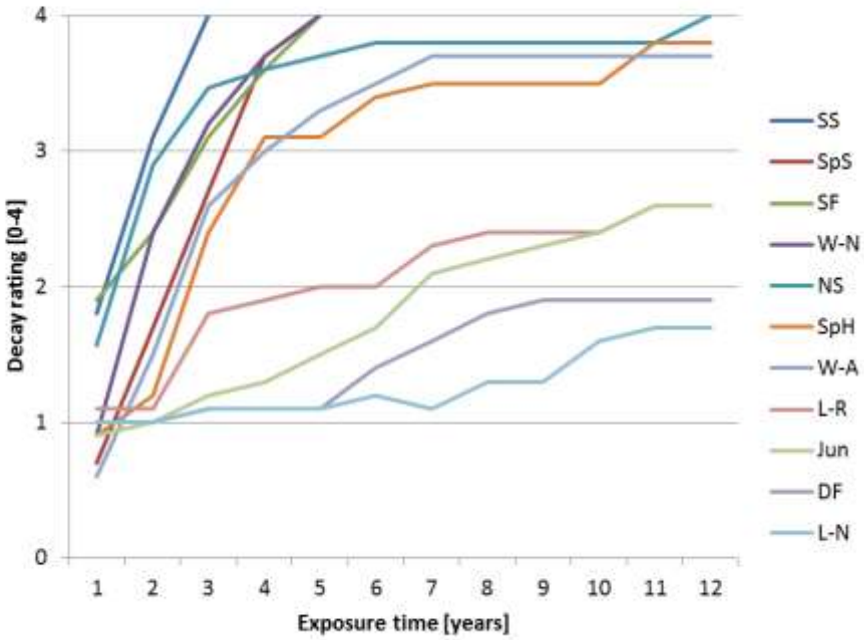


Figure 5. Mean decay rating of softwood species in EN 252 (CEN 1989) in years – Sørkedalen test site. The material legends are listed starting with the least durable, ending with the most durable material.

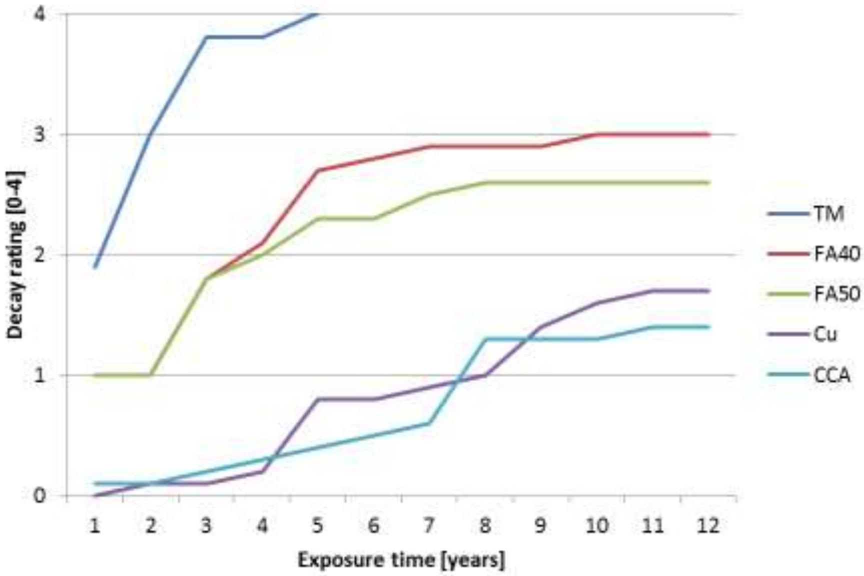


Figure 6. Mean decay rating of treated wood in EN 252 (CEN 1989) in years – Sørkedalen test site. The material legends are listed starting with the least durable, ending with the most durable material.

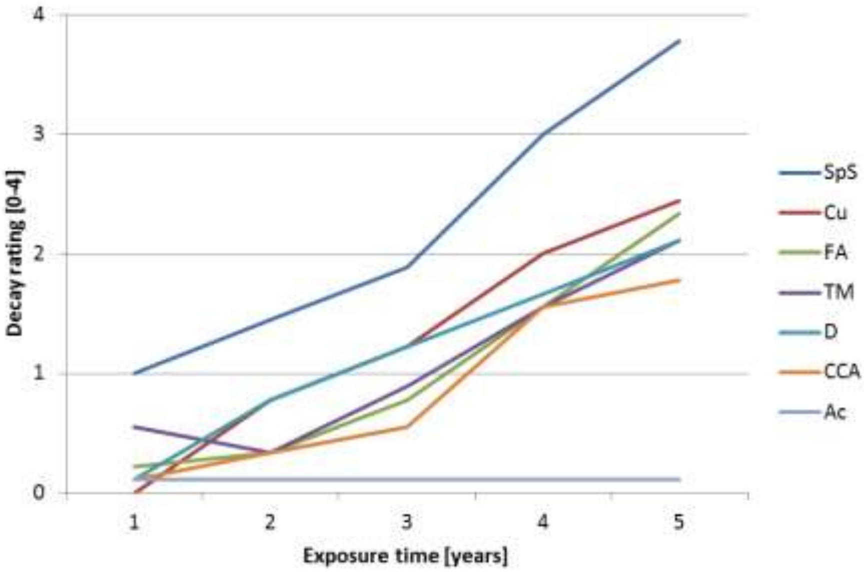


Figure 7. Mean decay rating of treated wood in EN 252 (CEN 1989) in years – Ås test site. The material legends are listed starting with the least durable, ending with the most durable material.

3.2.2 Horizontal double layer tests

Figures 8-10 illustrates the performance of the wood materials in the horizontal double layer test in Bergen. Materials that failed within the 11 years evaluation period include: maple, alder, beech, birch, Scots pine sapwood, Sitka spruce, silver fir and Norway spruce. The materials with mean decay ratings lower than 2 include: teak, juniper, merbau, copper and CCA.

It is interesting to note the time lag before the initiation of decay. For hardwood species the initial decay (soft rot) started after two years (except for wych elm, ash and oak year 3 and teak at year 7). For softwoods and treated wood initial signs of decay can be seen after four years (with the exception of merbau year 7). Stirling *et al*. (2016) found a similar trend for Norway spruce, Scots pine sapwood and beech (i.e. delayed decay initiation) as did other European tests (data from IRG-WP Durability Database).

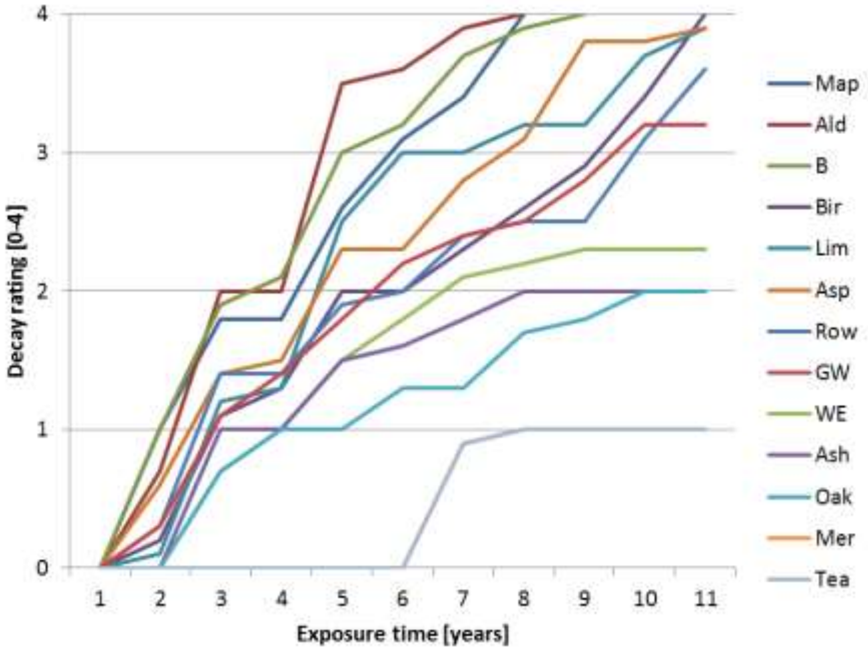


Figure 8: Mean decay rating of hardwood species in horizontal double layer exposure in years – Bergen test site. The material legends are listed starting with the least durable, ending with the most durable material. NB! merbau and teak have overlapping data.

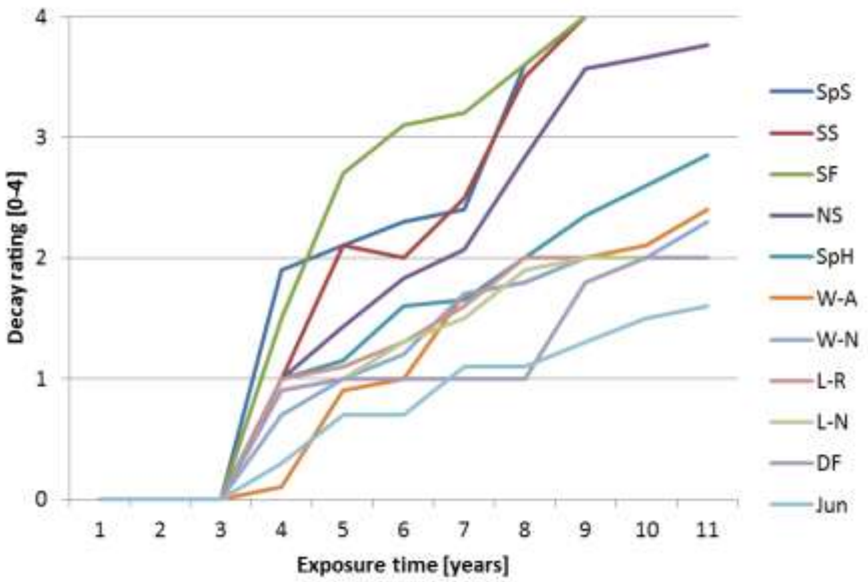


Figure 9: Mean decay rating of softwood species in horizontal double layer exposure in years – Bergen test site. The material legends are listed starting with the least durable, ending with the most durable material.

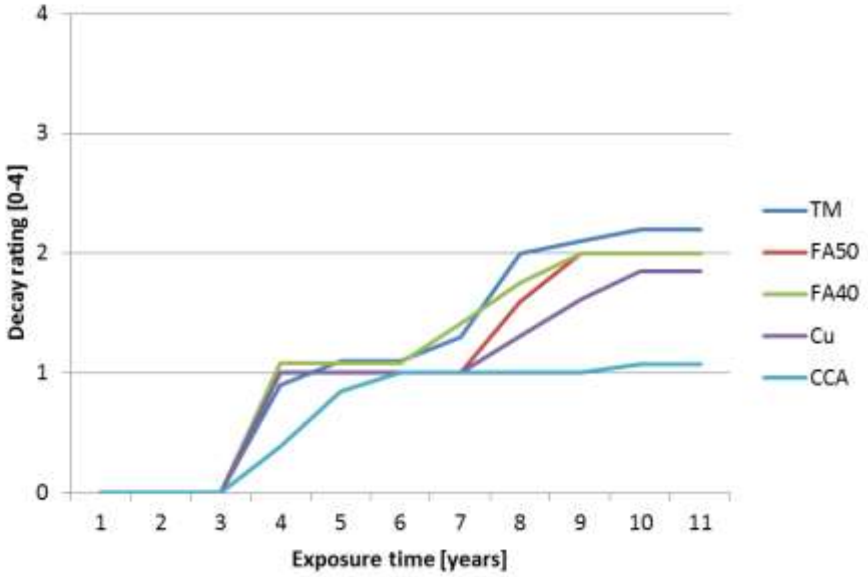


Figure 10: Mean decay rating of treated wood in horizontal double layer exposure in years - Bergen test site. The material legends are listed starting with the least durable, ending with the most durable material.

Figures 11-14 illustrates the performance of the wood materials in the horizontal double layer test in Ås. Materials that failed within the 11 years evaluation period include: maple, alder, beech, birch, Scots pine sapwood, Sitka spruce, silver fir and Norway spruce. The materials with mean decay rating lower than 2 include: teak, juniper, merbau, copper HDO and CCA. As seen from the field test in Bergen (Figure 5) there was also a time lag in the initiation of decay as in Ås. However, here the time lag was on average even longer. This can probably be explained by the warmer and wetter climate in Bergen.

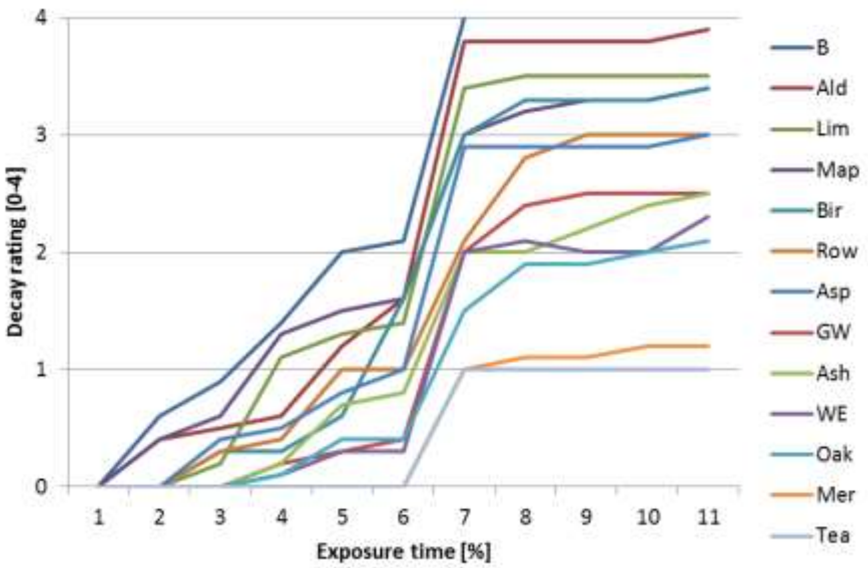


Figure 11: Mean decay rating of hardwoods in horizontal double layer exposure in years – Ås test site. The material legends are listed starting with the least durable, ending with the most durable material.

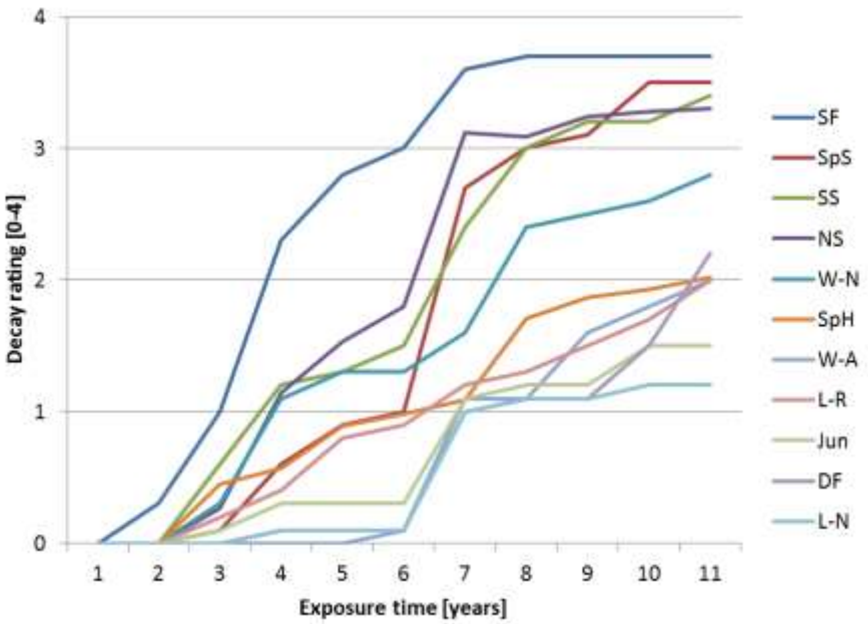


Figure 12: Mean decay rating of softwood species in horizontal double layer exposure in years – Ås test site. The material legends are listed starting with the least durable, ending with the most durable material.

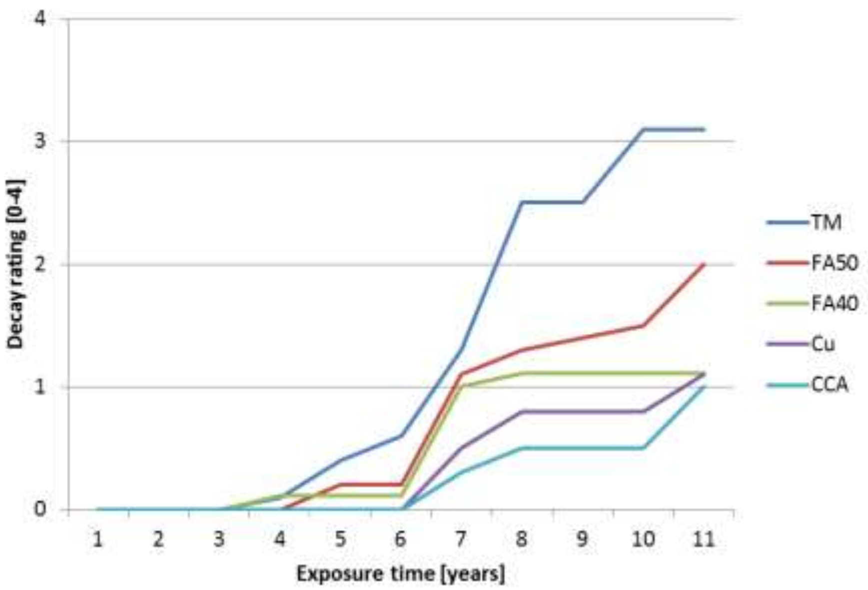


Figure 13: Mean decay rating of treated material in horizontal double layer exposure in years – Ås test site. The material legends are listed starting with the least durable, ending with the most durable material.

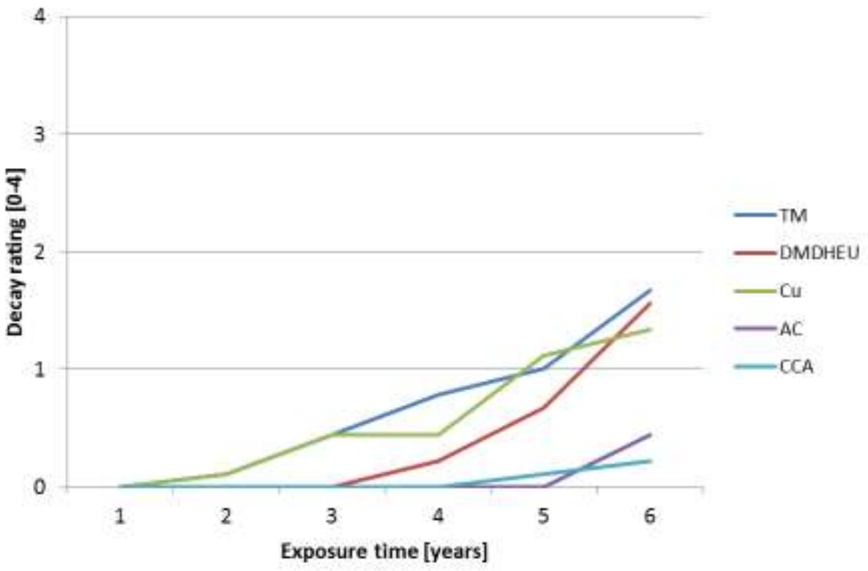


Figure 14: Mean decay rating of treated wood in horizontal double layer exposure in years – Ås test site. The material legends are listed starting with the least durable, ending with the most durable material.

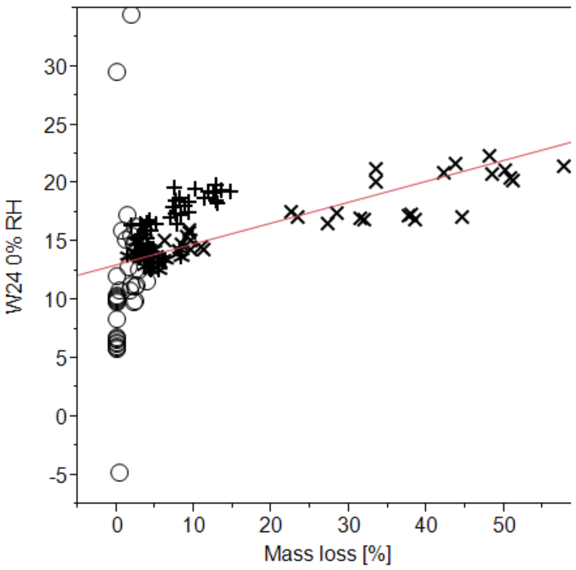
3.3 W 24 and capillary water uptake tests

Table 14 shows the data from the 24 hour tests and capillary water uptake. The two highest values for desorption were determined for aspen and Scots pine sapwood, the two lowest for acetylation and thermal modification. The two highest values for liquid water uptake by submersion were found for Scots pine sapwood and copper HDO, the two lowest for furfurylation and Douglas fir. For water vapour uptake in water saturated atmosphere the two highest values were found for CCA and copper HDO, the two lowest for acetylation and furfurylation. Capillary water uptake showed highest values for beech and alder, lowest values for furfurylation, thermal modification and DMDHEU.

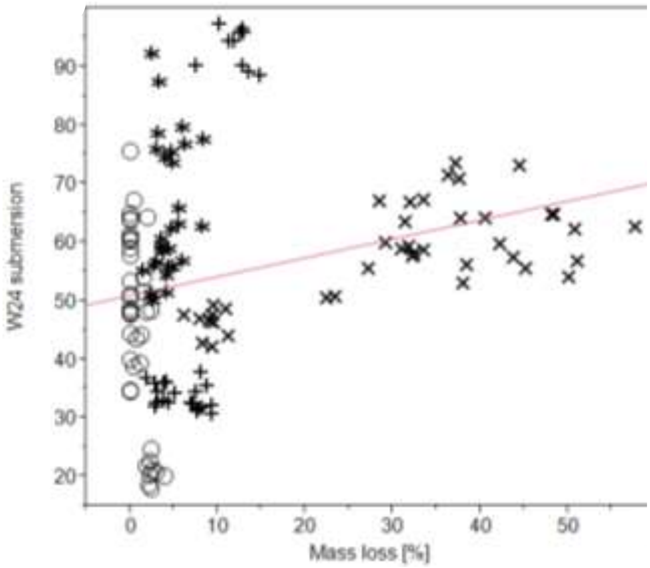
Table 14: W 24 tests (0% RH, submerged samples and 100% RH) and capillary water uptake.

	W 24 0% RH		W 24 submersion		W 24 100% RH		Capillary uptake	
	Mean [%]	SD [%]	Mean [%]	SD [%]	Mean [%]	SD [%]	Mean [%]	SD [%]
Aspen	21.1	±0.7	60.9	±4.2	15.7	±0.6	0.15	±0.04
Alder	19.5	±0.3	63.0	±6.6	14.4	±0.5	0.28	±0.03
Beech	14.6	±0.2	60.1	±7.9	15.5	±0.5	0.31	±0.04
Oak	13.0	±0.5	46.3	±2.4	12.4	±0.4	0.14	±0.02
S. pine sap.	17.2	±0.3	93.2	±3.4	17.2	±0.3	0.34	±0.03
E. larch	15.1	±0.5	33.0	±2.2	9.7	±0.4	0.13	±0.03
Douglas fir	13.9	±0.4	34.4	±1.7	11.3	±0.8	0.18	±0.02
Thermal	10.2	±0.3	60.6	±4.5	13.4	±0.6	0.11	±0.03
Furfurylation	12.3	±2.2	23.6	±8.9	7.6	±1.9	0.09	±0.01
Cu naphtenate	13.4	±0.7	60.0	±3.6	16.8	±1.3	0.20	±0.03
DMDHEU	15.9	±10.6	52.2	±12.2	15.9	±8.4	0.11	±0.03
Acetylation	6.5	±0.7	45.0	±6.5	6.5	±0.7	0.12	±0.02
Cu	13.7	±0.3	79.2	±6.0	24.1	±11.7	0.18	±0.02
CCA	14.6	±0.6	54.5	±3.4	23.3	±0.9	0.13	±0.02

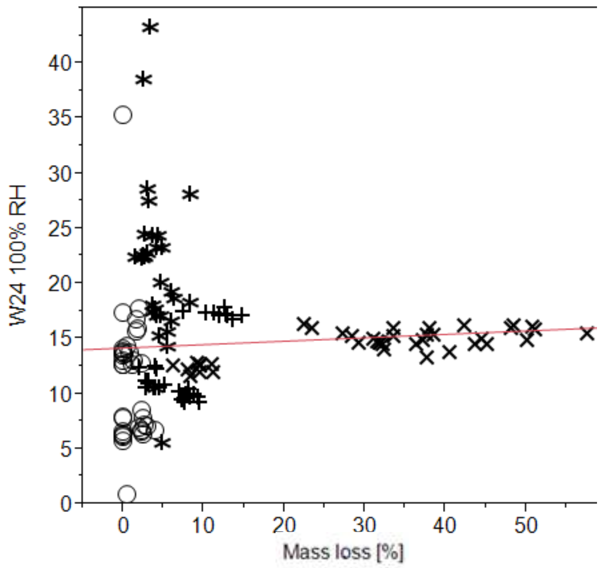
Figure 15 illustrates the mass loss vs. W 24 results and capillary water uptake for all tested materials. For all four tests the R^2 was low. The outliers with low mass loss and large variation in water release in W 24 desorption tests were the DMDHEU specimens. For the W 24 100% the modified and preservative treated samples showed a large variation in wood moisture content at mass loss below 10%.



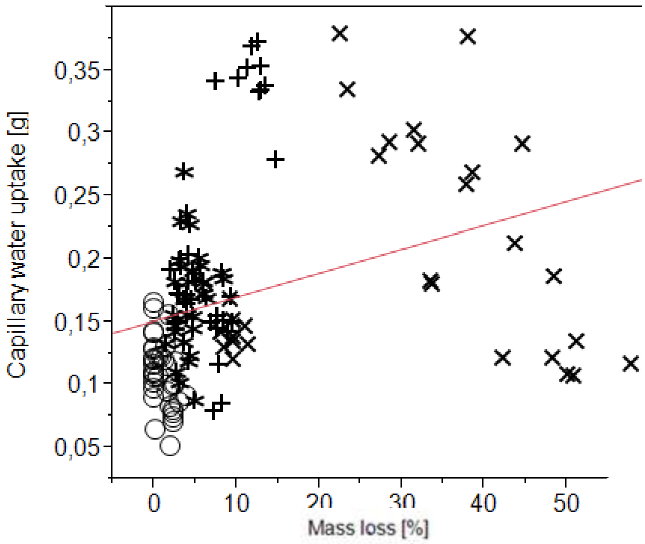
A W 24 0% RH, R^2 = 0.269, p = <0.0001*



B W 24 100% RH, R^2 = 0.005, p = 0.384



C W 24 submersion, R^2 = 0.065, p = 0.022*



D Capillary water uptake, R^2 = 0.110, p = 0.0001

Figure 15: Mass loss (%) vs. W 24 measurements (A, B, C) and capillary water uptake (D). + = softwoods, x = hardwoods, * = wood preservatives, o = modified wood.

3.5 Dynamic modulus of elasticity (MOE$_{dyn}$)

Figure 16 shows the MOE$_{dyn}$ after decay vs. mass loss data in the ENV 807 (CEN 2001). As expected the results show that MOE is a fairly good indicator of mass loss. It also illustrates the large MOE and mass loss in the less durable hardwood species. Previous studies have shown that MOE can be a good indicator of early mass loss (e.g. Machek *et al.* 2001) but this was not the case in this study (Figure 17). The figure includes only data from preservative treated wood and modified wood.

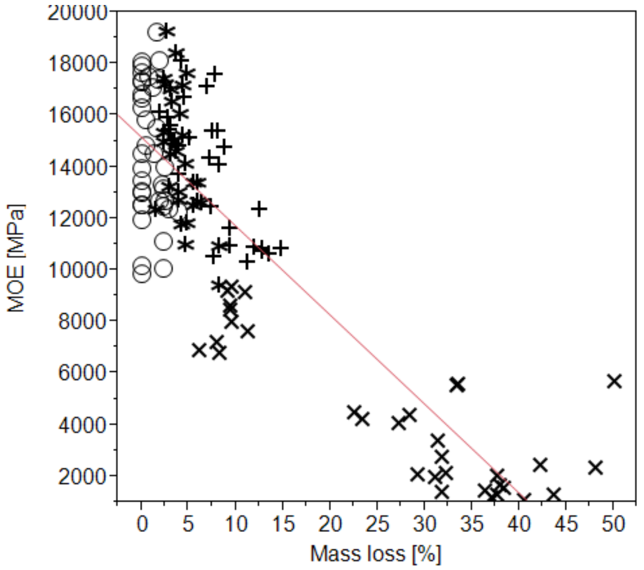


Figure 16: Mass loss vs. MOE$_{dyn}$ at 25°C/80% RH. $R^2 = 0.747$, $p = <0.0001$*.
+ = softwoods, x = hardwoods, * = wood preservatives, o = modified wood.

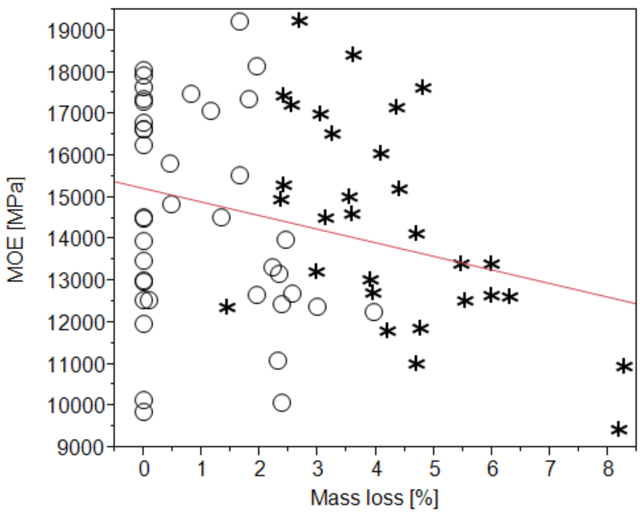


Figure 17: Mass loss vs. MOE$_{dyn}$ at 25°C/80% RH. $R^2 = 0.079$, $p = <0.0001$*.
* wood preservatives, o = modified wood.

3.6 Regression models

The ENV 807 (CEN 2001) mass loss at 25°C/80% RH, W 24 as well as capillary water uptake data, vs. field evaluation data were tested in regression models. Decay rating from the last field evaluation (autumn 2015) was used. Since not all samples had failed in the field tests samples that reached a rating of 4 *prior* to the 2015 rating was given a rating of 5. Wood materials treated with fungicides were not included. The regression modelling was performed in JMP, Version 10 (SAS Institute Inc., Cary, NC, USA). Only parameter estimates that gave significant contribution to the model was included. The best results were achieved in order to predict the HDL data from Bergen (Table 15) with the laboratory data (R^2 = 0.91). However, the root mean square error – RMSE - (the standard deviation of the residual error), was large (0.41). For the HDL in Ås (Table 16) and the EN 252 data from Sørkedalen (Table 17) the RMSEs were even larger. The authors are very well aware of that this is a very crude modelling approach. Hence, more sophisticated models are needed in order to give plausible estimation of service life. One approach is the one presented by Brischke *et al.* (2015).

Table 15: Test statistics and parameter estimates of the model for Bergen HDL.

	Variance components:	
R^2	0.91	
R^2 adj	0.91	
RMSE	0.41	
N	78	
Parameter estimates for the covariates in the model and P-values from effect tests:		
	Parameter estimates	P-values
Mass loss	0.0450	<0.0001*
EMC_{in}	-0.1102	0.0034*
W 24 submersion	0.0319	<0.0001*
W 24 100% RH	-0.1451	0.0026*
Capillary water uptake	9.4203	<0.0001*

Table 16: Test statistics and parameter estimates of the model for Ås HDL.

	Variance components:	
R^2	0.65	
R^2 adj	0.64	
RMSE	0.86	
N	109	
Parameter estimates for the covariates in the model and P-values from effect tests:		
	Parameter estimates	P-values
Mass loss	0.0297	<0.0001*
EMC_{in}	0.2326	<0.0001*
W 24 submersion	0.0282	<0.0001*

Table 17: Test statistics and parameter estimates of the model for Sørkedalen EN 252.

	Variance components:	
R^2	0.54	
R^2 adj	0.53	
RMSE	1.25	
N	110	
Parameter estimates for the covariates in the model and P-values from effect tests:		
	Parameter estimates	P-values
Mass loss	0.0542	<0.0001*
W 24 submersion	0.0392	<0.0001*

3.7 Material ranking and PSL

Table 18 summarises the durability rating for the laboratory tests above. The only material that had the same durability class rating for all tests was acetylated wood (DC1). When only looking at 22°C/70% RH for mini block, EN 113 and ENV 807 25°C/80% RH (i.e. comparable climates) also teak, merbau and Norwegian grown western red cedar had the same classification between the tests (DC1). When excluding the ENV 807 also Scots pine sapwood had similar rating (DC 5).

Table 18: A summary of the durability class ranking according to CEN/TS 15083-1 and 15083-2 for mini block tests after 11 and 20 weeks, EN 113 and ENV 807 in different climates.

	Mini block 11 weeks *P. placenta*									Mini block 20 weeks *P. placenta*									EN 113 20°C/70% RH									ENV 807								
	15083-1			15083-2						15083-1			15083-2						15083-1			15083-2						15083-1			15083-2					
				22/70		16/70		11/70					22/70		16/70		11/70					*C.p.*		*P. p.*		*T.v.*					25/80		25/60		10/85	
	22/70	16/70	11/70	SpS	B	SpS	B	SpS	B	22/70	16/70	11/70	SpS	B	SpS	B	SpS	B	*C.p.*	*P. p.*	*T.v.*	SpS	B	SpS	B	SpS	B	25/80	25/60	10/85	SpS	B	SpS	B	SpS	B
Wood modifications																																				
FA										5	5	4	4	4	4	4	3	4										1	1	1	2	1	3	1	5	2
TM										5	5	3	4	4	4	4	3	3										1	1	1	1	1	1	1	2	1
D										4	4	1	3	3	3	3	1	2										1	1	1	1	1	2	1	4	1
Ac										1	1	1	1	1	1	1	1	1										1	1	1	1	1	1	1	1	1
Hardwoods																																				
Asp	4	4	3	4	5	4	5	4	5	5	5	5	5	5	4	5	4	5	5		5	5	5			5	5	5	5	4	5	5	5	5	5	5
Map	4	4	2	4	5	4	5	3	5										5		5	5	5			5	5									
Ald	4	4	2	4	5	4	5	3	5	5	5	5	5	5	5	5	4	5	5		5	5	5			5	5	5	5	3	5	5	5	5	5	5
Bir	4	4	2	4	5	4	5	3	5										5		5	5	5			5	5									
Row	4	4	2	4	5	4	5	3	5										5		5	5	5			5	5									
Lim	4	4	2	4	5	4	5	3	5										5		5	5	5			5	5									
GW	4	3	1	4	5	3	5	3	5										4		4	4	4			5	5									
B	4	3	1	4	5	3	5	1	5	5	5	5	5	5	5	5	4	5	5		4	5	5			5	5	5	5	3	5	5	5	5	5	5
Ash	4	3	1	4	5	3	5	3	5										1		5	1	1			5	5									
Oak	4	2	1	3	4	2	4	1	5	4	3	1	3	3	3	3	1	2	1		1	1	1			1	1	2	2	1	4	3	5	3	5	3
WE	2	1	1	2	3	1	3	1	3										1		5	1	1			5	5									
Mer	1	1	1	1	1	1	1	1	3										1		1	1	1			1	1									
Tea	1	1	1	1	1	1	1	1	3										1		1	1	1			1	1									
Softwoods																																				
SpS	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5		5	5	3	2	1	5	3	5	3	5	2
NS	5	5	4	5	5	5	5	5	5										4	4	5	4	5	4		5	5									
SS	5	5	4	4	5	5	5	5	5										3	4	4	3	3	4		5	5									
SF	4	4	3	4	5	4	5	4	5										4	4	4	3	4	4		5	5									
SL	4	4	2	4	5	4	5	3	5										1	4	4	1	1	4		4	4									
SpH	4	4	3	4	5	4	5	4	5																											
DF	4	3	2	3	5	3	5	3	5	5	5	3	5	5	5	5	4	5	1	2	1	1	1	3		1	2	1	1	1	3	2	3	2	5	2
EL	3	2	1	3	4	3	4	2	5	5	5	4	4	4	4	4	3	4	1	3	1	1	1	3		1	1	2	2	1	4	3	4	2	5	3
Jun	3	1	1	3	4	1	3	1	1										1	1	1	1	1	1		2	2									
W-A	1	1	1	1	1	1	1	1	5										1	1	1	1	1	1		2	2									
W-N	1	1	1	1	1	1	1	1	4										1	1	1	1	1	1		1	1									
Reference preservatives																																				
Cu										5	5	4	5	5	5	5	4	4										1	1	1	3	2	1	1	4	1
QN										5	5	3	5	5	4	4	3	3										1	1	1	3	2	1	2	5	3
CCA										1	1	1	1	1	1	1	1	1										1	1	1	3	1	1	1	4	2

Based on this dataset the effect of climate tended to affect the most durable materials the least (i.e. less statistical difference between the climates). An obvious explanation is that the lack of differentiation is due to low mass loss. For the other materials it was hard to find a trend except for Scots pine sapwood where the effect of climate and type of test was less obvious than for the other wood species. Whatever the reason is it implies that durability classification of moderately durable materials, and ranking between materials, need to be done with great caution. It also suggests that Scots pine sapwood is a good reference species.

In Table 19 the durability classification from the field trials are listed based on decay rate. Decay rates are obviously higher in soil contact than in the above ground HDL tests. But also between the two HDL tests there are rather large differences. The warmer and wetter climate in Bergen compared to Ås can partly explain the differences in the HDL decay rates.

Table 19: Decay rate comparison between field trials. The shades of grey are based on the rating scale from CEN/TS 15083-2 (CEN 2005) but based on decay rate (i.e. not x value).

Material	Decay rate [rating/year]		
	EN 252 Sørkedalen	HDL Bergen	HDL Ås
Wood modifications			
Thermal	0.80	0.20	0.28
FA40	0.25	0.18	0.10
FA50	0.22	0.18	0.18
Hardwoods			
Birch	1.00	0.36	0.31
Alder	0.80	0.50	0.35
Beech	0.80	0.44	0.57
Lime	0.80	0.35	0.32
Maple	0.57	0.50	0.31
Aspen	0.50	0.35	0.27
Rowan	0.50	0.33	0.27
Goat willow	0.50	0.29	0.23
Ash	0.50	0.18	0.23
Wych elm	0.33	0.21	0.21
Oak	0.18	0.18	0.19
Merbau	0.09	0.09	0.11
Teak	0.09	0.09	0.09
Softwoods			
Sitka spruce	1.33	0.44	0.31
Silver fir	0.80	0.44	0.34
Scots pine sap.	0.80	0.44	0.32
W. red cedar (N)	0.80	0.21	0.25
Norway spruce	0.33	0.34	0.27
Scots pine heart.	0.32	0.26	0.18
W. red cedar (N-Am)	0.31	0.22	0.18
Siberian larch	0.22	0.18	0.18
Juniper	0.22	0.15	0.14
Douglas fir	0.16	0.18	0.20
European larch	0.14	0.18	0.11
Reference preservatives			
Copper HDO	0.12	0.17	0.10
CCA	0.14	0.10	0.09

4. CONCLUSIONS

- Durability classification varies depending on the test fungus, exposure time, climate, and type of decay test. Therefore, the durability classification of a material, and the ranking between materials, is not a fixed value that can be based on one single test.
- The most durable materials together with Scots pine sapwood seemed to be less affected by different climates and type of test than the intermediate semi durable materials.
- More sophisticated models are needed in order to make good predictions of service life of different wood materials based on laboratory tests, if possible at all.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge: 1) Sigrun Kolstad, Kari Hollung and Eva Grodås (NIBIO) for their help in evaluating the field trials, 2) Thomas Bornemann, Sebastian Völling, and Carola Hesse (Leibniz Universität Hannover) for their contribution to the W 24 tests and to the capillary water uptake tests.

6. REFERENCES

Augusta, U (2007): Untersuchung der natürlichen Dauerhaftigkeit wirtschaftlich bedeutender Holzarten bei verschiedener Beanspruchung im Außenbereich. Doctoral thesis, University of Hamburg.

AWPA (2011): U1-11. Use category system: User specification for treated wood. *American Wood Protection Association Standard.*

Bravery, A F (1979): A miniaturised wood-block test for the rapid evaluation of wood preservative fungicides, *Rep. No. 136. Swedish Wood Preservation Institute*, Stockholm, p. 58-65.

Brischke C, Bayerbach R, Rapp A O (2006): Decay-influencing factors: A basis for service life prediction of wood and wood-based products. *Wood Material Science and Engineering*, **1**, 91-107.

Brischke, C, Thelandersson, S (2014): Modelling the outdoor performance of wood products – A review on excisting approaches. *Construction and Building Materials*, **66**, 384-397.

Brischke, C, Meyer, L, Alfredsen, G, Humar, M, Francis, L (2012): Durability of timber products – Part 2: Proposal for an IRGWP - durability data base. *Proceedings IRG Annual Meeting*, IRG/WP 12-20497, 13 pp.

Brischke C, Alfredsen G, Flæte P-O, Humar M, Isaksson, Meyer L (2015): The combined effect of wetting ability and durability on field performance – verification of a new prediction approach. *Proceedings IRG Annual Meeting*, IRG/WP 15-20565, 20 pp.

CEN (1997): *EN 84 - Wood preservatives. Accelerated ageing of treated wood prior to biological testing. Leaching procedure.* European Committee for Standardization (CEN), Brussels, Belgium.

CEN (1996): *EN 113 - Wood preservatives - Method of test for determining the protective effectiveness against wood destroying basidiomycetes - Determination of the toxic values*. European Committee for Standardization (CEN), Brussels, Belgium.

CEN (1997): *EN 1609 - Thermal insulating products for building applications - Determination of short term water absorption by partial immersion*. European Committee for Standardization (CEN), Brussels, Belgium.

CEN (2001): *ENV 807 - Wood preservatives. Determination of the effectiveness against soft rotting micro-fungi and other soil inhabiting micro-organisms.* European Committee for Standardization (CEN), Brussels, Belgium.

CEN (1990): *EN 252 - Wood preservatives. Field test methods for determining the relative protective effectiveness in ground contact.* European Committee for Standardization (CEN), Brussels, Belgium.

CEN/TS 15083-1 (2005): *Durability of wood and wood-based products - Determination of the natural durability of solid wood against wood-destroying fungi, test methods - Part 1: Basidiomycetes.* CEN (European committee for standardization), Brussels.

Flæte, P-O, Alfredsen, G, Evans, F (2006): Natural durability of Norwegian wood species for above ground applications – Project presentation and preliminary results. *Proceedings IRG Annual Meeting*, IRG/WP 06-10594, 14 pp.

Isaksson, T, Thelandersson, S, Jermer, J, Brischke, C (2014): *Beständighet för utomhusträ ovan mark. Guide för utformning och materialval*. Report TVBK-3066, Division of Structural Engineering, Lund University.

ISO 15686-1 (2011): *Building and constructed assets - Service life planning - Part 1: General principles.* International Standardization Organization.

ISO 15686-2 (2012): *Building and constructed assets - Service life planning - Part 2: Service life prediction procedures*. International Standardization Organization.

Machek, L, Militz, H, Sierra-Alvares, R (2001): The use of an acoustic technique to assess wood decay in laboratory soil-bed tests. *Wood Science and Technology,* **34**(1), 467-472.

MacKenzie, C E, Wang C-H, Leicester, R H, Foliente, G C, Nguyen, M N (2007): *Timber service life design guide.* Project report No. PN07.1052. Forest & Wood Products Australia Limited, Victoria.

Stirling R, Alfredsen G, Brischke C, De Windt I, Francis LP, Frühwald Hansson E, Humar M, Jermer J, Klamer M, Kutnik M, Laks PE, Le Bayon I, Metsä-Kortelainen S, Meyer-Veltrup L, Morris PI, Norton J, Singh T, Van Acker J, Van den Bulcke J, Venås TM, Viitanen H, Wong AHH (2016): Global survey on durability variation – on the effect of the reference species. *Proceedings IRG Annual Meeting*, IRG/WP 16-20573, 26 pp.

Thelandersson, S, Isaksson, T, Suttie, E, Frühwald, E, Toratti, T, Grüll, G, Viitanen, H, Jermer, J (2011): *Service life of wood in outdoor above ground applications - Engineering design guideline. Background document.* Report TVBK-3061. Div. of Structural Engineering. Lund University.