The combined effect of wetting ability and durability on outdoor performance of wood – development and verification of a new prediction approach

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Abstract Comprehensive approaches to predict performance of wood products are requested by international standards and the first attempts have been made in the frame of European research projects. However, there is still an imminent need for a methodology to implement the durability and moisture performance of wood in an engineering design method and performance classification system. The aim of this study was therefore to establish an approach to predict service life of wood above ground taking into account the combined effect of wetting ability and durability data.

A comprehensive data set was obtained from laboratory durability tests and still ongoing field trials in Norway, Germany, and Sweden. Supplementary, four different wetting ability tests were performed with the same material. Based on a dose-response concept decay rates for specimens exposed above ground were predicted implementing various indicating factors. A model was developed and optimised taking into account the resistance of wood against soft, white and brown rot as well as relevant types of water uptake and release. Decay rates from above ground field tests at different test sites in Norway were predicted with the model. In a second step the model was validated using data from lab and field tests performed in Germany and Sweden. The model was found to be fairly reliable and it has the advantage to get implemented into existing engineering design guidelines. The approach at hand might furthermore be used for implementing wetting ability data into performance classification as requested by European standardisation bodies.

1. Introduction

The resistance of wood against biological agents depends on the material properties (inherent natural durability, type of wood protection system), exposure conditions, wood deteriorating organisms present, design, and craftsmanship. The most crucial factors are wood moisture content (MC) and temperature combined with the durability of the respective material.

The first comprehensive document developed in Australia was a timber service life design guide which was based on predicting the mean time to reach specified performance states such as depth of decay or 30 % loss of initial strength; in later studies, for example Nguyen et al. (2008) and Leicester et al. (2009), the emphasis was on developing procedures for structural engineering design in accordance with concepts outlined in ISO 13823 (2008). Further approaches to predict performance of wood products have been developed in Europe (Thelandersson et al. 2011, Isaksson et al. 2014). They are basically following the idea of the factor method approach described in ISO 15686-1 (2011), but using different types of dose-response models (Isaksson et al. 2013, Niklewski et al. 2016). For service life planning according to the factor method a reference service life (RSL) is multiplied with a couple of different modifying factors, for instance accounting for material properties, indoor and outdoor environment, or maintenance. Instead of simple multiplication more complex algorithms can be used for each factor. Current rethinking within European standardisation bodies leads to the development of performance related classification systems for timber products and requires delivery of respective performance data (Kutnik et al. 2014). Within this process moisture behaviour of wood and wood-based products will, for the first time, be considered for performance classification.

Various standardised and non-standardised methods for determining the durability and wetting ability of wood have been reported (e. g. Van Acker et al. 2014), but no guidance for utilising them is so far provided by European standards. In the frame of the European research project PerformWOOD an inter-laboratory trial was performed examining different methods to determine the wetting ability of wood (Brischke et al. 2014a). A feasible set of test methods is not yet commonly accepted, but a pre-standard is under consideration (CEN prEN 16818 2015).

In the Nordic countries there is a long tradition for the utilisation of wood, mainly conifers, as construction materials, even though the local wood species generally are not regarded as particularly durable against biological deterioration. A decade ago two Norwegian research projects were initiated with the aim to determine service life data for Norwegian-grown wood species (Flæte et al. 2008, Evans et al. 2011). The comprehensive data sets from these two projects were used for modelling in this study. For a validation of the modelling approach, outcomes of a second research program named ‘WoodBuild’ which started in 2008 were used. The overall objective of this comparative program was to investigate different field and laboratory test methods with respect to relationships between test material, test method, and test site as well as their applicability to relevant wood-based materials.

The aim of the present study was to establish an approach to predict service life of wood exposed above ground taking into account the combined effect of wetting ability and durability. At the same time a tool was sought to provide wetting ability and durability data for a comprehensive engineering design and performance concept.

2. Materials and methods

2.1 Wood material

A first set of materials was used for quantifying the accuracy after developing the model. Therefore, the dataset obtained from various laboratory tests, performed in Norway, Slovenia and Germany and field tests performed in Norway as specified in Online Resource 1 was used. The same batch of raw material was used for all tests (except for the double layer tests in Oslo).

In a second step data from laboratory tests performed in Slovenia, Sweden and Germany and field tests performed in Germany and Sweden were used for a validation of the new model. All materials and tests used for the validation of the model are shown in Online Resource 2.

2.2 W24 – tests (24 h water uptake and release tests)

2.2.1 Specimens

Specimens of 100 (ax.) x 5 x 10 mm³ were used for the different W24 - tests.

2.2.2 Liquid water uptake by submersion

Specimens were oven-dried at 103 °C till constant mass and weighed to the nearest 0.001 g to determine oven-dry mass. Specimens were submerged in a container filled with demineralised water and placed in normal climate. Specimens were separated from each other by thin spacers (cross section 1 x 1 mm²). The specimens were weighed again after 24 h submersion. The water uptake of the specimens was determined and the resulting MC after submersion was calculated as follows (Eq. 1):

$$W24_{submersion} = \frac{(m_{submerged} - m_0)}{m_0} \cdot 100 \tag{1}$$

$W24_{submersion}$ liquid water uptake during 24 h submersion [%]; $m_{submerged}$ mass after 24 h of submersion [g]; m_0 oven-dry mass [g]

2.2.3 Water vapour uptake in water saturated atmosphere

Specimens were oven-dried at 103 °C till constant mass and weighed to the nearest 0.001 g to determine oven-dry mass. The bottom of a miniature climate chamber (plastic container with stainless steel trays and ventilator) was filled with demineralized water. Specimens were exposed using thin spacers (cross section 1 x 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 MC after 24 h was calculated as follows (Eq. 2):

$$W24_{100\,\%\,RH} = \frac{(m_{100\,\%\,RH} - m_0)}{m_0} \cdot 100 \tag{2}$$

$W24_{100\,\%\,RH}$ water vapour uptake during 24 h exposure at 100 % RH [%]; $m_{100\,\%\,RH}$ mass after 24 h of exposure to 100 % RH [g]; m_0 oven-dry mass [g]

2.2.4 Desorption

Specimens were stored in 100 % relative humidity (RH) till constant mass (approx. 2 weeks) and weighed to the nearest 0.001 g to determine mass at fibre saturation. 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 as follows (Eq. 3):.

$$W24_{0\,\%\,RH} = \frac{(m_{FS} - m_{0\,\%\,RH})}{m_{FS}} \cdot 100 \qquad (3)$$

$W24_{0\,\%\,RH}$ water release during 24 h exposure at 0 % RH [%]; $m_{0\,\%\,RH}$ mass after 24 h of exposure to 0 % RH [g]; m_{FS} mass at fibre saturation [g]

2.3 Capillary water uptake tests (CWU)

Short term water absorption was measured according to a modified EN 1609 (1997) procedure using a Krüss Processor Tensiometer K100MK2. Specimens of 100 (ax.) x 5 x 10 mm³ were conditioned at 20 °C/65 % RH till constant mass was achieved. 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 as follows (Eq. 4):

$$CWU = \frac{m_{200\,s} - m_{65\,\%\,RH}}{A} \qquad (4)$$

CWU capillary water uptake during 200 s [g/cm²]; $m_{200\,s}$ mass after 200 s in contact with water [g]; $m_{65\,\%\,RH}$ mass at 20 °C/65 % RH [g]; A cross section of specimens [cm²]

2.4 Durability tests according to EN 113 (1996)

For determining the durability against wood destroying basidiomycetes tests were performed according to EN 113 (1996) using five replicates (50 (ax.) x 25 x 15 mm^3). The softwoods were challenged with the two brown rot fungi *Coniophora puteana* (Schumach.) P. Karst. and *Postia placenta* (Fr.) M.J. Larsen & Lombard and the white rot fungus *Trametes versicolor* (L.) Lloyd. For hardwoods *C. puteana* and *T. versicolor* were used. Mass loss (ML) by fungal decay after incubation was determined as follows (Eq. 5):

$$ML = \frac{m_0 - m_{0,i}}{m_0} \qquad (5)$$

ML = mass loss by fungal decay [%]; $m_{0,\,i}$ = oven dry mass after incubation [g]; m_0 = oven dry mass before incubation [g]

2.5 Mini-block tests against basidiomycetes

Matched samples (5 x 10 x 30 (ax.) mm^3) of all materials (Online Resource 2) were tested against *C. puteana* and *T. versicolor* in a ‘mini-block test’ (MB) (Bravery and Dickinson 1978). The specimens were put in petri dishes filled with malt agar where the test fungi had been cultivated. After steam sterilization the specimens were placed on stainless steel washers. The incubation period was 12 weeks. All specimens were oven-dried before and after incubation at 103 °C for 24 h till constant mass and weighed to the nearest 0.001 g to determine ML. Mass loss (ML) by fungal decay after incubation was determined according to Eq. 5.

2.6 Resistance tests in terrestrial microcosms (TMC)

The resistance against soft-rotting fungi was determined according to CEN/TS 15083-2 (2005). Three sets of matched samples (10 x 5 x 100 (ax.) mm^3) were exposed in terrestrial microcosms (TMC). Therefore, unsterile soil from the test fields in Hannover (Germany) and Borås (Sweden) as well as compost soil was used at 95 % of its water holding capacity, which was determined according to CEN/TS 15083-2 (2005). The specimens were buried to 4/5 of their length and stored at 27 °C and 75% RH for 24 weeks. All specimens were oven-dried before and after incubation at 103 °C for 24 h till constant mass and weighed to the nearest 0.001 g to determine ML according to Eq. 5.

2.7 In-ground durability tests

Ten replicate stakes (25 x 50 x 500 (ax.) mm^3) were prepared from each wood type and exposed in 2003 at the test field in Sørkedalen, Norway, and in 2011 at the test fields in Hannover and Borås in accordance with EN 252 (2015).

2.8 Above ground durability tests

2.8.1 Horizontal double layer tests

Stakes (25 x 50 x 500 (ax.) mm^3) were prepared from each wood species and exposed at Ås (2004), Bergen (2004), Oslo (2002), Hannover (2011) and Borås (2011). The specimens were placed horizontally in double layers according to Rapp and Augusta (2004) with the upper layer displaced laterally by 25 mm to the lower layer (Online Resource 3). Supports were 25 cm above ground and made from aluminium L-profiles.

2.8.2 Sandwich tests

Sandwich tests were carried out according to Zahora (2008). One bottom segment (25 x 100 x 200 (ax.) mm^3) and two top segments (25 x 49 x 200 (ax.) mm^3) were fastened together with stainless steel clamps, and exposed horizontally on supports made from aluminum L-profiles on test rigs 1 m above ground in Hannover (Online Resource 3). Specimens in Borås were exposed 0.3 m above ground. The top layers were rounded on the edges (r = 5 mm). At both sites the tests were exposed in 2011.

2.8.3 Lap-joint tests

In accordance with CEN/TS 12037 (2003) Lap-joint specimens (38 x 85 x 180 (ax.) mm^3) were exposed horizontally on supports made from aluminum L-profiles on test rigs 1 m above ground. The end-grains of the specimens were sealed with a polyurethane sealant. The two segments of one specimen were fastened together with stainless steel clamps (Online Resource 3). At both sites the tests were exposed in 2011.

2.9 Decay assessment

All specimens, in and above ground, were assessed annually with the help of a pick test. Depth and distribution of decay were determined and rated using the five-step scheme according to EN 252 (2015) as follows: 0 = Sound, 1 = Slight attack, 2 = Moderate attack, 3 = Severe attack, 4 = Failure.

To be able to determine the mean lifetime (time to reach decay rating 4 according to EN 252, 2015, i.e. failure) all specimens of a specific material must have failed. This was not the case for all materials. Therefore the decay rate v was calculated as follows (Eq. 6):

$$v_{mean} = \frac{\sum_i^n v_i}{n} = \frac{\sum_i^n \frac{R}{t}}{n} \qquad (6)$$

v_{mean} mean decay rate of specimens (decay expressed in terms of the five-step scheme according to EN 252 (2015) / exposure time [decay rating/year]; v_{i} decay rate of a single specimen [decay rating/year]; R decay rating according to EN 252 (2015); t exposure time [year]; n number of replicate specimens.

2.10 Factor approach to predict field performance of wood

A model approach has been applied according to Brischke et al. (2014b) and Isaksson et al. (2014) in order to predict the field performance of wood based materials. The model describes the climatic exposure on one hand and the resistance of the material on the other hand.

Acceptance for a chosen design and material is expressed as:

$$\text{Exposure} \leq \text{Resistance} \qquad (7)$$

The exposure can be expressed as an exposure dose (D_{Ed}) determined by daily averages of temperature and MC. The material property is expressed as a resistance dose (D_{Rd}). The daily dose is a complex function considering the mean daily moisture content (MC) and the mean daily temperature (T) of the wood in test specimens; methods have been derived for estimating the MC and T values (see Isaksson et al. 2013).

$$D_{Ed} \leq D_{Rd} \qquad (8)$$

D_{Ed} exposure dose [days]; D_{Rd} resistance dose [days].

The exposure dose D_{Ed} depends on an annual dose at a specific geographical location and several factors describing the effect of driving rain, local climate, sheltering, distance from ground, and detailed design. A detailed description of the development of the corresponding exposure model is given by Isaksson et al. (2014) where the dose is a summation of the daily doses for the exposure time considered.

The present study focused on the counter part of the exposure dose, which is the resistance, expressed as resistance dose D_{Rd}. The latter is considered to be the product of a critical dose D_{crit} and two factors taking into account the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}). The approach to do this is given by the following Eq. 9 according to Isaksson et al. (2014):

$$D_{Rd} = D_{crit} \cdot k_{wa} \cdot k_{inh} \tag{9}$$

D_{crit} critical dose corresponding to decay rating 1 according to EN 252 (2015) [days]; k_{wa} factor accounting for the wetting ability of the tested materials [-], relative to the reference Norway spruce; k_{inh} factor accounting for the inherent protective properties of the tested materials against decay [-], relative to the reference Norway spruce.

D_{crit} was evaluated for Scots pine sapwood and Douglas fir heartwood according to Isaksson et al. (2013). It was found that the critical dose corresponding to decay rating 1 according to EN 252 (2015) can be seen as more or less independent from the wood species (Online Resource 4). Instead, differences between species and/or treatments can be accounted for by defining differences in moisture uptake and decay inhibiting properties. For the two wood species the critical dose was found to be around 325 days with favourable conditions for fungal decay (Isaksson et al. 2013). This critical dose can be determined for example by outdoor exposure of double-layer tests (Brischke 2007).

Based on the results from the various moisture tests presented in this paper the wetting ability factor k_{wa} was evaluated. Results from durability tests were used to evaluate the inherent resistance factor k_{inh}. To quantify the accuracy of the chosen approach both factors have been used to calculate the resistance dose D_{Rd} of the various wood materials shown in Online Resource 1 first, which was then correlated with decay rates observed in above ground horizontal double layer field tests at three different Norwegian test sites.

In a second step results from moisture and durability tests as shown in Online Resource 2 were used to validate the model. In both cases Norway spruce (*Picea abies*) was chosen as reference material, having low amount of extractives, low durability, but is frequently used outdoors all over Europe.

3. Results and discussion

3.1 Model development

3.1.1 Wetting ability indicators

In order to reflect different relevant mechanisms responsible for moisture behaviour of wood under real service life situations four different test procedures were applied and the results as well as the factors describing the wetting ability (k_{wa}) are given in Table 1. The results differed between both, wood species and test methods. The widest range of data among all tested wood species was found in CWU tests with a tensiometer, the narrowest range was found in the 24 h desorption tests.

3.1.2 Durability indicators

The results from the different durability tests are given in Table 2. For the Basidiomycete test according to EN 113 (1996) the ML caused by all three test fungi fulfilled the validity criteria required in EN 113 (1996) and were therefore used for further modelling. Negative ML was considered to be equal to zero for further calculations. In order to avoid unrealistically high relative values (factors) a threshold was set for both factors leaving the values in the following range: $0 < k_{wa} \leq 5$ and $0 < k_{inh} \leq 5$ according to the model developed.

For 58 % of the wood species all replicate specimens had failed after eleven years of in-ground exposure in the Sørkedalen test field (Table 2). Hence it was possible to calculate their mean service life. However, in order to obtain data for further modelling with all wood species the decay rate v_{mean} was calculated according to Eq. 6 . The dominating decay type on all wood species was soft rot as earlier reported for the Sørkedalen test field by Edlund (1998) and Edlund and Nilsson (1998).

3.1.3 Durability above ground

The target measures for quantifying the accuracy of the model were the results from horizontal double layer tests performed at three test sites in Norway as summarised in Table 3. As expected, mean lifetime of the specimens could be calculated only for a few of the wood species tested. Therefore, again the mean decay rate was used instead. In general, at all three sites soft rot occurred first; later on white, brown and soft rot were present.

3.2 Modelling above-ground field performance

In Europe durability classification of wood is still exclusively based on test results from in-ground field tests according to EN 252 (2015) and laboratory Basidiomycete tests according to EN 113 (1996) or CEN/TS 15083-1 (2005) (Kutnik et al. 2014). There are only two above ground field test methods standardised, i.e. the Lap-joint method (CEN/TS 12037, 2003) and the L-joint method (EN 330, 1993), but in Europe they are rarely used for durability classification of untreated wood (Meyer et al. 2015).

To improve the predictability of above ground performance of wood the resistance dose (D_{Rd}) was calculated as a product of a critical dose component (D_{crit} = 325 d) and factors describing the wetting ability (k_{wa}) and inherent protective material properties (k_{inh}) according to Eq. 9 as shown in Table 1 to Table 3.

The relationship between D_{Rd} and v_{mean} at the three Norwegian above ground test sites has been established based on different combinations of wetting ability and durability tests for calculating k_{wa} and k_{inh}. It turned out that the relationships obtained differed only marginally between the three test sites (Figure 1). Thus, for further modelling a relative decay rate was calculated with Norway spruce as a reference species (Eq. 10).

$$v_{rel.} = \frac{v_{species\ x}}{v_{reference}} \qquad (10)$$

$v_{rel.}$ relative decay rate [-]; $v_{species\ x}$ decay rate of species x [a^{-1}]; $v_{reference}$ decay rate of reference, here: Norway spruce, [a^{-1}]

To identify the most suitable indicators, different factors and factor combinations (based on results from the wetting ability and durability tests) were used to correlate the relative resistance dose D_{Rd} with the relative mean decay rate (i.e. both measures relative to the reference species Norway spruce). For calculating k_{inh} from laboratory Basidiomycete tests ML was factorized and either used as mean of the three test fungi used (EN 113_{mean}) or as worst case, *i.e.* the maximum relative ML (EN 113_{max}).

The coefficients of determination R^2 for the various combinations are summarised in Table 4.

The best fit ($R^2 = 0.912$; Figure 2) between v_{rel} (Eq. 10) and the relative resistance dose ($D_{Rd, rel}$) (Eq. 11) was achieved by using the mean value of the four k_{wa} factors multiplied with the k_{inh} factors based on soil contact tests and k_{inh} factors based on non-soil contact tests weighted equally (Eq. 12):

$$D_{Rd,\ rel.} = \frac{D_{Rd,\ species\ x}}{D_{Rd,\ reference}} \tag{11}$$

$D_{Rd, rel.}$ relative resistance dose [-]; $D_{Rd, species\ x}$ decay rate of species x [a^{-1}]; $D_{Rd, reference}$ decay rate of reference, here: Norway spruce, [a^{-1}]

$$k_{inh} = \frac{\frac{\sum_{i=1}^{n} k_{inh,\ soil,\ i}}{n} + \frac{\sum_{j=1}^{n} k_{inh,\ non-soil,\ j}}{n}}{2} \tag{12}$$

k_{inh} factor accounting for the inherent protective properties of the material against decay [-]; $k_{inh, soil, i}$ factor accounting for the inherent protective properties of the material against decay in tests with soil contact [-]; $k_{inh, non\text{-}soil, j}$ factor accounting for the inherent protective properties of the material against decay in tests without soil contact [-]; n number of tests.

Predicting decay rates with only one factor showed that k_{inh} had the more pronounced effect in the model. However, considering wetting ability led to higher accuracy of the model and is expected to become even more important for materials with altered moisture performance either through cell wall modification or impregnation through water repellents. Based on the materials included in this study it became not evident that one factor alone could predict the decay rate more precisely than a combination of both factors.

With decreasing durability of wood species (= increasing $v_{rel.}$) the uncertainty of the prediction model clearly increased. When examining the outliers the majority turned out to be wood species showing a relative material resistance less than Norway spruce ($D_{Rd, rel.} < 1$).

The reliability of the model was examined by predicting the decay rate on the basis of $D_{Rd, rel.}$ the relative resistance dose D_{Rd} according to the fitting curve function shown in Figure 2 as follows (Eq. 13):

$$v_{pred.,\ site\ x} = v_{rel.,\ HDL\ (Ås,\ Bergen,\ Oslo)} \cdot v_{reference,\ site\ x} \tag{13}$$

$v_{pred., site\ x}$ predicted decay rate for site x [a^{-1}]; $v_{rel., HDL\ (Ås,\ Bergen,\ Oslo)}$ relative decay rate of horizontal double layer specimens averaged for three Norwegian test sites [-]; $v_{reference, site\ x}$ decay rate of reference, here: Norway spruce, [a^{-1}]

The predicted decay rate was then compared with the determined decay rate at the three Norwegian test sites as shown in Figure 3. For all three sites predicted and determined decay rate were fairly well correlated. Although wood species showing a relative resistance dose less than Norway spruce ($D_{Rd, rel.} < 1$) were already excluded, it became obvious that with increasing decay rate (*i.e.* with decreasing material resistance) the prediction became less accurate.

3.3 Validation of the model

3.3.1 Wetting ability indicators

For validation of the model obtained the same set of tests was applied to the second set of wood materials (*cf.* Online Resource 2). The results as well as the factors describing the wetting ability (k_{wa}) are given in Table 5. Again, the results differed between both, wood species and test methods.

3.3.2 Durability indicators

The results from the different durability tests for the second set of wood materials are given in Table 6. After five years of in-ground exposure in both test fields, Hannover and Borås not all replicate specimens of the wood species tested failed. Therefore, it was not possible to calculate their mean lifetime. To obtain data for further modelling the mean decay rate was calculated according to Eq. 1.

3.3.3 Durability above ground

The target measures for quantifying the accuracy of the model were the results from horizontal double layer tests, sandwich tests and lap-joint tests performed at the two test sites in Germany and Sweden as summarised in Table 7. As expected, after five years of exposure no service life could be calculated for the wood species tested. Therefore, again v_{mean} was used instead (see Eq. 1).

3.4 Predicting above ground field performance

The relationship between resistance dose D_{Rd} and v_{mean} at the two test sites in Germany and Sweden in the horizontal double layer test, sandwich test and lap-joint test is shown in Figure 4. In general, the two measures correlated fairly well for the three test set ups at both sites. However, compared with using the data from the double layer field tests in Norway the model turned out to be less accurate. To some extent this might be explained by the higher decay rate of Norway spruce exposed in Hannover ($v = 1.44\ a^{-1}$) and Borås ($v = 0.80\ a^{-1}$; *cf.* Table 7) compared to the three Norwegian sites ($v = 0.35 – 0.54\ a^{-1}$; *cf.* Table 3).

To finally validate the model the decay rate was predicted on the basis of $D_{Rd,\ rel}$ and $v_{reference,\ site\ x}$. Considering the variety of test materials, test methods and corresponding exposure situations a surprisingly high prediction accuracy was achieved for both test sites (Figure 5), i.e. Hannover ($R^2 = 0.558$) and Borås ($R^2 = 0.613$).

With this approach a transparent model for predicting above ground performance of wood based on wetting ability and inherent durability was provided. For further optimisation one might consider including new factors, e. g. accounting for the formation of cracks, ageing, discolouring fungi, detoxification, and leaching. In addition, exposure related factors need to be considered, e. g. macroclimate, microclimate, and deteriorating organisms present. Furthermore, the critical dose might need to be adopted since it was established on the basis of two soft wood species only (Isaksson *et al.* 2013). Several design guidelines are already considering such exposure related effects in a quantitative manner (MacKenzie et al. 2007, Thelandersson et al. 2011, Isaksson et al. 2014). Finally, the site-specific climate load can also be estimated on the base of dose-response relationships as described by Frühwald Hansson et al. (2012).

4. CONCLUSIONS

In order to strengthen the position of wood as a building material predicting service life needs to be as precise as possible. The approach at hand shows that the required data sets can be obtained with reasonable efforts. To further verify the model more data sets including preservative treated and modified materials are needed and sought. In this respect scientific exchange of durability test data could be supplemented with short-term moisture trials.

The results obtained in this study led to the following conclusions:

- For the first time a model approach based on the combined effect of wetting ability and durability has been applied to long-term field test data to predict field performance of wood.
- The model has been optimised with respect to different modifying factors taking into account the resistance of wood against soft, white and brown rot as well as relevant types of water uptake and release (*i.e.* capillary water uptake from end-grain and side grain, water vapour uptake and release).
- The model has been verified using above ground field test data from different test sites and surprisingly high prediction accuracy was found for three test set ups exposed in Germany and Sweden.
- The model has the advantage to get implemented into engineering design guidelines.
- Further improvements of the approach can include climatic aspects as well as the effect of crack formation and other ageing agents. Results from further wetting ability tests might be included.
- The laboratory wetting ability test results should be verified by long-term moisture recordings from field tests.
- The approach at hand has the potential for implementing wetting ability data into performance classification as requested for the revision of the European standard EN 460 (1994) “Durability of wood and wood-based products - Natural durability of solid wood - Guide to the durability requirements for wood to be used in hazard classes”.

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Table 1 Moisture content after exposure to different moistening regimes, water release during drying, and capillary water uptake. Factors accounting for the wetting ability (k_{wa}) of the various materials tested. (W24 = 24 h water uptake and release tests; CWU = capillary water uptake tests)

Wood species	**W24** $_{\text{submersion}}$		**W24** $_{100\ \%\ \text{RH}}$		**W24** $_{0\ \%\ \text{RH}}$		**CWU**	
	mean [%]	**k_{wa} [-]**	**mean [%]**	**k_{wa} [-]**	**mean [%]**	**k_{wa} [-]**	**mean [g/cm²]**	**k_{wa} [-]**
Hardwoods								
Norway maple	59.0	0.94	15.1	1.18	15.9	0.99	0.26	0.37
Lime	60.1	0.92	12.4	1.43	13.3	0.83	0.25	0.38
Aspen	60.9	0.91	15.7	1.13	17.4	1.09	0.15	0.65
Birch	66.0	0.84	15.3	1.16	17.4	1.09	0.26	0.36
Alder	63.0	0.88	14.4	1.23	19.5	1.22	0.28	0.35
Rowan	61.2	0.90	15.1	1.18	16.3	1.02	0.25	0.39
Goat willow	47.4	1.16	13.1	1.36	13.6	0.85	0.16	0.60
European oak	46.3	1.19	12.4	1.44	13.0	0.82	0.14	0.67
Ash	56.4	0.98	14.3	1.25	16.3	1.02	0.24	0.39
Wych elm	48.6	1.14	13.6	1.31	14.6	0.91	0.20	0.49
Beech	60.1	0.92	15.5	1.15	14.6	0.92	0.31	0.31
Cherry	82.6	0.67	15.8	1.13	17.0	1.06	0.39	0.24
Teak	23.2	2.38	6.10	2.90	14.1	0.88	0.08	1.28
Merbau	26.0	2.12	10.9	1.63	10.2	0.64	0.02	4.62
Softwoods								
Sitka spruce	57.2	0.96	16.7	1.07	16.6	1.04	0.13	0.76
Norway spruce 6 mm	55.2	1.00	17.8	1.00	16.0	1.00	0.10	1.00
Silver fir	56.7	0.97	17.5	1.01	14.6	0.92	0.15	0.66
Scots pine 3 mm	66.5	0.83	16.2	1.10	14.7	0.92	0.08	1.19
Scots pine sap	93.2	0.59	17.2	1.03	16.1	1.01	0.34	0.28
WRC (NA)	49.8	1.11	11.1	1.61	11.6	0.72	0.36	0.27
WRC (NO)	69.4	0.80	15.6	1.14	13.4	0.84	0.32	0.30
Juniper	42.6	1.30	12.4	1.43	12.3	0.77	0.08	1.20
Siberian larch	52.9	1.04	13.7	1.30	14.6	0.91	0.21	0.46
European larch	33.0	1.67	9.7	1.83	15.1	0.94	0.13	0.72
Douglas fir	34.4	1.61	11.3	1.57	13.9	0.87	0.18	0.54

Table 2 Mass loss (ML) of wood samples after 16 weeks incubation according to EN 113 (1996), decay rate v (a^{-1}), and factors accounting for the inherent protective material properties (k_{inh}) of the various materials exposed for eleven years in ground (EN 252) at the Sørkedalen test field, Norway.

	EN 113						**EN 252**	
Wood species	*T. versicolor*		*C. puteana*		*P. placenta*		v_{mean}	k_{inh}
	ML [%]	k_{inh} **[ ]**	**ML [%]**	k_{inh} **[ ]**	**ML [%]**	k_{inh} **[ ]**	**[a^{-1}]**	**[ ]**
Hardwoods								
Norway maple	33.0	1.10	40.3	0.65	-	-	1.20	1.56
Lime	34.9	1.04	46.2	0.57	-	-	1.35	1.39
Aspen	36.9	0.99	42.4	0.62	-	-	1.15	1.62
Birch	39.3	0.93	50.4	0.52	-	-	1.43	1.30
Alder	34.9	1.04	40.6	0.64	-	-	1.68	1.11
Rowan	41.4	0.88	36.8	0.71	-	-	1.04	1.79
Goat willow	31.4	1.16	26.4	0.99	-	-	0.76	2.47
European oak	2.5	5.00	0.0	5.00	-	-	0.20	5.00
Ash	32.5	1.12	2.1	5.00	-	-	0.77	2.43
Wych elm	32.6	1.12	2.5	5.00	-	-	0.80	2.32
Beech	30.0	1.21	32.1	0.81	-	-	1.41	1.32
Cherry	17.3	2.11	11.2	2.32	-	-	-	-
Teak	-3.2	5.00	-4.2	5.00	-	-	0.10	5.00
Merbau	2.8	5.00	0.9	5.00	-	-	0.10	5.00
Softwoods								
Sitka spruce	31.6	1.15	16.0	1.63	26.4	0.95	1.67	1.12
Norway spruce 6 mm	36.4	1.00	26.1	1.00	25.0	1.00	1.87	1.00
Norway spruce 3 mm	38.2	0.95	27.3	0.96	23.2	1.08	1.73	1.08
Norway spruce 1 mm	33.2	1.10	27.8	0.94	25.3	0.99	0.92	2.02
Silver fir	29.9	1.22	15.5	1.67	18.4	1.36	1.19	1.56
Scots pine 3 mm	15.1	2.42	0.5	5.00	21.9	1.14	0.79	2.36
Scots pine 1 mm	13.9	2.62	3.4	5.00	16.8	1.49	-	-
Scots pine sap	33.6	1.08	41.8	0.62	35.5	0.70	1.06	1.76
WRC (NA)	0.8	5.00	0.0	5.00	0.0	5.00	0.95	1.97
WRC (NO)	8.7	4.19	0.0	5.00	0.0	5.00	1.43	1.31
Juniper	2.8	5.00	0.4	5.00	0.4	5.00	0.26	5.00
Siberian larch	23.6	1.55	3.4	5.00	24.7	1.01	0.31	5.00
European larch	3.7	5.00	3.1	5.00	10.5	2.38	0.15	5.00
Douglas fir	3.8	5.00	0.7	5.00	16.8	2.59	0.17	5.00

Table 3 Decay rate v (a^{-1}) and service life (a) of above ground horizontal double layer test specimens exposed at three different test fields in Norway (SD = standard deviation).

Wood species	**Bergen**				**Ås**				**Oslo**			
	v [a^{-1}]		**Service life [a]**		**v [a^{-1}]**		**Service life [a]**		**v [a^{-1}]**		**Service life [a]**	
	mean	**SD**	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**
Hardwoods												
Norway maple	0.58	0.12	7.10	1.20	0.40	0.15	n.a.	n.a.	-	-	-	-
Lime	0.39	0.07	n.a.	n.a.	0.44	0.14	n.a.	n.a.	-	-	-	-
Aspen	0.42	0.07	n.a.	n.a.	0.29	0.03	n.a.	n.a.	0.48	0.05	8.35	0.99
Birch	0.35	0.07	n.a.	n.a.	0.38	0.13	n.a.	n.a.	0.44	0.04	9.15	0.93
Alder	0.70	0.13	5.90	1.20	0.52	0.11	n.a.	n.a.	0.48	0.05	8.35	0.81
Rowan	0.31	0.06	n.a.	n.a.	0.30	0.00	n.a.	n.a.	-	-	-	-
Goat willow	0.33	0.07	n.a.	n.a.	0.25	0.05	n.a.	n.a.	-	-	-	-
European oak	0.20	0.00	n.a.	n.a.	0.19	0.03	n.a.	n.a.	0.17	0.00	n.a.	n.a.
Ash	0.20	0.00	n.a.	n.a.	0.24	0.05	n.a.	n.a.	-	-	-	-
Wych elm	0.23	0.05	n.a.	n.a.	0.20	0.00	n.a.	n.a.	-	-	-	-
Beech	0.64	0.15	6.60	1.51	0.58	0.03	6.90	0.32	-	-	-	-
Cherry	0.30	0.00	n.a.	n.a.	-	-	-	-	-	-	-	-
Teak	0.10	0.00	n.a.	n.a.	0.09	0.03	n.a.	n.a.	-	-	-	-
Merbau	0.10	0.00	n.a.	n.a.	0.12	0.04	n.a.	n.a.	-	-	-	-
Softwoods												
Sitka spruce	0.48	0.03	8.40	0.52	0.35	0.10	n.a.	n.a.	0.28	0.10	n.a.	n.a.
Norway spruce 6 mm	0.44	0.06	n.a.	n.a.	0.54	0.08	7.60	1.26	-	-	-	-
Norway spruce 3 mm	0.43	0.05	n.a.	n.a.	0.57	0.00	7.00	0.00	0.35	0.11	n.a.	n.a.
Norway spruce 1 mm	0.33	0.06	n.a.	n.a.	0.35	0.11	n.a.	n.a.	-	-	-	-
Silver fir	0.50	0.07	8.10	0.99	0.52	0.17	n.a.	n.a.	-	-	-	-
Scots pine 1 mm	0.27	0.05	n.a.	n.a.	0.22	0.04	n.a.	n.a.	0.16	0.02	n.a.	n.a.
Scots pine 3 mm	0.25	0.05	n.a.	n.a.	0.20	0.00	n.a.	n.a.	0.18	0.04	n.a.	n.a.
Scots pine sap	0.35	0.10	n.a.	n.a.	0.41	0.13	n.a.	n.a.	0.48	0.34	8.64	1.00
WRC (NA)	0.21	0.03	n.a.	n.a.	0.18	0.04	n.a.	n.a.	-	-	-	-
WRC (NO)	0.20	0.00	n.a.	n.a.	0.26	0.05	n.a.	n.a.	-	-	-	-
Juniper	0.15	0.07	n.a.	n.a.	0.15	0.05	n.a.	n.a.	-	-	-	-
Siberian larch	0.20	0.00	n.a.	n.a.	0.17	0.05	n.a.	n.a.	0.19	0.01	n.a.	n.a.
European larch	0.20	0.00	n.a.	n.a.	0.12	0.04	n.a.	n.a.	-	-	-	-
Douglas fir	0.20	0.00	n.a.	n.a.	0.15	0.05	n.a.	n.a.	-	-	-	-

Table 4 Coefficient of determination R² for relationship between the relative resistance dose D_{Rd} and the relative mean decay rate of double layer specimens at the Norwegian test sites Oslo, Bergen and Ås. D_{Rd} was calculated on the basis of different combinations of k_{wa} and k_{inh} using data from the wetting ability and durability tests. Reference for calculation of factors was Norway spruce.

		k_{wa}					
		W24$_{submersion}$	**W24 $_{100\%\ RH}$**	**W24 $_{0\%\ RH}$**	**CWU**	**Mean (k_{wa})****	**1*****
k_{inh}	**EN 252**	0.775	0.796	0.642	0.809	0.781	0.750
	EN 113 $_{mean}$	0.830	0.837	0.736	0.753	0.848	0.772
	EN 113 $_{max}$	0.837	0.829	0.672	0.771	0.844	0.735
	Soil/no Soil, 1:1	0.882	0.898	0.851	0.719	0.912	0.879
	Mean (k_{inh})*	0.870	0.884	0.821	0.719	0.848	0.849
	1***	0.486	0.542	0.396	0.213	0.221	-

* Mean of the four different k_{wa} values was used for modelling

** Mean of the four different k_{inh} values was used for modelling

*** Factor set to 1

Table 5 Moisture content after exposure to different moistening regimes, water release during drying, and capillary water uptake. Factors accounting for the wetting ability (k_{wa}) of the various materials tested. (W24 = 24 h water uptake and release tests; CWU = capillary water uptake tests)

Wood species	**$W24_{\text{submersion}}$**		**$W24_{\text{100 \% RH}}$**		**$W24_{\text{0 \% RH}}$**		**CWU**	
	mean [%]	**k_{wa} [ ]**	**mean [%]**	**k_{wa} [ ]**	**mean [%]**	**k_{wa} [ ]**	**mean [g/cm^2]**	**k_{wa} [ ]**
Hardwoods								
Beech	55.22	0.95	17.99	1.20	21.29	0.93	0.06	3.78
English oak	40.60	1.30	18.23	1.19	8.80	2.26	0.27	0.77
Black locust	22.63	2.33	10.25	2.11	12.42	1.60	0.16	1.29
Ash	55.66	0.95	19.70	1.10	20.55	0.97	0.19	1.09
Maple	60.03	0.88	18.70	1.16	15.83	1.26	0.22	0.95
Softwoods								
Scots pine sap	60.79	0.87	21.43	1.01	21.26	0.94	0.20	1.04
Scots pine I	38.20	1.38	14.94	1.45	13.14	1.51	0.22	0.94
Scots pine II	58.47	0.90	22.31	0.97	16.05	1.24	0.11	2.00
Norway spruce	52.65	1.00	21.62	1.00	19.88	1.00	0.21	1.00
Douglas fir	34.82	1.51	18.63	1.16	16.40	1.21	0.22	0.94
Douglas fir sap	45.21	1.16	20.88	1.04	20.80	0.96	0.29	0.73
SYP	59.41	0.89	21.46	1.01	13.75	1.45	0.36	0.58
Radiata pine sap	64.85	0.81	21.78	0.99	13.81	1.44	0.18	1.21
Larch	36.98	1.42	15.77	1.37	17.72	1.12	0.23	0.91
Modified materials								
OHT Ash	26.51	1.99	7.44	2.91	11.91	1.67	0.13	1.60
OHT Spruce	30.43	1.73	9.18	2.35	10.21	1.95	0.24	0.88
TM Scots pine	44.68	1.18	9.09	2.38	7.90	2.52	0.15	1.39

Table 6 Mass loss of wood samples after 12 weeks incubation in a mini-block test, and 24 weeks in a terrestrial microcosm test (TMC), decay rate v [a^{-1}] of EN 252 test specimens exposed for five years in ground at the test fields in Hannover and Borås, and factors accounting for inherent protective material properties (k_{inh}).

	Mini-block tests				**TMC**						**EN 252**			
Wood species	***T. versicolor***		***C. puteana***		**Hannover**		**Borås**		**Compost**		**Hannover**		**Borås**	
	mean [%]	**k_{inh} [ ]**	**mean [%]**	**k_{inh} [ ]**	**mean [%]**	**k_{inh} [ ]**	**mean [%]**	**k_{inh} [ ]**	**mean [%]**	**k_{inh} [ ]**	**v [a^{-1}]**	**k_{inh} [ ]**	**v [a^{-1}]**	**k_{inh} [ ]**
Hardwoods														
Beech	20.60	0.52	20.60	2.53	22.58	0.56	17.21	0.18	54.71	0.55	4.66	0.64	2.07	0.82
English oak	24.01	0.45	0.00	5.00	26.48	0.48	12.98	0.24	47.08	0.63	1.16	2.57	-	-
Black locust	0.02	5.00	0.00	5.00	11.02	1.16	3.97	0.78	18.11	1.65	0.44	5.00	0.26	5.00
Ash	27.49	0.39	4.69	5.00	24.14	0.53	17.36	0.18	47.94	0.62	3.60	0.83	-	-
Maple	27.00	0.40	9.85	5.00	-	-	-	-	-	-	-	-	-	-
Softwoods														
Scots pine sap	11.37	0.94	25.84	2.01	13.69	0.93	2.28	1.36	44.54	0.67	2.65	1.13	1.62	1.04
Scots pine I	0.24	5.00	41.14	1.27	13.58	0.94	4.85	0.64	24.54	1.22	1.13	2.64	1.37	1.24
Scots pine II	0.00	5.00	38.71	1.34	-	-	-	-	-	-	2.19	1.36	1.22	1.39
Norway spruce	10.71	1.00	52.06	1.00	12.74	1.00	3.11	1.00	29.90	1.00	2.99	1.00	1.69	1.00
Douglas fir	0.00	5.00	0.00	5.00	8.67	1.47	1.41	2.20	13.48	2.22	0.89	3.35	-	-
Douglas fir sap	0.98	5.00	19.85	2.62	11.18	1.14	4.27	0.73	22.50	1.33	1.69	1.77	-	-
SYP	0.98	5.00	21.87	2.38	15.13	0.84	4.93	0.63	34.45	0.87	3.48	0.86	1.49	1.14
Radiata pine	12.06	0.89	26.75	1.95	7.85	1.62	2.03	1.53	34.83	0.86	3.51	0.85	1.82	0.93
Larch	0.00	5.00	0.00	5.00	-	-	-	-	-	-	-	-	0.81	2.10
Modified materials														
OHT Spruce	1.10	5.00	0.00	5.00	0.00	5.00	0.00	5.00	6.71	4.46	0.50	5.00	-	-
OHT Ash	0.03	5.00	0.00	5.00	1.12	5.00	0.00	5.00	2.37	5.00	0.77	3.87	-	-
TM Scots pine	0.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00	4.23	5.00	0.62	4.82	0.77	2.19

Table 7 Decay rate v $[a^{-1}]$ of horizontal double layer, sandwich and lap-joint test specimens exposed at the test fields Hannover (H) and Borås (B).

Wood species	**Double layer**		**Sandwich**		**Lap-joint**	
	v $[a^{-1}]$		**v** $[a^{-1}]$		**v** $[a^{-1}]$	
	H	**B**	**H**	**B**	**H**	**B**
Hardwoods						
Beech	0.76	-	1.40	0.80	1.47	1.13
English oak	0.24	-	0.18	-	0.48	-
Black locust	-	0.14	-	0.16	0.04	0.00
Ash	0.36	-	0.54	-	0.56	-
Maple	-	-	-	0.68	-	0.76
Softwoods						
Scots pine sap	0.33	0.52	0.73	0.40	0.84	0.30
Scots pine I	0.33	0.24	0.60	0.42	0.30	-
Scots pine II	-	0.26	0.08	0.26	-	0.14
Norway spruce	1.44	0.80	1.27	0.78	0.80	0.91
Douglas fir	-	-	-	-	0.08	-
Douglas fir sap	0.18	-	-	-	0.90	-
SYP	0.96	0.50	0.71	0.52	-	0.26
Radiata pine	0.59	0.62	1.30	0.70	1.48	0.70
Larch	0.09	0.22	-	0.24	-	0.18
Modified materials						
OHT Spruce	0.07	-	0.18	-	0.00	-
OHT Ash	0.24	-	-	-	0.00	-
TM Scots pine	0.29	0.00	0.04	0.06	0.16	0.00

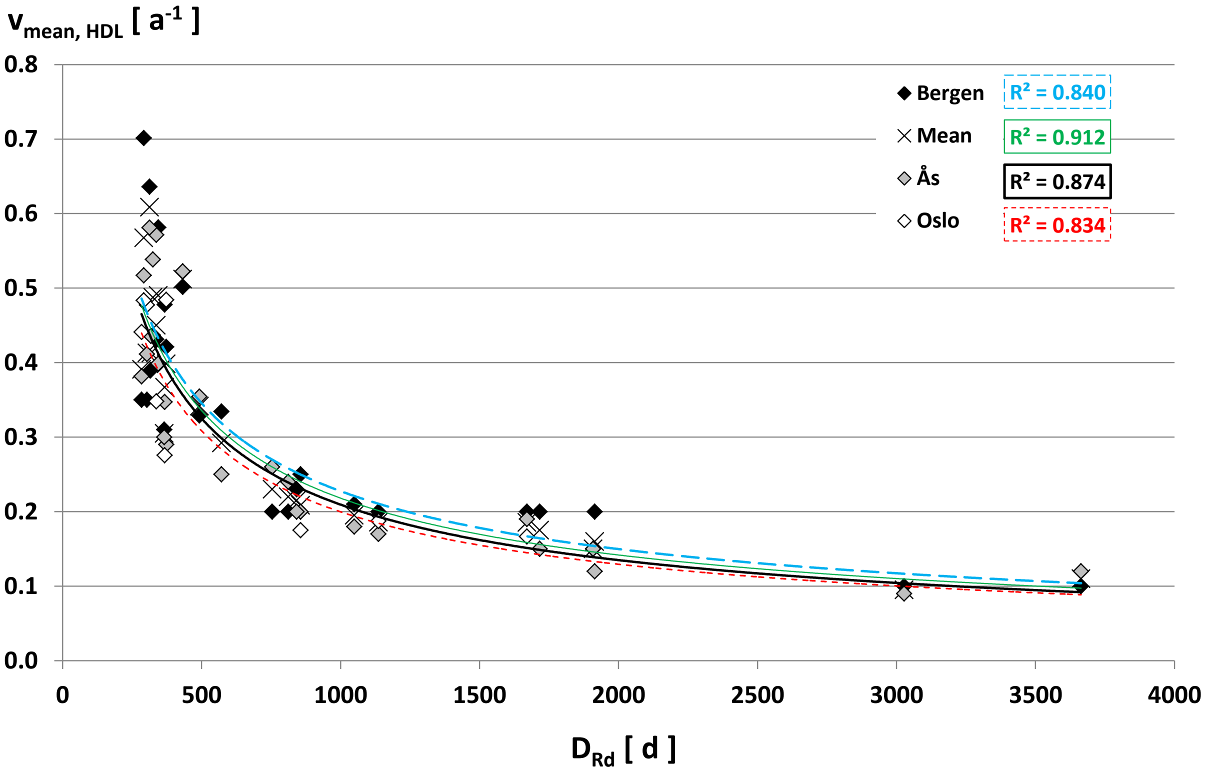

Figure 1: Relationship between calculated D_{Rd} and mean decay rate of horizontal double layer ($v_{mean, HDL}$) specimens exposed at three Norwegian test sites. In addition, the average mean value for all three test sites is given (k_{inh} factors based on soil contact tests and k_{inh} factors based on non-soil contact tests weighted equally; k_{wa} factors of all wetting ability tests weighted equally).

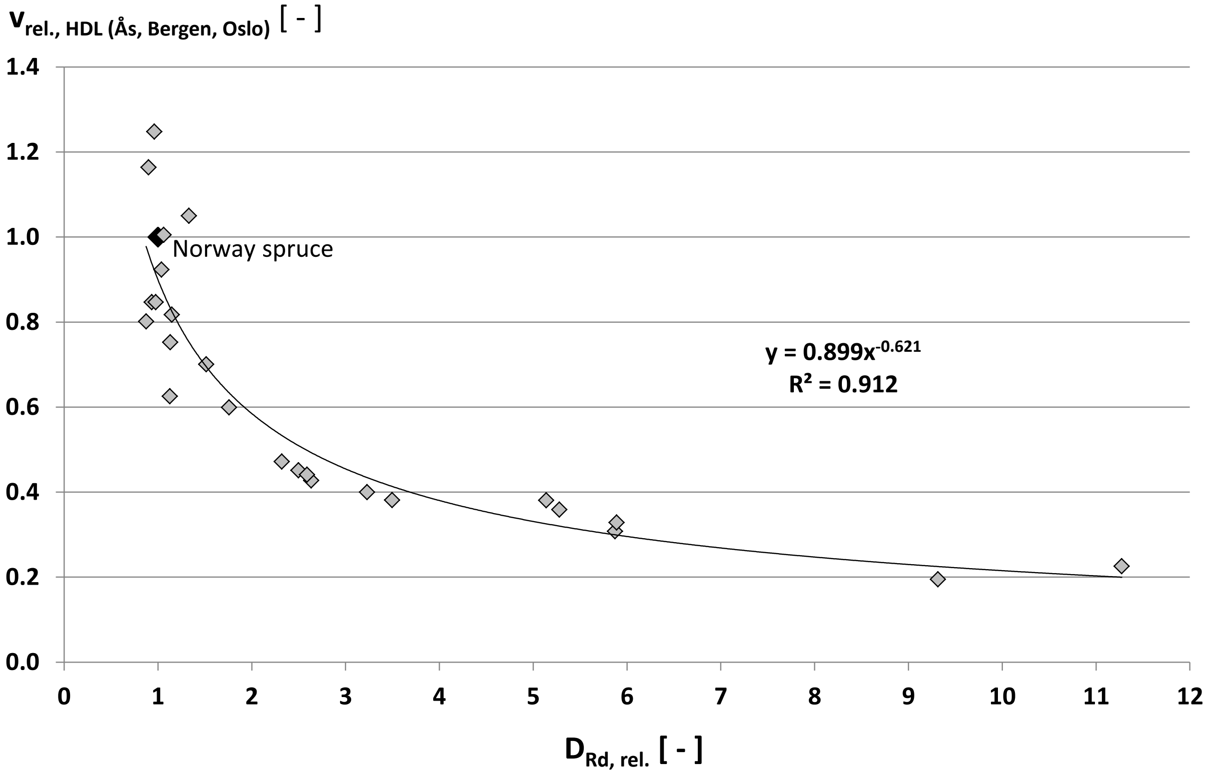

Figure 2: Relationship between mean relative decay rate of horizontal double layer specimens averaged for three Norwegian test sites ($v_{rel., HDL (Ås, Bergen, Oslo)}$) and relative calculated resistance dose $D_{Rd, rel.}$. Reference species Norway spruce is marked.

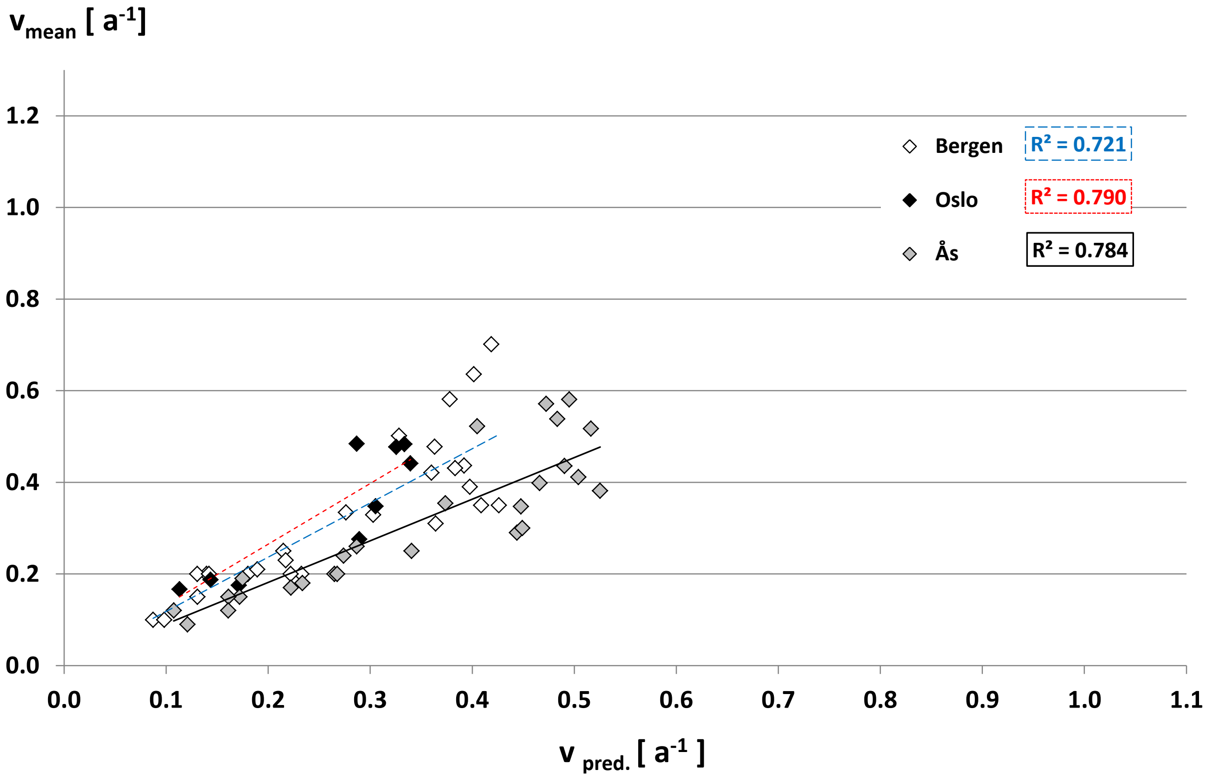

Figure 3: Relationship between decay rates predicted on the basis of the relative material resistance D_{Rd} ($v_{pred.}$) according to the function shown in Figure 2 and the determined decay rate of horizontal double layer specimens for three Norwegian test sites (v_{mean}).

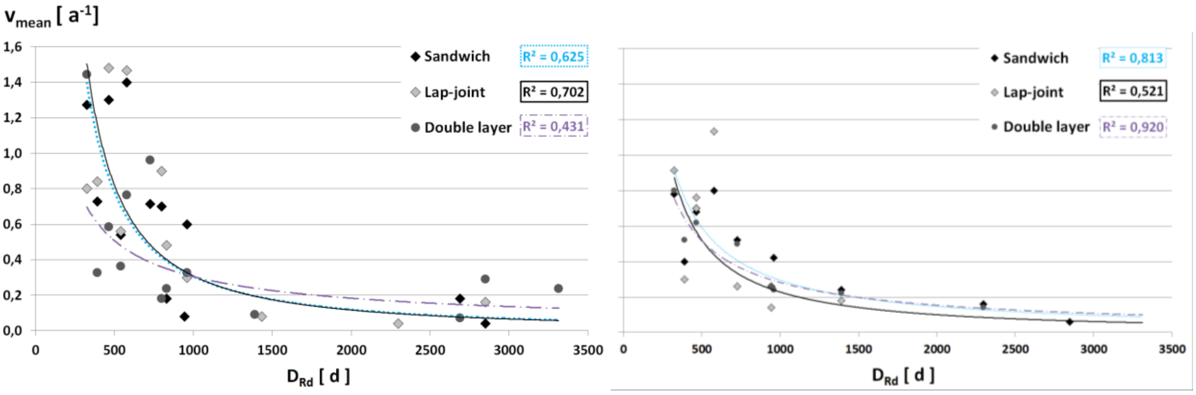

Figure 4: Relationship between v_{mean} of sandwich, lap-joint and horizontal double layer specimens exposed at Hannover, Germany (left) and Borås, Sweden (right), and calculated resistance dose D_{Rd}.

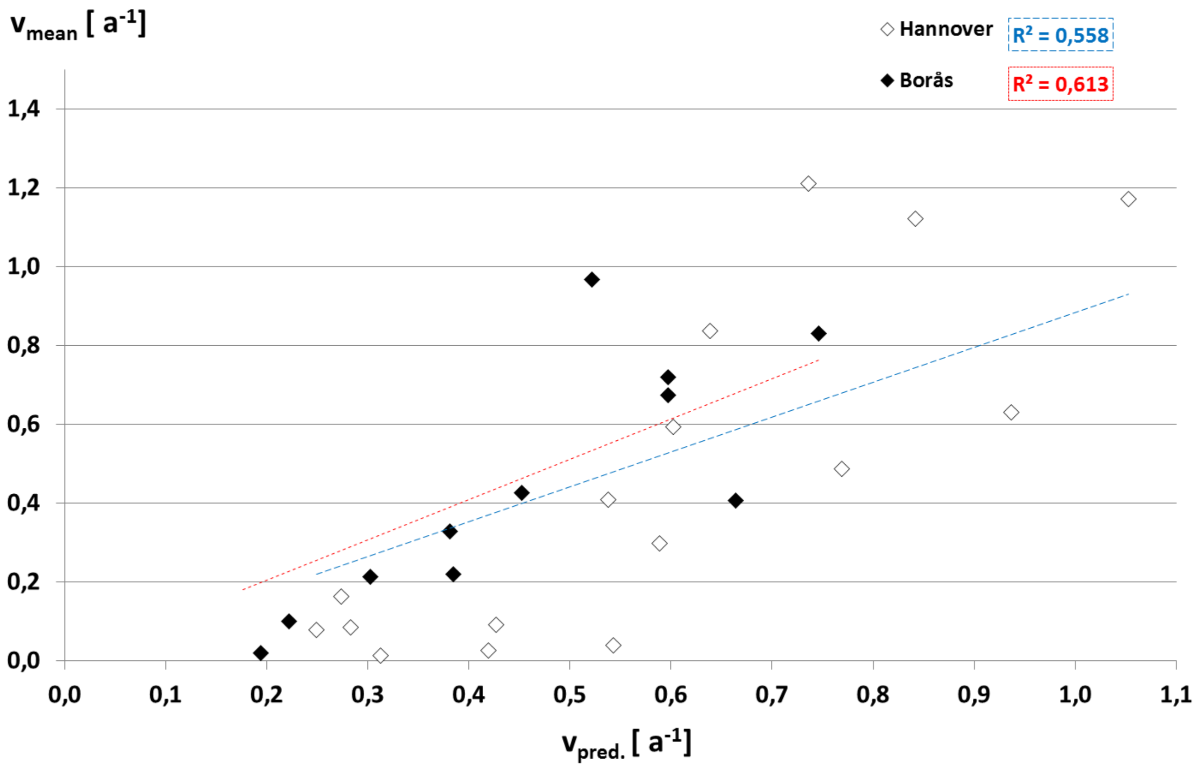

Figure 5: Relationship between decay rates predicted on the basis of the relative material resistance D_{Rd} ($v_{pred.}$) according to the function shown in Figure 2 and the determined decay rate v_{mean} of horizontal double layer, sandwich and lap-joint specimens for the Hannover and Borås test sites.

Online Resource 1

Wood species and number of replicate specimens used for field tests in Norway and different laboratory tests. (W24 = 24 h water uptake and release tests; CWU = capillary water uptake tests)

Wood species**	Botanical name	W24*	CWU	EN 113	EN 252	Double layer		
						Oslo	**Ås**	**Bergen**
Hardwoods								
Norway maple	*Acer platanoides* L.	10	10	2 x 5	10	-	10	10
Lime	*Tilia cordata* Mill.	10	10	2 x 5	10	-	10	10
Aspen	*Populus tremula* L.	10	10	2 x 5	10	20	10	10
Silver birch / Downy birch	*Betula pendula* Roth / *B.pubescens* Ehrh.	10	10	2 x 5	10	20	10	10
Alder / Grey alder	*Alnus glutinosa* (L.) Gaertn.	10	10	2 x 5	10	20	10	10
Rowan	*Sorbus aucuparia* L.	10	10	2 x 5	10	-	10	10
Goat willow	*Salix caprea* L.	10	10	2 x 5	10	-	10	10
European oak	*Quercus* spp.	10	10	2 x 5	10	20	10	10
European ash	*Fraxinus excelsior* L.	10	10	2 x 5	10	-	10	10
Wych elm	*Ulmus glabra* Huds.	10	10	2 x 5	10	-	10	10
Beech	*Fagus sylvatica* L.	10	10	2 x 5	10	-	10	10
Cherry	*Prunus* spp.	10	10	2 x 5	-	-	-	10
Teak	*Tectona grandis* L.F.	10	10	2 x 5	10	-	10	10
Merbau	*Intsia bijuga* Thouars	10	10	2 x 5	10	-	10	10
Softwoods								
Sitka spruce	*Picea sitchensis* (Bong.) Carrière	10	10	3 x 5	10	20	10	10
Norway spruce 6 mm rings***	*Picea abies* Karst.	10	10	3 x 5	10	-	10	10
Norway spruce 3 mm rings****	*Picea abies* Karst.	-	-	3 x 5	10	23	10	10
Norway spruce 1 mm rings	*Picea abies* Karst.	-	-	3 x 5	10	-	10	10
Silver fir	*Abies alba* Mill.	10	10	3 x 5	10	-	10	10
Scots pine 3 mm rings	*Pinus sylvestris* L.	10	10	3 x 5	10	20	10	10
Scots pine 1 mm rings	*Pinus sylvestris* L.	10	10	3 x 5	10	20	10	10
Scots pine sap	*Pinus sylvestris* L.	10	10	3 x 8	10	22	10	10
Western red cedar WRC (N-America NA)	*Thuja plicata* Donn ex D.Don	10	10	3 x 5	10	-	10	10
Western red cedar WRC (Norway NO)	*Thuja plicata* Donn ex D.Don	10	10	3 x 5	10	-	10	10
Juniper	*Juniperus communis* L.	10	10	3 x 5	10	-	10	10
Siberian larch (Russia)	*Larix sibirica* Ledeb.	10	10	3 x 5	10	18	10	10
European larch (Norway)	*Larix decidua* Mill.	10	10	3 x 5	10	-	10	10
Douglas fir (N-America)	*Pseudotsuga menziesii* Franco	10	10	3 x 5	10	-	10	10

[*] *W24 =Liquid water uptake by submersion / water vapour uptake in water saturated atmosphere / desorption*

[**] *If not indicated, heartwood was used*

[***] *Used as reference species in Ås and Bergen*

[****] *Used as reference species in Oslo*

Online Resource 2

Wood species and number of replicate specimens used for different tests in Hannover (H), Germany, and Borås (B), Sweden. (W24 = 24 h water uptake and release tests; CWU = capillary water uptake tests; TMC = terrestrial microcosms; MB = mini block; OHT = Oil heat treated timber; TM = Thermal modification)

Wood species	Botanical name	W24*	CWU	TMC	MB	EN 252		Double layer		Sandwich		Lap-joint	
						H	B	H	B	H	B	H	B
Hardwoods													
Beech	*Fagus sylvatica* L.	7/8/10	10	8	12	10	-	11	-	10	10	10	10
English oak	*Quercus robur* L.	7/8/10	10	8	12	10	-	11	-	10	-	10	-
Black locust	*Robinia pseudoacacia* L.	7/8/10	10	8	12	10	10	11	10	10	10	10	10
Ash	*Fraxinus excelsior* L.	7/8/10	10	8	12	10	-	11	-	10	-	10	-
Maple	*Acer* spp.	7/8/9	9	8	12	-	-	-	-	-	10	-	10
Softwoods													
Scots pine	*Pinus sylvestris* L.	7/8/10	10	8	12	10	10	11	11	10	10	-	-
Scots pine sap	*Pinus sylvestris* L.	7/8/10	10	8	12	10	10	11	11	10	10	10	10
Norway spruce	*Picea abies* Karst.	7/8/10	10	8	12	10	10	11	10	10	10	10	10
Douglas fir	*Pseudotsuga menziesii* Franco	7/8/10	10	8	12	10	-	11	-	10	-	10	-
Douglas fir sap	*Pseudotsuga menziesii* Franco	7/8/10	10	8	12	10	-	11	-	10	-	10	-
SYP	*Pinus* spp.	7/8/9	9	8	12	10	10	11	10	10	10	-	10
Radiata pine	*Pinus radiata* D. Don.	7/8/10	10	8	12	10	10	11	10	10	10	10	10
Scots pine II	*Pinus sylvestris* L.	7/8/10	10	8	12	10	10	11	10	10	10	-	10
European larch	*Larix decidua* L.	7/8/10	10	8	12	-	10	11	10	-	10	-	10
European larch sap	*Larix decidua* L.	3/3/6	10	8	12	-	-	11	-	-	-	-	-
Modified materials													
OHT Norway spruce	*Picea abies* Karst.	7/8/10	10	8	12	10	10	11	-	10	-	10	-
OHT European ash	*Fraxinus excelsior* L.	7/8/10	10	8	12	10	-	11	-	10	-	10	-
TM Scots pine	*Pinus sylvestris* L.	7/8/4	4	8	12	10	10	11	10	10	10	10	10

* Liquid water uptake by submersion / water vapour uptake in water saturated atmosphere / desorption

Online Resource 3

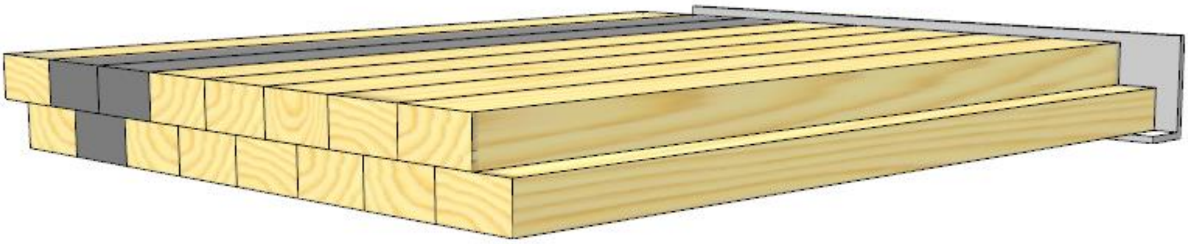

Figure 1: Horizontal double layer test

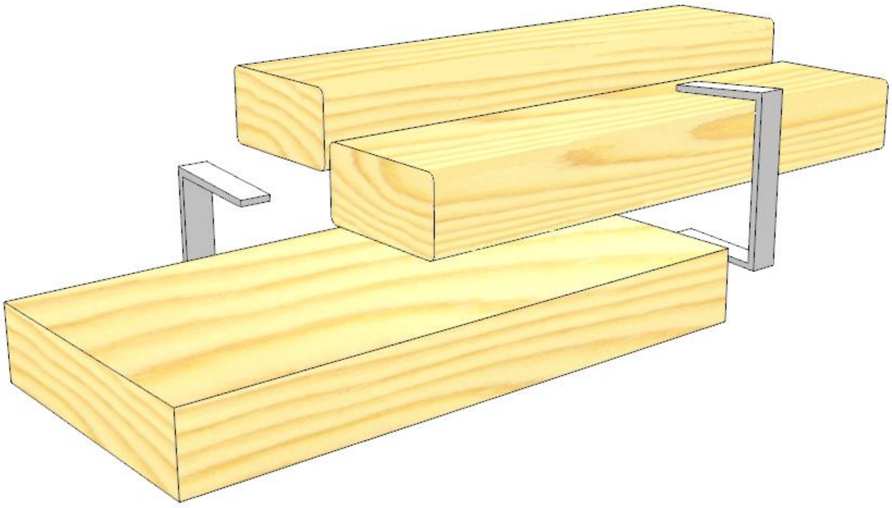

Figure 2: Sandwich test, lap-joint test

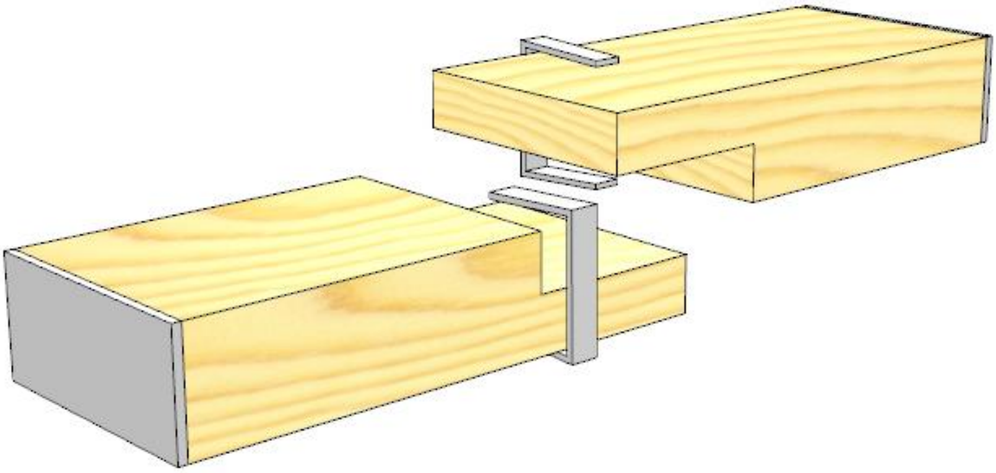

Figure 3: Lap-joint test